UNIVERSITY OF CALIFORNIA,
IRVINE

Telescope: Earth

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Physics

by

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Dissertation Committee:
Professor Daniel O. Whiteson, Chair
Professor Steven W. Barwick
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2020

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DEDICATION

Mary, Ken, Scott and Rusty – my strength and shelter,

and Lizzy – my enduring sputnik and favorite lab partner

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Although this dissertation showcases my work by necessity, CRAYFIS has always been a team effort. As such, my contributions were not only made possible, but bettered by my immediate team members, Professor Michael Mulhearn, Dr. Chase O. Shimmin, Jeffrey Swaney, Maxim Borisyak, and Dr. Andrew Nelson.

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Lastly, I acknowledge many insightful (yet often one-sided) discussions with Debbie, Boone and their 15 hachlings—my roommates and household pest emergency response team.

VITA

RESEARCH

ASTROPARTICLE PHYSICS | CRAYFIS Global Array
2017 – 2020 | Irvine, CA

- Cosmic RAYs Found In Smartphones (https://crayfis.io) is software developed to turn cameras on mobile devices into particle detectors
- Worked with PhD-advisor Prof Daniel Whiteson of UC Irvine to develop a distributed data acquisition and analysis platform for our planet-sized cosmic ray telescope
- First-author of two (soon to be published) papers
- Awarded NSF fellowship for machine learning in the physical sciences
- Data Science/Machine Learning, Distributed Computing, Monte-Carlo Methods, Databases, Android/iOS App Development, Technical Writing

ASTROPARTICLE PHYSICS | Fermi Space Telescope
2012 – 2014 | Irvine, CA & SLAC National Accelerator Laboratory

- Worked with Prof Simona Murgia of UC Irvine to indirectly-detect dark matter in the Andromeda galaxy via characteristic self-annihilation gamma-rays
- Computed energy spectra for hypothetical halo profiles and annihilation decay channels; convolved computations with the point-spread function, effective area efficiency, and energy dispersion models to perform maximum-likelihood analyses
- First to detect a 3σ anomaly at 130 GeV in solar data
- Awarded attendance of the Fermi-LAT summer school
- Source Analysis, Point-Spread Function Characterization, Data Science/Statistics, Technical Writing

PARTICLE PHYSICS | LHC-ATLAS experiment
2010 – 2012 | Irvine, CA & CERN, Geneva, Switzerland

- Worked with PhD-advisor Prof Daniel Whiteson's group searching for exotic bosons and dark matter production
- Data Science/Statistics, High-Performance Computing

ASTRONOMY / COSMOLOGY | Hubble Space Telescope
2006 – 2009 | SLO, CA & Lawrence Berkeley National Laboratory

- Worked with Nobel Laureate George F. Smoot III of UC Berkeley and Prof Jodi Christiansen of CalPoly to detect cosmic string gravitational-lensing
- Second-author on two papers published in Phys. Rev. D.
- Developed analysis image processing and Monte-Carlo code
- Awarded NSF Summer Undergraduate Laboratory Internship at LBNL
- Numerical Methods, Computational Physics, Image Processing

CHEMISTRY AND ENGINEERING | Fuel Cells
Summers 2003, 2004 and 2010 | Pacific Northwest National Laboratory

- Worked with senior staff scientist Dr. Pete Rieke to discover and optimize materials for fuel cell applications
- Performed assays with volatile and hazardous compounds to synthesize materials
- Developed a precision electrochemical titration apparatus to study changes in oxidation states of synthesized materials
- Designed and built the hardware and software for a 3D conductive-ink printer for making complex fuel cell electrode contacts
- Laboratory Practice, Mixed-Signal Design, Software Development

EXPERIENCE

EXECUTIVE MANAGER | 1 Shirt Inc 2014 – 2016 | Sun Valley, CA

- Responsible for the construction, staffing and day-to-day operation of an internet startup apparel and merchandising company for leading YouTube new media celebrities with over a million dollars in gross sales in the first year
- Designed, purchased, assembled and maintained compressed air, heat-presses and Direct-To-Garment printing machinery
- Oversaw all aspects of production and shipping including fulfillment by Amazon
- Hired and managed a team of 12 full-time employees
- Organizational Management, Accounting, Human Resources, Customer Service, Logistics, Data Science, Light Construction

WRITING TUTOR | Graduate Resource Center, UC Irvine 2013 – 2014 | Irvine, CA

- Edited doctoral theses, publications, grant applications and other technical documents in the sciences
- Directed 5, 1-hour workshops to doctoral candidates on good writing and presentation skills
- Hosted colloquium speakers
- Technical Writing, Teaching, Communication Skills

TEACHING ASSISTANT | UC Irvine 2010 – 2017 | Irvine, CA

- Undergraduate astronomy, classical mechanics, electromagnetism, thermodynamics, waves and optics
- Science communication for doctoral candidates, run by syndicated radio personality Sandra Tsing Loh
- 12 courses with 1-hour discussions
- 8 courses with 3-hour laboratories
- Exemplary student evaluations
- Teaching, Communication Skills

PUBLICATIONS

2020 E. Albin, D. Whiteson, "Feasibility of Global Dual Shower Detection with a Distributed Cosmic Ray Network," in preparation. role: primary author and investigator

2020 E. Albin, D. Whiteson, "Calibrating a Globally-Distributed UHECR Detection Network of Smartphones," in preparation. role: primary author and investigator

2014 M. Adbullah, E. Albin *et al.*, "Systematically Searching for New Resonances at the Energy Frontier using Topological Models," arXiv:1401.1462 [hep-ph]. role: background model

2013 T. Aaltonen *et al.* [CDF Collaboration], "Search for pair-production of strongly-interacting particles decaying to pairs of jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," Submitted to: Phys.Rev.Lett. [arXiv:1303.2699 [hep-ex]]. role: background model

2013 (E. Albin), D. Whiteson, "Searching for Spurious Solar and Sky Lines in the Fermi-LAT Spectrum," arXiv:1302.0427 [astro-ph.HE]. role: primary investigator; however, collaboration publication rules prohibit my explicit authorship—reference acknowledgement

2012 D. Whiteson, (E. Albin), "Disentangling Instrumental Features of the 130 GeV Fermi Line," JCAP **1211**, 008 (2012) [arXiv:1208.3677 [astro-ph.HE]]. role: significant data analysis; however, collaboration publication rules prohibit my explicit authorship—reference acknowledgement

2011 E. Albin, S. Borrini, et al. [ATLAS Collaboration], "Search for resonant WW, WZ, ZZ production using the ATLAS detector in llqq final states." ATL-COM-PHYS-2011-1035. Geneva:CERN. role: data analysis

2011 D. Whiteson, A. Nelson, E. Albin, et al. [ATLAS Collaboration], "Search for New Physics in Events with Four Charged Leptons." ATL-COM-PHYS-2011-960.- Geneva:CERN. role: data analysis

2011 J. L. Christiansen, E. Albin, G.F. Smoot *et al.*, "Search for Cosmic Strings in the COSMOS Survey," Phys. Rev. D **83**, 122004 (2010) [arXiv:0803.0027 [astro-ph]]. role: data analysis, writing

2008 J. L. Christiansen, E. Albin, G.F. Smoot *et al.*, "Search for Cosmic Strings in the GOODS Survey," Phys. Rev. D **77**, 123509 (2008) [arXiv:0803.0027 [astro-ph]]. role: data analysis, writing

ABSTRACT OF THE DISSERTATION

Telescope: Earth

By

Eric Kenneth Albin

Doctor of Philosophy in Physics

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Professor Daniel O. Whiteson, Chair

Until the construction of the aptly-named cosmotron in the early 1950s, particle physicists relied on cosmic ray tracks in photographic emulsions and cloud chambers to discover antimatter and subatomic particles. Nearly 110 years since their discovery, the origin and composition of the highest energy cosmic rays remains largely a complete mystery.

In that time, solid-state pixel technology has become a mainstay in both particle detectors and consumer smartphone cameras, but for largely economic reasons, modern cosmic ray surface detectors are primarily water-Cherenkov or plastic-scintillator type. However, with both the worldwide number of smartphone users exceeding 3 billion and at least as many laptop computers in use, consumer solid-state pixel sensors (cameras) have a combined surface area over 5 times the cross-sectional area of the Pierre Auger Observatory's 1,660 water-Cherenkov detectors.

In this dissertation, I discuss the potential, the process and the problems faced in turning the populated planet into a cosmic ray telescope using smartphone cameras. In Chapter 2, I develop novel extensive air shower longitudinal muon and photon density models that clearly exhibit better agreement with CORSIKA simulations than popular alternatives. I also provide a parameterization scheme that spans variations in primary energy, inclination angle, and observation height. In Chapter 4, I identify muon and photon signatures present

in real CRAYFIS user data, propose a novel test array of CRAYFIS-enabled smartphones, and present a high-performance data acquisition application. At last, in Chapter 5, I calculate the sensitivity of a global CRAYFIS network to simultaneous extensive air showers as a function of observation time and incident flux, and find that at least 1 million CRAYFIS users worldwide are needed to identify novel phenomena signal over background at 3σ statistical significance over a reasonable time-span.

"Oh, I'm sure you'll figure it out Albin..."

— Various

Chapter 1

Introduction

The scientific method, as it is practiced in physics, is the iterative process of reconciling numerical measurements obtained from repeatable experimentation, with numerical results obtained from rote calculation. In this way, *Physics* amounts to devising a self-consistent logical framework (a *theory*) that can represent, at least in principle, all structure and behavior of the Universe as calculable numbers wherein the mathematical relationships that exist between these numbers become known as the *Laws of Physics*.

As a sub-discipline, *Astroparticle Physics* is the study of elementary particles of extraterrestrial (*cosmic*) origin, their relation to celestial objects, and their role in the evolution of the Universe. Although starlight (and sunlight) are beams of low-energy cosmic particles (photons), the particles of interest to astroparticle physicists are usually those invisible to the unaided eye—the same elementary particles observed in accelerator experiments.

But what *is* an elementary particle? In one form or another, this question represents a question as old as the act of questioning—it is the kindling for scientific reasoning[†], and the impetus for 3,000 years of scientific undertakings to reveal the fundamental constituents of Nature (*elementary particles*) and their associated fundamental interactions (formerly *forces*). Even still today, the state-of-the-art answer to this question is incomplete, albeit effective. A full technical listing of specifics can be found in a variety of sources[‡]; however, it will be sufficient to state simply that the modern calculable description of elementary particles and their interactions solidified around 1975 as the *Standard Model of Particle Physics*—receiving final experimental validation in 2012 when the last remaining Standard Model elementary particle was detected in accelerator experiments.

Although the Standard Model currently stands as the most experimentally successful theory in all of science in terms of its precise predictions, it nevertheless comes with limitations and caveats. Practical computation caveats relevant to this work are mostly with regards to calculating hadronic interactions in *extensive air showers* (EASs) described in Chapter 2; wherein, *ultra-high energy cosmic rays* (UHECRs)—elementary particles, nucleons and atomic nuclei of cosmic origin—up to 10^{12} times more energetic than those ever studied in high-energy collider experiments impact upon atmospheric nuclei. The ultra-high energy physics of these composite-particle collisions, and their forward development into hadronic and electromagnetic showers, are situations where Standard Model interactions must be approximated and/or extrapolated in ways that technological limitations, for the foreseeable future, inhibit explicit cross-validations in a controlled laboratory setting.

[†]Likely established sometime in the first millennium BCE, Singer, C., "A Short History of Science to the 19th Century," Streeter Press, 2008

[‡]A concise overview is provided in Appendix A, and comprehensive reviews can be found at `http://pdg.lbl.gov`

UHECRs are renowned as the most energetic particles and nuclei in the Universe, but what celestial object(s) produce and accelerate projectiles to such extraordinary energies? How is that done? Do UHECRs herald from our galaxy, or from the furthest corner of space? Do they gain or lose energy as they propagate to Earth? Does their composition stay the same, or are they the crumbling particulate remnants of an atomic nucleus? Are some interpretable as evidence for dark matter, or as something entirely unexpected? Are there constraints or fundamental limits to their energy and composition? And what would the answers to these (and other) questions require of the machinery of Nature (the Laws of Physics)? Would this necessary machinery be identifiable within the framework of the Standard Model, or if not, could it provide the insight for, or put restrictions on, a superseding theory?

At first, many of these questions may appear untenable considering that the practical experimental-means from which their answers must be drawn amounts to scrutinizing only a minuscule fraction of highly-fragmented and scattered remains of ultra-high energy particle collisions (of unknown *a priori* cosmic ray composition and atmospheric nuclei—both of which fundamentally out of our direct control), under circumstances outside the scope of fully-validated calculations, which have stochastically showered down through tens of kilometers of variable atmospheric and geomagnetic conditions before at last reaching detectors. All this variability obviously makes individual EAS reconstruction and interpretation challenging and often unreliable. However, with many EAS observations, it becomes statistically possible to test the consistency of the aggregated data with the expected results of hypothetical answers to one or more of these questions. Therefore, a challenge to the experimentalist is to devise apparatus that accumulate and reconstruct EAS events as rapidly and as efficiently as possible; although bearing in mind that the rate of collection fundamentally cannot exceed that which Nature has set for UHECR events—on the order of 1 event per square kilometer per century or less (for UHECR energies $\gtrsim 10^{20}$ eV).

To compensate for the naturally-low rate of occurrence, a successful detection scheme must strive for as large of a collection area as can be afforded. In terms of land-based surface particle detectors, there are less than 10 large-scale (over $1\,\mathrm{km}^2$) observatories in the world, and the combined land coverage of all active world-wide observatories reaches at most $4{,}000\,\mathrm{km}^2$—less than 0.001% of all land area[†]. EASs create several-kilometer radius footprints, so the combined cross-sectional area of actual detectors within all these observatories only constitutes a small fraction of the total sensitive surface area: around $0.02\,\mathrm{km}^2$ all together. Although each observatory collects and processes event-by-event data independently of each other within their own collaboration, together they are overseen in total by a couple thousand full-time professionals and support staff with combined operation and upgrade costs of a couple tens of millions of dollars in grants annually.

However, seemingly at first completely unrelated to cosmic rays and experimental physics, smartphones are renowned cutting-edge, ultra-portable and sophisticated computers complete with a suite of sensors and auxiliary abilities. Nevertheless, with the world's smartphone-using population believed to currently exceed 3 billion[‡], were a network of smartphone particle detectors possible, the land area coverage could be immense, the number of dedicated staff minimal and the costs to operate and upgrade would be almost entirely covered by the end-user. In Chapter 3, it will be demonstrated how it is not only theoretically possible to detect EASs with smartphone cameras, but proofs-of-concept have already been made (Whiteson et al. (2016), Vandenbroucke et al. (2016), Dhital et al. (2017)). The implications of this new detection technology are such that in terms of total detector area (where the average smartphone camera sensor has been found to be around $\sim 0.15\,\mathrm{cm}^2$), an upper-limit of $\sim 0.04\,\mathrm{km}^2$ is in principle possible—nearly twice the combined detector area of all existing cosmic ray observatories. Furthermore, again as an upper-limit, were the coverage of a global network of smartphones to extend throughout all inhabited

[†] 36th International Cosmic Ray Conference (2019), `https://pos.sissa.it/358/`

[‡] See `https://www.statista.com/`

lands (roughly 10% of all land-area), the detection area could extend, in principle, up to 10,000 times the surface area of these same observatories. Although these estimates are absolute upper bounds, and the actual performance of a practical network is substantively less, there is clearly merit in exploring the capabilities of this novel technology.

Therefore, this dissertation describes how a global detector network of consumer smartphones can be calibrated (Chapter 4), and what such a network might be well suited to detect (Chapter 5).

With the exception of the original CRAYFIS app, radionuclide (§4.2.1) and muon beam (§4.2.2) data, all work presented in this document is entirely my own.

Chapter 2

Extensive Air Showers

Ultra-high energy cosmic rays (UHECRs) come from unknown origins, but in all likelihood travel many millions of years from distant galaxies (*e.g.* Hillas (1984) and Aartsen et al. (2018)) before crashing into the Earth's atmosphere. The exceptional energy of an UHECR is dissipated through successive atmospheric collisions, converting one incident (primary) cosmic ray into billions of (secondary) particles on average. Raining down very nearly at the speed of light, this extensive air shower (EAS) of sub-atomic particles arrives as a disk-like wavefront only a few meters thick (between first and last-arriving particles) at the lateral center of the shower core. This wavefront thickness increases with increasing lateral distance up to a few hundred of meters far from the shower core from increasing variation in scattered particle headings with each subsequent collision or decay. Various technologies exist to detect EAS particles from an UHECR-atmosphere collision (Fig. 2.1), but owing to their extreme energy and unpredictable rarity, no practical technology exists that can directly observe an UHECR on its own. Therefore, UHECR quantities of interest (energy, composition and often incident direction) are statistically inferred from indirect observations (*e.g.*, EAS lateral particle density distributions). Without an analytical, first-principles likelihood expression to explicitly link UHECR parameters to observations,

effective models (curve-fits partially based on first-principles) are developed from computer simulations to provide that link, §2.1.3.

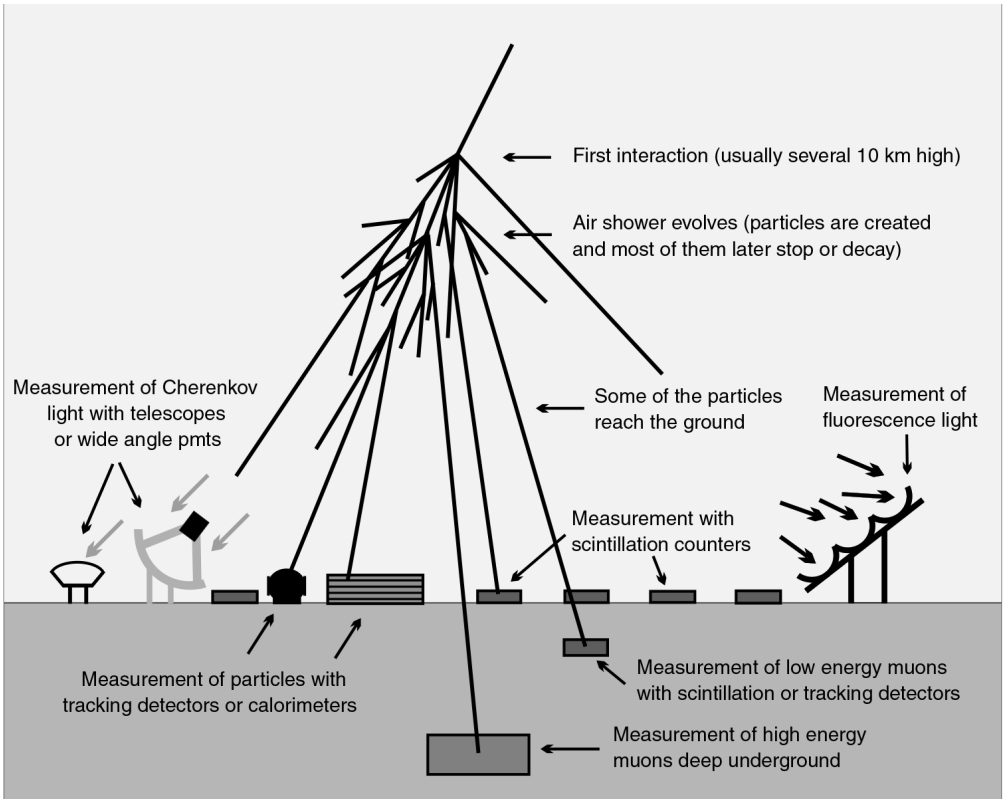


Figure 2.1: An illustration of an extensive air shower (EAS) and the modern means of detection. An energetic cosmic particle or nuclei (cosmic ray) strikes the nucleus of an atmospheric atom on average around 20 km in altitude—although there is considerable variability depending on the cosmic ray composition and how much energy it has. The energy of this collision splits or momentarily annihilates the cosmic ray and target nucleus into an unstable energy state that immediately decays into elementary particles and nuclear fragments. These very-high energy products decay and subsequently collide with atmospheric electrons and nuclei producing a laterally-growing cascade of sub-atomic debris. Most of the energy is eventually stopped and absorbed by the atmosphere, but a number of particles and nuclei usually survive to the surface. Surface scintillator panels and water-Cherenkov tanks commonly make up the bulk of an observatory, but several technologies are frequently used in concert. Near-UV optical telescopes for atmospheric fluorescence and Cherenkov radiation detection substantially increase coverage area as well as total energy, direction, and composition reconstruction accuracy; however, they are only effective on dark, clear nights. Surface or underground ionization calorimeters, multi-wire trackers and emulsion chambers, as well as some of the more rarer technologies including Askaryan radio arrays (not shown) are sometimes also part of an observatory. Image credit: Haungs et al. (2003).

2.1 CORSIKA

Adapted into its modern form in 1989 for the KASCADE experiment (Apel et al. (2010)), CORSIKA[†] (COsmic Ray SImulations for KAscade) is the most widely used and rigorously validated Monte Carlo EAS simulation tool used for UHECR reconstruction. The core algorithms of CORSIKA however date back to the early 1970s, making it one of the oldest simulations codes still in use today. In short, CORSIKA makes detailed Monte Carlo calculations for high energy strong and electromagnetic interactions (weak interactions are not treated) with support for subsequent particle decays, scattering and energy loss processes within a realistic atmospheric and geomagnetic context (Heck et al. (1998)).

However, as mentioned in Chapter 1, the most serious problem facing any EAS simulation program is the unavoidable extrapolation of hadronic interactions into higher energies and rapidity ranges than that covered by experimental data. These unvalidated hadronic interactions produce the most energetic secondary particles, which carry the largest energy fraction of each collision deep into the atmosphere. Therefore, the hadronic interaction model is also the largest influencer on the overall development of an EAS. To that end, CORSIKA is a merger of multiple interaction models and representations of collider data, and offers the user extensive choices on which to use; in part to leverage detail with performance, but also for assessing the robustness (systematics) of results.

2.1.1 Hadronic Interactions

The realm of hadronic interaction modeling has a rich and complex history. Prior to Standard Model Quantum Chromodynamics (QCD), Tullio Regge developed a successful non-relativistic phenomenological theory of scattering where angular momentum was allowed to take on any continuous, complex value (Regge (1959)). When promoted to a

[†]See `https://www.ikp.kit.edu/corsika/index.php`

relativistic context, the high energy behavior of scattering amplitudes are related to the singularities in the complex angular momentum plane (which represent *Reggeon* "particles") in a way consistent with experimentally-observed angular dependence. In high energy accelerator experiments, most inelastically-scattered protons remain closely aligned to the beam-line direction following interaction, which in the context of Regge theory calculations suggested that strongly-interacting particles were composite (as what were later called quarks and gluons in QCD). However, where the Regge formalism succeeded with inelastic scattering predictions, elastic scattering cross-sections measured in collider experiments were found to contradict predictions by growing logarithmically at very high energies. Vladimir Gribov successfully addressed this by introducing *Pomerons* (Reggeons with additional constraints, Gribov (1968), Gribov (1969)), and together the Gribov-Regge formalism was very successful; however as a phenomenological model, it was ultimately superseded by QCD.

Although QCD is the modern accepted theoretical basis of strong interactions (covering all energy ranges), Gribov-Regge theory can produce identical results for the very high energy range (albeit with notable exceptions to proton–anti-proton scattering) with substantially easier (non-perturbative) computations. As such, CORSIKA offers four modern ("HDPM" is a legacy model not further considered) interaction models based off of the Gribov-Regge theory of Pomerons: VENUS (Werner (1993)), two versions of QGSJET (Kalmykov et al. (1994), Ostapchenko (2006)), DPMJET (Roesler et al. (2000)), and SIBYLL (Fletcher et al. (1994)).

Another problem facing calculations of high energy hadronic collisions is that most events produce a large number of particles with small transverse momenta with respect to the collision axis. Processes with many particles in the final state are intrinsically complicated, since many variables are involved, but even so, in principle it should be possible to compute the properties of these "soft" multi-particle events directly from the Lagrangian of

QCD. However, there is no large momentum transfer involved in soft processes, and the running coupling constant becomes much too large for ordinary perturbation theory to be sensible. Therefore, alternative non-perturbative procedures must be adopted. At the present time, the best that can be done to describe soft hadronic physics is to construct models that incorporate all available theoretical ideas from both non-perturbative studies of QCD as well as general properties of the scattering matrix. Typical non-perturbative approaches consist of taking various large-N limits of QCD, where N can be either the number of colors, or the number of flavors. This procedure gives rise to *topological expansions* (akin to Feynman diagrams) where interactions represented by topologically complicated diagrams are suppressed by powers of N^{-1}.

VENUS (Very Energetic NUclear Scattering) represents nuclei and hadrons as Pomerons described by cylindrical bundles of gluons and "quark-loops" developed out of a topological expansion of QCD. Particle production (inelastic scattering) amounts to "cutting" these cylinders, however there is no mechanism in the model to describe minijet phenomena (small, several-GeV jets that are experimentally known to become important with increasing energy). As such, VENUS is not viable past $\sim 10^{16}$ eV where minijets become significant.

QGSJET (Quark Gluon String model with JETs) describes strong-interactions as exchanges of "supercritical" Pomerons (single gluons surrounded by a "soft background" of gluons). Like VENUS, particle production amounts to cutting Pomerons, but follows the Abramovsky-Gribov-Kancheli rule which limits cut diagrams to certain classes (Abramovsky et al. (1973)) to form two "strings" each (tubes of constant energy-per-length), which then fragment. Unlike VENUS, QGSJET includes minijet formation in its fragmentation procedure, making it applicable at high energies. Two versions of QGSJET are included with CORSIKA. QGSJET-II expands on QGSJET to

include nonlinear interaction effects when individual parton cascades start to overlap in the corresponding phase space and influence each other.

DPMJET (Dual Parton Model with JETs) like VENUS also describes interactions in terms of multi-Pomeron exchanges, however it incorporates a "dual topological unitarization scheme" in its topological expansion. Like QGSJET, DPMJET also uses supercritical Pomerons for soft processes and cuts Pomerons into strings which then fragment, but unlike QGSJET, DPMJET uses "hard" Pomerons for hard processes and a slightly different jet creation algorithm. Additional subtle differences appear in the choice of the number of participating nucleons for nuclear collisions, and all short living secondaries not known within CORSIKA's 50-member particle list[†] decay within DPMJET. Lastly, DPMJET produces charmed hadrons, which are not contained in CORSIKA's particle list, as such they are replaced with strange quarks for the remainder of their interactions or decays.

SIBYLL, like DPMJET, is based off of the Dual Parton Model (Capella and Krzywicki (1978)) with minijet production (Gaisser and Halzen (1985), Durand and Hong (1987)). There is a great deal of similarity, but SIBYLL distinguishes itself by being optimized (choices of parameterization, subtle hadron-nucleus interaction differences and algorithm) specifically for EAS applications. Short-lived secondaries decay instantly into particles known to CORSIKA, and particles like strange baryons are tracked, but decay without further interaction. In photonuclear interactions, the incident gamma-ray is replaced by a charged pion.

CORSIKA additionally supports two more hadronic models (EPOS and NEXUS); however they are not applicable at high energies. Additional details of quantitative differences between all models can be found in Knapp et al. (1996), and Knapp et al. (1997).

[†]Particles known to CORSIKA: γ, $e^{\pm}$, $\mu^{\pm}$, π^0, $\pi^{\pm}$, $K^{\pm}$, $K^0_{S/L}$, η, the baryons p, n, Λ, $\Sigma^{\pm}$, Σ^0, Ξ^0, Ξ^-, Ω^-, the corresponding anti-baryons, the resonance states $\rho^{\pm}$, ρ^0, $K^{*\pm}$, K^{*0}, $\bar{K}^{*0}$, Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}, the corresponding anti-baryonic resonances, (optionally, by explicit inclusion) neutrinos ν_e, ν_μ, and corresponding anti-neutrinos resulting from π, K, and μ decay, and fully ionized nuclei up to $A = 56$.

Interactions between hadronic projectiles and atmospheric nuclei below 80 GeV are handled by GHEISHA (Fesefeldt (1985)) in the same manor as GEANT3 (Brun et al. (1987)), which relies heavily on elastic and inelastic cross-sections derived from experimental data (where the type of interaction is drawn at random). Unfortunately, air is not a target frequently used in high energy particle experiments; therefore although GHEISHA relies heavily on experimental data, only elements H, Al, Cu and Pb are tabulated as target materials, so EAS interactions with relevant elements N, O, and Ar are necessarily interpolated from available data. CORSIKA also includes two other low-energy hadronic interaction models, FLUKA and URQMD; however GHEISHA is comparatively well validated.

Lastly, on one extreme, nuclear collisions leave the possibility of completely fragmenting the target nucleus into a spray of constituent spectator (non-interacting) nucleons, or on the other extreme, leaving the spectators bound together as a surviving nucleus. In nature somewhere in the middle happens, but the authors of CORSIKA claim the differences between these cases are small and the details are smeared out by the comparatively larger EAS fluctuations. The user is given the option to select which extreme to employ in simulation, with additional options for the "wounded nucleus" between-case of nucleon emission by "evaporation."

For additional details, reference the comments in the provided CORSIKA input file template in Appendix B.1, and the CORSIKA user's guide included in the github repository `https://github.com/ealbin/corsika7/tree/master/v77000/doc`.

2.1.2 Simulations

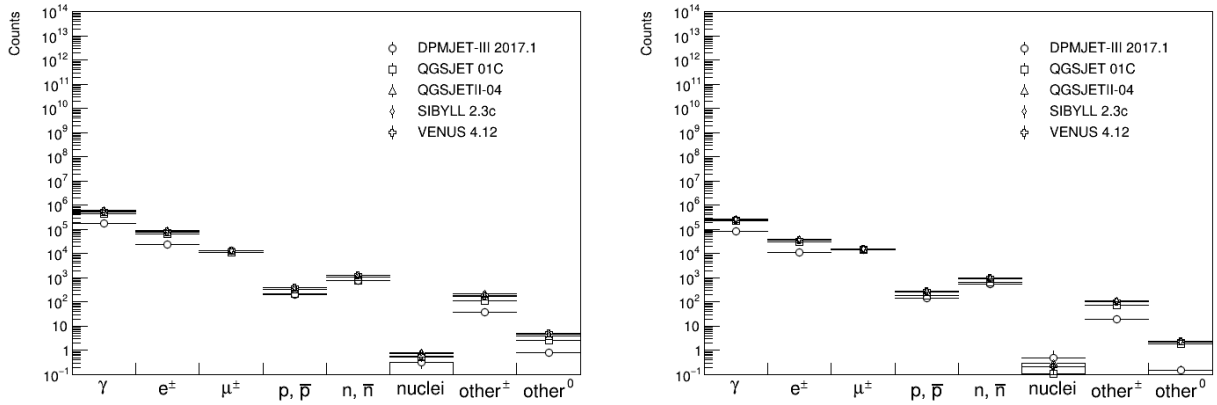
With so many options available to the user, a great deal of preliminary effort was expended studying the computational costs versus simulation accuracy benefits for CORSIKA simulations. A template of essential parameters believed to maximize the realism of the EAS simulations with acceptable computational time is provided in Appendix B.1. Each

build of CORSIKA was compiled in 64-bit mode with GHEISHA 2002d for a horizontal flat array with thinning (including LPM) support. When possible (for DPMJET, QGSJET and SIBYLL), the charmed particle / tau lepton PYTHIA option was also activated. For angled-incidence simulations, the curved atmosphere selection was enabled. Hadronic interaction models selected were DPMJET-III (2017.1) with PHOJET 1.20.0, QGSJET 01C (enlarged commons), QGSJETII-04, SIBYLL 2.3c and VENUS 4.12.

The results of a CORSIKA simulation consists of a binary file listing of multiple aspects of the simulation, but most importantly, a listing of particles with kinematic information at observational altitudes specified in the simulation input file mentioned above. Example particle content at sea level is shown in Fig. 2.2 where it can be seen that the three most numerous particle classes in an EAS are photons, electrons (including positrons), and muons (including anti-muons). As electrons are comparatively easily stopped by materials, photons and muons are of particular interest to CRAYFIS (Chapter 3). The lateral density and energy spectrum for muons and photons are presented in Figs. 2.3–2.6. Additional figures of lateral density and energy spectra for the remaining shower particle categories can be found in Appendix B.2. The relative particle content fractions of EASs is somewhat predictable, and all content typically scales linearly with primary energy.

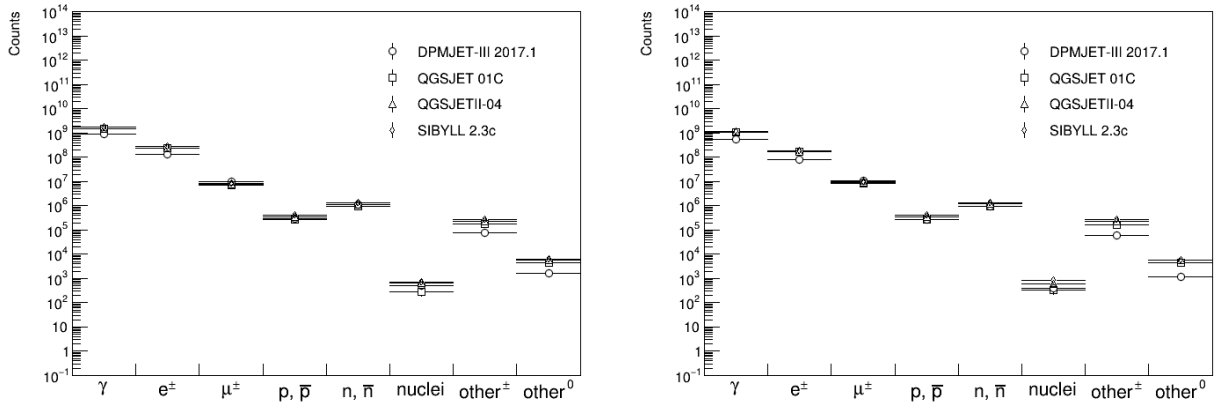
2.1.3 Extensive Air Shower Modeling

The computational time for an EAS simulation scales roughly linearly with primary energy. Consequently, performing high-statistic simulations for every possible primary projectile, incident angle and observational altitude as needed is not sensible. Instead, 100 EAS simulations were run for each of 5 hadronic interaction models (DPMJET, QGSJET, QGSJET-II, SIBYLL and VENUS), for each of 5 primary projectiles (photon, proton, Helium, Oxygen and Iron), for each of 8 primary energies (10^{14}, 10^{15}, 10^{16}, 10^{17}, 10^{18}, 10^{19}, 10^{20} and 10^{21} eV), and for each of 4 incident zenith angles (vertical, 30°, 60° and 80°). For



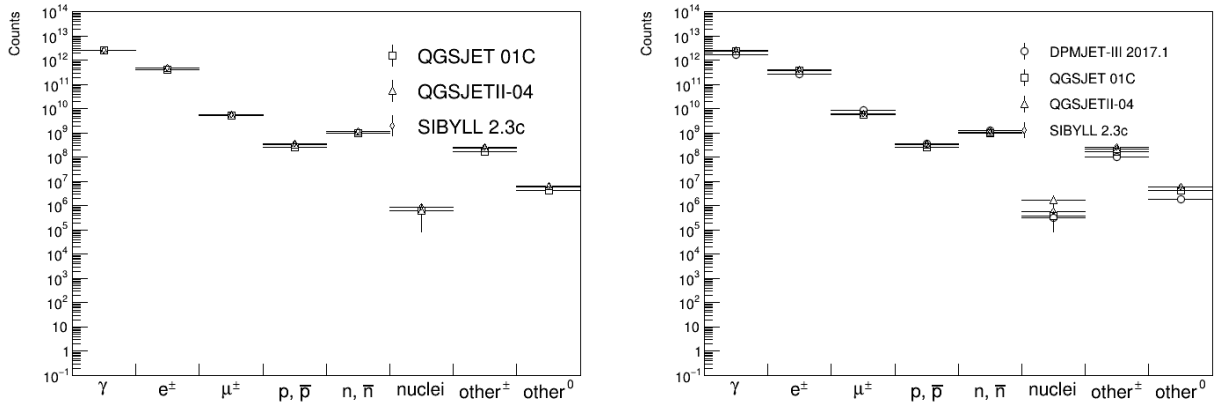
(a) 10^{15} eV Helium

(b) 10^{15} eV Iron



(c) 10^{18} eV Helium

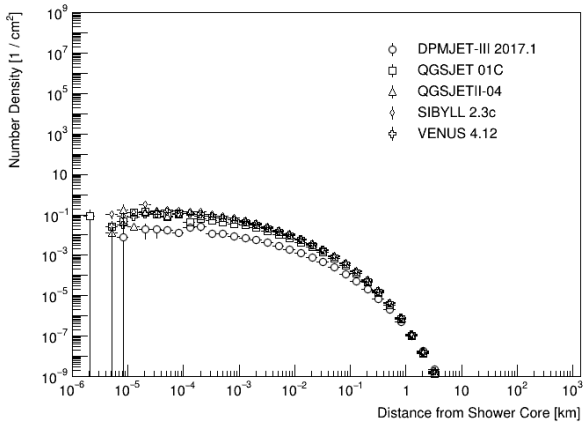
(d) 10^{18} eV Iron



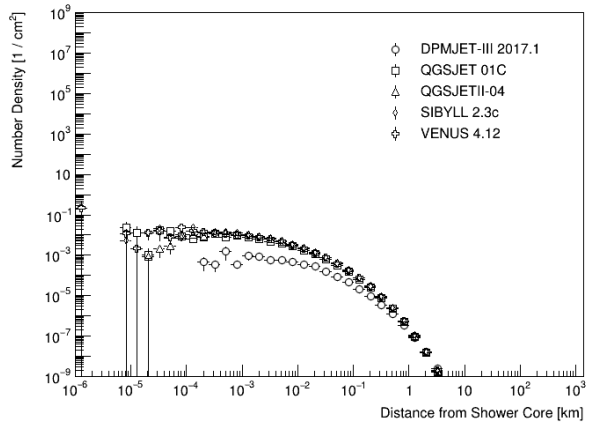
(e) 10^{21} eV Helium

(f) 10^{21} eV Iron

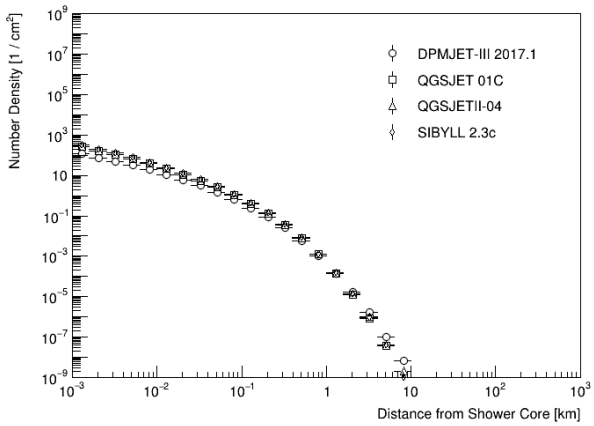
Figure 2.2: Sea-level, CORSIKA many-shower average simulation results for a selection of vertically-incident EASs. Five hadronic interaction models are shown to exhibit similar results. Left (right) column, an ultra-high energy Helium (Iron) primary, with energy 10^{15}, 10^{18}, and 10^{21} from top to bottom. EAS particle content is listed along the x-axis from left: photons, electrons, muons, proton, neutrons, nuclei, charged-other, neutral-other. The "other" particle categories are pion-dominated, and neutrino content is not included.



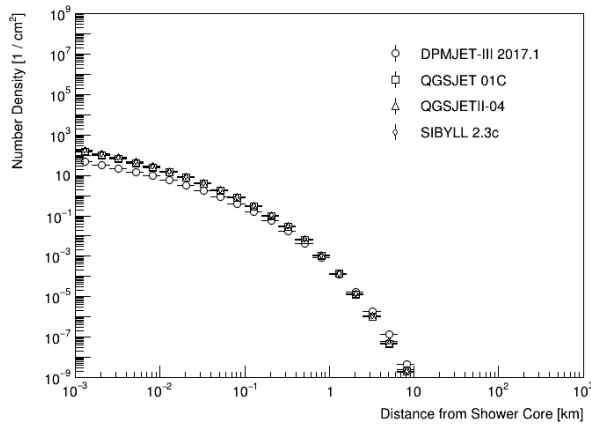
(a) 10^{15} eV Helium



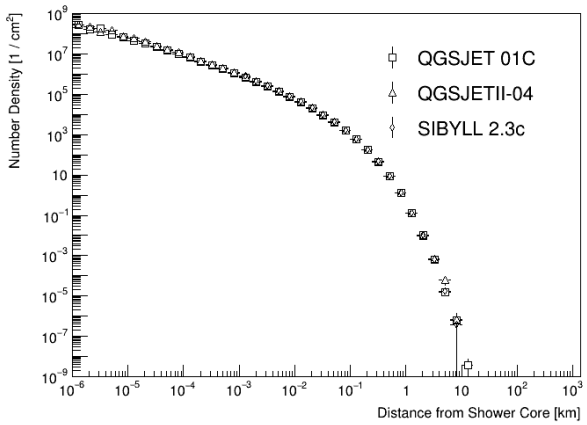
(b) 10^{15} eV Iron



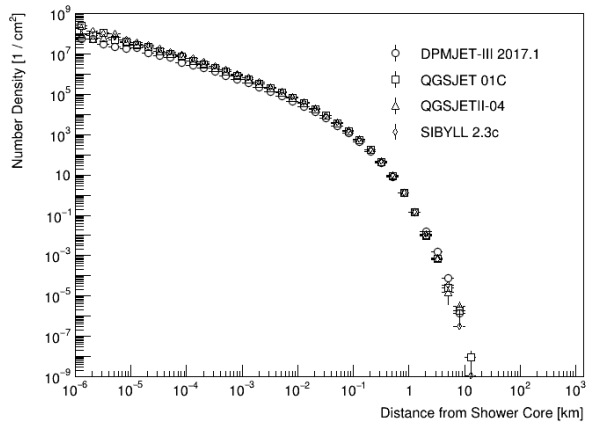
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

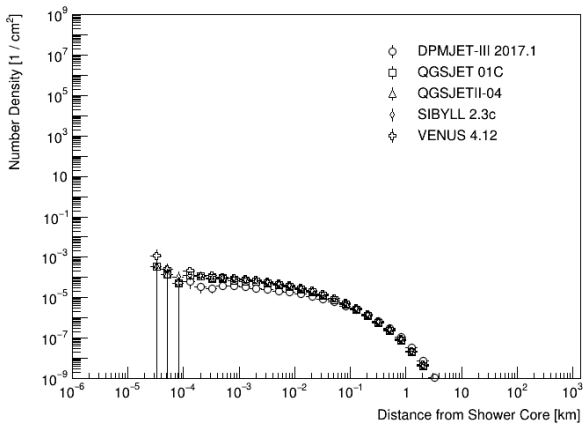


(e) 10^{21} eV Helium

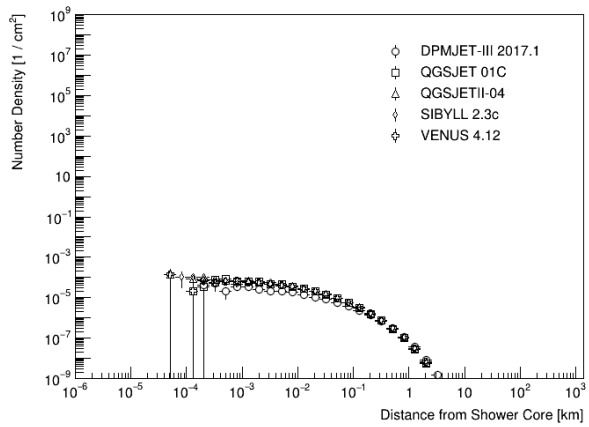


(f) 10^{21} eV Iron

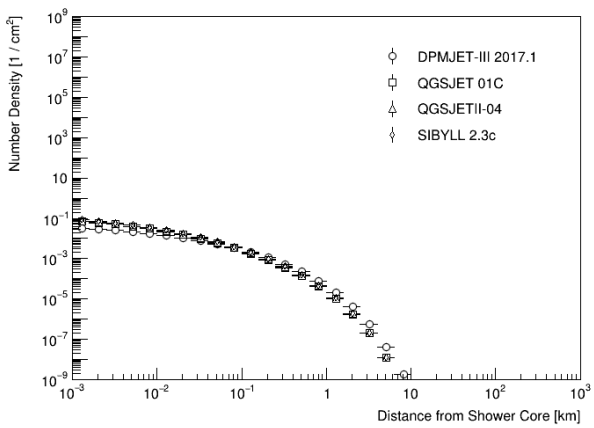
Figure 2.3: The lateral density distribution (in counts per annulus-area defined by the lower and upper edges of each bin) of the photons in Fig. 2.2.



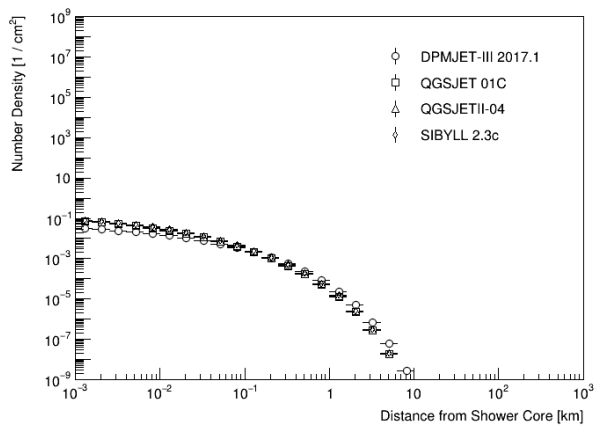
(a) 10^{15} eV Helium



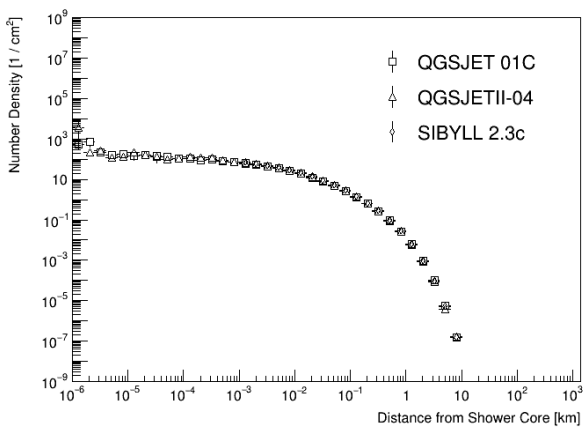
(b) 10^{15} eV Iron



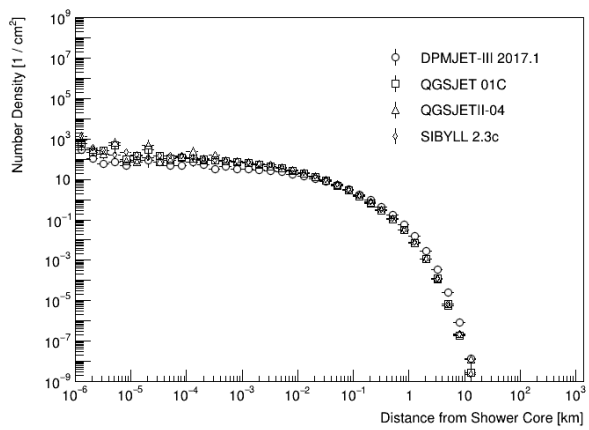
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

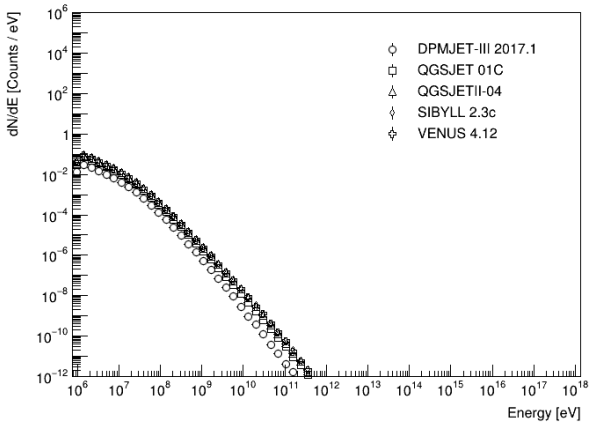


(e) 10^{21} eV Helium

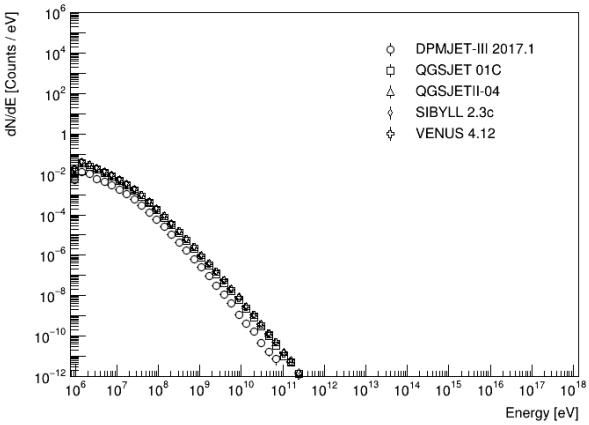


(f) 10^{21} eV Iron

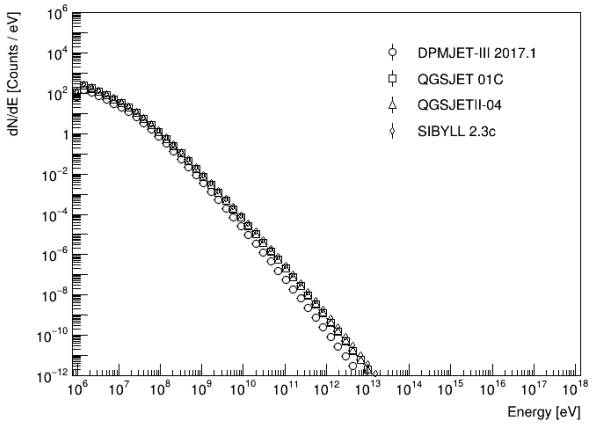
Figure 2.4: The lateral density distribution of the muons in Fig. 2.2.



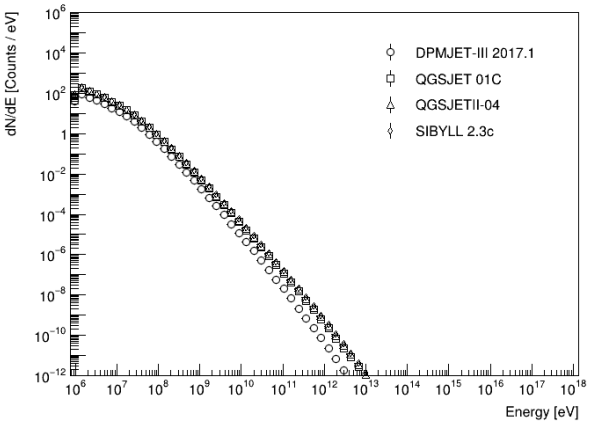
(a) 10^{15} eV Helium



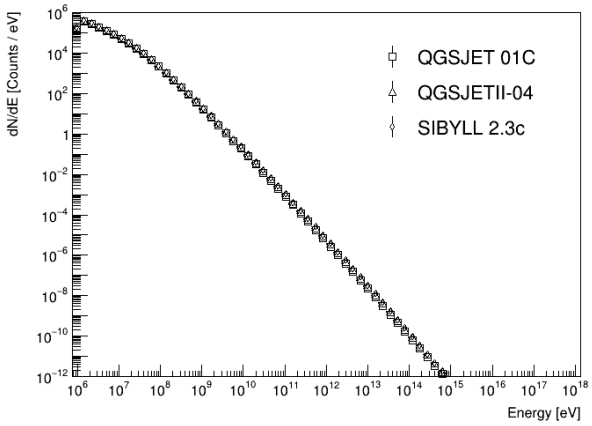
(b) 10^{15} eV Iron



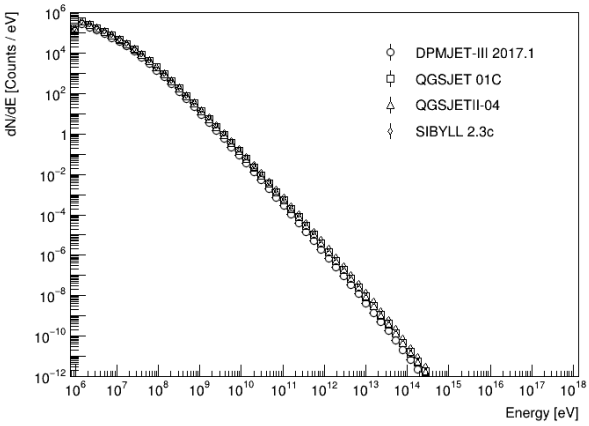
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

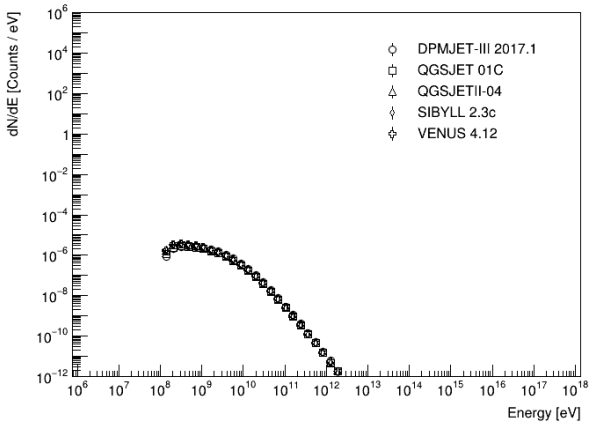


(e) 10^{21} eV Helium

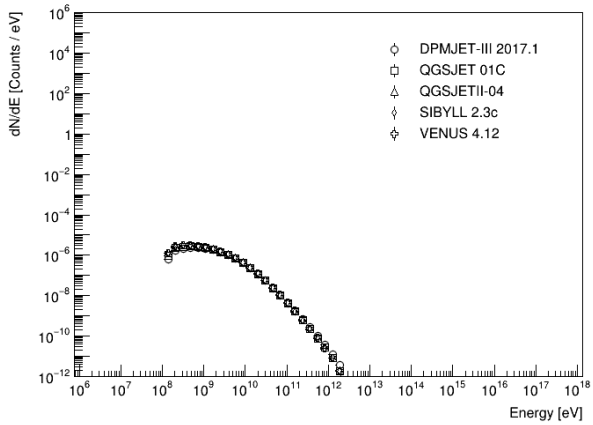


(f) 10^{21} eV Iron

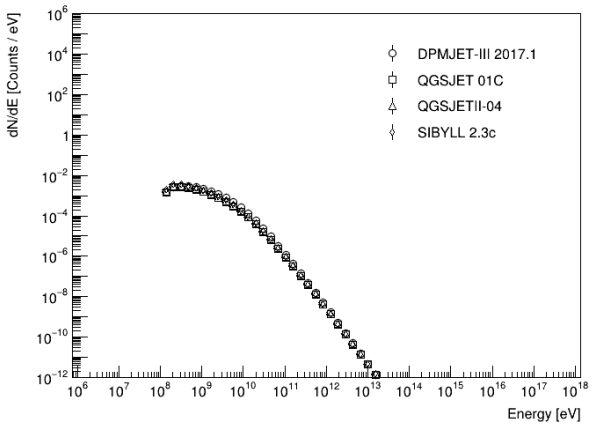
Figure 2.5: The energy spectrum of the photons in Fig. 2.2.



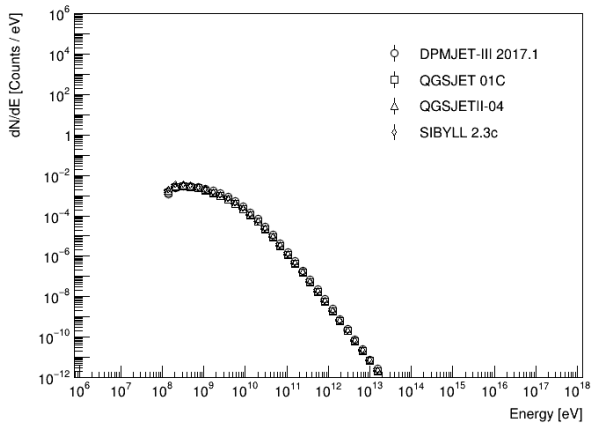
(a) 10^{15} eV Helium



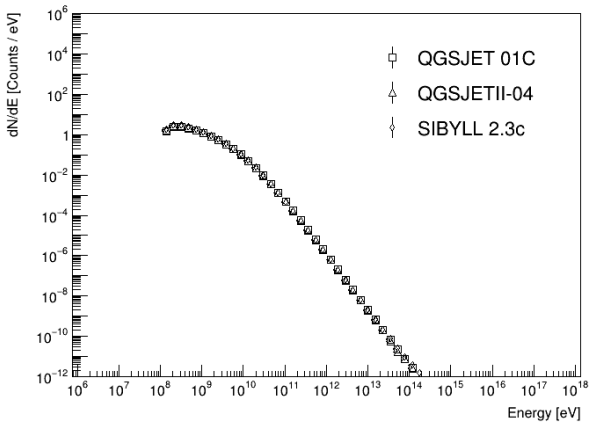
(b) 10^{15} eV Iron



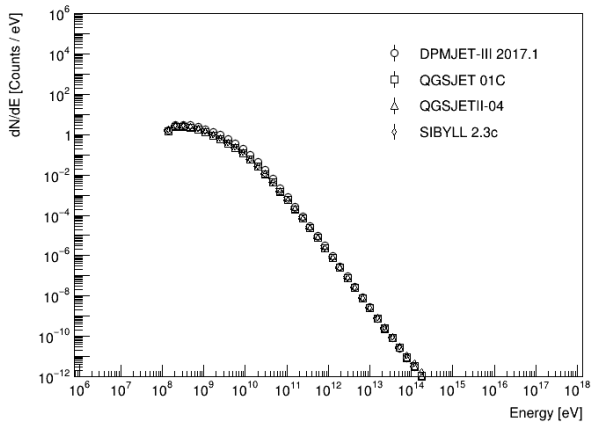
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron



(e) 10^{21} eV Helium



(f) 10^{21} eV Iron

Figure 2.6: The energy spectrum of the muons in Fig. 2.2. The abrupt start of the spectrum is due to the muon rest mass of 1.06×10^8 eV.

vertical simulations, 10 observation altitudes were specified at 0, 0.5, 1, 1.4, 2, 5, 10 and 20 km a.s.l. For angled-incident simulations where the curved atmosphere option limits observation altitudes to 1 per simulation, 5 simulations were performed for altitudes 0, 1, 2, 5 and 10 km (instead of all 5 hadronic models, only one was chosen at random per simulation). In total, around 100,000 simulations were performed.

It is desirable to link these simulation results back to practical UHECR parameters (energy, composition, incident direction and altitude of observation) for purposes of both generating toy data, and for (toy and real) likelihood data analysis. Commonly, the "NKG" (Nishimura-Kamata-Greisen) analytically-based model of the lateral density distribution of electromagnetic particles (photons, electrons and muons) is expressed as

$$\rho(r) = N_e\, C(s) \left(\frac{r}{r_M}\right)^{(s-\alpha)} \left(1 + \frac{r}{r_M}\right)^{(s-\beta)} \; [\mathrm{m}^{-2}] \tag{2.1}$$

Where N_e is the total number of electrons and positrons at shower age parameter s, which ranges from $s = 0$ at the moment of the first interaction to 1.0 at the shower maximum (by definition) to $\sim$1.5 at sea-level. $C(s)$ is a normalization factor that is commonly expressed using Gamma functions sometimes tailored to fit specific experiments, but generally of the form:

$$C(s) = \frac{1}{2\pi r_M^2} \left(\frac{\Gamma(\beta - s)}{\Gamma(s - \alpha + 2)\Gamma(\alpha - 2 + \beta - 2s)}\right) \tag{2.2}$$

where α and β are the same as in Eq. (2.1) with values close to 2 and 4.5 respectively. Lastly r_M is the Molière radius representing the characteristic scattering distance for an electron or positron, which in turn is dependent on atmospheric conditions approximately modeled by:

$$r_M \approx \frac{73.5}{P} \frac{T}{273} \; [\mathrm{m}] \tag{2.3}$$

with the absolute pressure, P in atmospheres and temperature, T in Kelvin.

For the purpose of good fit convergence for photon and muon lateral density distributions, and maximal applicability over a range of situations, the NKG expression was adapted as follows:

$$\rho(r; a_n) = e^{a_0} r^{-a_1} \left(1 + \frac{r}{e^{a_2}}\right)^{-a_3} \ [\mathrm{cm}^{-2}] \tag{2.4}$$

where r is in meters and the four a_n coefficients were best-fit as a function of first-order factors of transformed primary mass number, A, primary energy, ϵ, and altitude of observation, h as:

$$\begin{aligned} a_n(A^*, \epsilon^*, h^*) \cong c_n^0 + & \\ & c_n^1 A^* + c_n^2 \epsilon^* + c_n^3 h^* + \\ & c_n^4 A^* \epsilon^* + c_n^5 A^* h^* + c_n^6 \epsilon^* h^* + \\ & c_n^7 A^* \epsilon^* h^* \end{aligned} \tag{2.5}$$

where,

$$\begin{aligned} A^* &= \ln\,(A+1) \\ \epsilon^* &= \log_{10}\,(\epsilon/10^{18}) \\ h^* &= 100\ \ (1 - \log_{10}\,(10 - h_{\mathrm{eff}}/10)) \end{aligned} \tag{2.6}$$

with energy in electron-volts, altitude in kilometers and for vertical showers, h_{eff} is simply the altitude of observation, h. In general, for showers inclined by an angle θ_0 above the observation horizon at altitude h, and coming from azimuthal direction ϕ_0,

$$h_{\mathrm{eff}} = h' + r \sin\theta_0 \cos\,(\phi - \phi_0) \tag{2.7}$$

Table 2.1: Best-fit coefficients from Eq. 2.9

d_0	d_1	d_2	d_3
24.1	2.74	0.550	-0.061

where h' in turn is a function of the altitude of the first interaction, h_0:

$$h' = h_0 - (R_E + h)\left(\sqrt{\left(\frac{R_E + h_0}{R_E + h}\right)^2 - \cos^2\theta_0} - \sin\theta_0\right) \tag{2.8}$$

where R_E is the radius of the Earth in kilometers, and the average first interaction altitude, h_0, is modeled from simulation to good agreement as:

$$h_0(A^*, \epsilon^*) \cong d_0 + d_1 A^* + d_2 \epsilon^* + d_3 A^* \epsilon^* \tag{2.9}$$

with coefficients d_n provided in Table 2.1

It is not uncommon for experiments to find deviations from the NKG distribution near and far from the core (*e.g.*, Barnhill et al. (2005), and Fig. 2.7). This is often addressed by tacking on an additional product (*e.g.*, $(1 + r/a_4)^{-a_5}$) to the bare NKG expression (Eq. (2.1)), or truncating the distribution as a modified power-law. Nevertheless, the advantage of an NKG-like expression is that it is physically motivated by an analytical treatment of electromagnetic cascades of photons and electrons; yet on the other hand, this is also an over-simplification of the intricate physics of a real EAS. Striving to find a novel between-ground, the author proposes a closely-related Exponential NKG Alternative (EKA[†]) model inspired from the sequence-limit definition of Euler's Number:

$$\lim_{n\to\infty}\left(1 + \frac{r}{a\,n}\right)^{-b\,n} = e^{-\frac{b}{a}r} \tag{2.10}$$

[†]or, Eric K Albin

This EKA model has been found to describe the origin and tail better than the usual NKG-like functions while preserving the intermediate behavior:

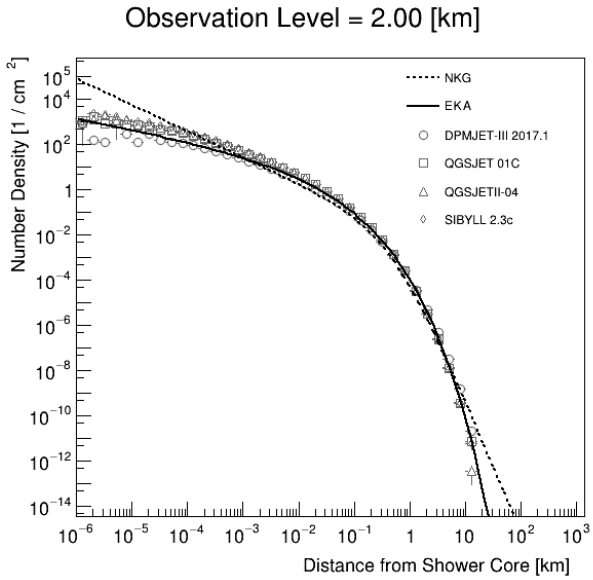
$$\rho(r; b_n) = e^{b_0} r^{-b_1} exp\left(-\frac{r^{b_3}}{e^{b_2}}\right) \ [\mathrm{cm}^{-2}] \tag{2.11}$$

where the four b_n coefficients are fit in the same manor as Eq. 2.5. Example plots are given in Fig. 2.7, with the coefficients for both models given in Tables 2.3 and 2.2.

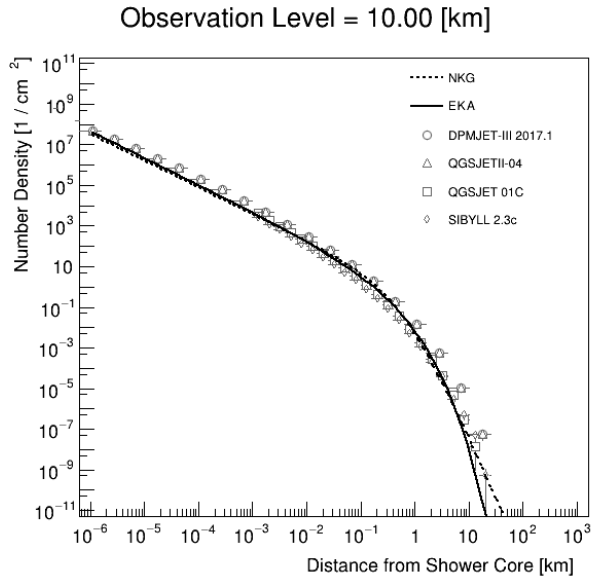
Owing to its better description of the core particle density (remaining finite at the origin), the EKA model also shows total photon and total muon count (Eq. (2.12)) agreement within the bounds of the hadronic model uncertainty of Fig. 2.2. NKG-like and power-law expressions, on the other hand, are prone to inherently and substantially over-predict total counts (possibly to infinity) unless the integration is begun an arbitrary-finite distance from the origin.

$$N = 2\pi \int_0^\infty \rho(r; b_n)\ r\ dr \tag{2.12}$$

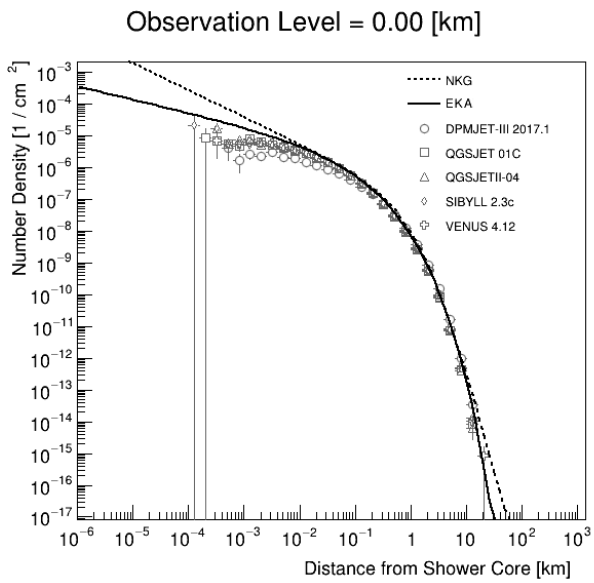
The EKA model will be drawn upon for assessing CRAYFIS sensitivity to EAS events (Chapter 4) following an overview of the CRAYFIS project in the next chapter.



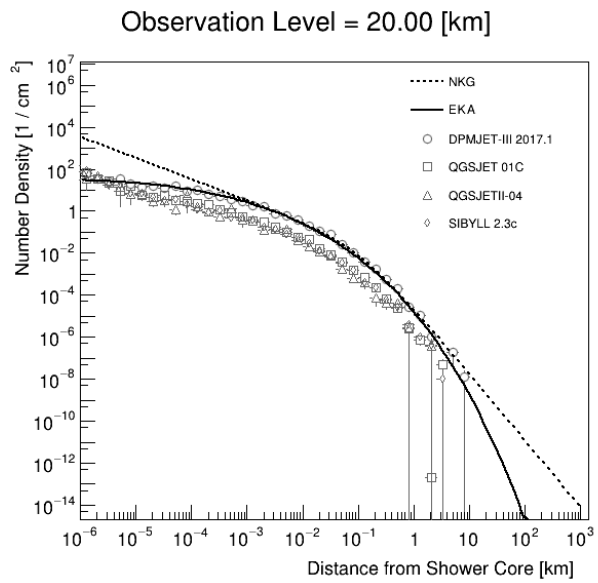
(a) photon-channel, 10^{17} eV ^{16}O nucleus primary



(b) photon-channel, 10^{20} eV ^{16}O nucleus primary



(c) muon-channel, 10^{14} eV ^{4}He nucleus primary



(d) muon-channel, 10^{21} eV ^{56}Fe nucleus primary

Figure 2.7: Lateral density models for photons (top) and muons (bottom) compared with CORSIKA simulations for various high-energy hadronic interaction packages, primary nuclei, energies and altitudes of observation. In general, the NKG (dashed) function is found to over-predict densities near the shower core and taper off slower than simulation results predict. The proposed EKA model (solid) was found to produce better simulation agreement in almost all cases.

Table 2.2: Best-fit coefficients from Eq. 2.5 for photons

	c_n^0	c_n^1	c_n^2	c_n^3	c_n^4	c_n^5	c_n^6	c_n^7
a_0	7.50	-0.311	2.64	-0.880	0.096	0.085	-0.140	0.001
a_1	1.30	-0.034	0.060	0.020	0.008	0.003	-0.025	0.002
a_2	6.19	-0.017	0.119	0.087	-0.025	0.013	-0.075	0.014
a_3	5.08	-0.062	0.166	-0.134	-0.035	0.005	0.015	0.005
b_0	7.51	-0.177	2.63	-0.860	0.001	0.085	-0.093	-0.004
b_1	0.843	-0.095	0.076	0.090	0.041	0.004	-0.018	0.002
b_2	0.697	-0.135	0.162	0.247	0.034	0.005	-0.016	0.013
b_3	0.414	-0.012	0.013	0.018	0.004	-0.001	0.004	0.000

Table 2.3: Best-fit coefficients from Eq. 2.5 for muons

	c_n^0	c_n^1	c_n^2	c_n^3	c_n^4	c_n^5	c_n^6	c_n^7
a_0	-0.912	-0.066	2.25	-0.418	0.022	0.050	-0.093	0.001
a_1	0.918	-0.021	0.002	0.016	0.004	0.002	-0.004	0.000
a_2	7.52	-0.020	-0.025	-0.261	0.007	0.011	-0.022	0.000
a_3	6.37	-0.100	0.077	-0.435	0.009	0.020	-0.019	-0.001
b_0	-1.74	-0.047	2.19	0.158	0.034	0.030	0.011	-0.011
b_1	0.573	-0.041	0.012	-0.078	0.008	0.005	-0.015	0.002
b_2	1.73	-0.066	-0.012	-0.357	0.022	0.011	-0.020	0.001
b_3	0.485	-0.007	0.001	-0.032	0.002	0.001	-0.001	0.000

Chapter 3

Cosmic RAYs Found In Smartphones

The objective of the CRAYFIS project (Whiteson et al. (2016)) is to ascertain the scientific power of a global ultra-high energy cosmic ray (UHECR) detection network of smartphones, and search for evidence of global-scale phenomena by reconstructing ground-level particle density distributions of extensive air showers (EASs) from measurements of individual particles detected in smartphones. This network is realized by everyday people who volunteer to install our smartphone application (*app*) which collects data while their device is otherwise inactive and charging—usually at night. The CRAYFIS app works by looking for signatures of particles that have passed through a smartphone camera sensor. No active participation of the user is required aside from downloading and installing the app, and its operation is meant to be as unobtrusive as feasible. In nearly all cases, no additional light shielding of the camera, such as tape, is required, other than placing the phone face-up (camera-down) on a table.

3.1 Dataflow

Video frames are sampled for candidate events—anomalously bright pixels above a dynamic sensor-wide threshold (Fig. 3.1), suggestive of passing particles. Selected pixel

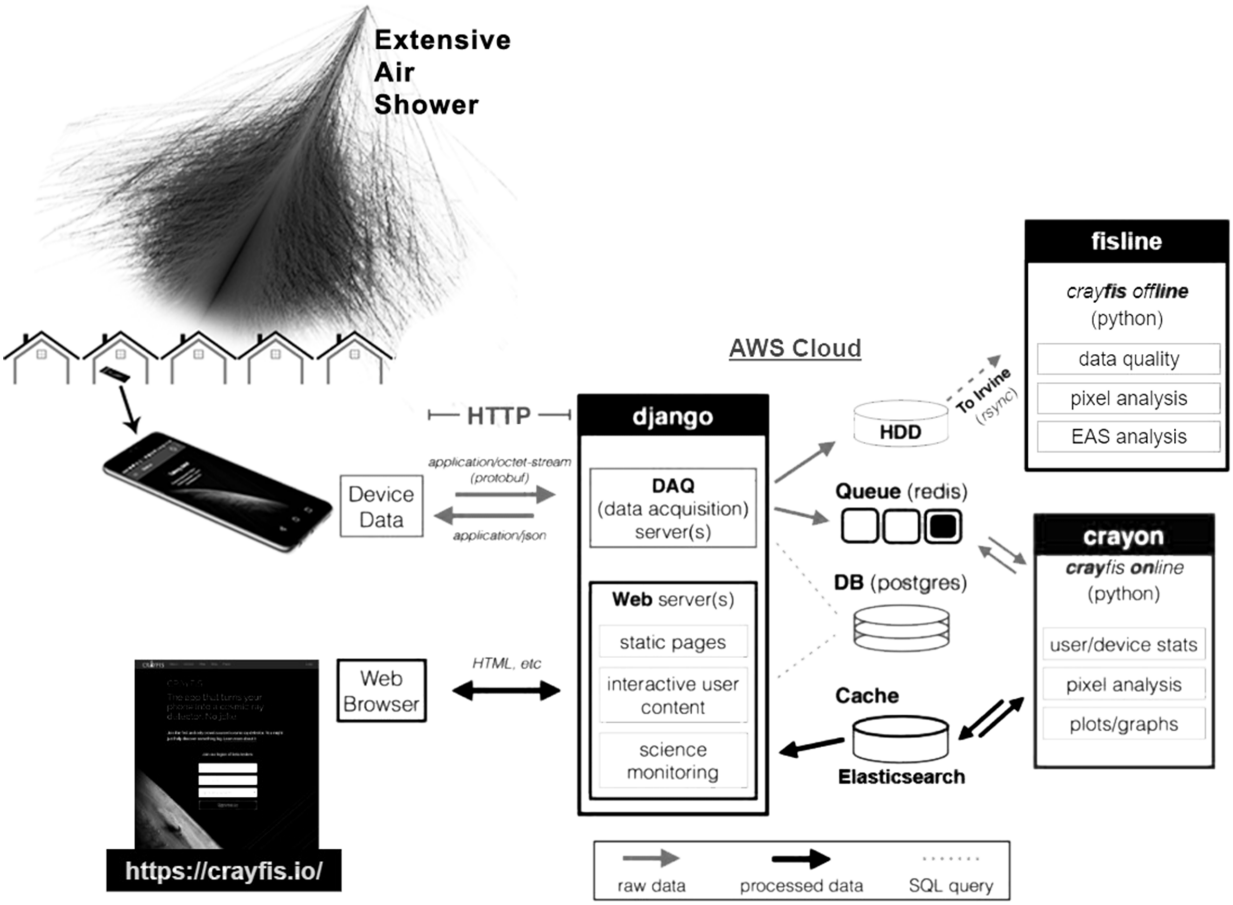


Figure 3.1: An illustration of the CRAYFIS dataflow. Ionizing radiation from an EAS illuminates smartphone pixels. This data is serialized and sent over HTTP as an ASCII string to be stored on our online server, and periodically downlinked to offline storage for analysis.

candidates are then stored in a sparse array along with arrival time, GPS location, and capture statistics; with most events being between 50-200 bytes of data. Individual devices are identified by a randomly assigned universally unique identifier that cannot be correlated with any personally-identifiable information beyond smartphone make, model and GPS coordinates of an event.

Aggregated data is serialized[†] and periodically uploaded as an HTML string over a WiFi network to a central server[‡] for offline processing. New data is then unpacked and checked for corruption before being stored in a central database (Appendix C). For user privacy, no

[†]`https://developers.google.com/protocol-buffers`

[‡]`https://crayfis.io`

complete frames are stored or uploaded, and a high-sparsity threshold prevents full images from being uploaded or reconstructed offline. Offline analysis removes mistakenly-triggered events usually caused by light leakage near the edge of the frame, or by noisy pixels. Evidence of potential EASs in data are found by searching for data recorded by 5 or more devices at approximately the same time (within a 100 ms window) and within a GPS proximity radius of 10 km.

3.2 Triggering

Data storage, transmission and privacy considerations prevent sending full sensor images for detailed post analysis; therefore, a real-time on-smartphone algorithm (*trigger*) for deciding a pixel event is worth further scrutiny is the most critical aspect of the CRAYFIS app. The trigger algorithm needs to be simple enough to maximize image throughput, yet sophisticated and robust enough to adapt to a wide range of sensors and variations in noise.

CRAYFIS (beta) operates on a two-level triggering mechanism. First, a short calibration run is made prior to a data cycle where the number of pixels above a level threshold (L1) is counted, N_{L1}. During data collection, if an image contains more than N_{L1} pixels above threshold, all pixels above a *lower* threshold (L2) are saved into a sparse array, and queued for transmission to the web server. The rate of triggering is monitored, and L1 is increased until the triggering rate has dropped below a rate threshold that is set globally for all CRAYFIS smartphones. This trigger algorithm is fast and simple; albeit frequently thwarted by very noisy and abnormally-active pixels, and changes in ambient light levels. A next-generation trigger algorithm is explored in Chapter 4.4.

3.3 Principles of Operation

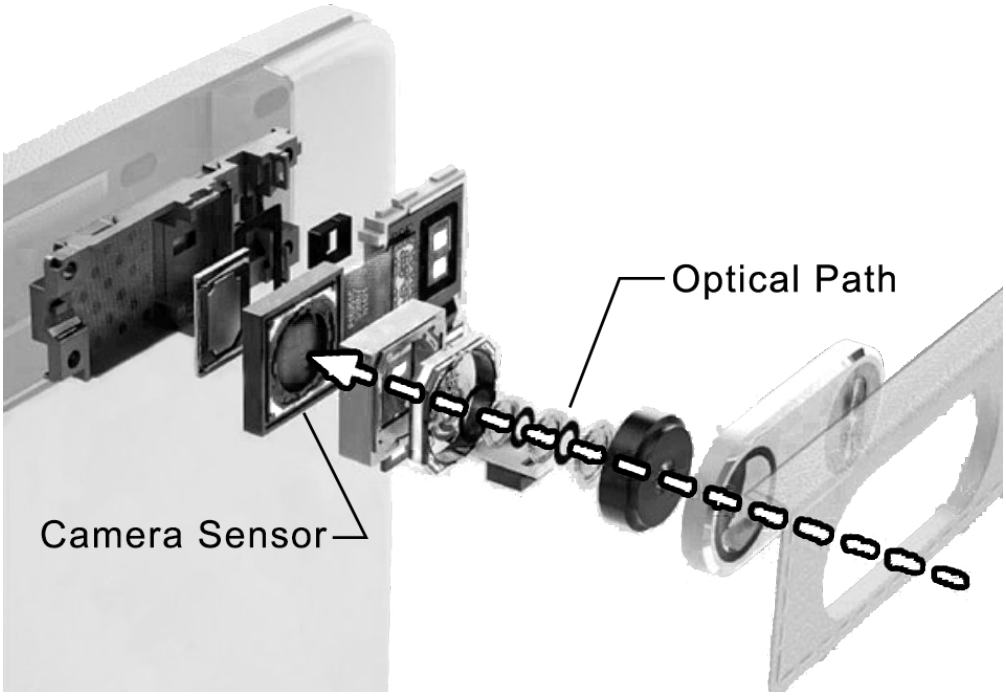


Figure 3.2: A typical smartphone camera sensor package, exploded view[†]. For photography applications, light enters from the right, passing through lenses as identified by the dashed-arrow, and strikes the camera sensor. The CRAYFIS application, however, detects elementary particles that have punched through the smartphone and sensor; the optical path in this case is not relevant as high-energy particles can pass through the entire device regardless the incident direction and relative orientation of the smartphone.

CRAYFIS is only possible due to the confluence of a couple of, now-ubiquitous technologies that have only just come to age in the last decade. The first smartphones—and separately, camera phones—hit the consumer marketplace in the early 1990s originally as cordless (landline) technologies. Nearly ten years later, in the early 2000s, modern (mobile) smartphones—with cameras—were developed, but it was not until another ten years later in 2010 when open application development was fully supported by major industry providers.

[†]Original image: `https://www.phonearena.com/news/Detailed-breakdown-of-the-unorthodox-camera-module-on-the-Oppo-N3-appears_id61983`

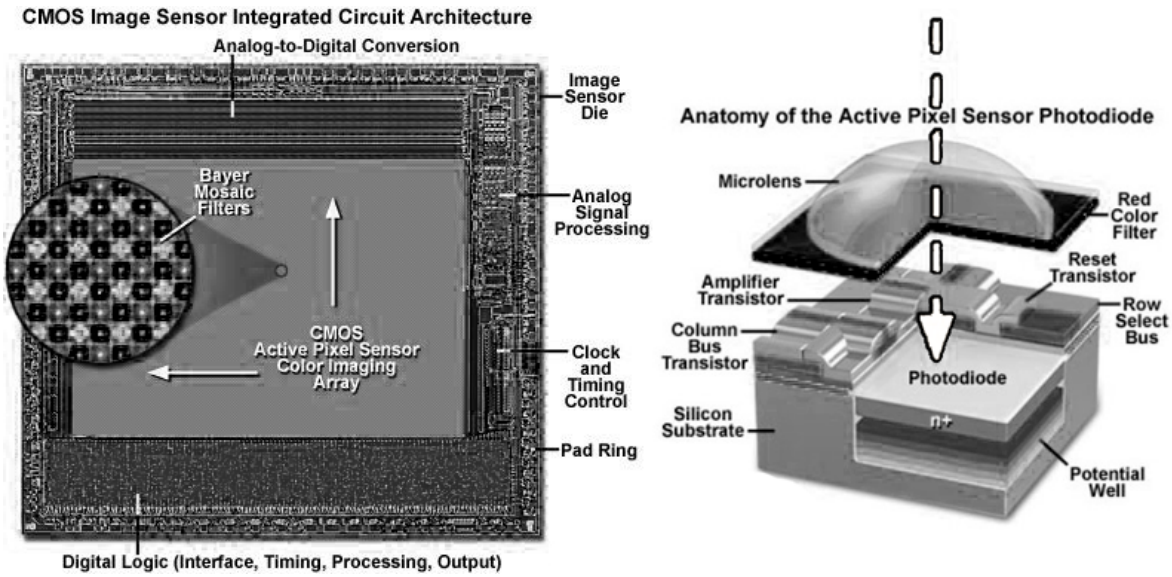


Figure 3.3: Left, an enlarged typical camera sensor die. The active sensing component is (with very few exceptions†) the CMOS pixel array shown central to the die. Right, a conceptual illustration of pixel technology, of which at least two general design sub-categories exist with a great variation in dimensions and component layouts, but those differences are not significant for this discussion. Incoming light is shown (as an arrow) passing through a microlens and color filter before striking the photodiode‡. The filter layer is an alternating pattern of red, green and blue wavelength filters known collectively as a *Bayer mosaic filter* as shown on the die (left). One photodiode (the active sensing element, typically under 1 µm×1 µm×5 µm in dimension) lies below each lens and filter, and in practice may only be a fraction of the total single-pixel area.

The modern smartphone camera (Fig. 3.2) is in essence an array of millions of microscopic *photodiodes* (Fig. 3.3). The photodiode pairs the photoelectric effect with semiconductor physics to act as a transducer of deposited energy into voltage (Fig. 3.4), which is then interpreted as pixel brightness by the camera. Despite being optimized for optical light conversion, any passing particle that deposits around an electrovolt of energy or more in the photodiode could be detectable, at least in principle. Broadly speaking, energy deposition is correlated with interpreted pixel brightness; however, the exact relationship is

†Advances in Complementary Metal-Oxide Semiconductor (CMOS) image sensor fabrication over the last two decades have shown better sensor performance and pixel density at substantially cheaper prices than comparable legacy Charged-Coupled Device (CCD) technologies. With only rare exceptions, all smartphone camera sensors are CMOS-fabrication based. In either case, both technologies exploit the photoelectric effect as their principle of operation, and are therefore both applicable to CRAYFIS.

‡Original images: `https://www.olympus-lifescience.com/en/microscope-resource/primer/digitalimaging/cmosimagesensors/`

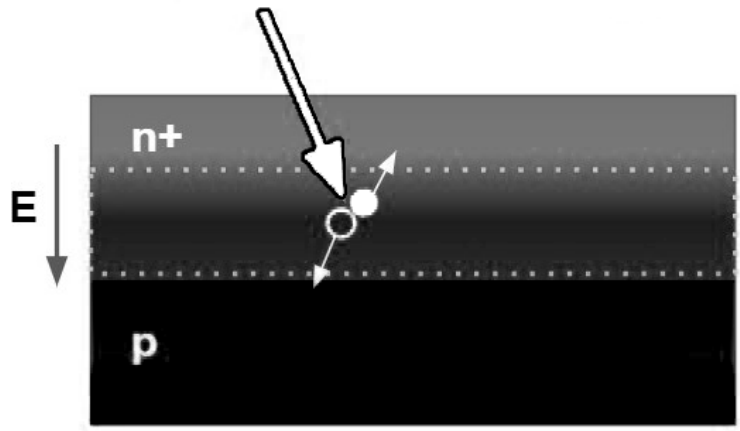


Figure 3.4: All solid-state light-sensitive sensors, regardless of the technological architecture (*e.g.*, CCD, CMOS and sub-variations), ultimately exploit the *photoelectric effect* for their operation. The energy of a photon is absorbed by an electron, liberating it from the crystal lattice valence (*i.e.*, bound) energy band into the conduction (*i.e.*, free) band where its excess energy allows it to migrate about the material. This crystalline material is typically Silicon for a number of practical and chemical advantages, which for brevity need not be addressed. *Intrinsic* (pure) Silicon forms a covalently-bonded lattice with 14 electrons surrounding each atom. *Dopants* (elements of neighboring chemical groups) are diffused into the intrinsic Silicon lattice, disrupting the uniform charge density. Dopants with more (less) than 14 electrons create *n-type* (*p-type*) Silicon, respectively. Unequal doping between n- and p-type Silicon is identified by one or more plusses ("+") following the greater dopant. The details of dopant selection, concentration and diffusion profile alter the performance of a photodiode, but does not affect the underlying principle of operation. The n-type doped region has greater electron concentration than the p-type, and some of the electrons naturally diffuse into the p-type lattice. However, this diffusion-driven migration causes a charge imbalance as both doped regions are initially electrically neutral. The loss (gain) of electrons in the n-type (p-type) region from diffusion creates a net positive (negative) charge. In short, the difference in electron concentration between regions drives charge diffusion, which results in a restorative electric field from n-type to p-type. This intrinsic electric field is the key to photovoltaic action wherein electrons excited out of the lattice into the conduction band can be swept back into the n-type Silicon and collected by a metal electrode (not shown). The area contained within the dotted lines represents the *depletion region*, or region where diffusion occurs resulting in the restorative electric field; many factors beyond the scope of this topic effect the size and charge profile of this region. The arrow shown represents an incident photon that partially passes through the photodiode before being absorbed by an electron (shown as a solid circle). The liberation of this electron creates a vacancy (a *hole*) in the lattice (shown as an empty circle) that effectively propagates into the p-type Silicon as other electrons take its place, creating a propagating vacancy as they do.

both complex and highly variable. In order to accurately distinguish these activated pixels in a camera image, the rest of the sensor must be made as dark as feasible. Therefore, our app is designed to operate when the smartphone is rested on a surface such as a table or nightstand, which mitigates ambient light from reaching the camera sensor through its optical path.

As mentioned, UHECRs collide with atmospheric nuclei to induce EASs of elementary particles and nuclear fragments; however, by the time the shower is only a couple kilometers above sea level, the diversity of shower products has been greatly reduced to mainly photons, electrons, neutrinos, muons, protons and neutrons (Fig. 2.2).

We focus our attention on muons, which have excellent penetrating power and high detection efficiency, and photons, which have high densities in EASs. Electrons, although numerous with high efficiency on an exposed sensor, may be blocked by buildings, phone cases or camera lenses. Hadronic particles, although penetrating and detection-efficient, are much less common at ground level. A detailed sensitivity analysis of CRAYFIS devices to EAS events follows in the next chapter, culminating in Fig. 4.11.

Chapter 4

Calibration

One of the greatest advantages to a global network of smartphones is also its greatest disadvantage—the hardware is purchased and maintained by the end-user. In order to reconstruct EASs, a remote and robust means of understanding the response of smartphones to various incident particle densities is needed for a network of *ad hoc* devices fundamentally and forever out of our reach. First, a discussion of baseline camera pixel sensor response is made (§4.1), followed by a three-pronged approach to calibration where particle detection efficiencies for a sample of individual test devices are measured in the laboratory (§4.2); then, *in situ* performance from 3 years of beta-tester data is evaluated and compared with laboratory-based expectations (§4.3); and lastly, the cross-calibration of a small test array with an existing precision observatory is outlined (§4.4).

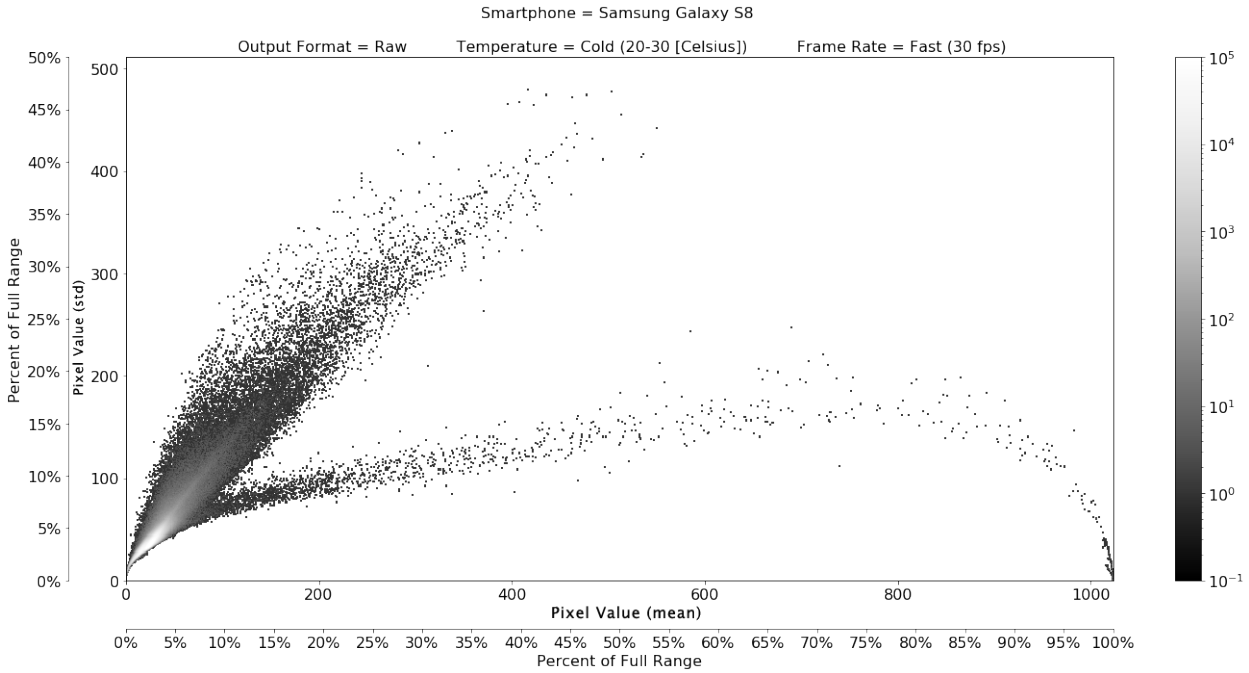
4.1 Sensor Response

With the camera sensor acting as a transducer of deposited energy from passing particles to pixel brightness, great care is taken to understand the baseline response. Although the chance for false-positive particle identification is minimized with maximal dynamic range

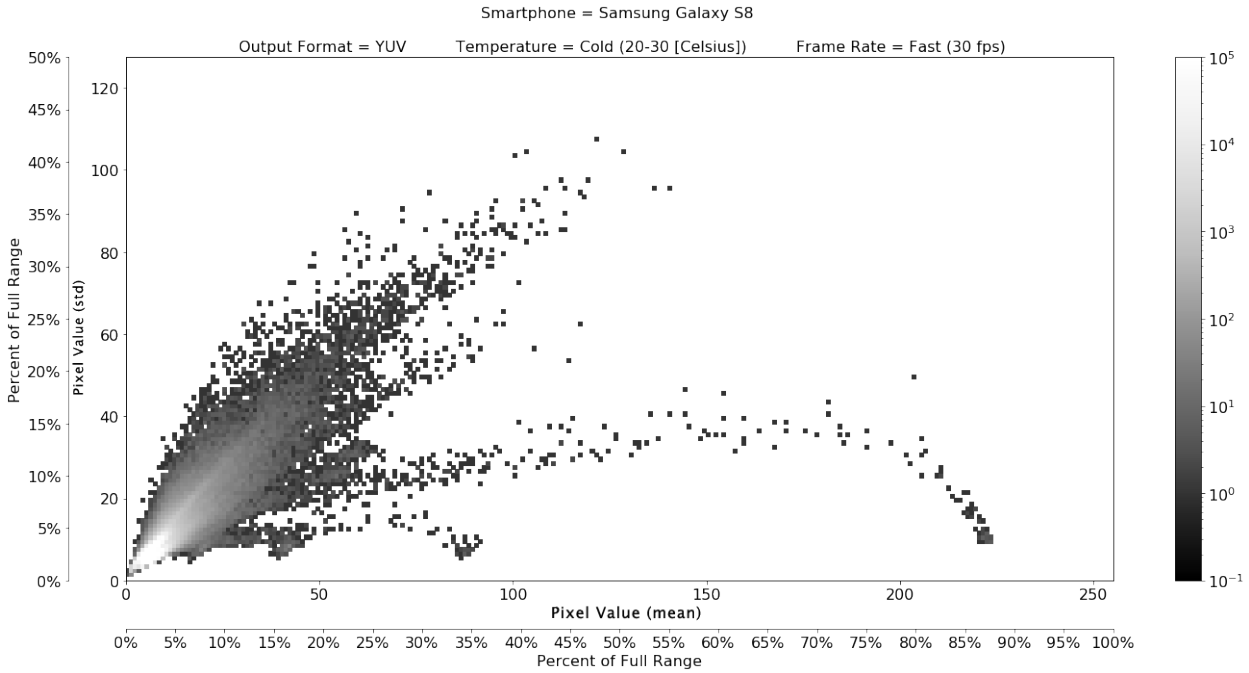
sensitivity if the sensor is otherwise shielded from ambient light, even when well-covered by tape or other means, a pixel sensor does not appear completely dark—a noise floor from various thermal, electrical and digital signal processing sources is always present mostly on the order of a few-percent of the full-scale brightness value (255 for standard 8-bit, and 1023 for 10-bit—read out as 16-bit—"raw" sensor data). Unfortunately, a model of the statistical relationship between types of particles, their energies and the digitized pixel brightness value has not yet been forthcoming despite ongoing efforts. Qualitatively, laboratory testing (§4.2) of photon energy deposition conversion appears to favor comparatively somewhat-lower pixel values, and *in situ* data (§4.3) suggests muons likely favor higher pixel values.

Figs. 4.1 and 4.2 demonstrate the variability of pixel noise for a single Samsung Galaxy S8 sensor (shielded with electrical tape) at different temperatures, exposures and image processing levels. Additional pixel characteristics for a Google Pixel 2XL and Huawei P9 Lite Mini are provided in Appendix D where it can be seen that there is great variation in pixel characteristics across different smartphone models (there is also variability between smartphones of the same model, but generally less so). All smartphones support the 8-bit YUV image format—the "Y" channel is the monochromatic representation of the image, with "U" and "V" channels providing (discardable) coloring information. However, YUV pixel output is always pre-processed by the camera hardware (identifiable by features in, for instance, Fig. 4.2b that are not present in Fig. 4.2a). A growing fraction of modern smartphones support the 10-bit (read as 16-bit) RAW image format that usually goes largely unprocessed by camera hardware; however this is not guaranteed (*e.g.*, Fig. D.3).

Most pixels fluctuate around 5% of the full dynamic range under "dark" conditions. Yet, a number pixel groupings distinguish themselves in these figures. Numerous studies have been unable to correlate these groupings with pixel locations (Fig. 4.3). The causes for these pixel distributions is not understood, but "good" ("bad") pixels generally *tend* to stay

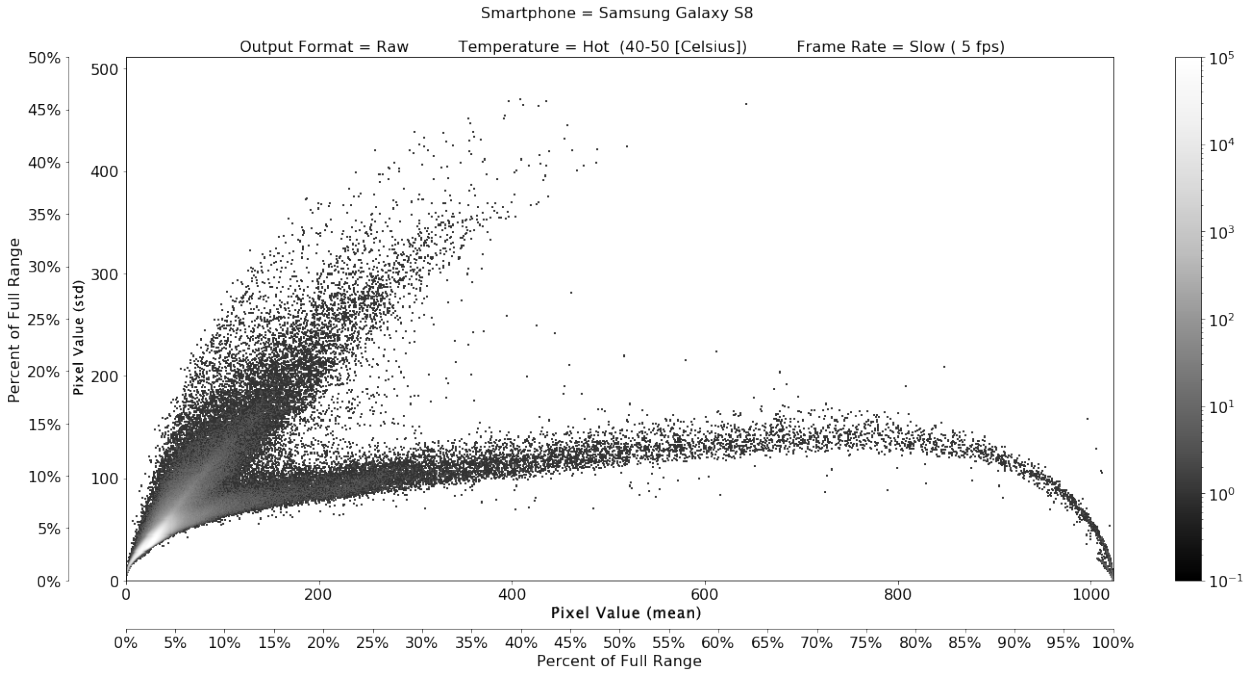


(a) RAW image format, cold bath, short exposure

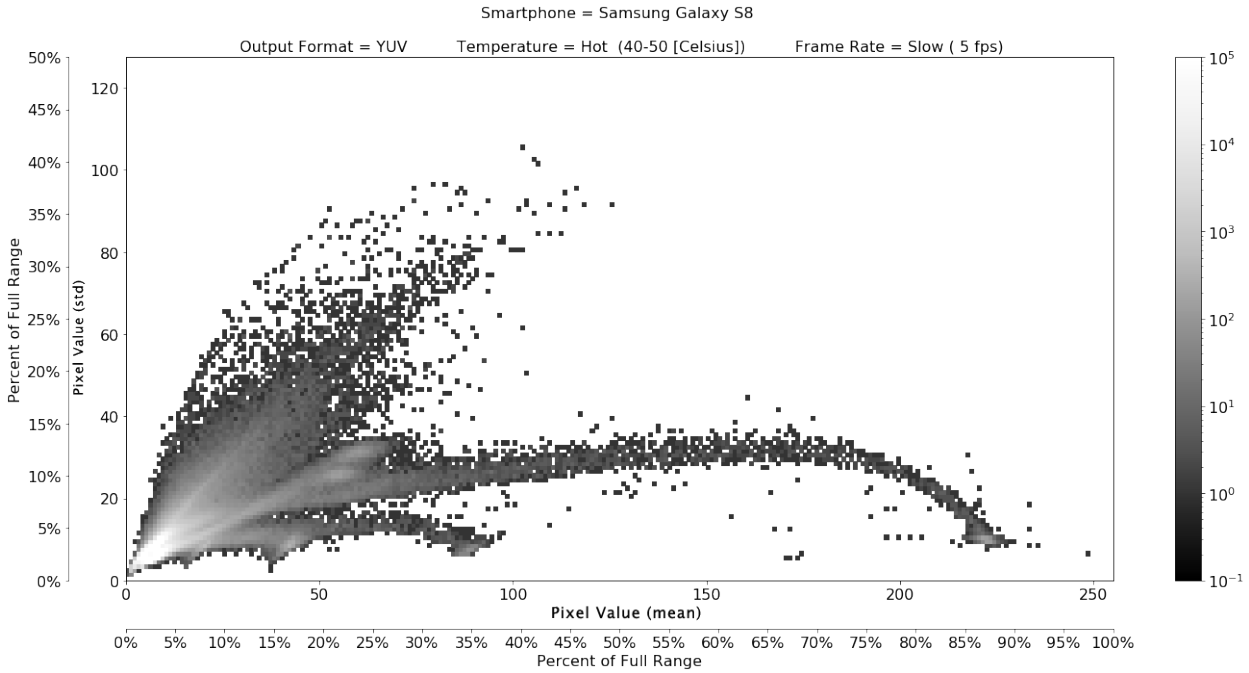


(b) YUV image format, cold bath, short exposure

Figure 4.1: Mean pixel value versus standard deviation from 1,000 image frames for a light-shielded Samsung Galaxy S8 camera sensor. The axes are binned in pixel brightness steps, with each point representing the aggregate contribution of each of 12,192,768 pixels. Data was taken under "cold" conditions ($20° - 30°$ C) at maximum frame rate (30 fps, or ∼30 ms exposure). Top, RAW (10-bit, minimally processed) pixel output. Bottom, YUV (8-bit, pre-processed) pixel output from the same sensor. See text for discussion.



(a) RAW image format, hot bath, long exposure



(b) YUV image format, hot bath, long exposure

Figure 4.2: Mean pixel value versus standard deviation from 1,000 image frames for a light-shielded Samsung Galaxy S8 camera sensor. The axes are binned in pixel brightness steps, with each point representing the aggregate contribution of each of 12,192,768 pixels. Data was taken under "hot" conditions ($40° - 50°$ C) at a low frame rate (5 fps, or $\sim$200 ms exposure). Top, RAW (10-bit, minimally processed) pixel output. Bottom, YUV (8-bit, pre-processed) pixel output from the same sensor. See text for discussion.

(a) RAW image format, hot bath, long exposure

(b) YUV image format, hot bath, long exposure

Figure 4.3: Locations (white) of poorly-performing pixels (those beyond 5% of full scale mean and standard deviation) for a Samsung Galaxy S8 camera sensor (reference Fig.4.2). Top (bottom) RAW (YUV) image format. See text for discussion.

good (bad) over time. Presumably, the distinct groupings in YUV pixel response images (versus those in RAW) stem from the camera hardware trying to correct for anomalous pixel responses. Extreme cases like the Huawei P9 Lite Mini (Fig. D.3) show that even when configured for RAW imagery, there can still be a substantial amount of pre-processing. It is not clear how this pre-processing limits the dynamic range of noisy pixels—to wit, were a hypothetical particle to strike a minimally-processed pixel that subsequently responds, say, at full-scale brightness, how would the brightness response differ had the pixel been pre-processed under otherwise identical conditions? Additionally, it has been found that when data is taken while ambient light is not entirely blocked from the camera sensor by tape (*e.g.*, simply setting the smartphone on a surface), the apparent pre-processing applied to a given pixel does not always appear consistent between data sessions. Consequently, before data collection (and amid long collection runs), some sort of calibration cycle must be performed where the response of each individual pixel is sampled so that "bad" (untrustworthy) pixels can be identified. Untrustworthy pixels must then be ignored during data triggering, and possibly omitted entirely from downstream data depending on the severity of the pixel performance issues.

4.2 Laboratory Testing

Preliminary studies were performed in a controlled laboratory setting to assess the observational power of smartphones to selected ionizing radiation. We focus on photons and muons as they are both numerous and highly-penetrating (Chapter 2). Laboratory photons were provided by calibrated radioactive sources (§4.2.1). Muon beams were provided by CERN in Geneva, Switzerland (§4.2.2), and Fermilab in Chicago[†].

Although measuring the detection efficiency of individual pixels is beyond the means of readily available test equipment, such a measurement in practice is not especially valuable

[†]The results of which are presented in a pending paper

as a typical smartphone contains on the order of 10 million pixels, and virtually no two perform exactly alike—a non-trivial number (typically on the order of a percent) are defectively-dark (dead) or hyper-active (hot), and nearly every pixel responds differently to changes with temperature, exposure and over time. In addition to an order of magnitude variation in overall pixel size across different camera sensors, and the manufacturing variations in geometric sizes of single pixels, there is neither a standard circuit board layout configuration nor standard sub-technology common across all sensors—some sensor pixels are only a very small fraction of the actual pixel footprint with buried photodiode wells, while others have larger surface-level photodiodes. And still others take on every variation in-between. There is also substantial variability in electron collection and amplification design layers such that when all these factors are taken together, pixel-level efficiency is not translatable across a sensor, let alone across devices.

The practical efficiency of interest then is an average total sensor response; yet, the measurement of such a quantity can only be made with knowledge of the incident flux of test particles that strike the sensor chip. Therefore, the geometric area of the sensor chip is intimately entangled with a measurement of efficiency. Bearing in mind that the sensor geometric area is substantially larger than the contained active pixel area (Fig. 3.3), the most sensible way to deal with this complication is to measure overall performance in terms of the product of geometric area and detection efficiency—the *effective area*, $A\epsilon$. Once the effective area is known, a conservative estimate of the *effective particle efficiency*, ϵ, can be made by dividing out the sensor area, A; however, for the reasons stated, this value doesn't directly represent the performance of an average pixel, rather, it is a sensor-wide average particle detection efficiency.

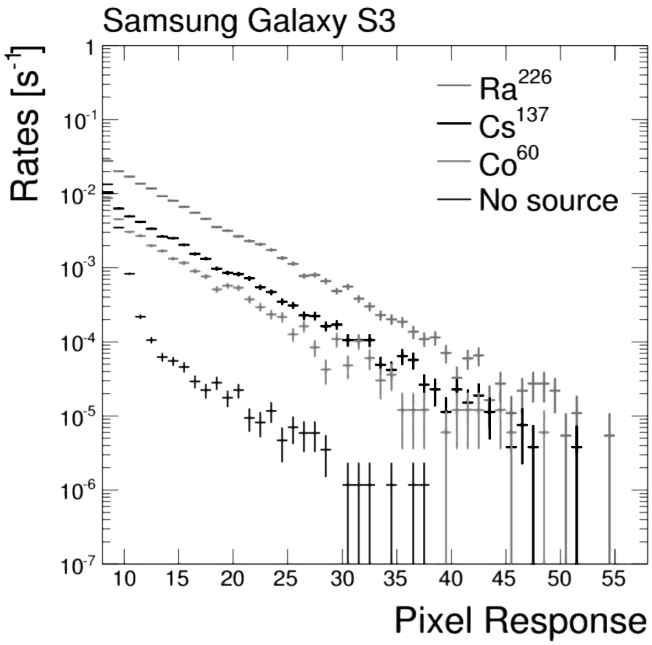


Figure 4.4: Distribution of observed pixel response values in a Samsung Galaxy S3 phone when exposed to sources which emit photons between 30–1200 keV, and without any source. The differences in rates are due to the different activity of the sources. The data with no source shows a falling noise distribution and a tail attributed to cosmic muons. Other phone models show qualitatively similar behavior. From top down, Ra^{226} (gray), Cs^{137} (black), Co^{60} (gray), No source (black).

4.2.1 Radioactive Sources

The response of several popular smartphone models to photons was measured in the lab using gamma rays from the radioactive decays of Ra^{226} ($E\gamma = 30 - 600$ keV), Co^{60} ($E\gamma = 1.2 - 1.3$ MeV) and Cs^{137} ($E\gamma \leq 700$ keV). These energies are consistent with the majority of photons expected at ground level (Fig. 2.5), and the activity of each source, R, was measured with a high-precision photon counter. As a representative example, the measured pixel response of a Samsung Galaxy S3 is shown in Fig. 4.4; similar spectra are seen in other Android models as well as iPhones. The photon sources were found to emit isotropically so that the effective area, $A\epsilon$, could be determined by exposing a smartphone to the source (N_{obs}) a distance d away for a duration Δt:

$$\frac{N_{\text{obs}}}{A\epsilon} = \frac{R\ \Delta t}{4\pi\ d^2} \tag{4.1}$$

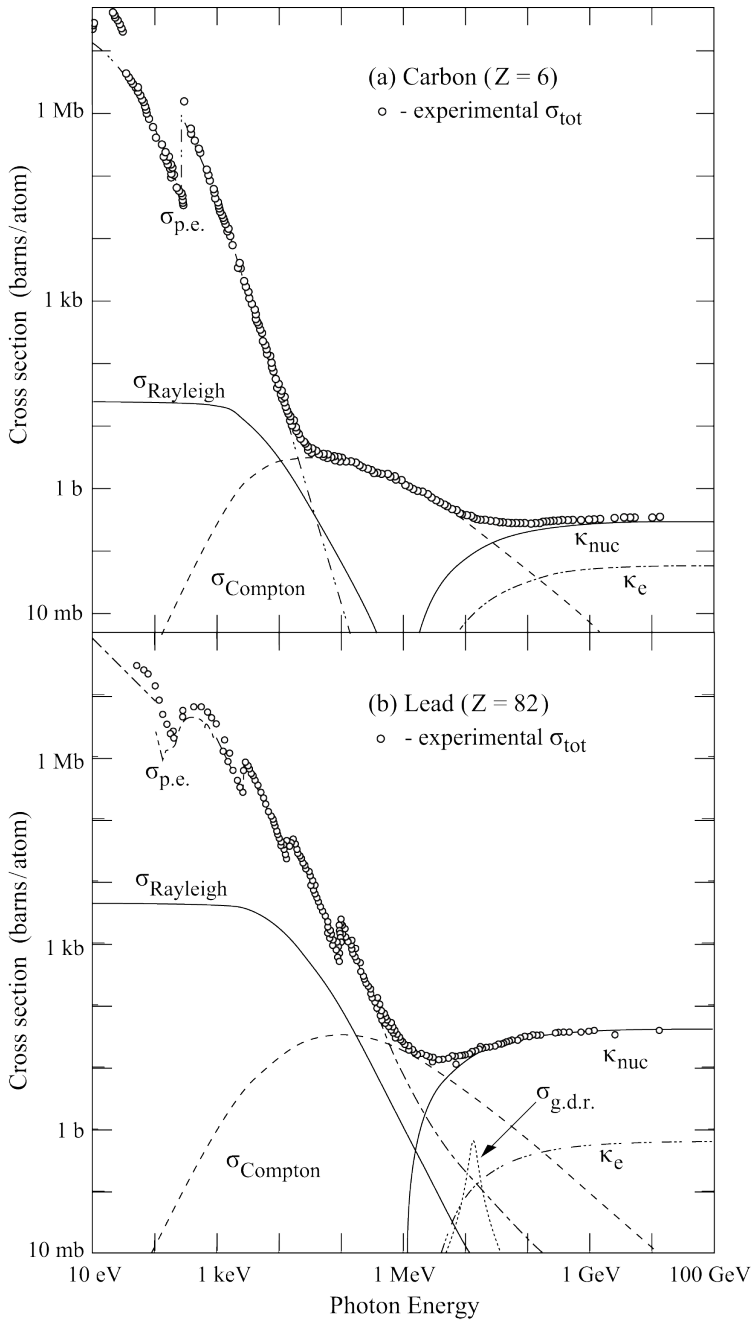


Figure 4.5: Photon total cross sections as a function of energy in Carbon and Lead, showing the contributions of different processes (reproduction of M. Tanabashi (2018), Fig. 33.15).

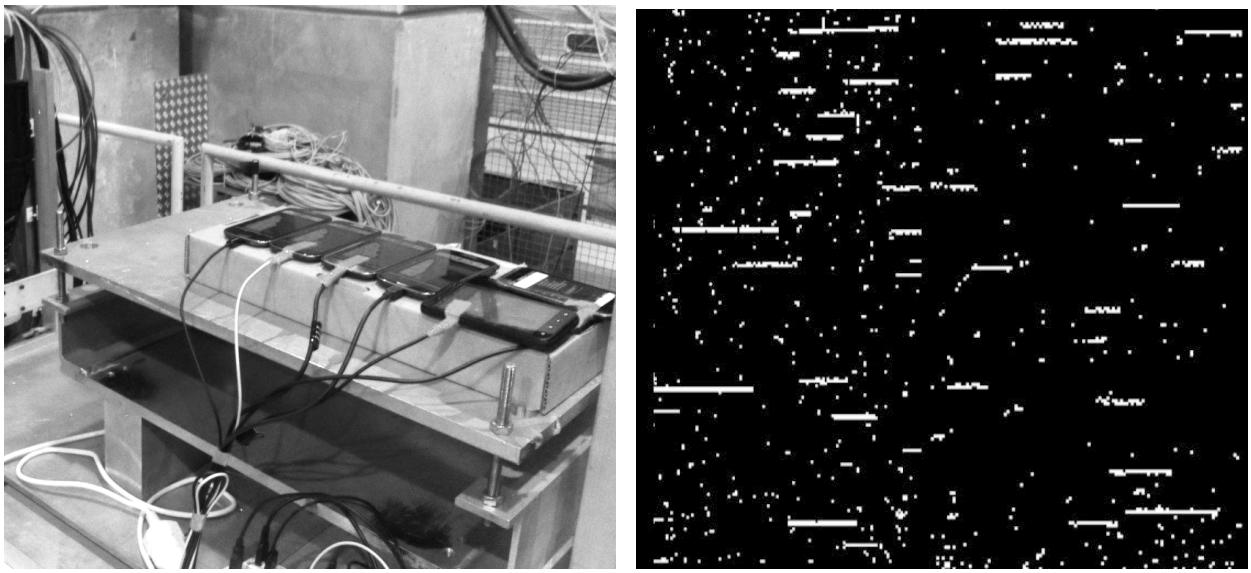
$\sigma_{\text{p.e.}}$	=	Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh}	=	Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton}	=	Incoherent scattering (Compton scattering off an electron)
κ_{nuc}	=	Pair production, nuclear field
κ_{e}	=	Pair production, electron field
$\sigma_{\text{g.d.r.}}$	=	Photonuclear interactions, most notably the Giant Dipole Resonance. In these interactions, the target nucleus is broken up.

The effective area for photons incident normal to the camera sensor was found to typically range from $A\epsilon \sim 10^{-5}$ to 10^{-4} cm^2. The typical sensor geometric area, A (which is notably larger than actual pixel area, Chapter 3), was found from manufacturer specification to vary around $\sim 10^{-1}$ cm^2. For older technology, the actual light-sensitive pixel element could be as small as a quarter the size of the total pixel footprint (the rest taken up by transistors and contacts), yet for the latest fabrication technologies, the sensitive area usually exceeds 90%. Therefore, to a first-order conservative approximation, we expect an effective high-energy photon detection performance efficiency for most smartphone camera sensors to be somewhere around $\epsilon \sim 0.01\%$ with the understanding that the actual response is highly variable across devices, and dependent on photon energy and angle of incidence.

As a cross-check of our measurements, the photon interaction cross section (Fig. 4.5) for EAS photons could be expected to range somewhere between 1 and 10 barns/atom (*i.e.*, for photon energies above several hundred keV), and the interaction will be likely dominated by Compton scattering and pair-production. Both processes are somewhat favorable to photoelectric conversion in terms of detection likelihood as at least one high-energy electron projectile can be produced with the potential of triggering nearby pixels—making the event more distinguishable from single-pixel shot noise. Estimating the density of a typical camera sensor to be on the order of 2.3 g/cm^3 with average molecular mass around 28 g/mol, the associated approximate mean interaction path for this cross-section could then be expected to be on the order of $\sim$1 cm. With a typical camera sensor thickness expected to be on the order of $\sim$1 µm, the fractional intensity of photons to interact is:

$$\epsilon^* \sim \frac{I}{I_0} = 1 - e^{-t/\lambda} \tag{4.2}$$

for thickness t and mean path λ. This gives a roughly-analytical approximate value for the interaction efficiency, $\epsilon^* \sim 0.01\%$. Although this result happens to numerically match our measured effective efficiency, ϵ, it in no way represents a firm justification or reason for it;



(a) Setup at CERN

(b) Composite image of activated pixels in data collected

Figure 4.6: Smartphones arranged at CERN such that the muon beam was incident on the side of the sensor, which gave visible tracks where muons pass through several pixels.

notwithstanding it does however serve its purpose of providing support that our result seems reasonable.

4.2.2 Accelerators

As the third-most abundant (and most penetrating) component of an EAS, muons are likely the most important particle for CRAYFIS EAS detection. Several popular smartphone models were exposed to a muon beam at CERN in Geneva, Switzerland as diagrammed in Fig. 4.6. The beam was incident on the side of the smartphone, and the image has clear muon tracks from that direction; the nearly unbroken nature of these tracks implies a fairly high detection efficiency, albeit it is not possible to extract an effective area for muon interaction from this test alone as the incident muon flux was not well known.

From Fig. 2.6, it is apparent that most surface-level muons have an energy between $\sim 0.1 - 10$ GeV. Muons at this energy are minimally ionizing (Fig. 4.7, although positive muons on Copper is shown, the figure is fairly representative of energy loss in Silicon) and

on the average lose around 1.7 MeV cm^2/g of energy passing through materials. As in §4.2.1, taking the density of a camera sensor to be that of Silicon and assuming a 1 µm thickness, a passing muon will likely deposit a few hundred eV of energy into the sensor, possibly sending an electron or two into neighboring pixels. This rough approximation is validated by GEANT4 (Agostinelli et al. (2003)) simulations of muons scattering normal to a solid block of intrinsic Silicon. However, a detailed model of muon interactions with camera sensors is still a work in progress. Preliminary considerations place a conservative effective efficiency to muons around 50%, so a typical sensor likely has an effective area, $A\epsilon$ around $\sim$0.05 cm^2.

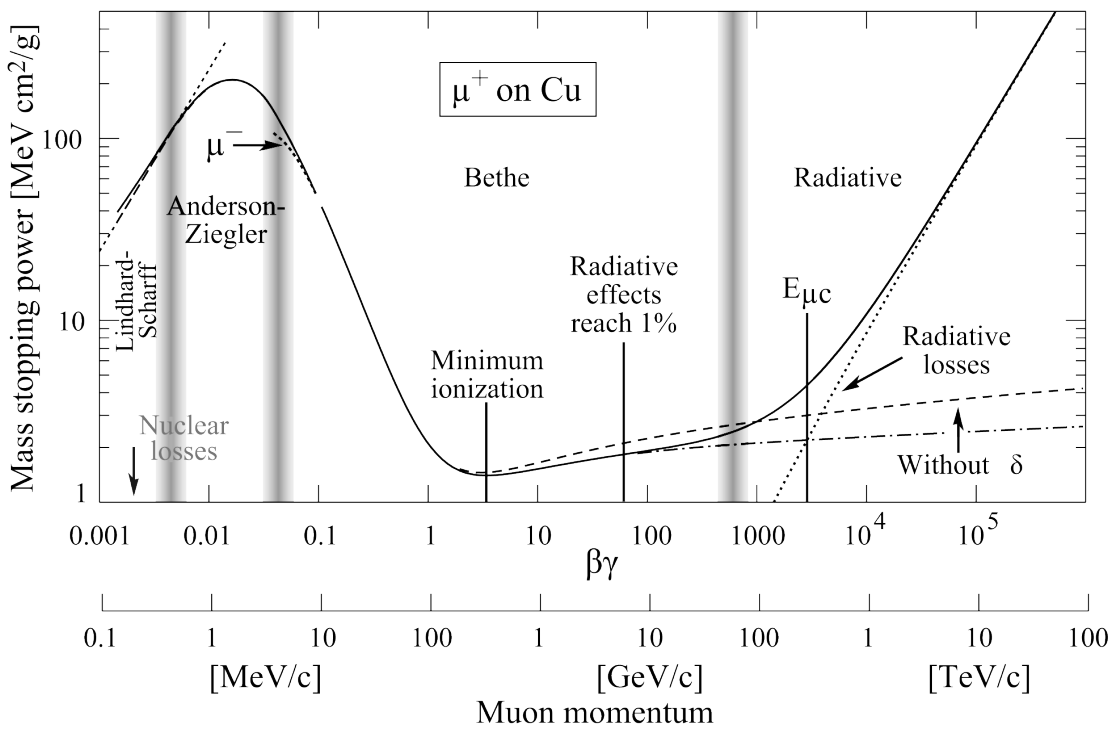


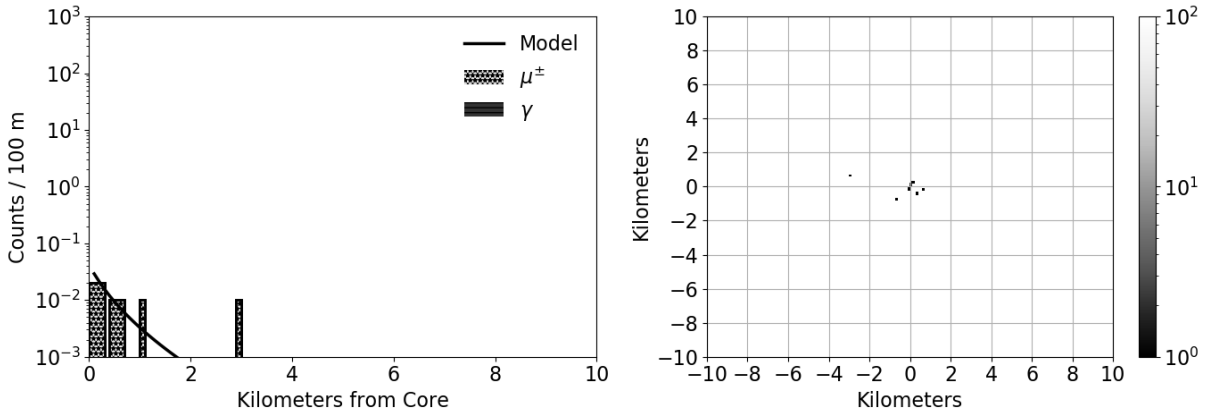
Figure 4.7: Mass stopping power ($= \langle -dE/dx \rangle$) for positive muons in Copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Vertical bands indicate the boundaries between different approximations (see source of this figure for more information). The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies. dE/dx in the radiative region is not simply a function of β. This figure is a reproduction of M. Tanabashi (2018), Fig. 33.1.

4.2.3 Preliminary Sensitivity

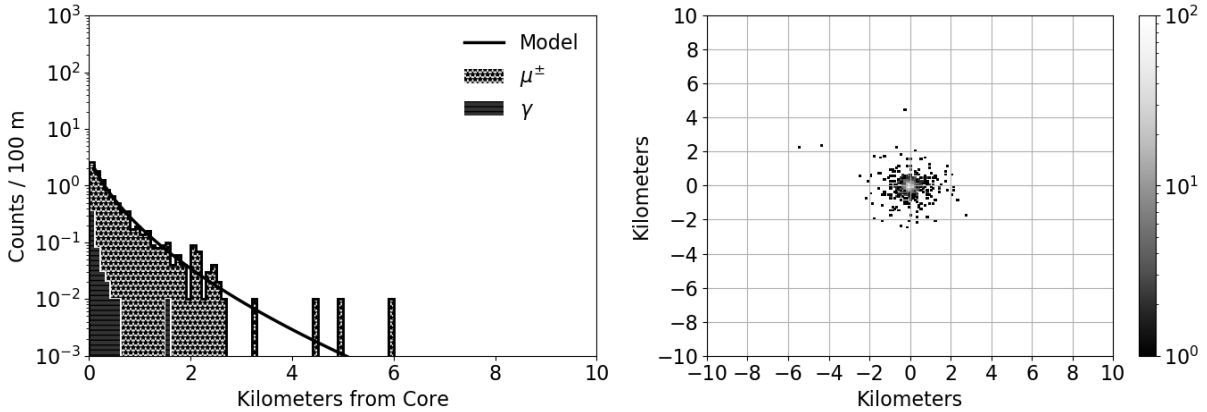
With conservative effective area measurements and the EKA EAS model, Eq. (2.11), Monte Carlo simulations can be performed to assess the tentative sensitivity of a CRAYFIS array. A real CRAYFIS array is sparse and *ad hoc*. However, to establish an upper limit on performance, a contiguous array of average-sized smartphones, A_{phone} (6.25 cm $\times$ 11.25 cm = 70.3 cm^2), each with an average-sized camera sensor (0.15 cm^2), are arranged on a virtual grid with no space between devices. Vertical photon and ^{238}U UHECR primaries were then generated with energies ranging from 10^{15} to 10^{21}. Individual randomly-drawn photons and muons were allowed to strike the array. Each virtual smartphone then either registers a "hit" or not based off the chance of passing through the camera sensor and being detected ($A\epsilon/A_{\text{phone}}$), where $A\epsilon$ is the effective area for either photon or muon. From Figs. 4.8 and 4.9, it is apparent that the muon channel dominates CRAYFIS detection, and photons are most likely to be observed within a kilometer of the shower core. Were it possible to disentangle the muon component from the photon component through image processing, an estimate on primary composition might be made (Fig. 4.10); however, machine learning-based attempts have yet to be able to distinguish muons from photons from noise with sufficient precision.

Obviously, a contiguous array represents an unrealistic scenario with a device density of around 5.7×10^8 smartphones/km^2. Therefore, the effect of smartphone density is explored by assuming at least 5† separate smartphones must register a hit at the same time within a 10 km radius to be considered a potential EAS event (Fig. 4.11). As an illustrative example, were 1% of the most population dense city in the United States (Los Angeles) to adopt CRAYFIS, an array of roughly 2.3 times the area of the largest EAS observatory (Pierre Auger Observatory, Aab et al. (2015)) would potentially be sensitive to $> 10^{15}$ eV EASs. This example shows both the potential power for CRAYFIS, but also its primary

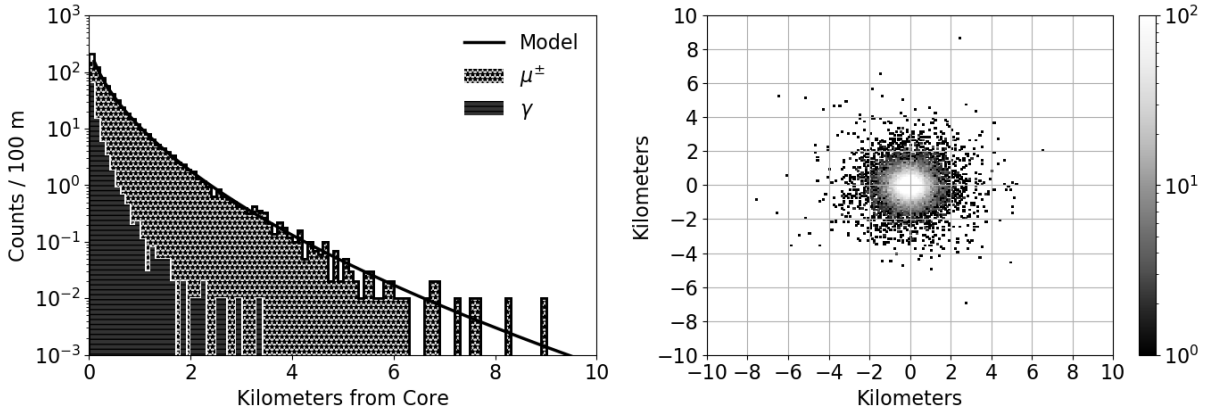
†A justification for this number is provided in §4.3.2.



(a) 10^{15} eV photon primary, sea level observation

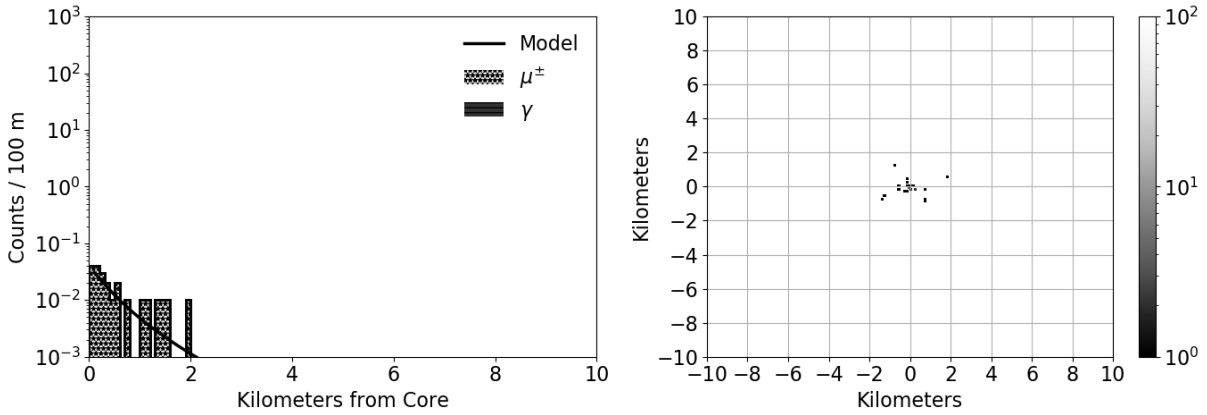


(b) 10^{17} eV photon primary, sea level observation

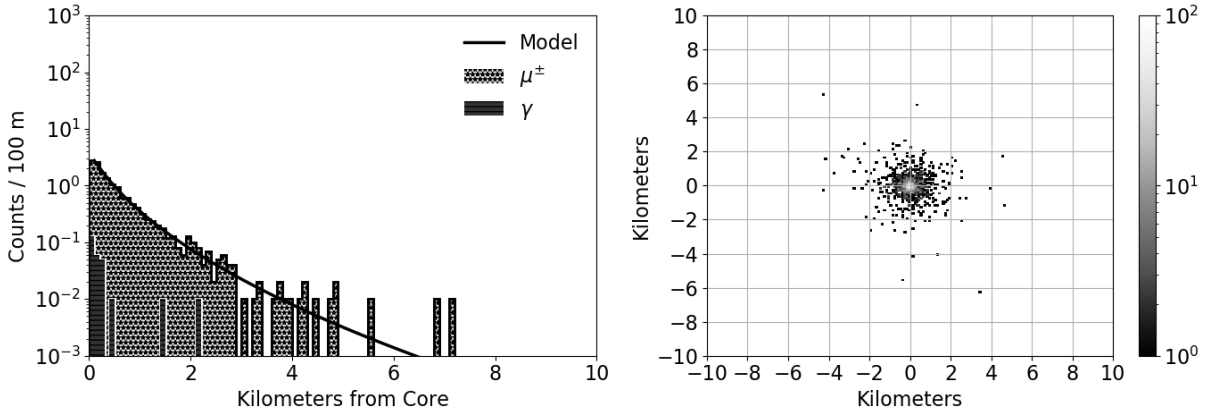


(c) 10^{19} eV photon primary, sea level observation

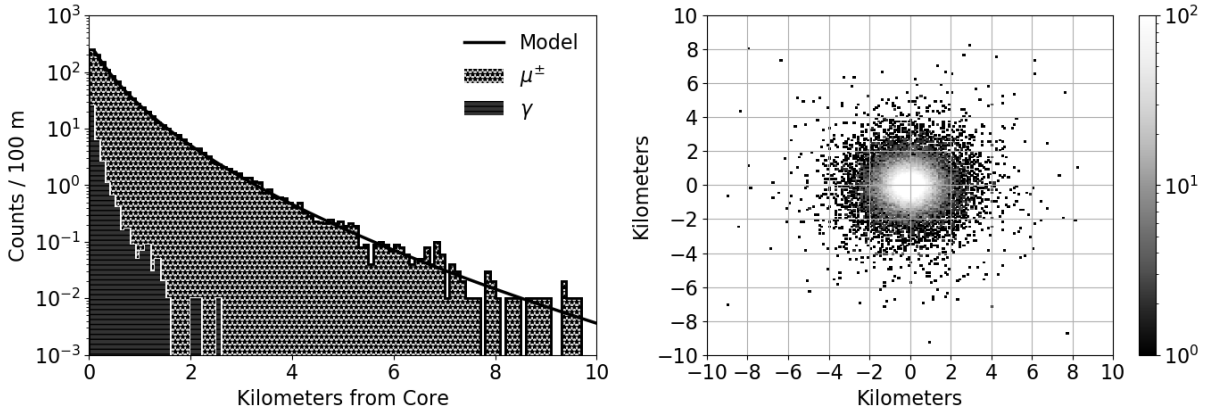
Figure 4.8: Left, simulated total smartphone camera sensor "hits" per 100 meters from the shower core from muons and photons. The total contribution of both, using effective areas measured in the laboratory and the EKA EAS model developed in Chapter 2.1.3, is also plotted [solid line]. Right, total particle detections on a virtual, contiguous CRAYFIS array. Each bin represents an area of 100 m $\times$ 100 m containing approximately 5.7×10^6 typical smartphones (see text).



(a) 10^{15} eV Uranium primary, sea level observation



(b) 10^{17} eV Uranium primary, sea level observation



(c) 10^{19} eV Uranium primary, sea level observation

Figure 4.9: Left, simulated total smartphone camera sensor "hits" per 100 meters from the shower core from muons and photons. The total contribution of both, using effective areas measured in the laboratory and the EKA EAS model developed in Chapter 2.1.3, is also plotted [solid line]. Right, total particle detections on a virtual, contiguous CRAYFIS array. Each bin represents an area of 100 m $\times$ 100 m containing approximately 5.7×10^6 typical smartphones (see text).

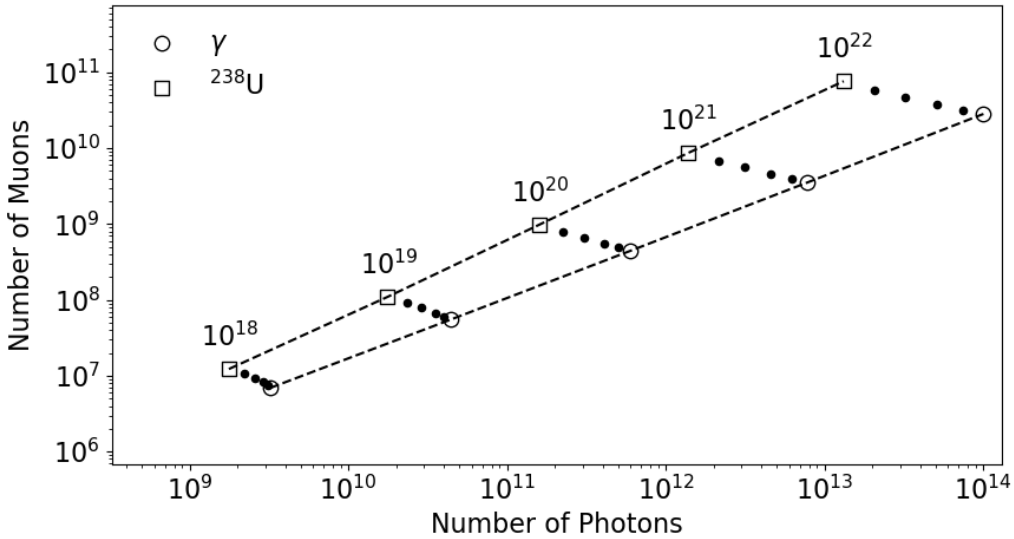
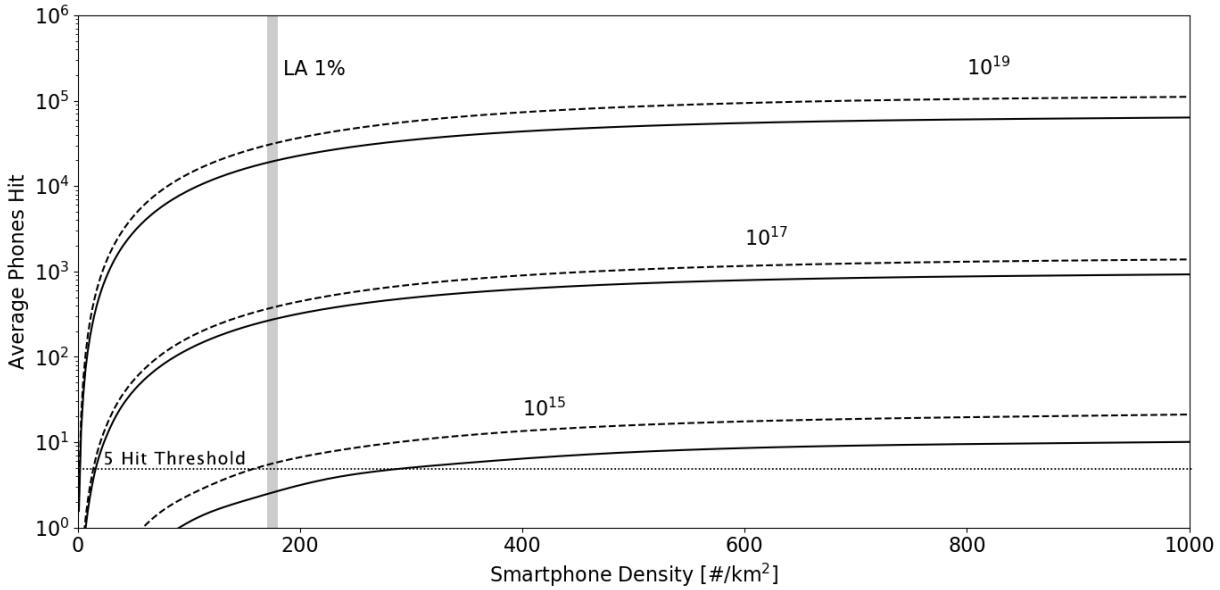


Figure 4.10: Total numbers of photons versus muons for EASs observed at sea level for primaries ranging from photons (open circles), protons, Helium, Oxygen, Iron to Uranium (open squares). Primary energies are shown next to each cluster.

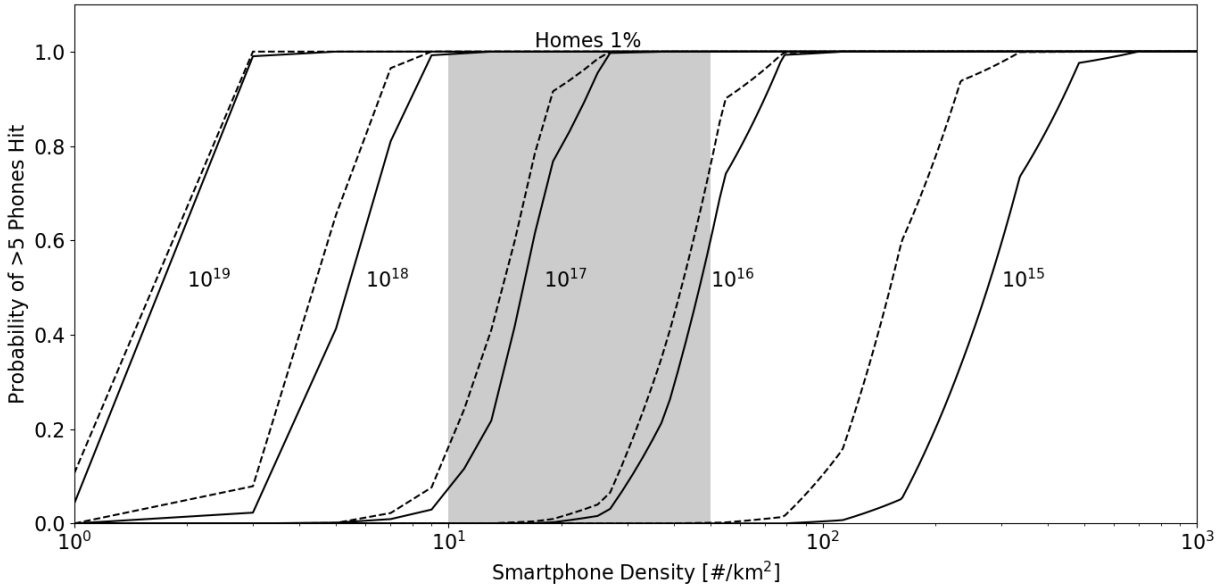
practical challenge: large-scale user adoption. Most cities are substantially less dense than Los Angeles, and for CRAYFIS to be effective, a substantial user adoption would be needed there. However, assuming CRAYFIS users plan to record data while sleeping at home, satellite imagery from Google Earth[‡] shows single-family residential housing density to commonly be around $\sim 1,000 - 5,000$ homes/km^2. Therefore, a density of 10 smartphones/km^2 (with potential sensitivity to $> 10^{17}$ eV EASs) could be made if 1% of residential homes had a single CRAYFIS smartphone. The user adoption threshold for dense residential housing complexes would be significantly lower, and residents living on ground floors of tall apartment buildings would still be fully sensitive to muons.

Lastly, although we have focused on photons and muons, other hadronic shower components, although not as penetrating as muons, are expected to have a comparable effective area for detection; therefore, by not considering their contribution to the number

[‡] `https://earth.google.com/`



(a) Expected CRAYFIS response to an EAS



(b) Expected sensitivity of CRAYFIS

Figure 4.11: Preliminary CRAYFIS sensitivity. Top, the average number of smartphones registering a "hit" from photons and muons as a function of smartphone density (linear scale) within 10 km radius of an EAS. Primary energies are listed by each curve. Photon primaries are shown in solid, Uranium primaries are shown dashed. The vertical bar denotes the smartphone density of 1% user adoption in the city of Los Angeles. Bottom, the probability for 5 or more smartphones to be hit in a single EAS as a function of smartphone density (logarithmic scale). The vertical band denotes the potential sensitivity threshold of 1% user adoption in single-family home communities.

of smartphones hit following an EAS, our estimated thresholds for sensitivity are slightly conservative.

4.3 *In Situ* Analysis

The CRAYFIS app has been in beta-testing development since 2015 with several thousand users contributing data across 4 continents. Whenever a new device joins the CRAYFIS network (and periodically after joining), the device must be calibrated and vetted for data quality before its data can be trusted in downstream analyses. Therefore, this section discusses strategies to accomplish this critical *in situ* calibration.

Strategies for individual smartphones can (in time) also lead to cross-check strategies for testing array-wide consistency across recurring device metrics such as smartphone model. These sorts of cross-checks obviously become more powerful with an increasing user-base, and currently only a handful of devices exist in data with matching smartphone models. Of these, only one pair of devices are relatively close (∼200 km) to each other with comparable exposures at different altitudes (Fig. 4.12). This pair becomes an interesting case study (§4.3.1) as it has long been established (as of 1912—translated into English, Hess (2018)) that air shower radiation increases with altitude, and most data collected so far (including data taken during air travel) supports this.

The most useful quantity to extract from any smartphone in calibration is its "all-particle" (assumed to be well-dominated by muons in practice) net effective area, $\langle A\epsilon \rangle$. Were the altitude-dependent total muon flux, $\Phi_\mu(h)$, known or otherwise estimated (Chapter 2), then $\langle A\epsilon \rangle$ could be estimated from,

$$\frac{N_{\text{obs}}}{\langle A\epsilon \rangle \, T_{\text{exp}}} = \Phi_\mu(h) \tag{4.3}$$

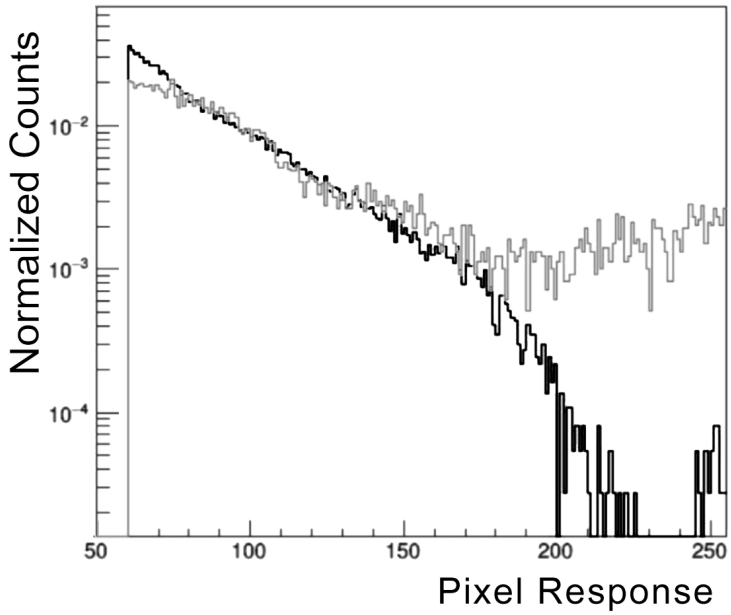


Figure 4.12: Two recorded aggregate spectra in beta-tester data†, illustrating likely cosmic muon detection attributed to the tail excess. One smartphone is near sea level (70 m a.s.l.) in Venice, Itally (black); the other (exhibiting the pronounced excess) at 810 m a.s.l. in Montalto, Itally (gray). Both smartphones are the same make and model. The spectra begins at pixel value 50 because of the L1 threshold (Chapter 4.1). The slow roll-off is indicative of many false-positives (noise) are present in data.

where N_{obs} is the number of events reported by the smartphone over its total exposure period, T_{exp}. However, several complications arise. For instance, there is unfortunately no record of the integrated exposure for each device in data as the CRAYFIS (beta) app operates in (nominally) 120 sec exposure blocks, with no guarantee that blocks with 0 events are transmitted. Furthermore, data might get deleted from devices before transmission under abnormal conditions (such as an out-of-memory crash or re-installation) that might introduce bias into what is received by the CRAYFIS data server. The most trustworthy candidate devices, then, are potentially those who reliably report exposure blocks regardless of event content, but it is not possible to identify such devices at this time.

†We express distinguished gratitude to CRAYFIS beta-tester Alex Passi for providing over 3 years of dual-altitude data.

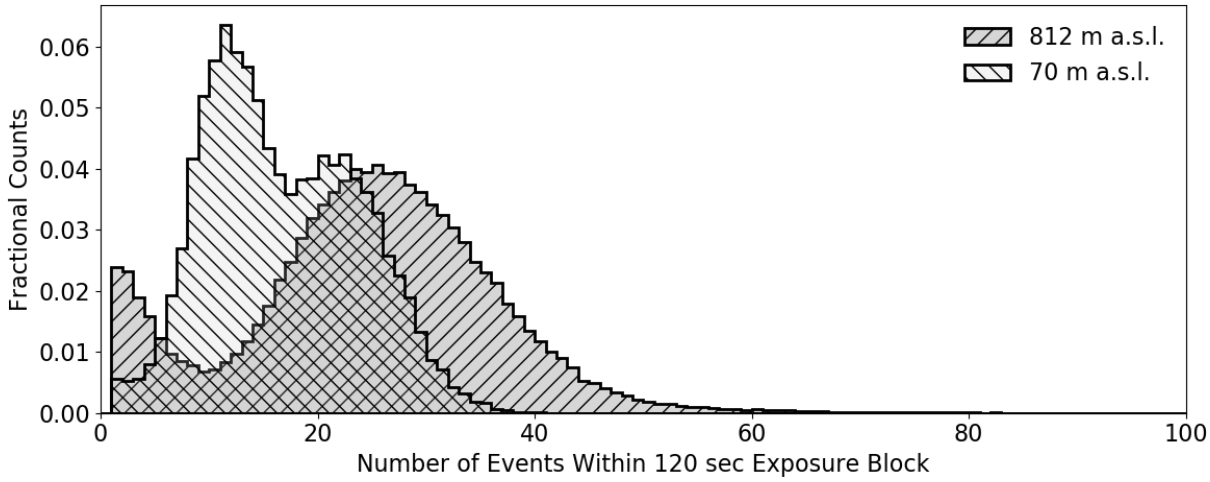
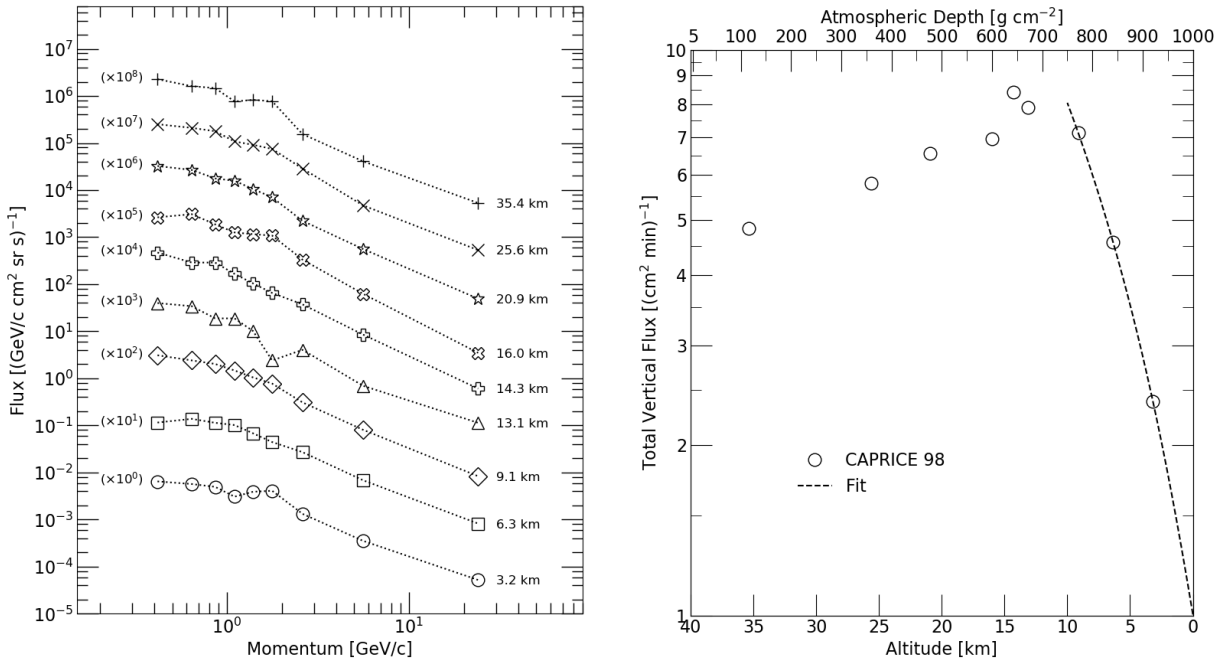


Figure 4.13: Anomalous pixel event distributions for the smartphones shown in Fig. 4.12. Despite being identical devices, there is a substantial difference in the typical number of suspect events within an exposure block. It is unlikely the different altitudes alone can justify the differences; however the longer tail for the higher altitude smartphone is consistent with expectations of being exposed to more radiation. It is not known why the low-tail of the high altitude smartphone exhibits the rise in zero-event exposure blocks, or why the low altitude smartphone exhibits two distinct peaks.

4.3.1 Case Study

As an *in situ* case study, same-model (Huawei Ascend G252)/different-altitude smartphone composite spectra are demonstrated in Fig. 4.12. These devices have transmitted (within a factor of 4) comparable numbers of exposure blocks over approximately the same time-span. The distribution of numbers of potential particle detections (events) within these exposure blocks for both devices is shown in Fig. 4.13. It is concerning that the distributions appear almost orthogonal to each other—proposed explanations are only speculative, and will not be discussed further at this time.

Nevertheless, to estimate their effective areas from data (via Eq. (4.3)), the experimental measurement of the altitude dependence of muon flux is provided by the CAPRICE98 balloon flight (Boezio et al. (2003)) in Fig. 4.14b. The figure is consistent with both the well-known rule-of-thumb flux of $\sim$1 muon/cm^2/min at sea-level, and the well-known average altitude for muon creation ($\sim$15 km). A quadratic fit was made for the



(a) Reproduction of CAPRICE98 data

(b) Total vertical muon flux

Figure 4.14: Left, a reproduction of the combined (positive and negative) muon flux as a function of muon momentum at various altitudes as measured by Boezio et al. (2003). Right, the total (summed over energy) vertical muon flux as a function of altitude with a quadratic fit to the low-altitude tail.

low-altitude tail, giving estimated fluxes of 1.03 and 1.28 muons/cm^2/min for 70 m and 810 m altitudes respectively. Both smartphones camera sensors have 5 MP 2616×1968 pixel resolution with 1.4 µm pixels, equating to 0.10 cm^2 geometric area.

The effective areas for these case study smartphones is provided in Table 4.1. Right away it can be seen that both $\langle A\epsilon \rangle$ results are around 130% to 160% times greater than physically possible (with $A = 0.1$ cm^2), meaning the data is potentially dominated by noise and (or) the total exposure is being under reported. On the other hand, with ∼20% relative difference between the the Venice versus Montalto effective areas, it might be possible that the particle flux is being under-estimated due to exposure to hadronic particles (it is assumed that the photon flux fraction could not be responsible, reference Figs. 4.8 and 4.9). Were this true, a lower-limit of the hadronic contribution (*i.e.*, so that

Table 4.1: Case study of two same-model smartphones at different altitudes. The estimated muon flux is taken from Fig. 4.14.

Location	Altitude [meters]	$\sum N_{\text{obs}}$	$\sum T_{\text{exp}}$ [sec]	$\Phi_\mu(h)$ [cm^{-2} min^{-1}]	$\langle A\epsilon \rangle$ [cm^2]
Montalto	810	2,736,031	13,566,000	1.28	0.16
Venice	70	527,784	3,899,040	1.03	0.13

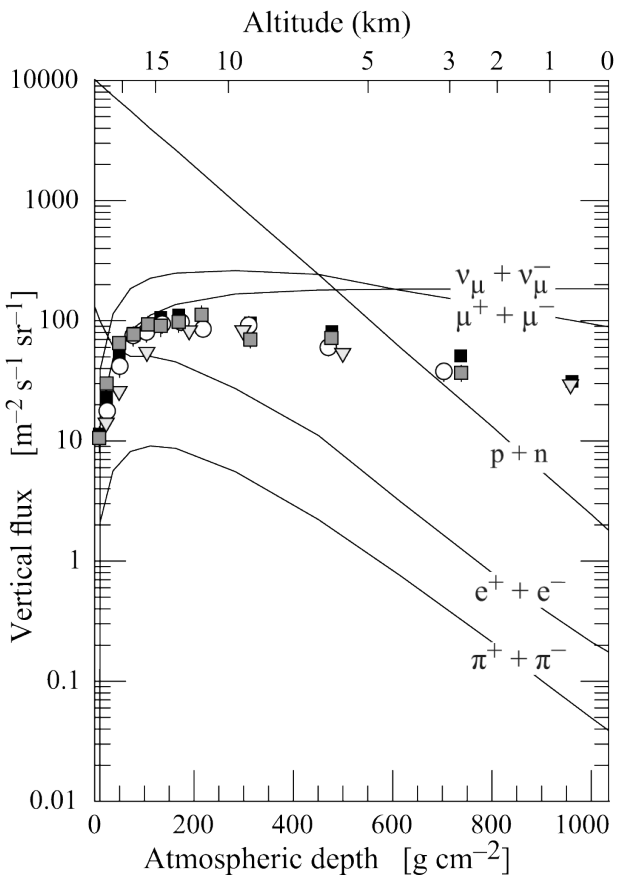


Figure 4.15: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from primary-nucleon flux. The points show measurements of negative muons with $E_\mu > 1$ GeV. Replication of Fig. 29.4 from M. Tanabashi (2018).

$\langle A\epsilon \rangle = 0.10$ cm^2, or 100% effective efficiency) would be $\Phi_{\text{had}} = 0.32$ and 0.27 cm^{-2} min^{-1}. However, expectations (Fig. 4.15) are such that the entire non-muon contribution likely cannot exceed $\sim$0.08 cm^{-2} min^{-1}. Even still, it is worth consideration that the curves in Fig. 4.15 are not experimental measurements, but estimations from simulations that at least for the case of muons, slightly over-predicts this flux—note that the points in this figure are for negative muons only, and the total experimental muon flux is roughly twice this. Lastly, were the discrepancy from noise alone, the rate of false triggering is at least 1 false trigger per 3.2 and 1.7 correct triggerings for Venice and Montalto respectively.

4.3.2 Coincidence Triggering

CRAYFIS is not intended to (nor can it) be a single-smartphone EAS detector, and inherent tolerance to some mild noise (such as that present in the previous case study) is a convenient side-effect when an array of smartphones is examined collectively. Unfortunately, to date there are no devices with time-overlapping data within 10 km of each other, so a coincidence analysis cannot yet be performed. However, in anticipation of this, we outline our expectations.

For an individual sea-level smartphone with an expected-typical muon effective area of $\sim$0.08 cm^2 (§4.2.3), the average number of camera sensor hits within a 100 ms window is, 1 muon/cm^2/min $\times$ 0.08 cm^2 $\times$ 1 min/60 sec $\times$ 0.1 sec = $\sim 10^{-4}$ "hits". However, most of these hits are from the comparatively proliferate lower-energy EASs.

To estimate the contribution of sea-level muon flux from UHECRs, the alternative EAS model developed in Chapter 2.1.3 was integrated over lateral distance (Eq. (2.12)) to find the expected average number of muons observed, $\langle N(E) \rangle$, Fig. 4.16. The bottom energy spectrum is scaled by the same factor of $E^{2.6}$ as in the top plot to emphasize spectral breaks; *i.e.*, despite appearing to grow, the energy spectrum is still greatly suppressed, falling with $\sim E^{-2.2}$. The total muon flux from UHECRs with primary energies above 10^{15}

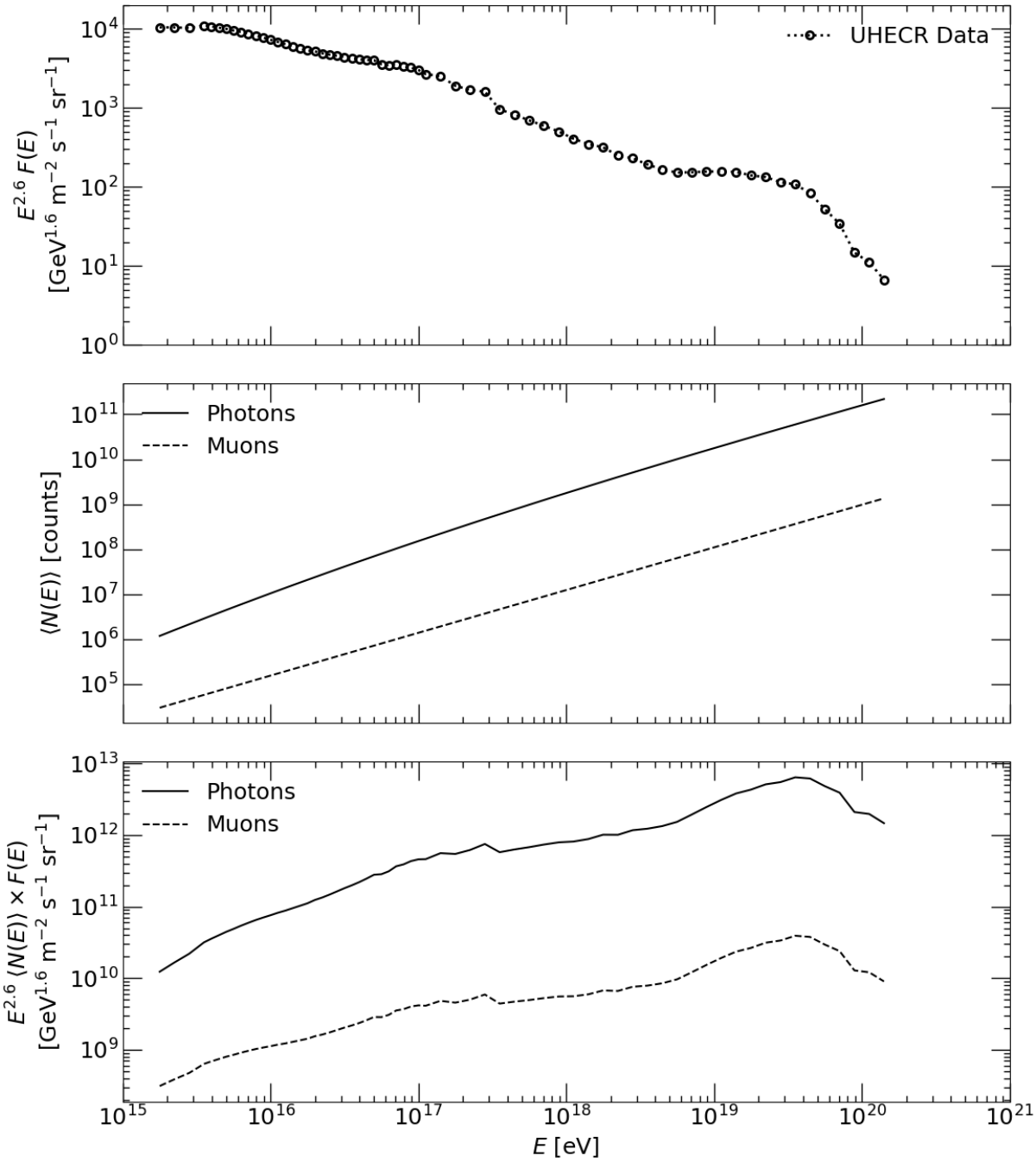


Figure 4.16: Top, the established energy spectrum of UHECR primaries (as measured by the Auger Observatory, Fenu (2017), and IceTop-73, Aartsen et al. (2013)). Middle, the average number of UHECR-induced photons and muons present at sea-level as a function of primary energy. Bottom, the product of the above two plots—the flux of photons and muons observed at sea-level as a function of primary energy. See text for discussion.

eV was found to be 1.4×10^{-3} muons/cm^2/min, with the implication that primary energies below 10^{15} eV supply on the order 10^3 times as many muons/cm^2/min as those above 10^{15} eV. EASs below the primary energy of 10^{15} eV do not produce (comparatively) many muons in single shower events, rather their dominant flux contribution exists because they are orders of magnitude more common.

Therefore, the average number of camera sensor hits within the same 100 ms window for an UHECR is on the order of 10^3 times less, or $\sim 10^{-7}$ hits. By requiring time-coincidence on nearby smartphones, the average rate of chance-coincidence among n smartphones (from low-energy EAS backgrounds) diminishes with $\sim 10^{-4n}$ as there is very low likelihood for a single low-energy EAS to trigger multiple smartphones in close proximity (Figs. 4.8–4.11). Whereas the average number of camera sensor hits for an UHECR remains largely unchanged as an UHECR EAS produces enough muons to trigger multiple nearby smartphones; therefore, the coincidence of (minimally 3) proximal devices should eventually lead to a favorable signal-to-noise ratio in EAS searches.

4.4 Cross-Calibration

Laboratory tests (§4.2) have demonstrated that it is possible to detect photons and muons, and with toy models of EAS particle distributions, preliminary sensitivities have been evaluated. Yet, laboratory sources are not representative of the same energy and composition distributions of a real EAS, and the toy models have not been validated against real CRAYFIS data. Additionally, pixel-spectra features in beta-tester data (§4.3) suggest that CRAYFIS users are detecting actual EAS radiation; although, the data to date appears to be dominated by miss-triggered and hard to untangle noise. Therefore, it is essential that a small test array of CRAYFIS smartphones be deployed to co-observe actual EASs with an established observatory—specifically, we consider a small, dense,

Figure 4.17: A prototype CRAYTAR surface detector from different points of view. See text for a description.

independent and self-sustaining CRAYFIS prototype array situated among Telescope Array (TA) surface detectors (Kawai et al. (2008)) in Millard County, Utah.

Two avenues of calibration will be investigated. First, the integrated radiation flux detected by TA would be used to validate net smartphone effective areas (and triggering algorithms) by comparing the area-scaled total radiation counts seen by TA with those seen in an individual camera sensor. Secondly, EAS-driven time-correlations between CRAYFIS and TA surface detectors would allow assessments of per-shower efficiency and reconstruction resolution validation.

4.4.1 CRAYFIS at Telescope ARray

The CRAYTAR test array is composed of individual smartphone detectors as shown in (Fig. 4.17). Each smartphone and its battery backup is contained in a solar-powered plastic mailbox pounded 18" into soil (standing ∼48" above ground), and secured with three paracord guy-lines. Smartphones capturing and processing images typically consume around 5 W or less; as such, each detector unit will include a 24 W southerly-facing panel

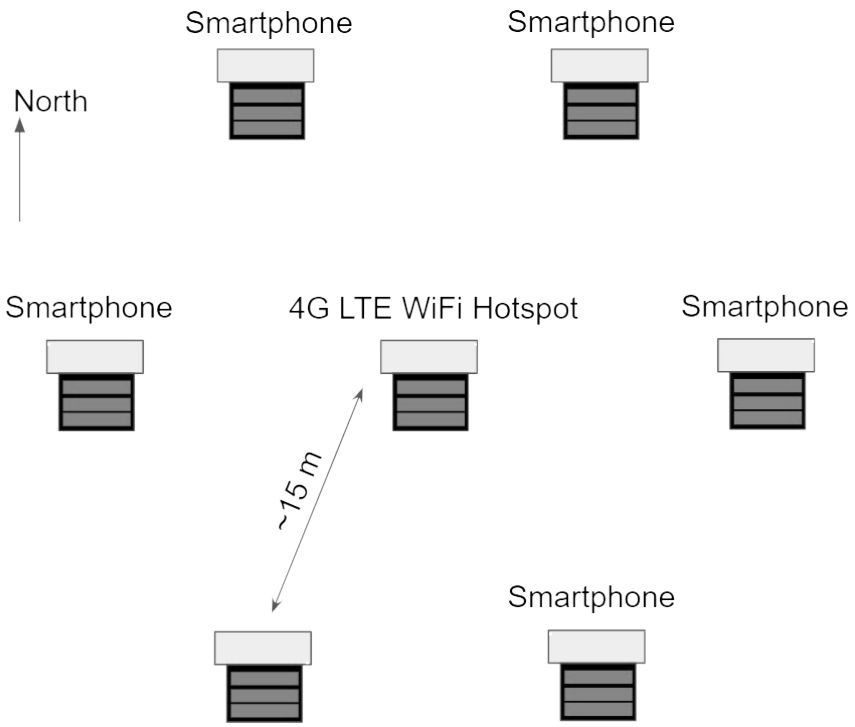


Figure 4.18: Planned CRAYTAR sub-cluster surface detectors (top-down view). A 5 GHz WiFi hotspot unit is placed near a TA surface detector (not shown), and surrounded by 6 CRAYTAR smartphone detectors. Solar panels are shown facing South. 5 sub-clusters are planned, spaced 1.2 km apart around 5 TA surface detectors.

paired with a 27 Ah USB battery backup to provide 24 hour operation under ideal conditions. The smartphone is air-cooled by convection through holes drilled into the sides of the housing that in turn are covered by household HVAC register filter to minimize dust. Lastly, the smartphone is supported above the base of the housing using a *Heckmaier Trimaran*[†] to increase convective cooling and minimize exposure to water.

Rather than burden the smartphones with data transmission over a cellular network, some surface detector units are repurposed with a mobile wireless hotspot in place of a smartphone. A single WiFi hotspot consumes around 5 W of power supporting 6 to 8 smartphones within a ∼20 m radius. To avoid radio interference with TA surface

[†]Colorfully-painted wooden shims hot-glued to perforated household aluminum foil.

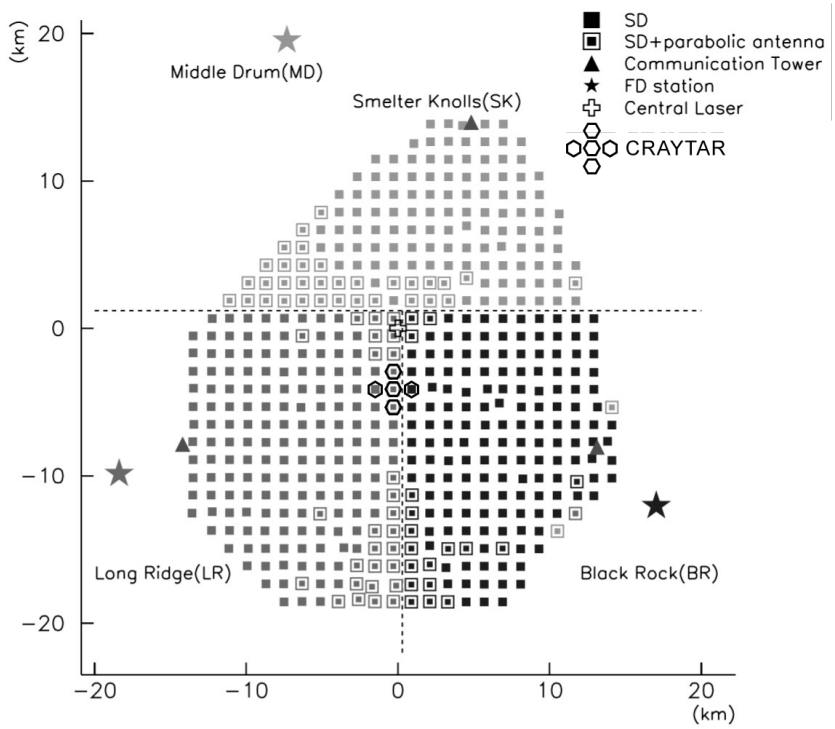


Figure 4.19: Layout of the Telescope Array in Utah, USA. Squares denote 507 surface detectors (SDs). There are three subarrays controlled by three communication towers denoted by triangles. The three star symbols denote the atmospheric florescence detector (FD) stations. A potential central location for the CRAYTAR test array is denoted by five hexagons in a "plus" pattern. Original image courtesy of Tsunesada et al. (2018), Fig. 1.

detectors that transmit over 2.4 GHz, 5 GHz WiFi and < 1 GHz cellular communication will be used.

TA's surface detectors are spaced approximately 1.2 km apart, so it is preferable to surround a single TA surface detector with a single hotspot sub-cluster of detectors (Fig. 4.18). Five sub-clusters are planned to surround five adjacent, central TA surface detectors in a "plus" or "cross" pattern (Fig. 4.19).

4.4.2 Expectations

The effective smartphone density in the immediate vicinity of a single sub-cluster is $\sim$8,500 devices/km^2, and $\sim$20 devices/km^2 near the full CRAYTAR array. Based on

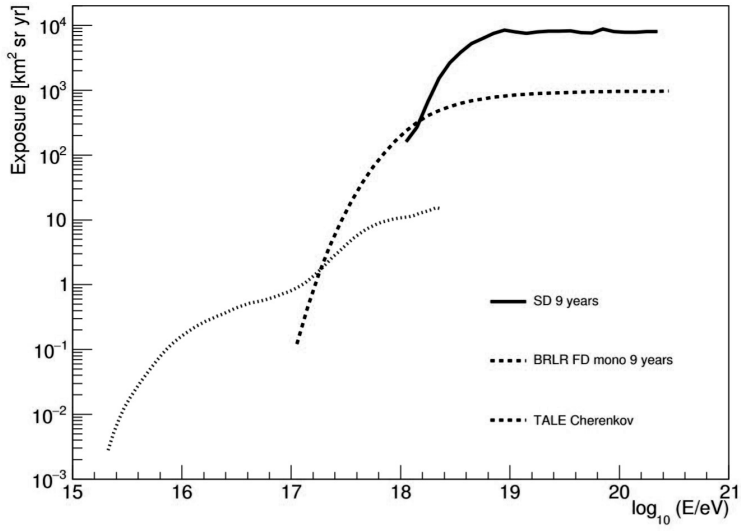


Figure 4.20: TA 9-year surface detector (SD), atmospheric florescence detector (FD) and Cherenkov telescope exposure as a function of energy (reproduction of Fig. 4 from Tsunesada et al. (2018)).

simulation studies (Fig. 4.11), a directly-overhead 10^{15} eV EAS would trigger five or six smartphones on average within a kilometer or two from its core.

Therefore, from the established UHECR flux data (Fig. 4.16, top), the expected rate for one of five sub-clusters to be in the direct path of such an EAS is at most once a minute. Tentatively requiring coincidence in at least four smartphones plus the surrounded TA surface detector, we expect to observe possibly around a thousand sub-cluster time-coincidences from low-energy EASs per day.

On the other hand, a time-coincidence across the entire CRAYTAR array potentially has sensitivity to $> 10^{17}$ eV EASs at a rate of at most once every ten minutes or so. Tentatively requiring coincidence in at least four surrounded TA surface detectors, and at least four of each sub-cluster smartphones, we expect to observe around a hundred intermediate-energy EASs per day.

Lastly, TA is a 700 km^2 installation comprised of surface detectors, atmospheric fluorescent telescopes and Cherenkov telescopes. The surface detectors are efficient for showers with

Table 4.2: Summary of CRAYTAR expectations.

Coincidence Conditions (100 ms Window)	Energy Threshold	Event Rate
Sub-Cluster (4 out of 5 sensors with TA SD)	$\sim 10^{15}$ eV	$\sim$1,000 per day
CRAYTAR Array (4 out of 5 sub-clusters, with above)	$\sim 10^{17}$ eV	$\sim$100 per day
TA (EAS core within 10 km of CRAYTAR)	$\sim 10^{19}$ eV	$\sim$3 per week

primary energies above $\sim 10^{18.2}$ eV (Fig. 4.20), and have accumulated a total exposure of 8×10^3 km^2 yr sr over 9 years (Tsunesada et al. (2018)). Although we expect TA to observe at most one $> 10^{19}$ eV EAS per day, the chance of CRAYTAR being within 10 km of such an event reduces our expectations to co-observing at most 3 such events per week.

Expectations are summarized in Table 4.2.

4.4.3 Software

While user privacy, bandwidth and server storage space considerations prevent the CRAYFIS app from saving or transmitting full images, there will be no such restrictions on the CRAYTAR test array. This freedom will allow for experimentation with new trigger algorithms both in real-time on test smartphones, and offline on our local server. The Shower-Reconstructing Application for Mobile Phones (ShRAMP) was developed by the author in anticipation of this freedom, and to solve challenges with high-speed asynchronous RAW-image capture, pixel-wise calibration and advanced triggering. The class backbone is diagrammed in Fig. 4.21, and the capture cycle is expanded upon in Fig. 4.22.

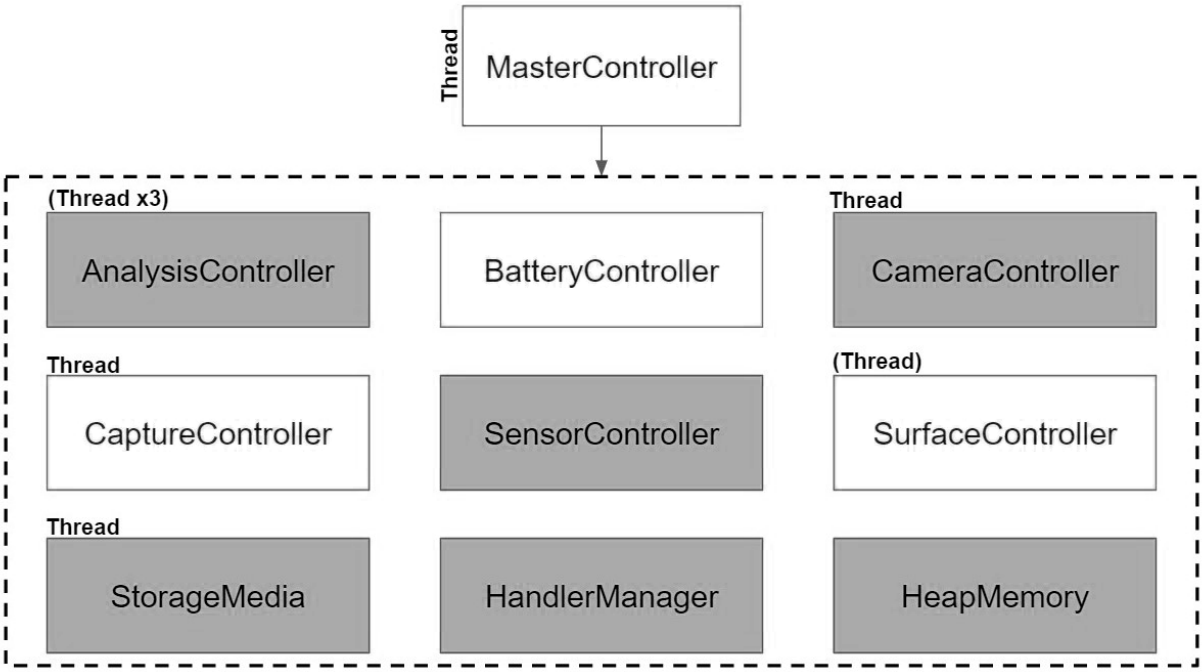


Figure 4.21: Core Java classes for the ShRAMP Android application. Singleton design patterns (white) wrap and protect single-instance system resources. Abstract interfaces (gray) modularize critical aspects and controls for ease of exploring alternative algorithms. The app its self is governed at the highest level by the *MasterController* in tandem with *HandlerManager*, which provides an interface to all active threads. Camera hardware and output datastreams are overseen by *CameraController* and *CaptureController* classes respectively. The *SurfaceController* and *AnalysisController* receive and processes (respectively) the camera datastream. A dedicated *BatteryController* carefully monitors battery temperature and condition, while the smartphone auxillary sensor package (pressure, temperature, humidity, *etc*) is monitored by *SensorController*. *HeapMemory* prevents an Out-Of-Memory (OOM) terminal crash from occurring, and lastly *StorageMedia* performs all I/O operations (including transpondence over WiFi).

Modern smartphones generally have between 4 and 8 CPU cores with usually mixed optimizations (*e.g.*, 1 or 2 low-power, low-performance cores separated from 3 or 4 full-power, full-performance cores). For minimal power consumption and physical size, each core is built to handle one process thread at a time, typically giving the developer at most 8 concurrent threads (plus the GPU) before bottlenecking the device. Additionally, most smartphones only offer 200 to 600 Mb of heap memory—a very challenging constraint for memory-intensive apps like CRAYFIS and ShRAMP.

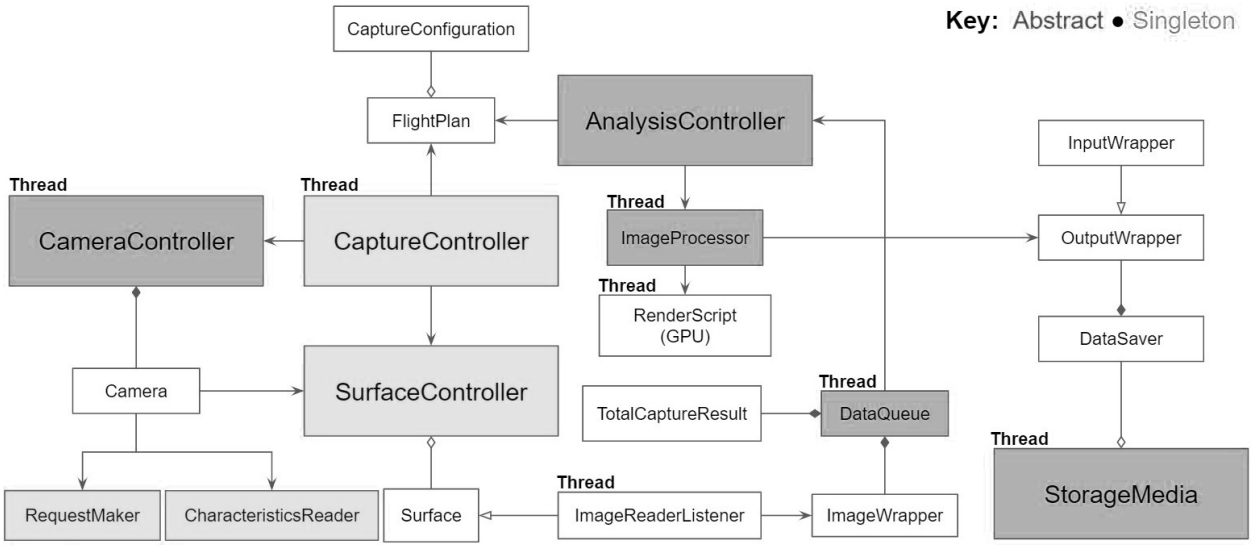


Figure 4.22: A simplified illustration of the data capture workflow and class relationships of the ShRAMP application. The Android camera produces two outputs—pixel data, and metadata—that arrive asynchronously on different threads, *ImageReaderListener* and *TotalCaptureResult* respectively. Pixel data and metadata are queued until matched on the *DataQueue* thread, and sent to the *ImageProcessor* to perform pixel-wise analyses that exploit GPU (*RenderScript*) parallel processing. The *AnalysisController* and *CaptureController* monitor high-level data products and the camera datastream respectively, signaling for mode changes according to the *FlightPlan*.

Execution of the ShRAMP application starts and ends with the *MasterController* thread. The *MasterController* is notified if the battery temperature drops below or goes above preset safety limits via the asynchronous *BatteryController* monitor—idling or shutting down the app as needed. The heap memory is also closely monitored asynchronously by *HeapMemory* to prevent an out-of-memory (OOM) crash—suspending capture or purging image queues via the *MasterController*.

On startup, the device camera hardware is scanned for support of 57 characteristic abilities and sub-options[†]. Based on this camera profile, each of 43 capture parameters[‡] are optimally configured for minimal pre-processing and maximal sensitivity. Then, a pre-programmed, but dynamically customizatizable state machine (the *FlightPlan*) guides

[†]See `https://developer.android.com/reference/android/hardware/camera2/CameraCharacteristics`

[‡]See `https://developer.android.com/reference/android/hardware/camera2/CaptureRequest`

the smartphone through warm-up, cool-down, calibration and data-taking modes. The most basic Android capture cycle is still a complex interplay of over 10 classes[†]; however, for high-speed processing of either 8- or 16-bit images, something far more complex is needed (Fig. 4.23).

The true power of the ShRAMP application processing pipeline is its ability to perform pixel-wise calibration, which for the average sized camera sensor, RAW output at 10 fps or greater amounts to processing data on the order of 300 Gb/s. By sampling over various pixel exposures and device temperatures (that naturally rise with running time), ShRAMP can identify pixels that are largely exposure and temperature insensitive (typically ∼95% of the total sensor), and mask out the remaining pixels from further analysis (Fig. 4.24–4.26). The full ShRAMP application is provided in Appendix E.

4.5 Outlook

The cost-advantage of user-provided hardware has been shown to come at the expense of performance uniformity across devices (§4.1). However, the degree of variability in smartphone camera sensor hardware has also been shown to not preclude their use as particle detectors. Laboratory (§4.2) and *in situ* (§4.3) studies have established that long-term exposure to photons and muons are clearly identifiable in data. Further, the remaining challenges of noise removal and individual EAS detection appear addressable with field testing (§4.4) and software trigger improvements. With an optimistic gaze into the future, the next chapter explores discoveries that may lie in waiting.

[†]For the most straightforward Android camera app, see `https://github.com/ealbin/simplecam`

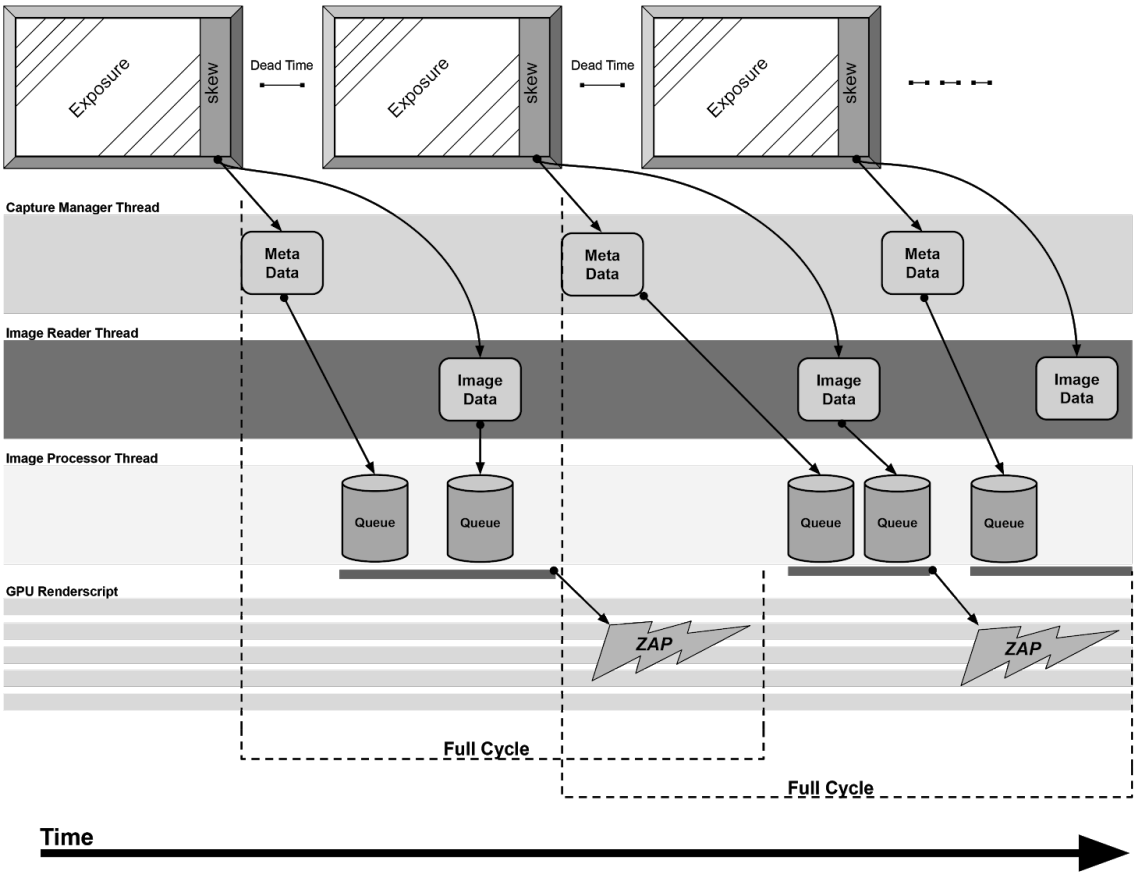
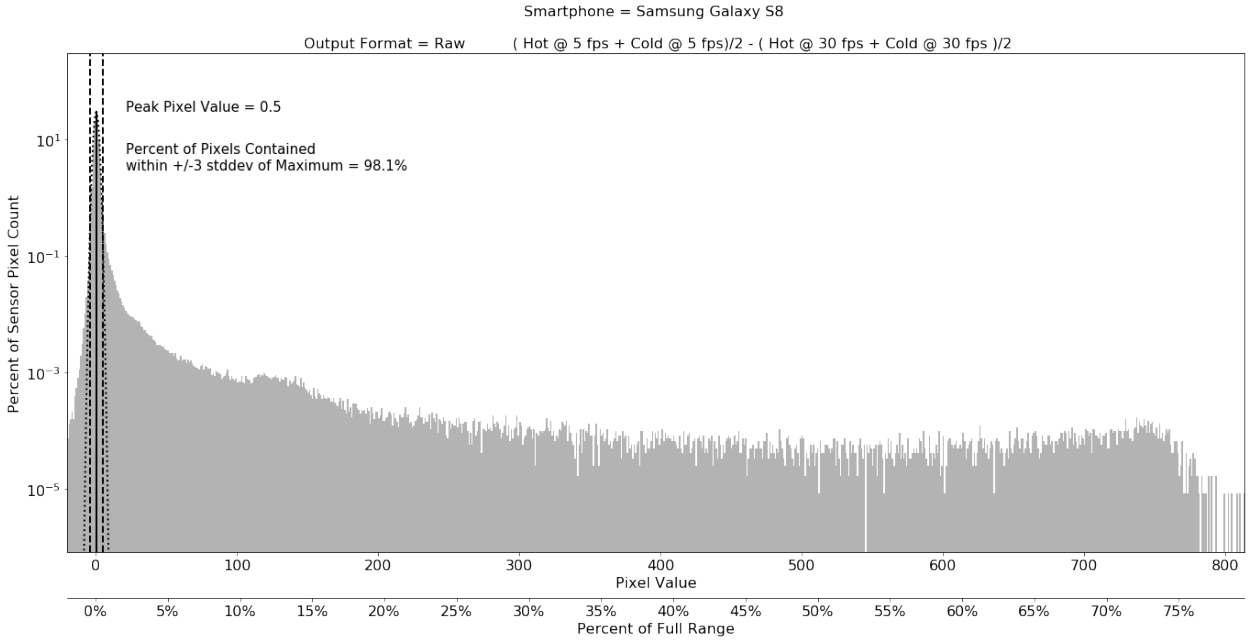
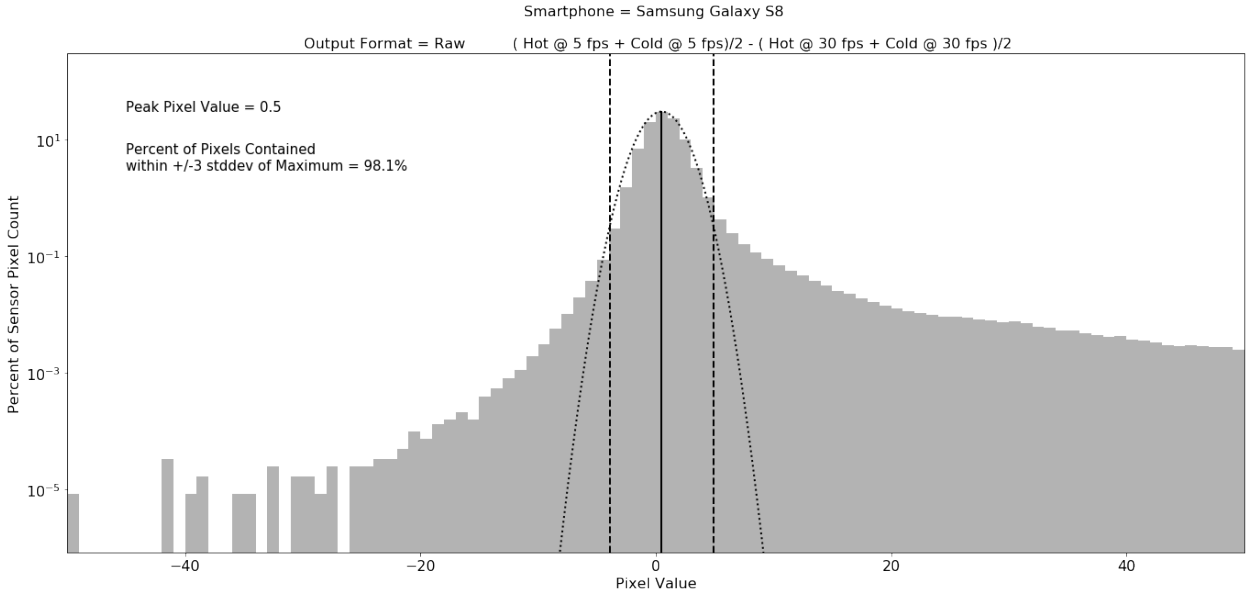


Figure 4.23: An illustration of the data capture process pipeline. The ShRAMP application automatically adjusts exposure duration to minimize dead time between frames with a maximal frame rate. This timing is balanced against the analysis queue backlog, which receives pixel data and image metadata asynchronously. Once pixel data and metadata are matched, the GPU carries out image processing operations returning results asynchronously to the analysis engine.

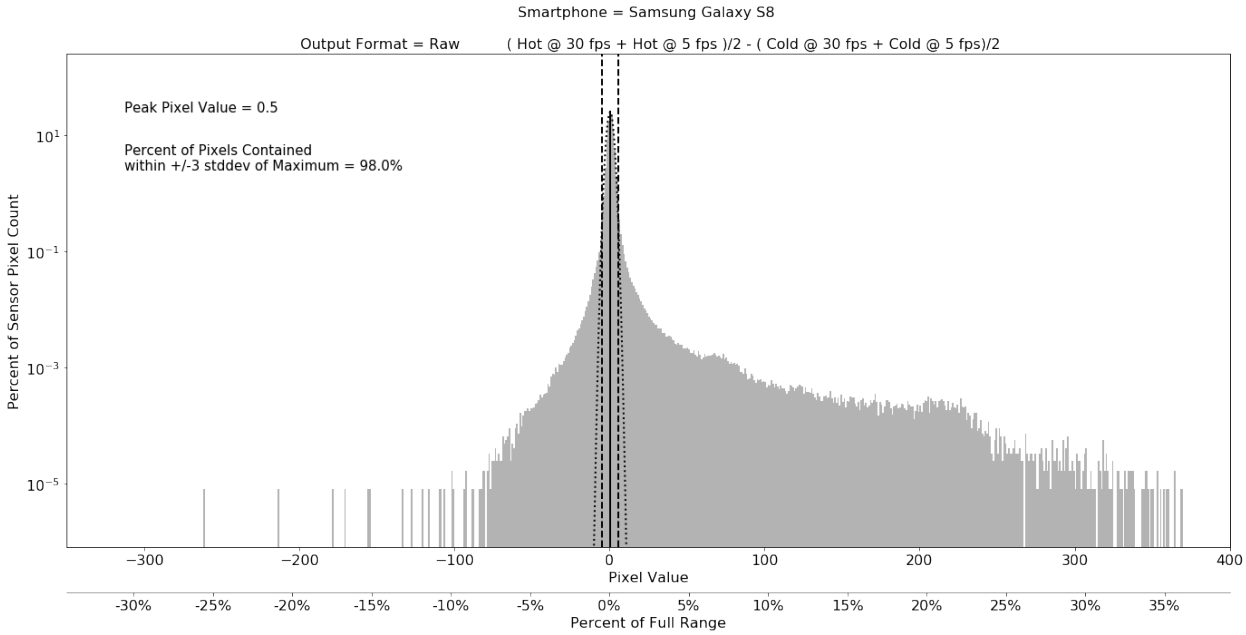


(a) All pixel spectrum

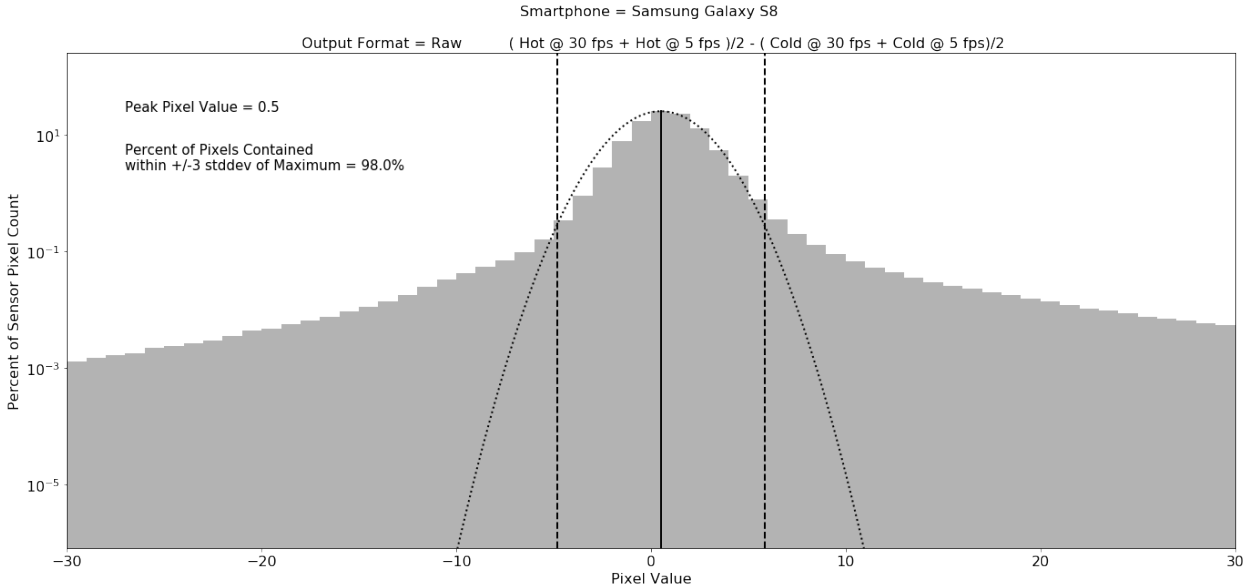


(b) Zoomed-in range

Figure 4.24: Pixel-wise exposure duration sensitivity of a Samsung Galaxy S8 smartphone. Each pixel is sampled 1,000 times for each combination of temperature ($\sim$20° C and $\sim$50° C) and exposure duration (5 and 30 frames-per-second). The pixel-wise sensitivity to exposure duration is estimated by marginalizing over temperature for each exposure, and then taking the difference. Values near zero on the x-axis represent insensitivity; conversely, large positive values represent pixels whose values tend to creep with longer exposure; and negative values are (usually faulty or excessively noisy) pixels that appear to diminish in average value with exposure duration. Top, the full pixel spectrum is shown. Bottom, ShRAMP identifies the peak pixel response (central line), fits a Gaussian distribution (dotted curve), and retains pixels within $\pm 3\sigma$ of the peak (vertical lines).

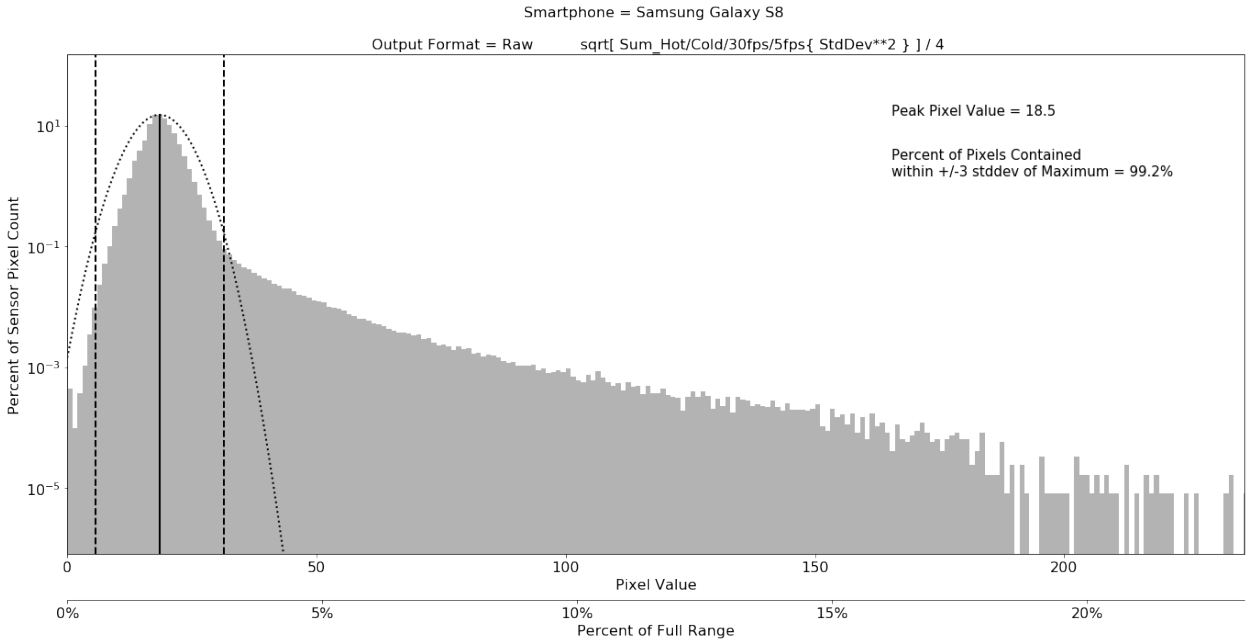


(a) All pixel spectrum



(b) Zoomed-in range

Figure 4.25: Pixel-wise temperature sensitivity of a Samsung Galaxy S8 smartphone. Each pixel is sampled 1,000 times for each combination of temperature (∼20° C and ∼50° C) and exposure duration (5 and 30 frames-per-second). The pixel-wise sensitivity to temperature is estimated by marginalizing over exposure duration at each temperature, and then taking the difference. Values near zero on the x-axis represent insensitivity; conversely, large positive values represent pixels whose values tend to creep with higher temperatures; and negative values are (often faulty or excessively noisy) pixels that appear to diminish in average value with increasing temperature. Top, the full pixel spectrum is shown. Bottom, ShRAMP identifies the peak pixel response (central line), fits a Gaussian distribution (dotted curve), and retains pixels within $\pm 3\sigma$ of the peak (vertical lines).



(a) All pixel spectrum

(b) Pixels removed from detection considerations (white)

Figure 4.26: Pixel-wise noise level of a Samsung Galaxy S8 smartphone. Each pixel is sampled 1,000 times for each combination of temperature (∼20° C and ∼50° C) and exposure duration (5 and 30 frames-per-second). The pixel-wise noise level is defined as the quadature sum of standard deviations measured under the four combinations of temperature and exposure duration, divided by four. Values near zero on the x-axis represent low noise levels; conversely, large positive values represent very noisy pixels. Top, the full pixel spectrum is shown—ShRAMP identifies the peak pixel response (central line), fits a Gaussian distribution (dotted curve), and retains pixels within $\pm 3\sigma$ of the peak (dashed lines). Bottom, the locations of pixels found to be too sensitive to changes in exposure duration, temperature, or otherwise too noisy. The sensor location of "undesirable" pixels usually appears to be randomly distributed.

Chapter 5

Sensitivity to Global Phenomena

A world-wide CRAYFIS detector network is a new instrument for exploration, and the history of experimental science is abound with examples of discoveries that have come unexpectedly with new technologies. For instance, the portable electroscope lead to the discovery of cosmic rays by Victor Hess in 1911, an ultra-sensitive microwave antenna lead to the discovery of cosmic microwave background radiation by Arno Penzias and Robert Wilson in 1964, and in the last decade, the Fermi Gamma-Ray Space Telescope uncovered mysterious gas clouds protruding from the Milky Way Galaxy that span an area as large as the galaxy itself (the Fermi Bubbles). It cannot be predicted what discovery(-ies) might lie in waiting for a global CRAYFIS network; however, the ability to study correlations between EAS events on a global scale may prove a reasonable starting point for such explorations. A review of previous works on time-correlated EAS measurements and distributed arrays is provided in §5.1, with an overview of possible theoretical causes in §5.2. A description of the dominant background to all simultaneous EAS searches (the random chance combinations of otherwise independent showers) is presented in §5.3, and the Gerizimosa-Zatsepin Effect is simulated in §5.4. After a brief discussion of simulation results in §5.5, the sensitivity of CRAYFIS is then evaluated in §5.6.

5.1 Review of Previous Works

Although the extensive nature of the EAS was first established by Pierre Auger in 1938 (Auger et al. (1939)), the last 80 years have seen comparatively little experimental investment in studying time-correlated, spatially-separated EASs until only recently, despite an early theoretical treatment of the photodisintegration of UHECR nuclei by Doppler-boosted solar photons (Zatsepin (1951)), and the possibility of nearly simultaneous EASs (Gerasimova and Zatsepin (1960))—the Gerizimosa-Zatsepin, or GZ Effect (see §5.2 for details).

Nevertheless, notable works include an observation by Fegan et al. (1983) where an unusual time-correlated increase of events between two EAS detection stations separated by 460 km in Ireland were attributed to fluctuation in gamma-rays from the Crab Pulsar, which was in the field of view of both stations at the time of the observation. 10 years later, Carrel and Martin (1994) recognized the newly cost-effective economy of commercial gigbyte storage, radio-synchronizable precision clocks and radio transmitters, and arranged a system of four scintillation detectors spanning 5.000 km^2 of Switzerland. Although Carrel and Martin found significant time-correlations in their network, the limitations of their minimalist detectors precluded the reconstruction of shower energies and direction, and thus prevented further interpretation of their findings.

Kitamura et al. (1997) and Unno et al. (1997) published their interpretations of coincidences between 4 detector arrays separated maximally by 460 km in Japan, quoting strong evidence that the variations in observed coincidence were not statistical fluctuations. Operating in some capacity around the same time in 1996, but extending nearly the entire length of Japan (covering in effect 130,000 km^2, the Large Area Air Shower (LAAS) observatory (Ochi et al. (2001)) became the first networked installation constructed with consideration of the GZ Effect in addition to general coincidence (Ochi et al. (2003)).

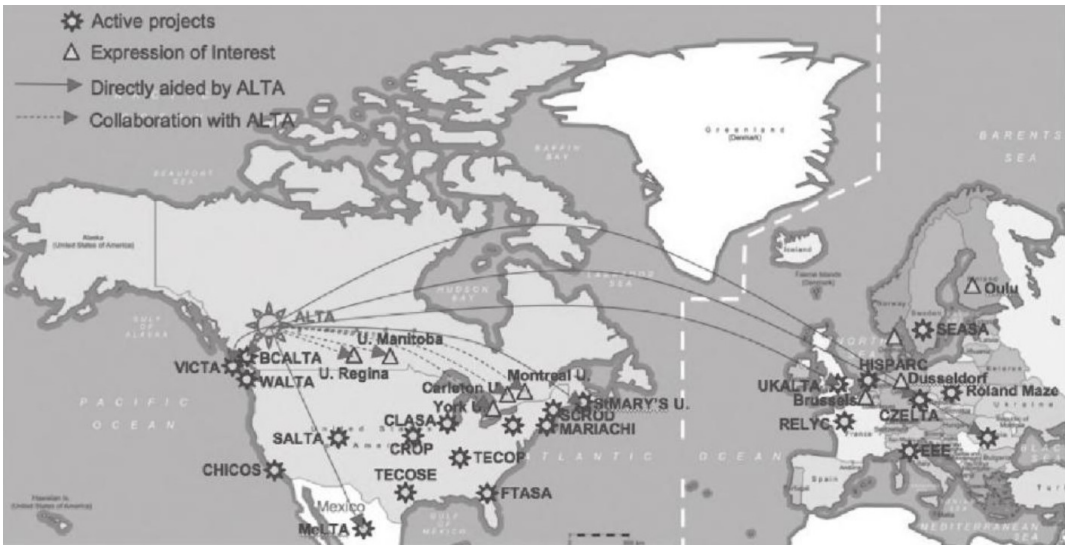


Figure 5.1: Geographic distribution of a partial list of large-area, time-coincidence array networks involving middle schools, high schools and colleges (see text). Image credit: Giani et al. (2011), page 96.

A number of various small-scale time-coincidence arrays were developed in the late 90s and early 2000s (see Potgieter et al. (1998), Kieda et al. (1999) and Kampert et al. (2001)). Beginning in this same time period and continuing through today as the closest analogy to CRAYFIS, a large number of middle schools, high schools and colleges across North America and Europe (Fig. 5.1) have networked simple detectors in search of EAS time-coincidence †

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†An incomplete list (continued on the next page) of amateur arrays involving many tens, if not hundreds of schools and colleges mostly in the Northern Hemisphere:

- Alberta Large-area Time-coincidence Array (ALTA)
- California High School Cosmic Ray Observatory (CHICOS)
- Chicago Air Shower Array (CASA)
- Cosmic Ray Observatory Project (CROP)
- CosRayHS (Universities of Pittsburgh and Missouri at St. Louis)
- CZEch Large-area Time coincidence Array (CZELTA)
- EuroCosmics
- Fulwood Extensive Air Shower Array (FEASA)
- High School Project on Astrophysics Research with Cosmics (HiSPARC)
- Nijmegen Area High School Array (NAHSA)
- Sky-View (University of Wuppertal)

5.2 Candidate Mechanisms

Besides variability and bursts from celestial sources, a number of possible sources of simultaneous EASs have been proposed. As mentioned in §5.1, the possibility of nearly simultaneous EASs were first identified with treatment of the GZ Effect (Gerasimova and Zatsepin (1960)). At the time however, Gerizimosa and Zatsepin severely underestimated the heliospheric magnetic field (HMF) to be a homogeneous 10^{-5} Gauss, and calculated the resulting EAS separation to be on on the order of a kilometer. Although Zatsepin later realized this error[†], no subsequent paper or published calculation was made. As such, it was not until nearly 40 years after Gerizimosa and Zatsepin that Medina-Tanco and Watson (1999), and immediately following, Epele et al. (1999), revisited this calculation with an improved HMF model based off the work of Akasofu et al. (1980). Both Medina-Tanco et al. and Epele et al. found potentially substantial separations of hundreds, if not thousands of kilometers. This topic was addressed once more by Lafebre et al. (2008) in relation to detection rates in existing or future experiments using the Pierre Auger Observatory (Abraham et al. (2004)) and the LOw Frequency ARray (LOFAR) radio telescopes (Falcke et al. (2007)) as prototypical examples. Common to all analyses however, was an anticipated rarity of occurrence maximally on the order of 1 in a few hundred-thousand of UHECR events with primary energies near 10^{18} eV (where UHECR events at this energy are comparatively rare themselves). The GZ effect is again revisited in full detail §5.4 (and in a paper-in-progress) as a means of evaluating the sensitivity of a hypothetical CRAYFIS network.

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continued from the previous page:

- Snowmass Area Large-scale Time-coincidence Array (SALTA)
- VICtoria Time-coincidence Array (VICTA)
- Vijlen Air Shower Experiment (VASE)
- WAshington Large-area Time-coincidence Array (WALTA)

[†]Ginzburg V. L. and Syrovatsky S. I., 1964, in 'The Origin of Cosmic Rays', p127, Pergammon Press.

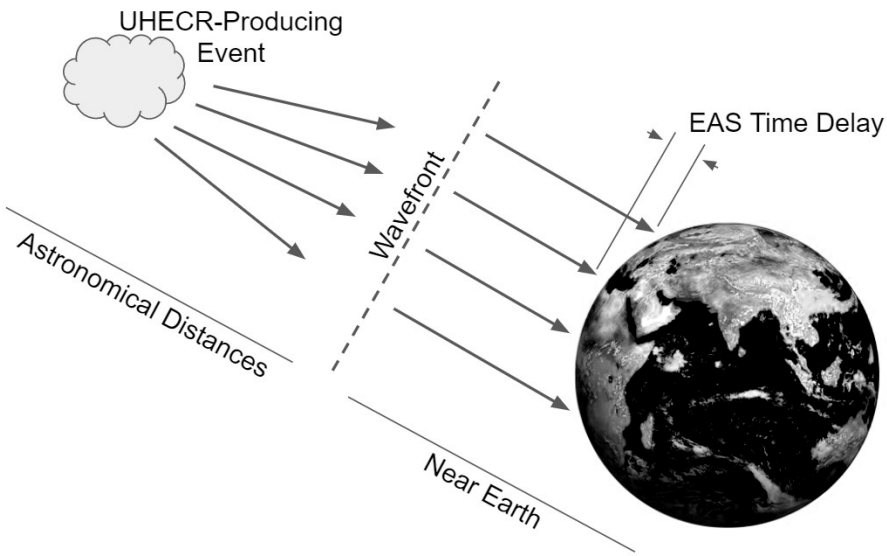


Figure 5.2: Illustration of a general near-simultaneous, greatly-separated EAS mechanism. Left, a physical process occurs (see text) resulting in either direct UHECR particles and nuclei creation, or products that are subsequently accelerated by shocks or other methods not depicted. If such an occurrence happens far enough away from the Earth (shown at right) either as a near-culminated beam, or a highly-dense dispersion, then their Earthly arrival will appear parallel along a wavefront. UHECRs are highly-relativistic, and therefore to good approximation, the maximal time delay between near-simultaneous EASs (assuming a unified arrival wavefront) is 21 ms; the time it would take light to travel the distance of one Earth radius.

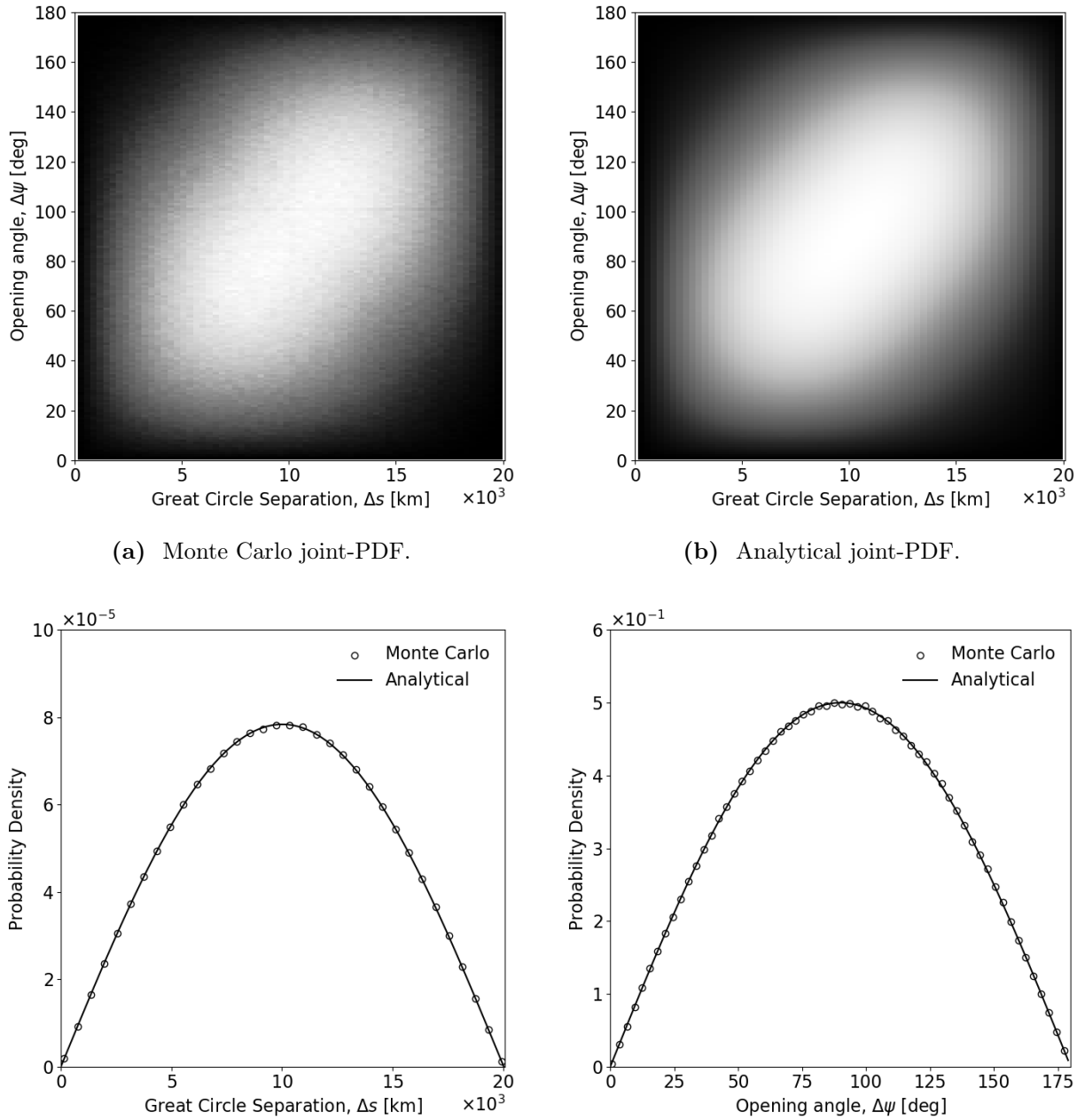
A class of other possible mechanisms is illustrated by Fig. 5.2, where some physical process results in either the direct production of UHECR products, or the first step of subsequent shock accelerations which result in UHECRs. Mechanisms that have been considered in the past have included relativistic dust grains expelled into the interstellar medium by radiation pressure from cool stars (Spitzer (1949), Wickramasinghe (1972), Wickramasinghe (1974), and Epstein (1980)); electromagnetic cascades (as a form of *pre-showering*) where ultra-high energy gamma-rays pair-produce prior to reaching the Earth through various interactions (Nikishov (1962), Goldreich and Morrison (1964), Jelley (1966), Gould and Schréder (1967), and Stecker (1969)) into UHECR products that may radiate high-energy photons via synchrotron and/or bremsstrahlung processes, which may then repeat the pre-showering process; super-GZK neutrinos (the *Z-Burst scenario*) that

may be produced from super-GZK protons or others from interactions with the cosmic microwave background resulting in a culminated jet of hadrons and/or ultra-high energy gamma-rays from neutrino annihilation or interaction with dark matter (Berezinsky and Zatsepin (1969), Weiler (1982), Roulet (1993), and Fargion et al. (1999)); extra-dimensions and localized gravity (Randall and Sundrum (1999)) call for Kaluza-Klein gravitons that provide lower-energy resonance thresholds for interactions with ultra-high energy neutrinos to produce Z-Burst hadronic jets (the *Gravi-Burst scenario*, Davoudiasl et al. (2002)); and lastly a collection of so-called *top-down exotics* that usually are thought to result in hadronic jets, lepton bursts, and ultra-high energy gamma-rays through radiation, annihilation or collapse—these exotics include topological defects in the early Universe associated with reconciliation of minimum Higgs potentials (Kibble (1976), Vilenkin (1985), Brandenberger (1994), and Hindmarsh and Kibble (1995)), magnetic monopoles (Hill (1983) and Bhattacharjee and Sigl (1995)), superconducting cosmic strings (Hill et al. (1987), Bhattacharjee (1989), and Bhattacharjee and Rana (1990)), vortons (Masperi and Silva (1998) and Masperi and Orsaria (2002)), cosmic necklaces (Berezinsky and Vilenkin (1997)), evaporating primordial black holes (Hawking (1974) and Dave and Taboada (2019)), and the decay of superheavy dark matter (Chung et al. (1998)).

To date, no evidence of these mechanisms have been experimentally observed.

5.3 Combinatorial Background

As diagrammed in Fig. 5.2, meaningful time-correlated EAS events could be anticipated to arrive in a roughly parallel fashion; albeit with a range of energies and composition dependent upon the phenomenon. Conversely, the non-meaningful chance-correlation of



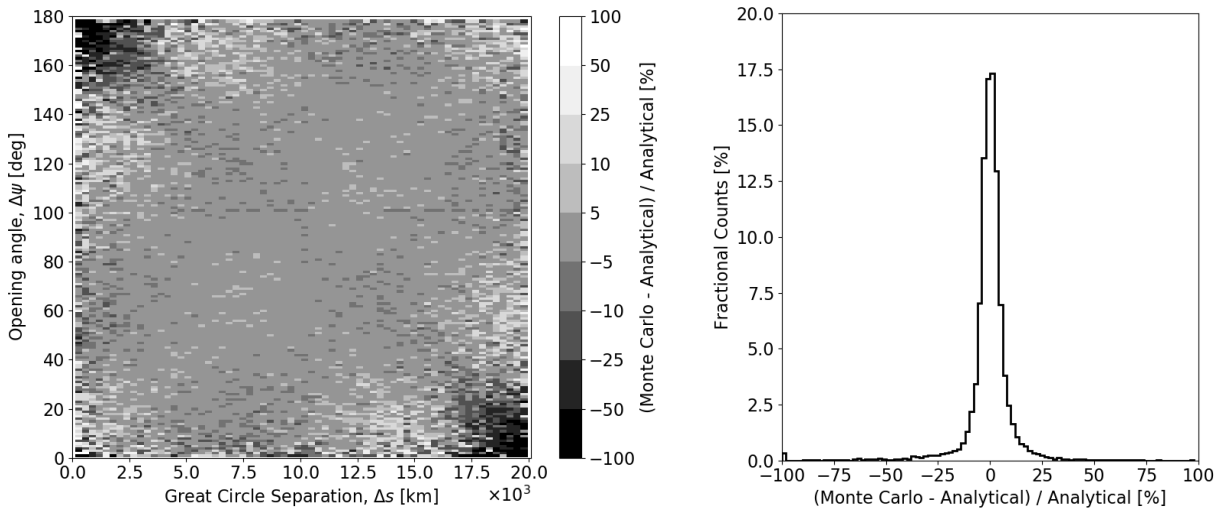
(a) Monte Carlo joint-PDF.

(b) Analytical joint-PDF.

(c) Separation marginalized over angle.

(d) Angle marginalized over separation.

Figure 5.3: The combinatorial background distributions of any two time-coincident cosmic rays. The top row (left) shows the Monte Carlo joint-PDF for both variables, and (right) the analytical model. The bottom row presents marginalized PDFs. See text for analytical functions forms.



(a) Bin-wise relative difference. **(b)** Aggregated relative difference.

Figure 5.4: Representations of the relative difference between Fig. 5.3a and Fig. 5.3b. Left, a bin-wise representation. Right, a one-dimensional aggregation of all bins. See text for the joint-PDF model.

any two showers (combinatorial background) is found by Monte Carlo methods† to follow the distributions shown in Fig. 5.3. In their marginalized form, both geographic separation and opening angle are found to follow sine-distributions,

$$\begin{aligned} \mathrm{PDF}(\Delta s) &= \frac{1}{2R_E}\ \sin\left(\frac{\Delta s}{R_E}\right)\ ;\ \Delta s \in [0, \pi R_E] \\ \mathrm{PDF}(\Delta\psi) &= \frac{1}{2}\ \sin\left(\Delta\psi\right)\ ;\ \Delta\psi \in [0, \pi] \end{aligned} \tag{5.1}$$

where R_E is the radius of the Earth. An analytical representation of the joint-PDF distribution (that correctly reduces to the marginalized forms in Eq. (5.1)) was found to

†Two random points ($i = 1,\ 2$) on Earth are drawn with uniform spherical density (*i.e.*, polar-angle $\cos\theta^i = 1 - 2X_1^i$, and azimuthal-angle $\phi^i = 2\pi X_2^i$ for random variables $X_n^i \in [0,\ 1)$), each with a random heading relative to the local zenith (*i.e.*, local zenith-angle $\cos\hat{\theta}^i = 1 - X_3^i$, and local azimuthal-angle $\hat{\phi}^i = 2\pi X_4^i$). With the local-coordinate headings transformed back into global coordinates, the "opening angle", $\Delta\psi$, between headings (unit vectors, $\hat{n}_1$ and $\hat{n}_2$) is $\cos\Delta\psi = \hat{n}_1 \cdot \hat{n}_2$. Lastly, the great-circle separation, Δs, is computed from the well-known haversine distance formula.

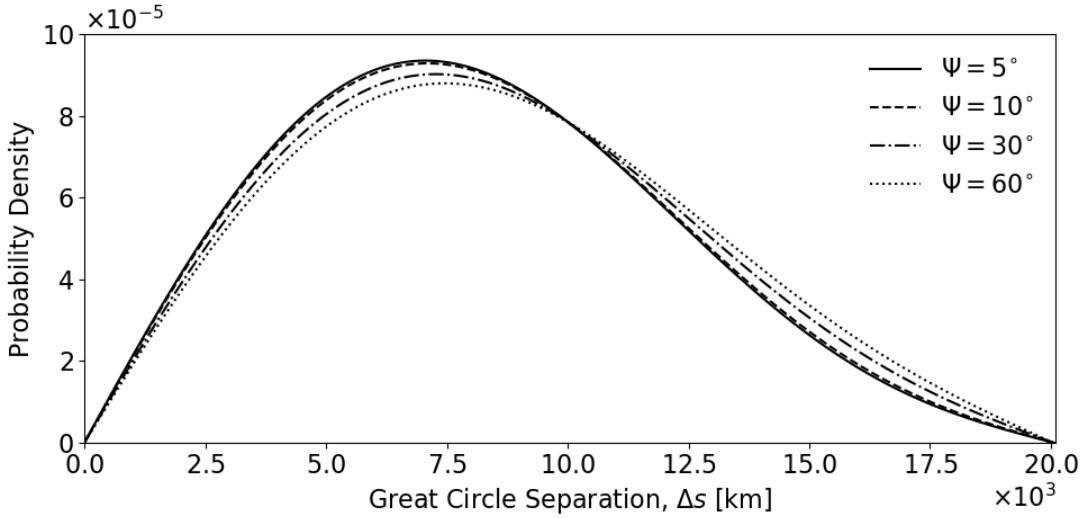


Figure 5.5: Relative likelihood distribution for the combinatorial geographic separation of coincident cosmic rays with opening angles $\Delta\psi \leq \Psi$.

agree with Monte Carlo results of 10^7 simulated cosmic ray pairs (Fig. 5.4),

$$\mathrm{PDF}(\Delta s, \Delta\psi) = \frac{1}{4R_E} \sin\left(\frac{\Delta s}{R_E}\right) \sin(\Delta\psi) \left[1 + \frac{3}{4} \cos\left(\frac{\Delta s}{R_E}\right) \cos(\Delta\psi)\right] \tag{5.2}$$

For searches of coincident cosmic rays such that $0 < \Delta\psi < \Psi$, Eq. (5.2) becomes (Fig. 5.5),

$$\mathrm{PDF}(\Delta s; \Delta\psi \leq \Psi) = \frac{1}{4R_E} \csc^2\left(\frac{\Psi}{2}\right) \sin\left(\frac{\Delta s}{R_E}\right) \left[1 - \cos\Psi + \frac{3}{8} \sin^2\Psi \cos\left(\frac{\Delta s}{R_E}\right)\right] \tag{5.3}$$

5.4 The Gerizimosa-Zatsepin Effect

With the combinatorial background model of Eq. (5.3), we now turn our attention to the distribution of a specific candidate signal. As discussed in §5.2, the Gerizimosa-Zatsepin (GZ) Effect provides a phenomenological mechanism for nearly-simultaneous, but greatly separated EASs resulting from a photodisintegration process in which UHECR nuclei are split by solar photons on their way to Earth. Critical parameters for this process are the

solar blackbody photon field density that rapidly falls as an inverse-square law, and the relative alignment of nuclei-photon momenta that determines the Doppler-boost of the solar photon as seen by the nucleus.

To first-order, daughter products (predominantly either proton with Z-1 nuclear fragment, or neutron with Z fragment) are expected to divide energy in proportion to nucleon number, A,

$$\begin{aligned} E_{\text{nucleon}} &= \frac{1}{A} E_{\text{primary}} \\ E_{\text{fragment}} &= \frac{A-1}{A} E_{\text{primary}}. \end{aligned} \tag{5.4}$$

The kinematics of an UHECR nucleus interacting with a low energy photon ($E_\gamma / E_{\text{primary}} \ll 10^{-12}$) are such that there is negligible transverse momentum, and the emitted photodisintegration products separate in the laboratory frame within a kinematic boundary cone of virtually zero to great accuracy on solar system scales (see Appendix F). The daughter product separation is then dominated completely by the heliospheric magnetic field (HMF). In this way, simultaneous but spatially-separated EASs are possible, however to-date unobserved.

5.4.1 Photodisintegration

First, the photon field model is described §5.4.1.1 with a model for the photodisintegration cross section §5.4.1.2 so that the probability for photodisintegration of an UHECR can be computed §5.4.1.3.

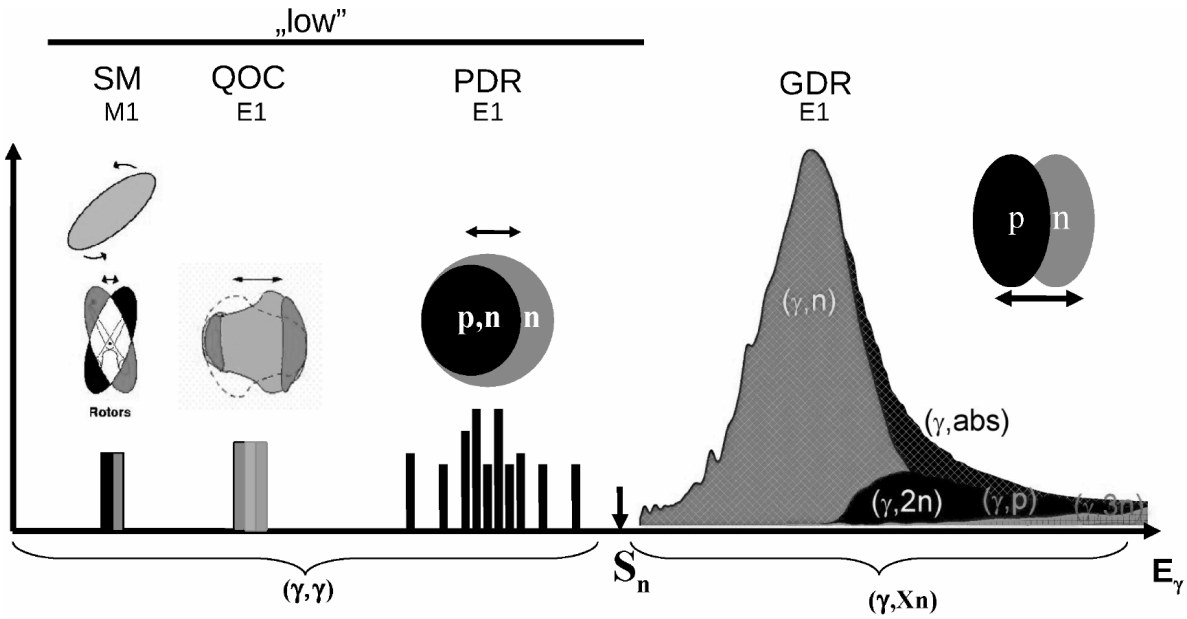


Figure 5.6: Typical relative cross section strengths for electric dipole (E1) and magnetic dipole (M1) nuclear excitations with increasing photon energy. SM=Scissors Mode, QOC=Quadrupole-OctupoleMode, PDR=Pygmy Dipole Resonance, and GDR=Giant Dipole Resonance. Reproduction of Fig. 2 from Habs et al. (2012).

5.4.1.1 Photon Field

The photon density of the Sun is approximated by a blackbody spectra with $T = 5770$ K ($k_B T \simeq 0.5$ eV).

$$\frac{\mathrm{d}n_\odot}{\mathrm{d}\epsilon} = 7.2 \times 10^7 \frac{\epsilon^2}{\exp(\epsilon/0.5) - 1} \left(\frac{1\ \mathrm{AU}}{r}\right)^2 \tag{5.5}$$

with units eV/cm^3, and the solar spectra is normalized to the measured solar luminosity, $\int \mathrm{d}\epsilon\ \mathrm{d}n/\mathrm{d}\epsilon = 4\pi r^2 c \int \mathrm{d}\epsilon\ \epsilon\ \mathrm{d}n/\mathrm{d}\epsilon = L_\odot$.

5.4.1.2 Cross Section

The photonuclear interaction is complex and nuanced as illustrated in Fig. 5.6. Conceptually, an incident photon electrically couples to protons, and magnetically to either protons or neutrons. The electromagnetic difference between protons and neutrons drives a

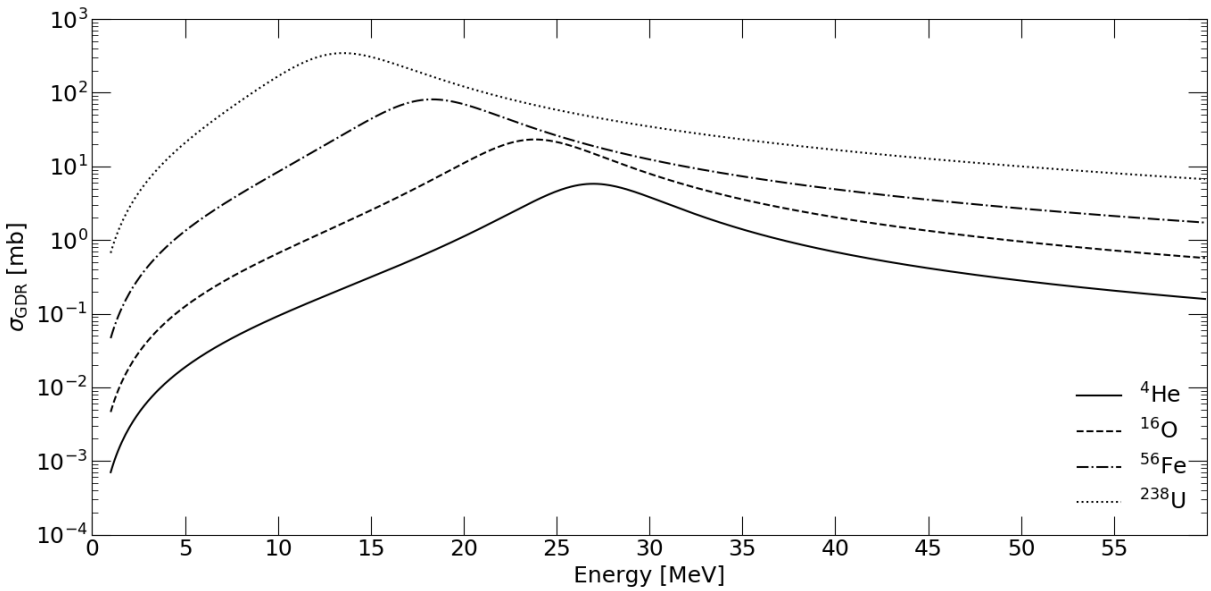


Figure 5.7: Giant Dipole Resonance cross sections (model) for various elements.

dynamical segregation of the two species, while nuclear forces fight to maintain an equilibrium. For photon energies below ∼10 MeV, the absorbed energy excites the nucleus into vibrational modes that relax by photon emission. However, as the photon energy increases (usually) between ∼10 and ∼30 MeV, the magnitude of the excitation becomes such that the degree of segregation between protons and neutrons exceeds the retentive facility of the nuclear forces, and results in the emission of one or more nucleons—the so-called giant dipole resonance (GDR). Beyond this energy, alpha particle, pion and lastly fission processes become significant.

As the first mechanism for nucleon emission, the GDR process cross section is the most important (most likely) instigator for the GZ Effect. As indicated by Fig. 5.6, the GDR process is not easily modeled, and it is a strong function of the number and kinds of nucleons present. However, a reasonably simple Breit-Wigner (Breit and Wigner (1936)) cross section model is given in Karakula and Tkaczyk (1993), and repeated here (Fig. 5.7):

$$\sigma_{\mathrm{GDR}}(\epsilon^*) = 1.45A\frac{(\epsilon^* T)^2}{(\epsilon^{*2} - \epsilon_0^2)^2 + (\epsilon^* T)^2} \tag{5.6}$$

where $\sigma_{GDR}(\epsilon^*)$ carries units of mb, ϵ^* is the Doppler-boosted photon energy observed in the nuclei rest frame, $T = 8$ MeV (an average energy bandwidth of the GDR), $\epsilon_0 = 42.65 \times A^{-0.21}$ MeV for $A > 4$ and $\epsilon_0 = 0.925 \times A^{2.433}$ MeV for $A \leq 4$ (the peak energy of the GDR). For energies between 30 MeV $< \epsilon^* <$ 150 MeV, multiple nucleon ejection becomes increasingly favorable leading up to the pion production threshold.

As multi-nucleon ejection final states are important contributors to the total GDR cross-section with increasing energy, we consider only the single-nucleon ejection final state in simulation to establish a conservative limit for dual-EAS searches.

5.4.1.3 Probability

The inverse mean free path, λ^{-1}, for the photodisintegration of a target nuclei in a photon field density $\mathrm{d}n/\mathrm{d}\epsilon$ [#/cm^3 eV] with GDR cross section $\sigma_{\mathrm{GDR}}(\epsilon^*)$ is,

$$\lambda^{-1} = \int_0^\infty \mathrm{d}\epsilon \, \frac{\mathrm{d}n(\epsilon)}{\mathrm{d}\epsilon} \, \sigma\left(\gamma \, \epsilon \, g(\alpha)\right) g(\alpha), \tag{5.7}$$

where ϵ is the photon energy in the solar rest frame, $g(\alpha) = (1 + \beta \cos \alpha) \simeq 2\cos^2\alpha/2$ is the geometrical Doppler shift alignment between photon and nuclei momenta for α as

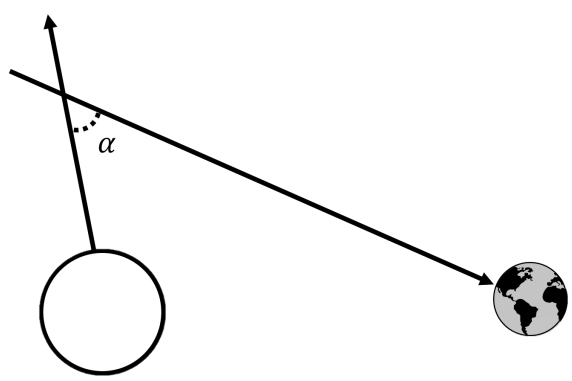


Figure 5.8: Definition of angle α between the outgoing solar photon (Sun, left) and the incoming UHECR (Earth, right).

defined in Fig. 5.8, relativistic $\beta = v/c$, the ratio of the UHECR velocity to the speed of light, and Lorentz factor $\gamma = (1-\beta^2)^{-1}$ as observed in the solar rest frame .

Therefore, the probabilistic upper-limit (for one or more GDR interactions) fraction of UHECRs to photodisintegrate along a trajectory, s is,

$$P_s = 1 - e^{-\int \mathrm{d}s/\lambda(s)} \tag{5.8}$$

or, for a simulation step such that λ is reasonably constant within each step, Δs, and $\Delta s \ll \lambda$,

$$P\left(s \to s + \Delta s\right) = 1 - e^{-\Delta s/\lambda} \simeq \Delta s/\lambda \tag{5.9}$$

as shown in Fig. 5.9.

5.4.2 Heliospheric Magnetic Field

Solar system dynamics for charged particle propagation are dominated by interaction with the heliospheric magnetic field (HMF). The HMF for distances up to 20 AU (approximately the orbit of Uranus) can be modeled as a sum of four primary components (Akasofu et al. (1980)). These four components are illustrated in Fig. 5.10 and given analytically for an odd solar cycle, *i.e.*, the geographical north polar region has the S magnetic pole. All components will change sign for even solar cycles. The cylindrical coordinate system for this model places the Sun at the origin and the Earth at $(z, \rho, \phi) = (0, 1, 0)$ AU. The Earth therefore orbits the Sun in the increasing θ direction. Visualizations of the model are provided in in Figs. 5.12 and 5.11.

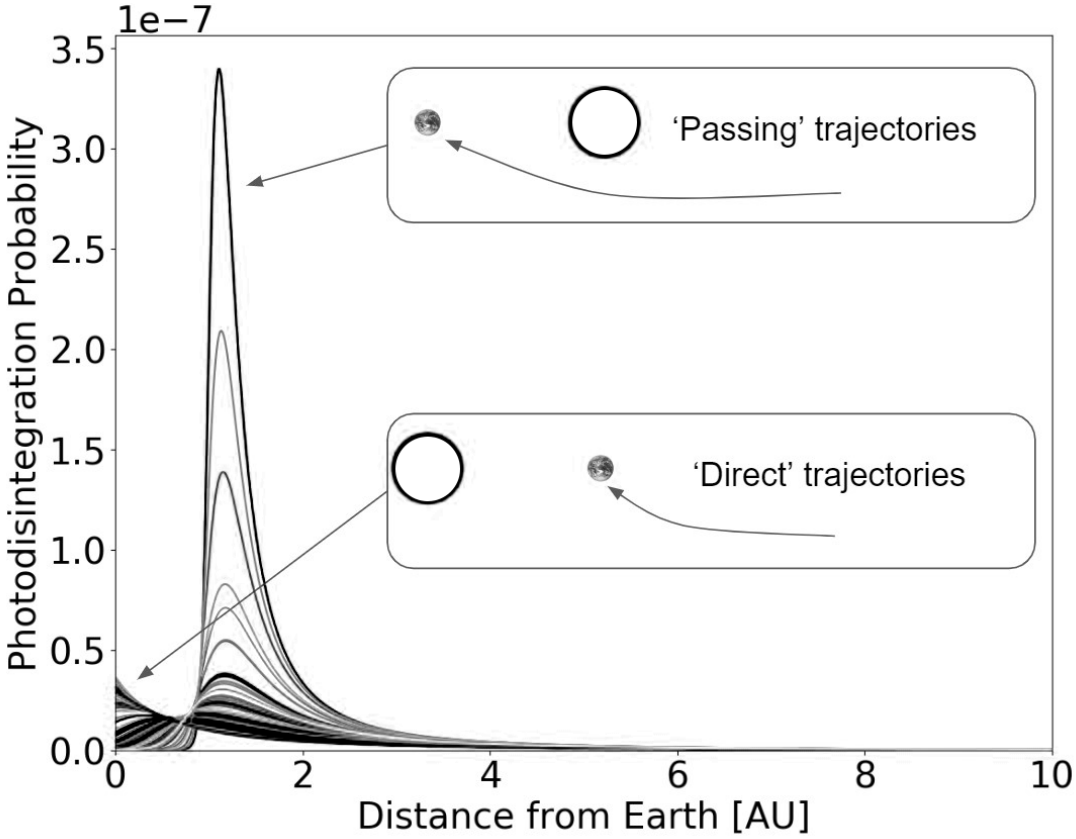


Figure 5.9: Many 1 EeV Oxygen nuclei are propagated through the solar system (paths go from right-to-left, where the Earth is at $x = 0$, and Sun at $x = 1$). The probability at each point along the way to photodisintegrate is overlayed for each separate trajectory. Trajectories passing near the Sun benefit from both head-on incident geometry ($\alpha \sim 0°$) and proximity (photon flux falls with distance squared), and exhibit the greatest likelihood of disintegration only to fall dramatically upon passing the Sun ($\alpha \sim 180°$). The probabilities of those traveling directly inbound to the Earth are virtually driven by proximity to the Sun. Trajectory curvature is due to the HMF (see text).

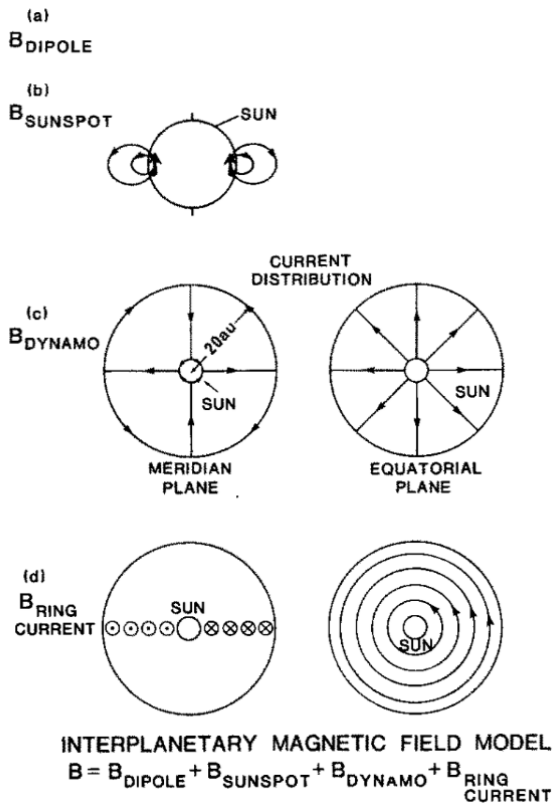


Figure 5.10: Reproduction Fig. 1 in Akasofu et al. (1980) illustrating the four components of the heliospheric magnetic field model.

1. **The Dipole Component**

   The dipole component is modeled as a spherical dipole that diminishes with r^{-3}:

$$
\begin{aligned}
B_z &= -\left(\frac{B_s r_1^3}{2}\right)\left(2z^2-\rho^2\right)\left(z^2+\rho^2\right)^{-5/2} \\
B_\rho &= -\left(\frac{3B_s r_1^3}{2}\right)\rho z\left(z^2+\rho^2\right)^{-5/2} \\
B_\phi &= 0
\end{aligned}
\tag{5.10}
$$

   where $B_s r_1^3/2$ is the magnetic dipole moment of the sun. Following convention, r_1 is chosen to be the solar radius $R_\odot = 0.00465$ AU, yielding $B_s = 2$ G, the dipole field at the north pole of the Sun.

2. **The Sunspot Component**

   The sunspot component, which serve to close magnetic field lines on the equatorial surface, is modeled by an ensemble of 180 evenly-spaced dipoles of the kind in Eq. (5.10) at a radius of $0.8R_\odot$ and $B_s = 1000$ G.

3. **The Dynamo Component**

   The dynamo component stems from current in the photosphere drawn by the rotation of the Sun under the influence of the main dipole field. It is described by a current sheet which flows out from the axial poles, along the heliosphere and returns at the equator. Along with the ring current, the dynamo component falls with r^{-1} and dominates the field contribution to B_ϕ at large distances.

$$\begin{aligned} B_z &= 0 \\ B_\rho &= 0 \\ B_\phi &= sign(z) B_{\phi_0} \frac{\rho_0}{\rho} \end{aligned} \tag{5.11}$$

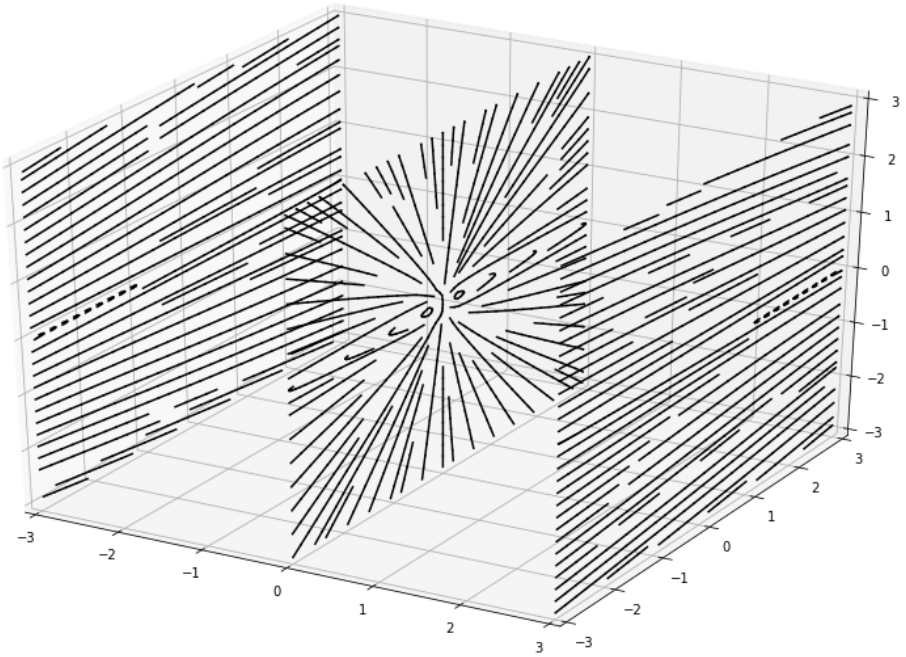
   where $B_{\phi_0} = 3.5 \times 10^{-5}$ G, and $\rho_0 = 1$ AU.

4. **The Ring Current Component**

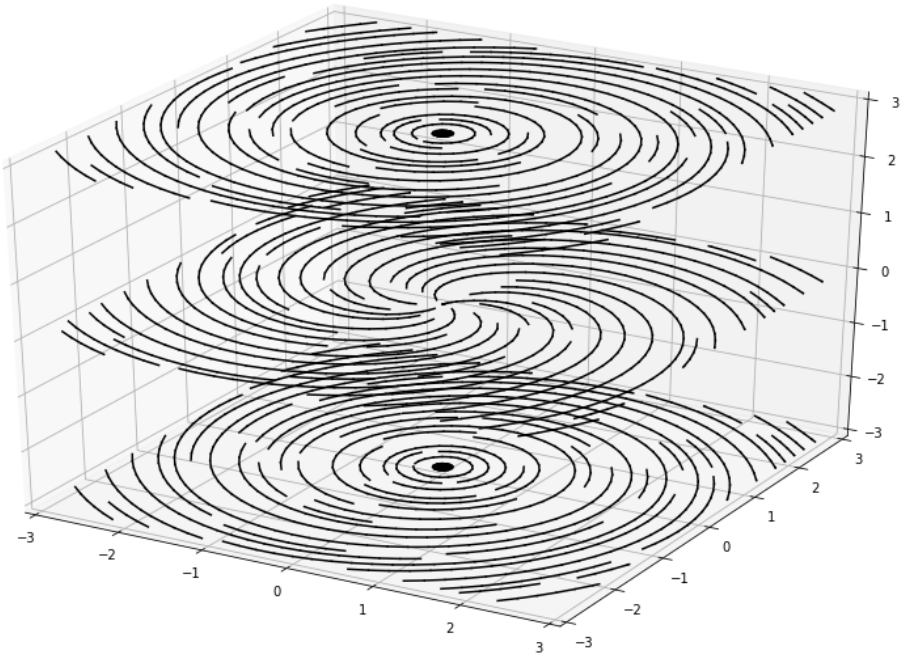
   The ring current component arises from an equatorial current sheet that diminishes with r^{-2}, thus dominating B_z and B_ρ at large distances. The exact solution to this sheet is well approximated (Epele et al. (1999)) by:

$$\begin{aligned} B_z &\simeq B_{\rho_0} \rho_0^2 |z| \left(z^2 + \rho^2\right)^{-3/2} \\ B_\rho &\simeq sign(z) B_{\rho_0} \rho_0^2 \, \rho \left(z^2 + \rho^2\right)^{-3/2} \\ B_\phi &= 0 \end{aligned} \tag{5.12}$$

   where $B_{\rho_0} = -3.5 \times 10^{-5}$ G and $\rho_0 = 1$ AU.



(a) Radial streamlines (distances are in AU)



(b) Azimuthal streamlines (distances are in AU)

Figure 5.11: A visualization of heliospheric magnetic field streamlines.

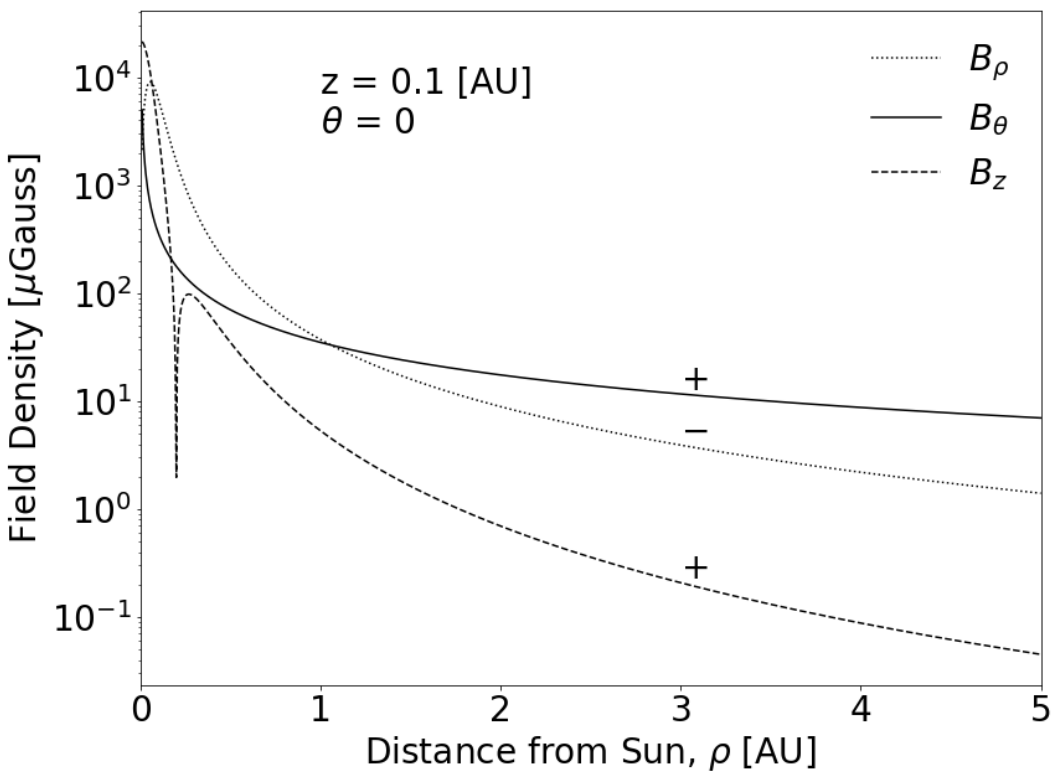


Figure 5.12: Relative strengths of heliospheric magnetic field components at $z = 0.1$ AU and $\theta = 0°$, as a function of planar distance from the Sun. The signs of the components are denoted by plus or minus, [dotted] planar, [solid] azimuthal, [dashed] vertical.

In practice, numerical propagation of nuclei can be expedited by at least an order of magnitude by making interpolation maps of the HMF. For this analysis, a precomputed map of the HMF sampled every 0.02 AU within 0.6 AU of the Sun and 0.2 AU everywhere else was found to be sufficient for interpolating the HMF to at least 5 figures of accuracy for distances > 0.01 AU of the Sun. For trajectories that fall closer than 0.01 AU, or further than 6 AU, the numerical result is calculated from the full four-component model as needed.

5.4.3 Dynamics

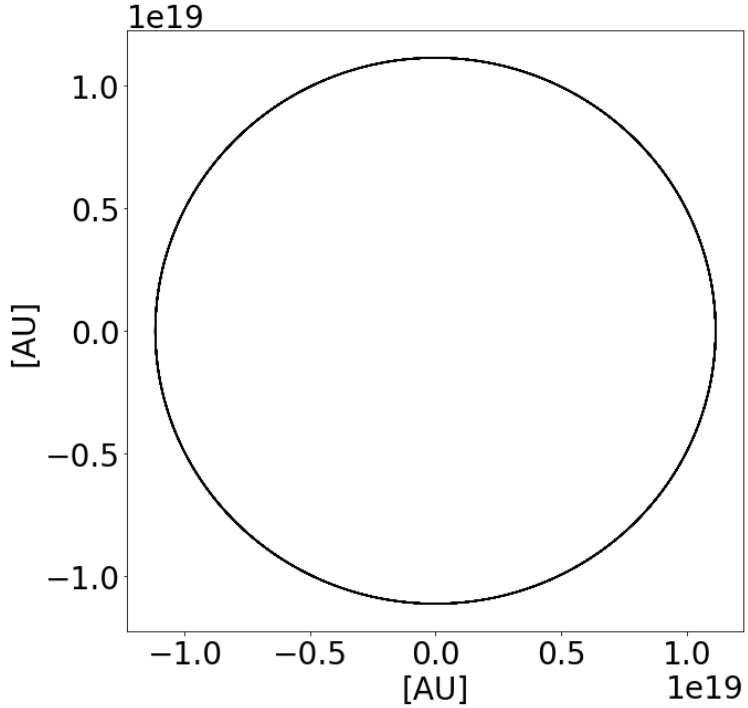
Gravitational attraction has negligible influence on UHECR propagation, especially over solar system distance scales, as such, the dynamics of propagation are well governed exclusively by the Lorentz-force law:

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\ (\boldsymbol{v} \times \boldsymbol{B}) \tag{5.13}$$

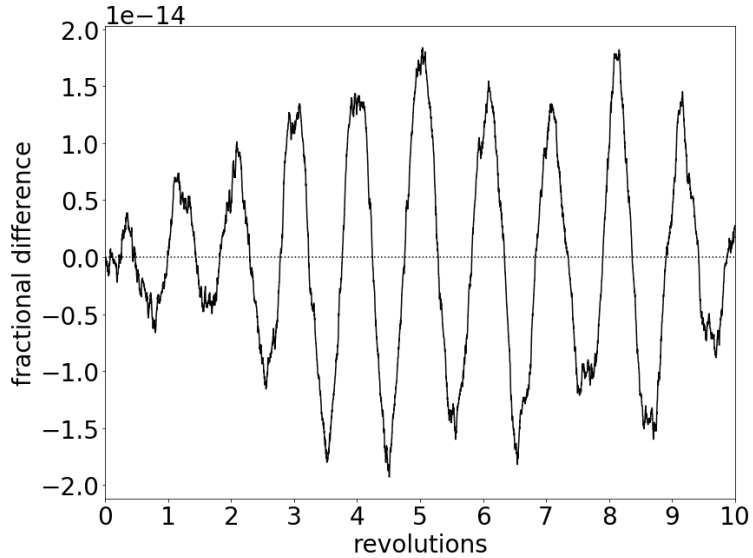
Where relativistic substitutions are made: $\boldsymbol{p} = \gamma m \boldsymbol{v}$, $\gamma = 1/\sqrt{1-\beta^2}$, $\boldsymbol{\beta} = \boldsymbol{v}/c$, time is measured in the solar rest frame, and $\boldsymbol{B}$ is the heliospheric magnetic field. m and q are mass and electric charge respectively, with all quantities in SI units. For nuclei in the EeV to ZeV energy range of interest, $10^6 < \gamma < 10^{10}$, and $.99999999999994\bar{9} < \beta < 0.\bar{9}$. With negligible error, $\boldsymbol{\beta} = \hat{\boldsymbol{\beta}}$, and it is possible to re-write Eq. (5.13) in a numerically-convenient form:

$$\frac{\mathrm{d}\hat{\boldsymbol{\beta}}}{\mathrm{d}\lambda} = \frac{Z}{E_{eV}} \left(\hat{\boldsymbol{\beta}} \times c\boldsymbol{B}\right) \tag{5.14}$$

where λ is the space-coordinate along the path of the nuclei, Z is the atomic number, E_{eV} the energy of the nucleus in electron-volts and c the speed of light.



(a) An example test simulation of a 100 EeV Helium nucleus looping 10 times in a constant 10^{-15} Gauss magnetic field—a field strength nearly 1,000 times less than that at the edge of the solar system.



(b) Relative difference between the instantaneous radius of the simulation, and the analytical gyroradius in Eq. 5.15

Figure 5.13: Many extreme-case simulation tests were performed for various nuclei, energies, and constant magnetic field strengths to validate sufficient numerical precision for actual HMF propagation. The numerical step size is taken as $1/100^{\text{th}}$ the analytical gyroradius, or for actual HMF propagation, maximally 0.01 AU. The trajectory is integrated using a DOP853 ODE numerical integrator, Dormand and Prince (1980).

Great care must be taken to ensure numerical accuracy. For spatial precision within one meter following a propagation of 10 AU, numerical precision is needed at least to the 13th decimal place. To aid in validating simulation results, the gyroradius of a relativistic particle under a constant field is known to be:

$$r = \frac{1}{c}\frac{E_{eV}\ \beta}{Z\ B} \tag{5.15}$$

A validation of Eq. (5.14) with Eq. (5.15) is demonstrated in Fig. 5.13. For all extreme cases tested (low Z and B, high Z and B), the fractional difference within the first half-revolution was below 5×10^{-15}, which bodes well for typical propagation distances for actual simulations where only a very small fraction of a full revolution is traversed. Several ODE solver algorithms were tried, and a Runge-Kutta order 8(5,3) method "DOP853," Dormand and Prince (1980), was found to exhibit the optimal trade-off between performance and accuracy. The numerical step size is computed at each step as $1/100^{\text{th}}$ the analytical gyroradius for the instantaneous magnetic field strength and energy, or maximally 0.01 AU in GZ Effect simulations with a full HMF model; as object come within a step size of the Earth, the step size was further reduced to fractions of Earth-radii to assure accuracy in termination.

5.4.4 Algorithm

The radius of the Earth is around 10^{-6} the distance of the orbital radius of Neptune. As such, the probability of a single, randomly propagating cosmic ray on solar system scales to strike the Earth is extremely low. Therefore, for computational efficiency, seed trajectories are propagated from the Earth outward before reversing and propagating back.

100,000 points were selected at random on the surface of the Earth with uniform spherical density (uniform in azimuth, ϕ, and sin θ weighted in polar angle, θ). The azimuth and zenith angle headings for each point was in turn randomly assigned with uniform

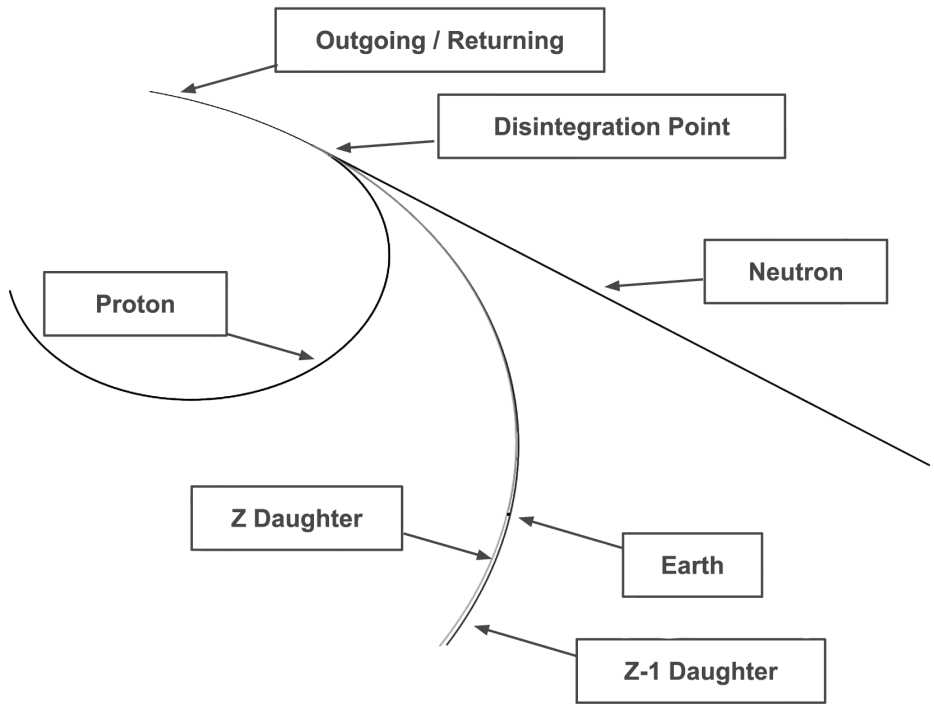


Figure 5.14: An illustrative example with an artificially strong magnetic field to show general characteristics. The outgoing initial trajectory begins at the Earth. The 'p' and 'n' channel are overlaid (see text) despite a real photodisintegration process where only one or the other would likely occur.

hemispherical density away from the surface (where the weighted zenith-polar angle is limited to $[0°, 90°]$). For each primary nucleus (^{4}He, ^{16}O, ^{56}Fe and ^{238}U), and for each primary energy (10^{15}, 10^{16}, 10^{17}, 10^{18}, 10^{19} and 10^{20} eV), a negative Z charge was temporally applied so the outgoing propagation would be analogous to the incoming positive Z return trajectory. For each step in the outgoing simulation, the equivalent (reversed heading, reversed charge) incoming probability to photodisintegrate was sampled and stored. After propagating 10 AU, the total probability of photodisintegrating along that trajectory is found from summing the stored probabilities, and drawing from this distribution, a disintegration point is randomly selected—further propagation out to 40 AU (Pluto) results in less than 1% increase in total probability. The nucleus is now situated at this disintegration point, and allowed to split into a two possible outcome channels we denote 'p' for (proton, Z-1 daughter), and 'n' for (neutron, Z daughter). Each channel

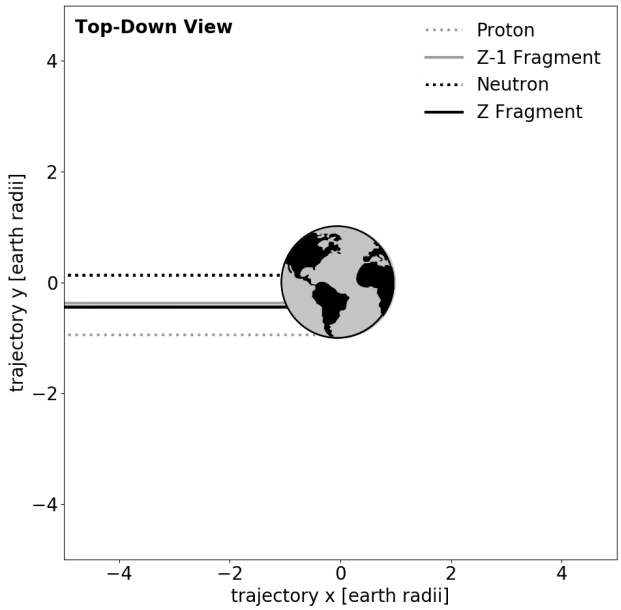


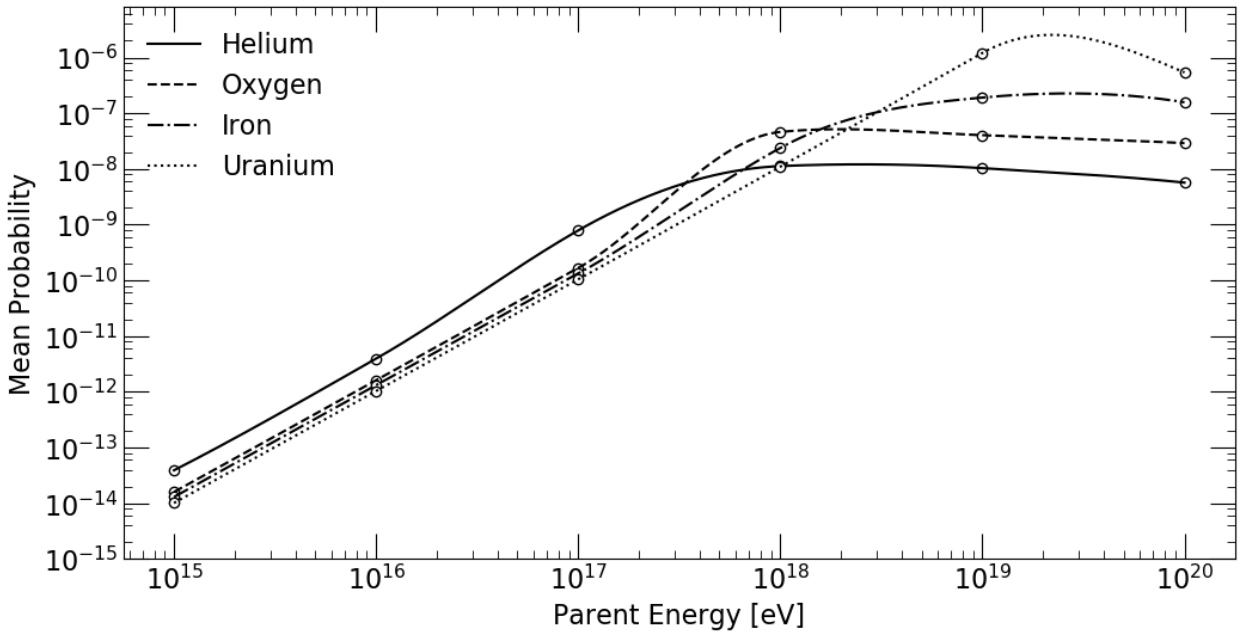
Figure 5.15: An example simulation resulting in dual-showers for both the 'p' (gray) and 'n' (black) channels, [dotted] nucleons, [solid] nuclear fragments. Channel pairs can either both miss the Earth, single shower (one partner misses), or dual shower. Dual showers can potentially be separated by an entire Earth diameter. The trajectory-x direction is taken as the direction of propagation of the proton, with the z direction parallel to the solar system z.

(nucleon, daughter fragment) is allowed to separately propagate Earth-bound, and the simulation ends for each fragment when it has either struck the Earth or passed it (Fig. 5.14, 5.15).

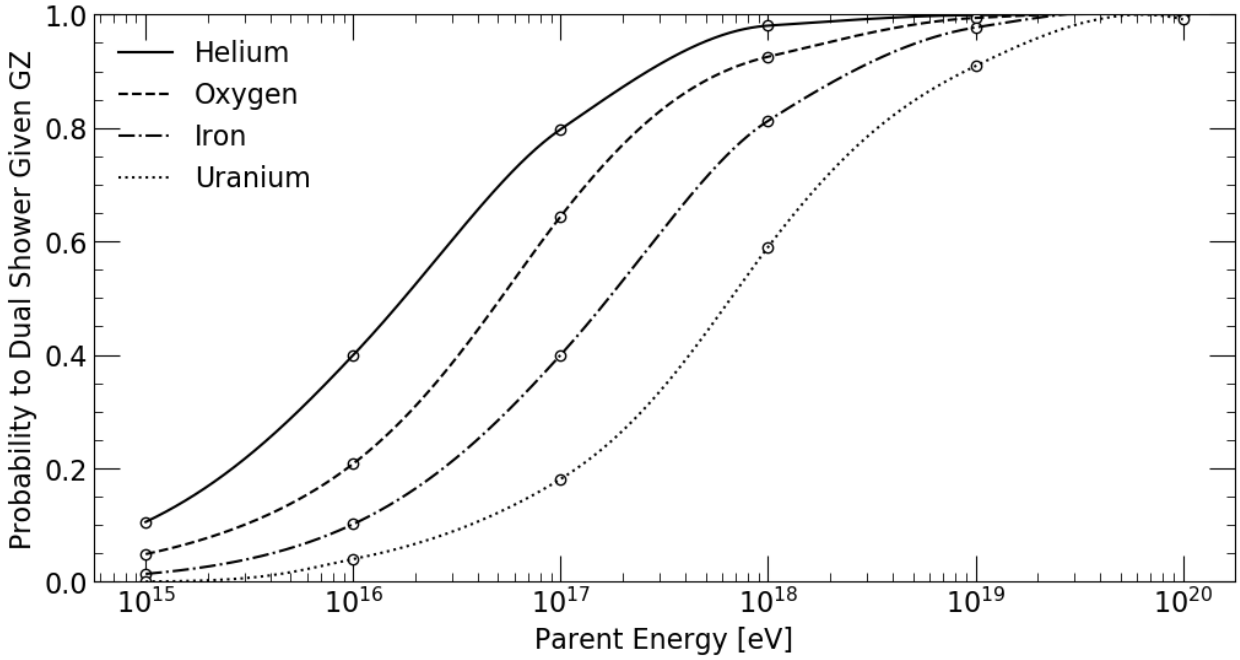
The simulation code is provided in Appendix G, and the results are discussed in the next section.

5.5 Dual Extended Air Shower Results

The average probability (over all incoming trajectories) to photodisintegrate via the Giant Dipole Resonance (Eqs. (5.6), (5.8) and (5.16)), and the subsequent fraction of these events that produce a dual-EAS (Eq. (5.18)) is presented in Fig. 5.16. The aforementioned

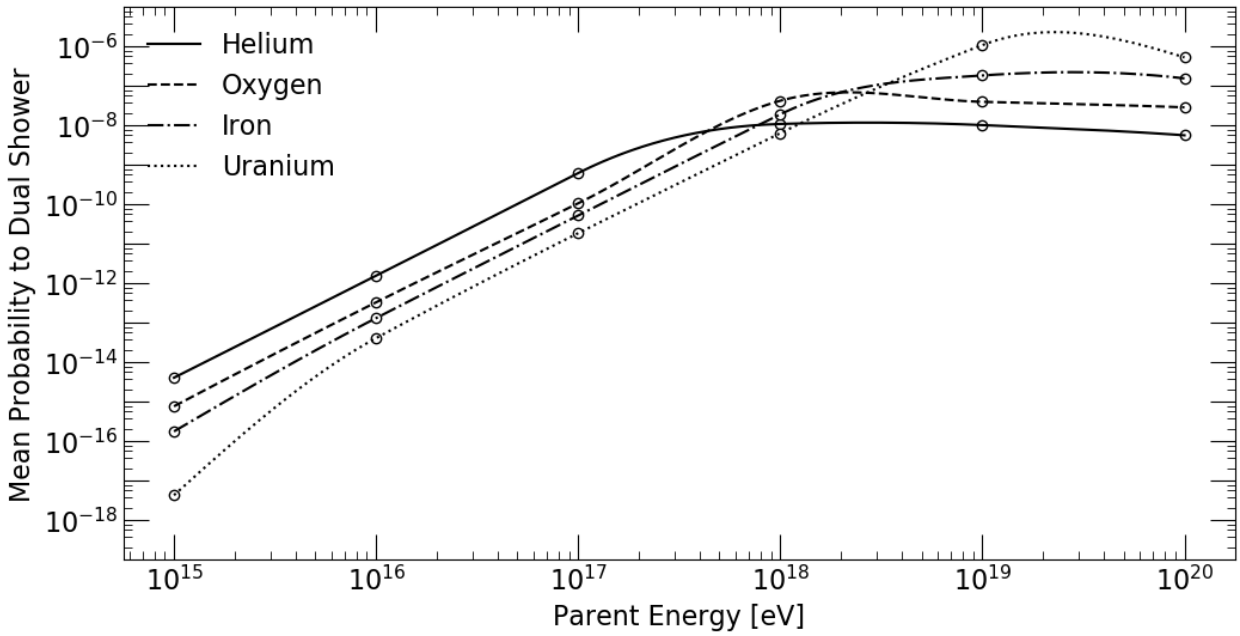


(a) Trajectory-averaged likelihood for photodisintegration regardless of EAS outcome.

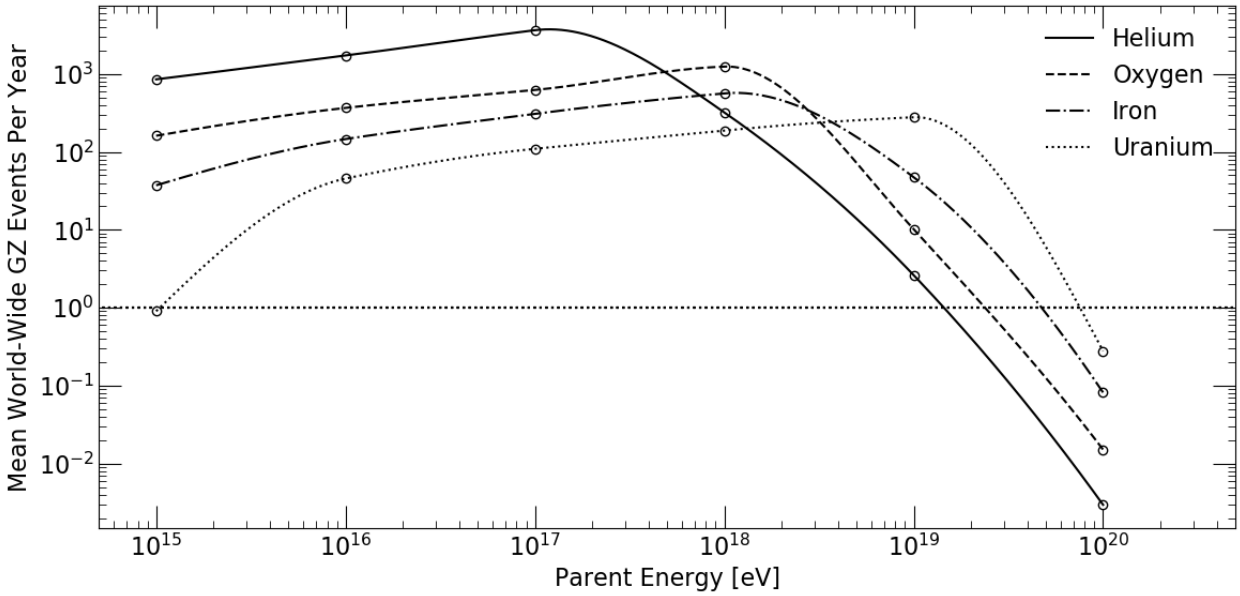


(b) Average likelihood for dual-EASs, given photodisintegration.

Figure 5.16: Top, the mean probability to photodisintegrate via the Giant Dipole Resonance, $\langle P_{\mathcal{S}}(Z,E)\rangle$, averaged over $N_{Z,E} = 100,000$ trajectories, $\mathcal{S}$, for same Z and E: $\langle P_{\mathcal{S}}(Z,E)\rangle = (1/N_{Z,E})\sum_{\mathcal{S}} P_{\mathcal{S}}(Z,E)$. Bottom, the probability to produce a dual-EAS (GZ Effect) given photodisintegration, $\langle P_{\text{dual}}(Z,E)\rangle = M_{\text{dual}}/N_{Z,E}$, where M_{dual} is the number of simulations resulting in a dual-EAS. The differences between n- and p-channels turn out to be negligible, and the results shown here are representative of either.



(a) Trajectory-averaged likelihood to photodisintegrate *and* produce a dual-EAS.



(b) Estimated GZ Effect world-wide yearly rate.

Figure 5.17: Top, the product of Fig. 5.16a and Fig. 5.16b—the mean probability to photodisintegrate *and* produce a dual-EAS, $\langle P_{\mathrm{GZ}}(Z,E)\rangle = \langle P_{\mathrm{S}}(Z,E)\rangle\langle P_{\mathrm{dual}}(Z,E)\rangle$. Bottom, the product of (a) and the established cosmic ray flux (Fig. 4.16, top), $F(E)$, times the surface area of the Earth, A_E, for one year, T_{yr}, giving an estimated number of world-wide GZ Effect events per year, $\langle N_{\mathrm{GZ}}(Z,E)\rangle = F(E)\ A_E\ T_{\mathrm{yr}}\ \langle P_{\mathrm{GZ}}(Z,E)\rangle$. A horizontal line is drawn to indicate the 1 event per year threshold. As the atomic number dependence of UHECRs is not precisely known, each element is listed as if they were the only species; therefore, these curves represent the absolute upper-limits for these averages.

average probability is simply,

$$\langle P_{\mathcal{S}}(Z,E)\rangle = \frac{1}{N_{Z,E}} \sum_{\mathcal{S}} P_{\mathcal{S}}(Z,E) \tag{5.16}$$

where the number of trajectory simulations for atomic number Z and parent energy E is $N_{Z,E} = 100,000$. As mentioned in the previous section, the result of a simulation can end in only one of three ways: dual-EASs (both the nucleon and fragment strike the Earth), a solo-EAS (either one of the nucleon or fragment miss the Earth), or null-EASs (both the nucleon and fragment miss the Earth),

$$N_{Z,E} = M_{\mathrm{dual}(Z,E)} + M_{\mathrm{solo}(Z,E)} + M_{\mathrm{null}(Z,E)} = 100,000 \tag{5.17}$$

Therefore, the mean fraction to dual-EAS is,

$$\langle P_{\mathrm{dual}}(Z,E)\rangle = \frac{M_{\mathrm{dual}(Z,E)}}{N_{Z,E}} \tag{5.18}$$

As evidenced by Fig. 5.16a, the Giant Dipole Resonance is most effective on nuclei with energy in excess of 10^{18} eV, generally plateauing somewhere between a 1 in 10 million likelihood for heavy elements, and 1 in 100 million for light elements. Somewhat conveniently, the gyroradius for fragments and protons at this energy range become large enough to almost ensure dual-EASs (Fig. 5.16b)—as the gyro-radius scales inversely with atomic number, Z, this is more the case for lighter elements than heavier.

In Fig. 5.17a, the product of the mean fraction of UHECRs to photodisintegrate along trajectory $\mathcal{S}$, $\langle P_{\mathcal{S}}(Z,E)\rangle$, with the probability to dual-EAS given photodisintegration, $\langle P_{\mathrm{dual}}(Z,E)\rangle$ (from Fig. 5.16), gives the mean expected fraction,

$$\langle P_{\mathrm{GZ}}(Z,E)\rangle = \langle P_{\mathcal{S}}(Z,E)\rangle \, \langle P_{\mathrm{dual}}(Z,E)\rangle \tag{5.19}$$

for any Earth-bound cosmic ray (which would otherwise produce a single EAS) to produce dual-EASs. Although the probability for a GZ Effect candidate event is no more than 1 in a million, the Earth is a very large (potential) detector, and the world-wide yearly cosmic ray flux is quite large. The estimated yearly rate of GZ Effect dual-EASs is shown in Fig. 5.17b, and it can be seen that despite the low probability for production at energies below 10^{18} eV, the substantially higher flux of cosmic rays at these lower energies produce the greater number of dual-EAS events.

As a counterpart to Fig. 5.17b, the geographically-binned (in ecliptic-plane latitude and longitude, $\varphi_\odot$ and $\lambda_\odot$ respectively) GZ Effect flux, $F_{\mathrm{GZ}}(\varphi_\odot, \lambda_\odot; E)$, as a function of UHECR energy is shown in Figs. 5.18–5.20. Unlike Fig. 5.17 where the individual event probability, $P_{\mathcal{S}}(Z, E)$, was averaged over all trajectories, $\mathcal{S}$, these aforementioned figures were instead built up on an event-by-event basis. Explicitly, for each GZ Effect flux bin centered at $(\varphi_\odot, \lambda_\odot)$,

$$F_{\mathrm{GZ}}(\varphi_\odot, \lambda_\odot; E) = \frac{1}{\sum\limits_{Z} W(Z)\, N_{Z,E}} \left(\frac{1}{2} \sum_{i=\text{nucleons}}^{\text{fragments}} f_i^c(E)\, W(Z_i)\, P_{\mathcal{S}}(Z_i, E) \right) \frac{F(E)\, 4\pi}{\cos(\varphi_\odot)\Delta\varphi_\odot \Delta\lambda_\odot} \tag{5.20}$$

where the sum of $W(Z)\, N_{Z,E}$ over Z represents the total (weighted) number of simulations with energy E (regardless if they resulted in a dual-EAS), which is 111,100. The sum over i implicitly covers only simulations resulting in dual-EASs, where each nucleon- or fragment-induced EAS is counted individually (implicitly referring only to those in geographic bin centered on $\varphi_\odot, \lambda_\odot$). The multiplicative factor of a half scales the sum over nucleons and fragments (individual EASs) back to GZ Effect events (pairs of EASs); *i.e.*, one GZ Effect event produces two individual EASs. Although the energy and separation spectra for proton-versus-neutron channels were found to contain negligible differences, the inclusion of both outcomes increases figure statistics. However, as *single*-nucleon ejection is

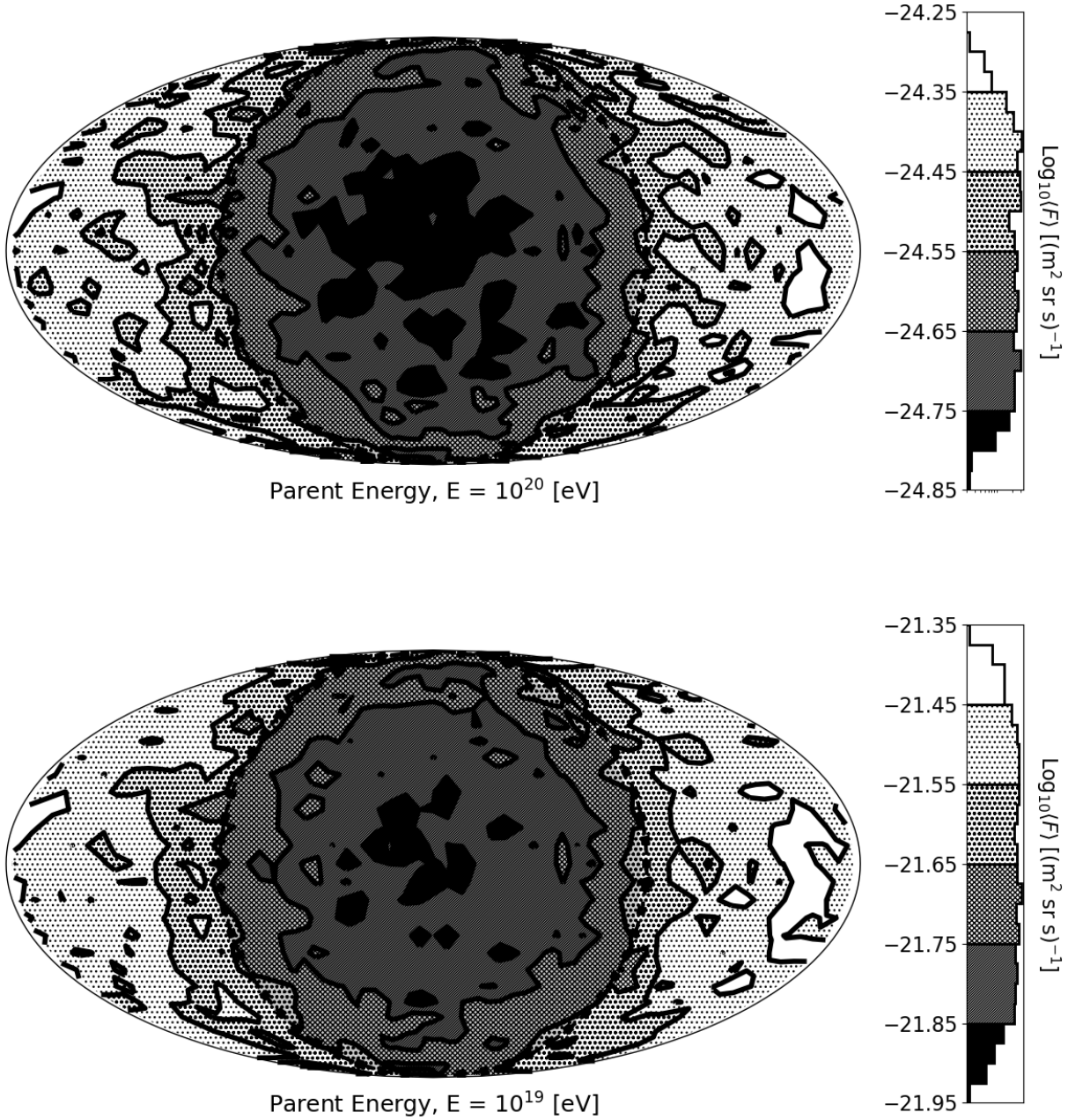


Figure 5.18: GZ Effect flux on Earth averaged over parent UHECR atomic number for various energies. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the geographic distribution of GZ Effect flux for 10^{20} eV UHECR parent nuclei with that of 10^{19} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

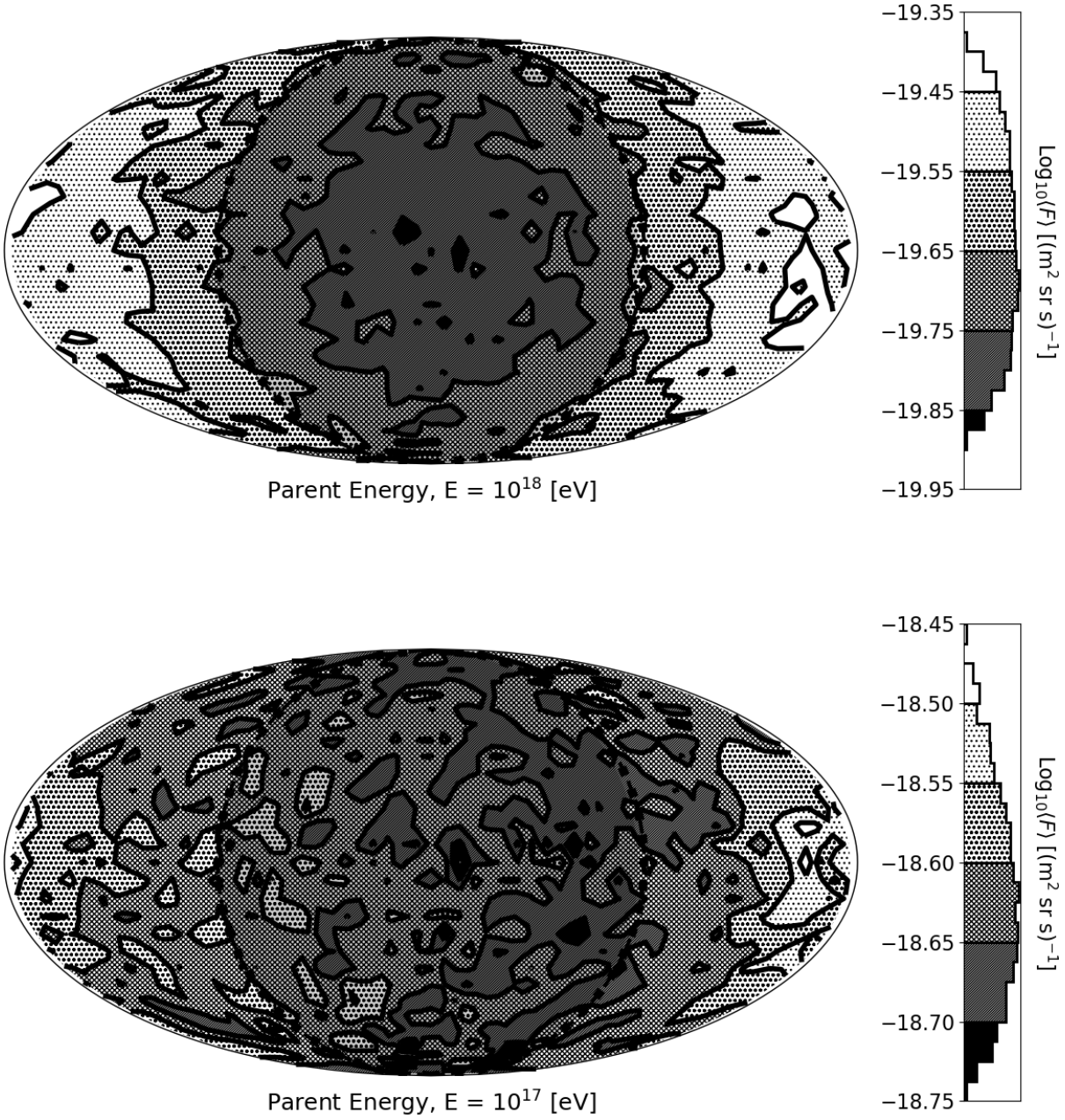


Figure 5.19: GZ Effect flux on Earth averaged over parent UHECR atomic number for various energies. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the geographic distribution of GZ Effect flux for 10^{18} eV UHECR parent nuclei with that of 10^{17} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

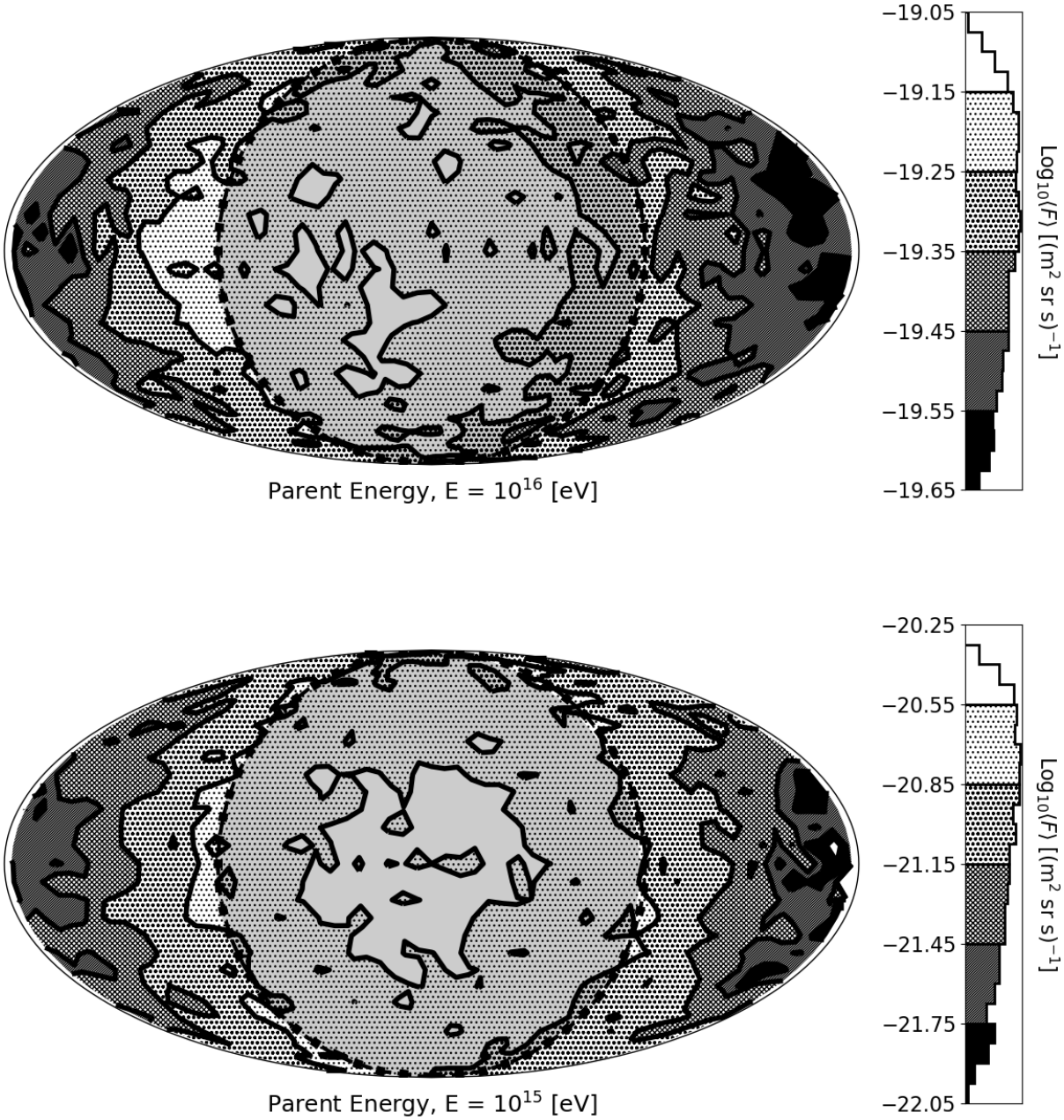


Figure 5.20: GZ Effect flux on Earth averaged over parent UHECR atomic number for various energies. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the geographic distribution of GZ Effect flux for 10^{16} eV UHECR parent nuclei with that of 10^{15} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

Table 5.1: Fractional contribution from n- and p-channel simulations, $f^c(E)$, to produce dual-EAS events as a function of parent energy, E, in eV

E	f^{p}	f^{n}
10^{15}	0.5028	0.4972
10^{16}	0.5090	0.4910
10^{17}	0.5021	0.4979
10^{18}	0.4988	0.5012
10^{19}	0.4991	0.5009
10^{20}	0.4997	0.5003

the dominant channel of photodisintegration outcomes via the Giant Dipole Resonance (Fig. 5.6), it would be incorrect to simply add up their contributions. On the other hand, the number of p-channel and n-channel events that produce dual-EASs are ever-so-slightly unbalanced with simulation statistics; therefore, as the sum progresses over p- and n-channel dual-EASs, $f^c(E)$, accounts for each channel's relative contribution with a statistical weighting factor given in Table 5.1.

$F(E)$ represents the established UHECR flux evaluated for the parent nucleus (Helium, Oxygen, Iron, or Uranium) of each EAS, i. However, as the relative elemental abundance in UHECRs is not precisely known, each parent element's flux contribution was suppressed by a weighting, $W(Z_i)$, as follows:

$$\begin{aligned}
&\text{Helium} && \rightarrow W(2) && = \times 10^{0} \\
&\text{Oxygen} && \rightarrow W(8) && = \times 10^{-1} \\
&\text{Iron} && \rightarrow W(26) && = \times 10^{-2} \\
&\text{Uranium} && \rightarrow W(92) && = \times 10^{-3}
\end{aligned} \tag{5.21}$$

And $P_{\mathcal{S}}(Z_i, E_i)$ again represents the probability for photodisintegration along the parent path corresponding to EAS, i. We note that the dual-EAS probability is already built into this expression as the sum over EASs implicitly only considers those which have duals, and the normalizing sum on $N_{Z,E}$ represents the total number of simulations (regardless of the EAS-result). Lastly, the final term is the ratio of Earth's surface area (shown as solid angle, as Earth's radii cancel in the numerator and denominator) to the patch area of the bin at $(\varphi_\odot, \lambda_\odot)$.

It can be seen that there is generally a day/night asymmetry—the highest-energy GZ parent UHECRs shown (10^{20} eV) are nearly 4-times more likely to dual-EAS on the sunny-side of Earth than the dark-side. This asymmetry reverses, however, around 10^{17} eV where it becomes nearly 60-times more likely to dual-EAS on the dark-side of the Earth with 10^{15} eV UHECRs. Further, as originally illustrated in Fig. 5.17b, the GZ Effect flux peaks somewhere near 10^{17} eV with a factor of order 1,000-times the rates at 10^{15} eV and 10^{19} eV.

In addition to the geographic distributions of GZ Effect flux, Figs. 5.21–5.23 show the geographic distribution of mean dual-EAS separations, $\langle \Delta s(\varphi_\odot, \lambda_\odot; E) \rangle$. Specifically, for an EAS that strikes a geographic bin, the mean separation radius to its partner EAS is,

$$\langle \Delta s(\varphi_\odot, \lambda_\odot; E) \rangle = \frac{\sum\limits_{i=\text{nucleons}}^{\text{fragments}} \Delta s_i \; [f_i^c(E)\, W(Z_i)\, P_{\mathcal{S}}(Z_i, E)]}{\sum\limits_{i=\text{nucleons}}^{\text{fragments}} f_i^c(E)\, W(Z_i)\, P_{\mathcal{S}}(Z_i, E)} \tag{5.22}$$

where terms from Eq. (5.20) common to both numerator and denominator have been canceled out.

Unlike the flux distributions where the geographic bias changes with energy, the dark-side of the Earth consistently receives more closely-separated EASs than the sunny-side over all

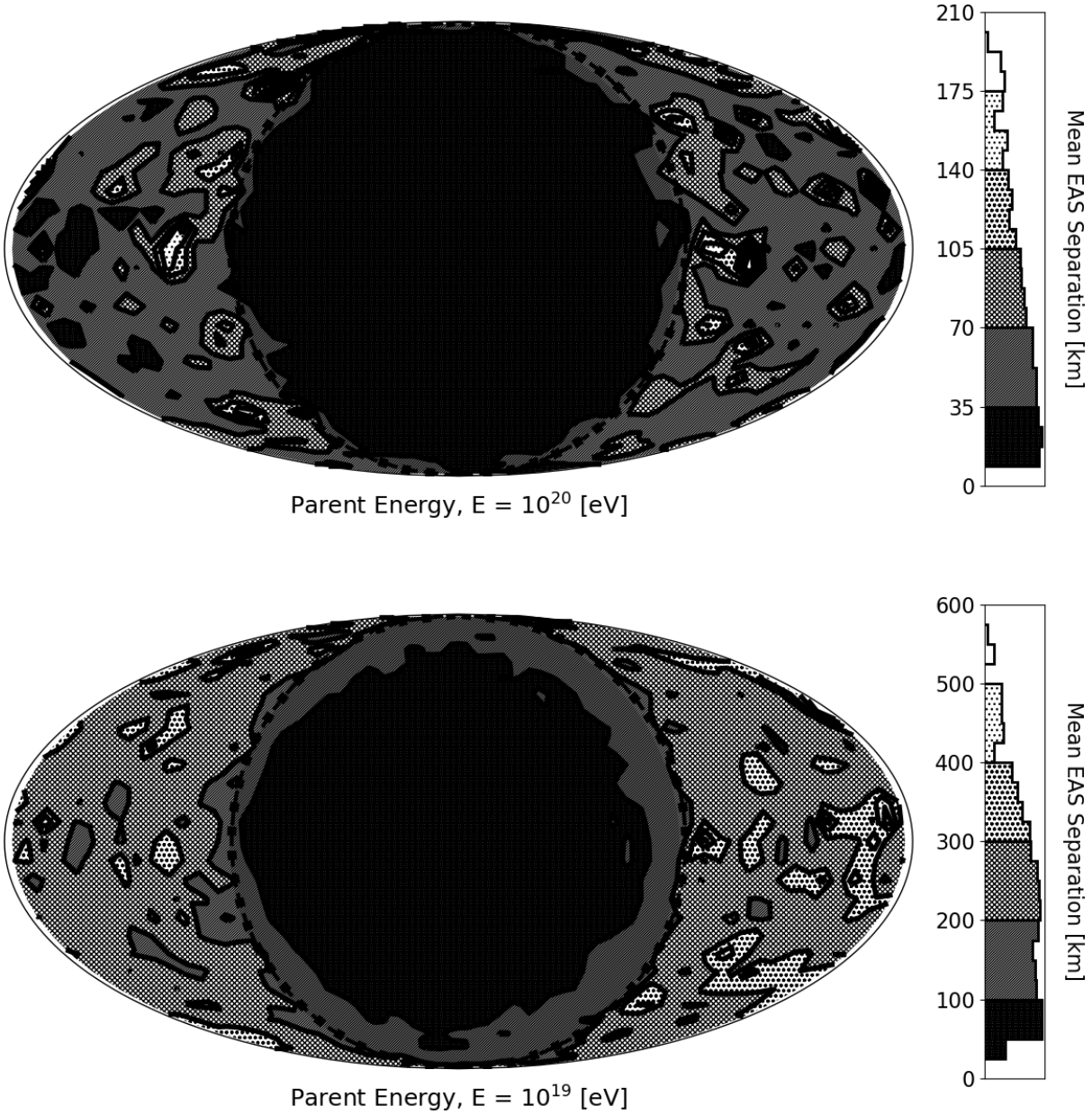


Figure 5.21: GZ Effect dual-EAS great circle separation distances averaged over parent UHECR atomic number for various energies. For each individual nucleon or fragment EAS that strikes a particular geographic location bin shown, the average separation radius to its pair is indicated by the value of this bin. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the separation distribution for 10^{20} eV UHECR parent nuclei with that of 10^{19} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

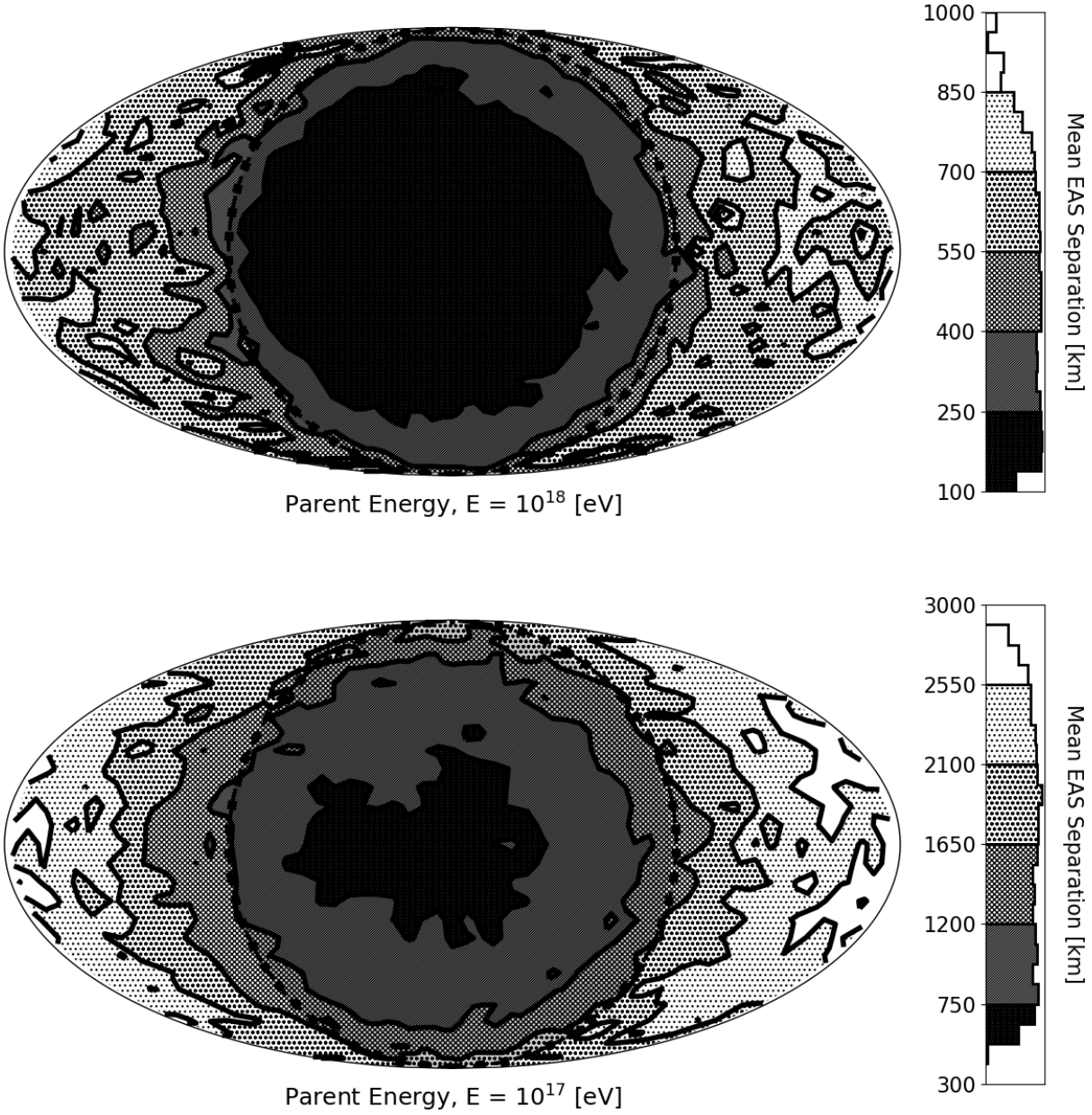


Figure 5.22: GZ Effect dual-EAS great circle separation distances averaged over parent UHECR atomic number for various energies. For each individual nucleon or fragment EAS that strikes a particular geographic location bin shown, the average separation radius to its pair is indicated by the value of this bin. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the separation distribution for 10^{18} eV UHECR parent nuclei with that of 10^{17} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

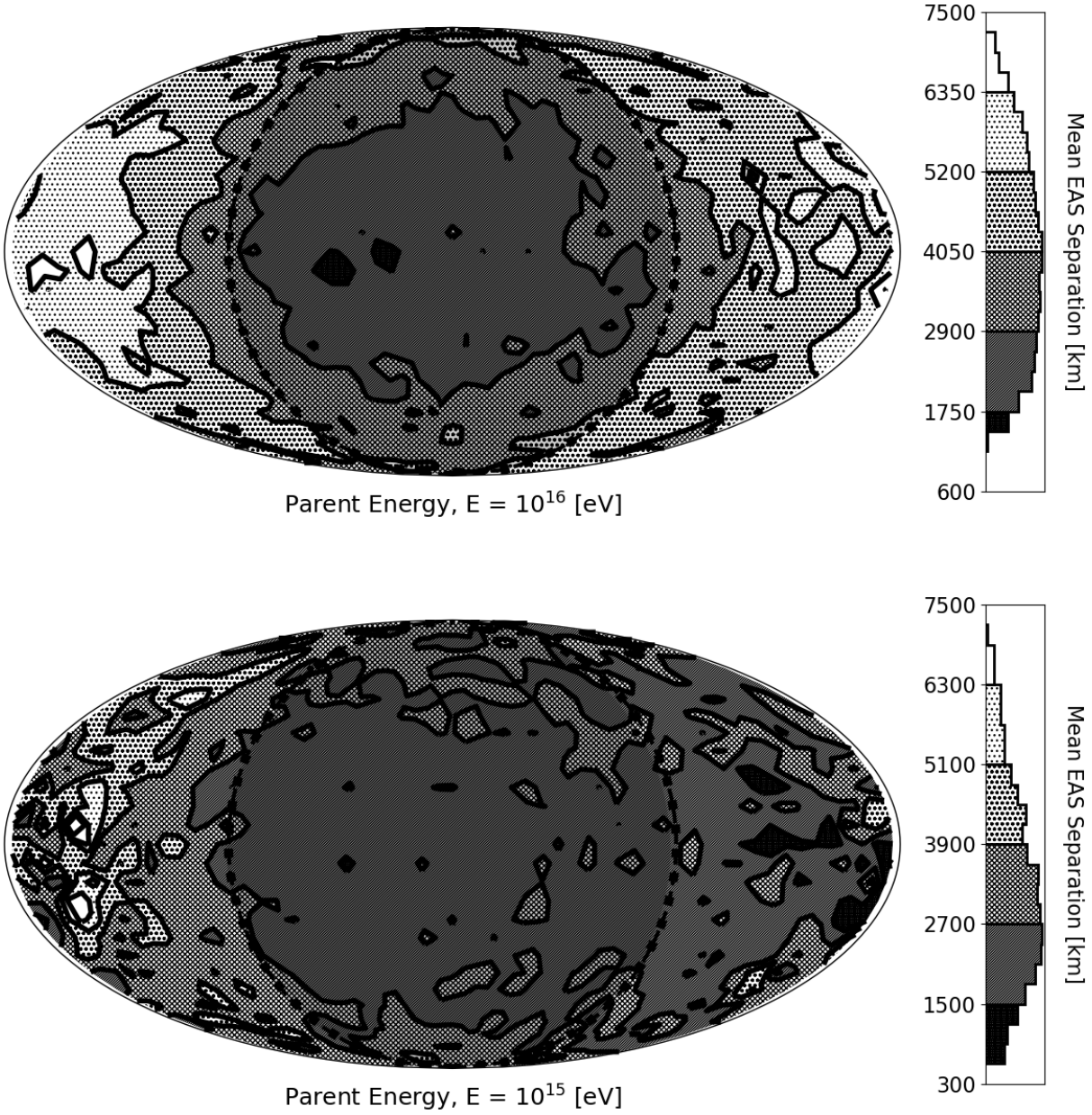


Figure 5.23: GZ Effect dual-EAS great circle separation distances averaged over parent UHECR atomic number for various energies. For each individual nucleon or fragment EAS that strikes a particular geographic location bin shown, the average separation radius to its pair is indicated by the value of this bin. The central darkened circle identifies the parts of the globe experiencing night (6pm to 6am), *i.e.* when CRAYFIS users are expected to most likely be taking data. The equator is aligned with the ecliptic plane with North-South perpendicular to it. Eastward rotation is to the right. Top, the separation distribution for 10^{16} eV UHECR parent nuclei with that of 10^{15} eV shown below. Color bars indicate the relative land-area coverage on a log scale that is not shown. See text for discussion.

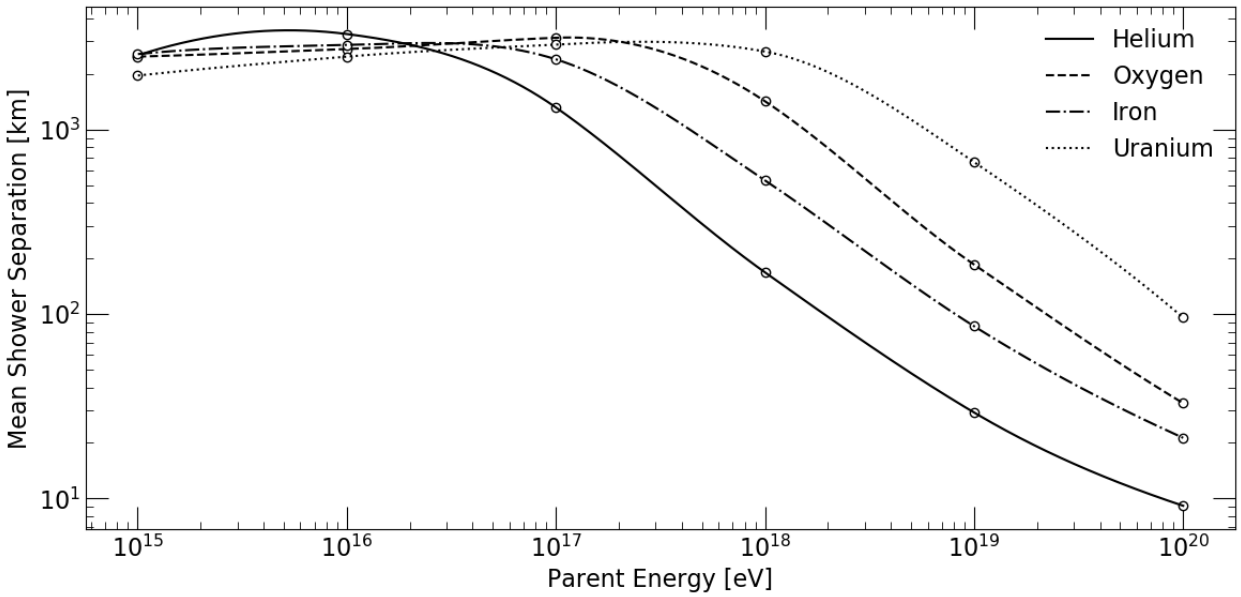


Figure 5.24: Average GZ Effect geographic separations for dual-EASs as a function of energy and primary atomic number.

UHECR parent energies. The overall separation is greatest for the lowest energies, and smallest for the highest energy. An average over all geographic bins is provided in Fig. 5.24.

5.5.1 Summary and Discussion

With hypothetical explanations deferred until the end of the section, nighttime CRAYFIS users on the whole are expected to observe fewer overall, lower-energy and lesser-separated dual-EASs than midday CRAYFIS users. In terms of flux, for UHECR parent energies above 10^{18} eV, the ratio of day and night fluxes is about 4× in favor of midday to midnight. By 10^{17} eV, this ratio drops by half to about 2×, then flips to favor midnight over midday by a factor of 4× by 10^{16} eV, and continues to favor midnight by 60× by 10^{15} eV. However, the flux of GZ Effect dual-EASs is maximized near 10^{17} eV, so on the whole from this alone, midday CRAYFIS users are around 1–2× more likely to catch a dual-EAS than midnight users. For a comparative reference, the established UHECR flux at $\sim 10^{17}$ eV (the approximate energy where GZ Effect dual-EASs are most prolific) is around $10^{10}\times$ more prolific than that of the GZ Effect—making GZ Effect detection challenging (see the

next section). In terms of separation, midnight users are more likely to see dual-EASs at 1/10× the distance of those seen at midday, and separation distances between 500 and 5,000 km are the most common overall.

Broadly speaking, the GZ dual-EAS flux is seen to be relatively constant along eastward and westward-facing meridians (with respect to the ecliptic plane, local dawn and twilight respectively). On the other hand, (ecliptic-)latitudinal variation of average flux and separation distance could lead to seasonal variations in geographic hemisphere asymmetry—specifically, nighttime CRAYFIS users in the Northern (Southern) hemispheres would be more centrally-aligned with the sunny-side of the Earth during the summer (winter); and conversely, hemisphere asymmetry would be minimized during the spring and fall (provided it is possible to detect the GZ Effect at all).

The time-of-day asymmetries in flux and EAS separation do not come so much as a surprise considering the probability to photodisintegrate is greatest for "solar-passing" trajectories (Fig. 5.9) that experience highly Doppler-shifted (head-on) photons and high photon field density. Solar-passing trajectories also experience the greatest HMF strengths, which tend to cause greater separations. As the gyroradius (Eq. (5.15)) for individual products scales in proportion to energy (and inversely with atomic number), one or both low-energy products increasingly misses the Earth (especially on the sunny-side of the Earth) resulting in the expected flux inversion favoring the dark-side of the Earth at low energies.

On the other hand, although "Earth-direct" trajectories benefit from head-on (highly Doppler-shifted) photons, the photon field density is dramatically lower from this direction, resulting in photodisintegrations happening closer to the Earth on the average where the comparatively weak HMF (and shorter product propagation distance) results in more closely-separated EASs.

Polar-going (and east/west direction) trajectories largely appear to be a smooth transition of conditions between those of solar-passing and Earth-direct.

5.6 CRAYFIS Sensitivity to the GZ Effect

In this section, two hypothetical world-wide CRAYFIS array scenarios are assessed for their sensitivity to GZ Effect dual-EAS events. In §5.6.1, "Scenario U" and "Scenario P" are outlined in terms of overall effective areas for each hypothetical CRAYFIS array. The geographic location and separation of the CRAYFIS detectors themselves is considered in §5.6.2. Following brief discussions on the effects of temporal and angular resolutions (§5.6.3), the expected background and signal rates are then evaluated in §5.6.4. A sensitivity analysis is at last presented in §5.6.5, with a discussion of results in §5.6.6.

5.6.1 An Effective Area for Earth

Previously, in Chapter 4.2, the concept of an effective area for individual smartphones was introduced as a practical figure of merit. This concept is now developed for arrays of smartphones, where the effective ground-coverage area becomes the quantity of interest. For an arbitrary patch of land, A_i, with CRAYFIS smartphone density, $\rho_C(A_i)$, the likelihood for at least 5 smartphones to register a "hit" from EAS particles, $P_5(\rho_C(A_i), E)$ (where E is the total energy of the EAS), is conservatively estimated from Fig. 4.11. For simplicity, P_5 is replaced with the Heaviside step-function, $\mathcal{H}\left(\langle\rho_C\rangle_i - \rho_{\text{thresh}}(E)\right)$, such that the threshold density, $\rho_{\text{thresh}}(E)$, needed for land area, A_i, to be sensitive to EASs is listed

Table 5.2: CRAYFIS smartphone density thresholds (see Fig. 4.11), ρ_{thresh}, to detect EAS events as a function of EAS primary energy, E.

E [eV]	ρ_{thresh} [#/km^2]
10^{15}	1,000
10^{16}	80
10^{17}	30
10^{18}	10
10^{19}	4

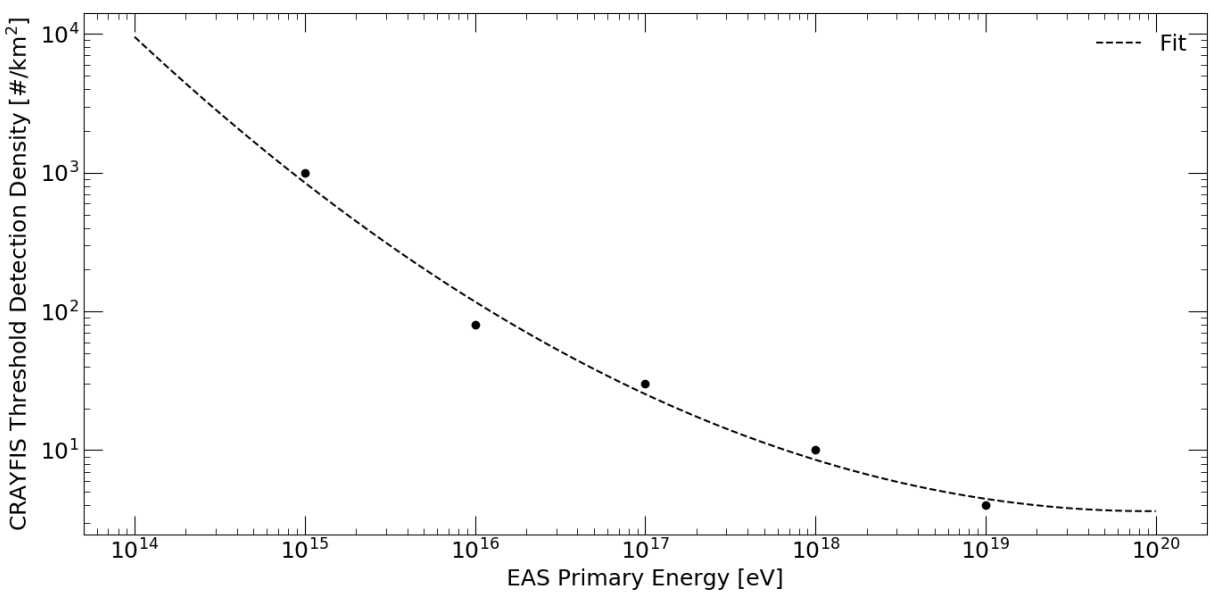


Figure 5.25: Table 5.2 is shown plotted with a quadratic fit given in Eq. (5.23).

in Table 5.2, plotted in Fig. 5.25, and fit as follows,

$$\begin{aligned}
\rho_{\text{thresh}}(E) &= 10\,\hat{}\,\left[a_0 + a_1 \log_{10} E + a_2 \left(\log_{10} E\right)^2\right] \\
a_0 &= 38.894 \\
a_1 &= -3.8407 \\
a_2 &= 0.09620
\end{aligned} \tag{5.23}$$

The average CRAYFIS smartphone density, $\langle \rho_C \rangle_i$, is considered for two scenarios,

$$\langle \rho_C \rangle_i = \frac{N_{\text{people}}}{A_i} \left\langle \frac{N_{\text{smartphones}}}{N_{\text{people}}} \right\rangle \left\langle \frac{N_{\text{CRAYFIS}}}{N_{\text{smartphones}}} \right\rangle = \rho_i \langle \xi \rangle \tag{5.24}$$

where ρ_i is the population density and $\langle \xi \rangle$ is the product of scenario-dependent quantities:

- 'Scenario U' (the Upper-limit scenario):

$$\begin{aligned}
&\left\langle \tfrac{N_{\text{smartphones}}}{N_{\text{people}}} \right\rangle_{\text{U}} = 1 \\
&\left\langle \tfrac{N_{\text{CRAYFIS}}}{N_{\text{smartphones}}} \right\rangle_{\text{U}} = 1 \\
&\implies \langle \xi \rangle_{\text{U}} = 1
\end{aligned}$$

- 'Scenario P' (the Pragmatic scenario):

$$\begin{aligned}
&\left\langle \tfrac{N_{\text{smartphones}}}{N_{\text{people}}} \right\rangle_{\text{P}} \simeq \tfrac{2.87\times10^9}{7.79\times10^9} = 0.368 \\
&\left\langle \tfrac{N_{\text{CRAYFIS}}}{N_{\text{smartphones}}} \right\rangle_{\text{P}} \simeq \tfrac{1}{1{,}000} \\
&\implies \langle \xi \rangle_{\text{P}} \simeq 3 \times 10^{-4}
\end{aligned}$$

The maximal sensitivity of CRAYFIS is explored in 'Scenario U', whereas a potential future scenario is explored in 'Scenario P'. In the latter case, the number of smartphone users world-wide[†] and the total world population[‡] are estimated for 2020, and the fraction

[†]See `https://quoracreative.com/article/mobile-marketing-statistics`

[‡]See `https://www.worldometers.info/world-population/`

of smartphone users with the CRAYFIS app is taken so that the total number of CRAYFIS devices is $\mathcal{O}\,[10^6]$.

Lastly, the effective area contribution from a patch of land is also dependent on the fraction of 24 hours where users are taking data at the same time, $\langle D \rangle = \langle T_{\rm data}/24\ {\rm hr} \rangle$, where $\langle D \rangle_{\rm U} = 1$ and $\langle D \rangle_{\rm P} \simeq 6/24 = 0.25$ are taken for 'Scenario U' and 'Scenario P' respectively. Altogether with the 2020 estimated population density dataset shown in Fig. 5.26, the effective areas for both scenarios are evaluated,

$$A\epsilon(E) = \langle D \rangle R_E^2 \Delta\theta \Delta\phi \sum_i \sin\theta_i \mathcal{H}\left(\rho_i \langle \xi \rangle - \rho_{\rm thresh}(E)\right) \tag{5.25}$$

where R_E is the radius of the Earth, and $(\Delta\theta,\ \Delta\phi)$ are the radian bin-widths for the $i^{\rm th}$ population density bin. The results are presented in Fig. 5.27.

Fig. 5.27 shows that ∼1 million (nighttime) CRAYFIS users world-wide could effectively cover as much land area as the two largest UHECR observatories. Although the energy, composition and incident direction resolutions of the Pierre Auger and Telescope Array Observatories would far exceed the abilities of an equal-effective-area CRAYFIS array, the geographically distributed nature of CRAYFIS inherently makes it the most sensitive observatory for coincident-EAS events, and is in this way complementary to existing detection technologies.

5.6.2 Detector Separation Distribution

The discrete geographic population density dependence of a CRAYFIS array inherently discretizes (and biases) the separation distances of dual-EAS observations. For "Scenario U," where the CRAYFIS array is assumed to be operating at 100% capacity 24 hours a day, 365 days a year, the total surface area of detector-pairings to observe a dual-EAS

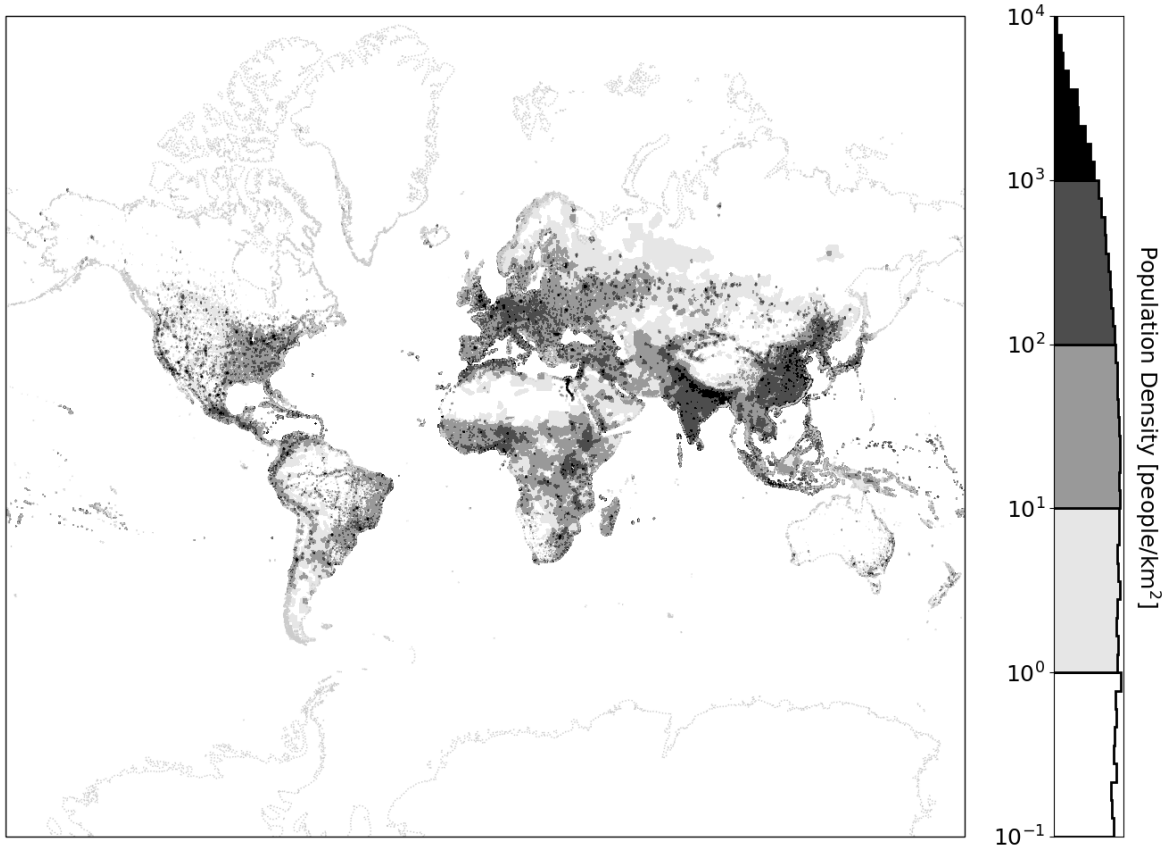


Figure 5.26: The estimated world population density by 2020 in $0.25° \times 0.25°$ bins (dataset courtesy of the Center for International Earth Science Information Network (CIESIN)). The horizontal direction of the colorbar indicates the relative frequency of population density bins on a log scale that is not shown.

separation, Δs, is simply the combined surface area of geographic locations separated Δs_{geo} from each other.

The separation between two geographic locations with latitude, φ, and longitude, λ, is

$$\Delta s_{\text{geo}} = R_E \, \text{hav}_{i,j} \left((\varphi_i, \lambda_i) \rightarrow (\varphi_j, \lambda_j) \right) \tag{5.26}$$

where the well-known Haversine formula is,

$$\text{hav}_{i,j} = 2 \sin^{-1} \left(\sqrt{\sin^2 \left(\frac{\varphi_j - \varphi_i}{2} \right) + \cos(\varphi_i) \cos(\varphi_j) \sin^2 \left(\frac{\lambda_j - \lambda_i}{2} \right)} \right) \tag{5.27}$$

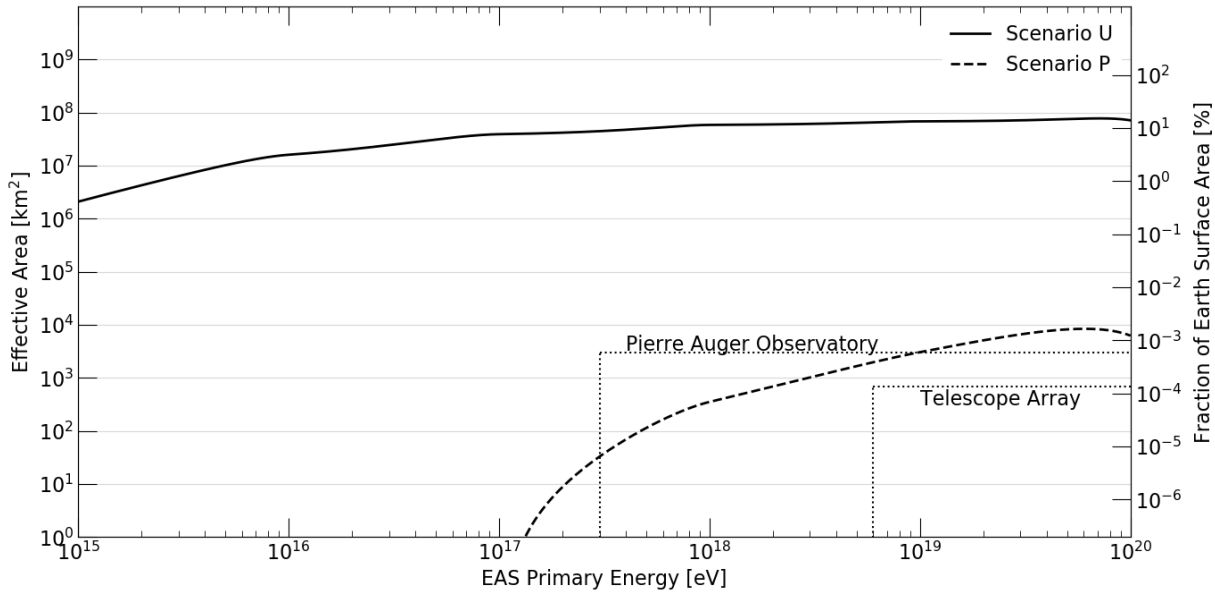
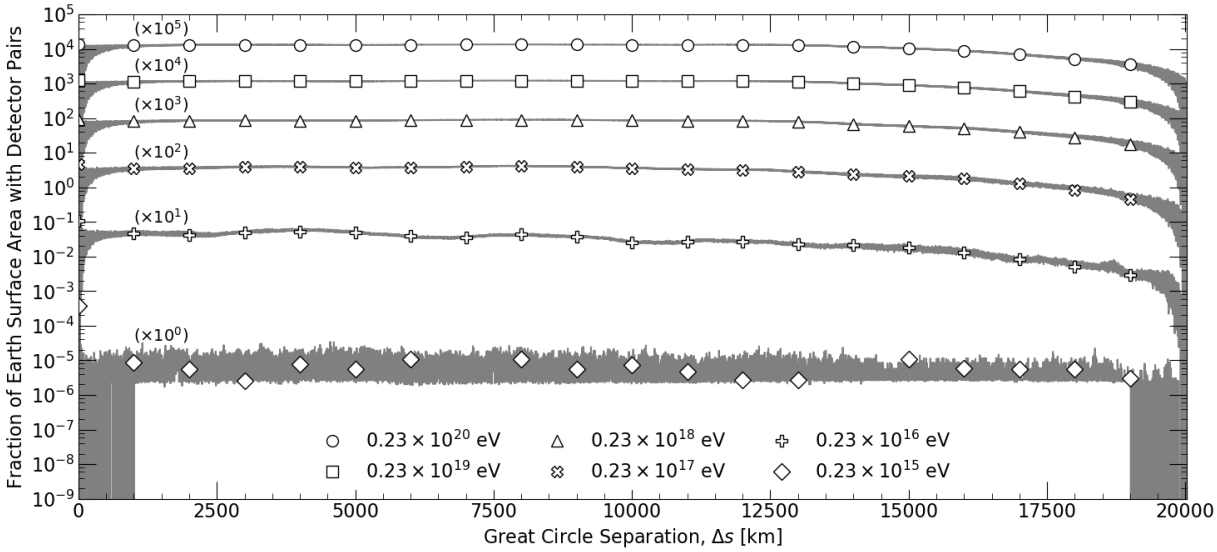


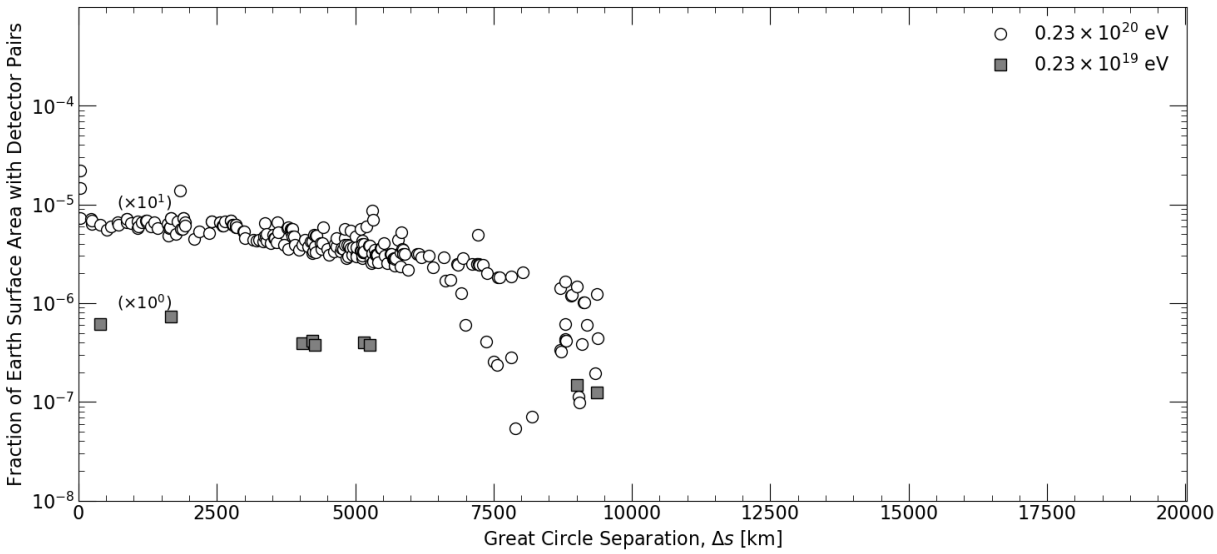
Figure 5.27: The upper-limit effective area for a CRAYFIS array ('Scenario U', solid), and a ∼1 million user expectation ('Scenario P', dashed). Also shown are the surface detector effective areas of the Pierre Auger, and Telescope Array Observatories (dotted).

and R_E is the radius of the Earth.

For "Scenario P," where it is assumed that CRAYFIS users are only recording data for 6 hours a day, between 11pm and 5am local time, a numerical simulation is performed. The geographic locations in Fig. 5.26 are rotated about the geographic z-axis as a function of the time of day (in hours, h) by 360° $h/24$ degrees, and then tilted by 23.5° with respect to the ecliptic plane (taken arbitrarily to be about the geographic x-axis). The central ecliptic meridian of midnight then advances as a function of the time of year (in accumulated hours, H) by 360° $H/(365 \times 24)$ degrees. The separations (Eq. (5.26)) and combined surface area for EAS-sensitive population centers within $-360°/24$ (11 pm) and $+360°$ 5/24 (5 am) degrees of the midnight ecliptic meridian are then collected. The hypothetical Earth is then allowed to advance for one year in 15 minute increments. The distribution of fractional surface area (interpretable as an estimate of the average probability for a dual-EAS with separation Δs to land on two EAS-sensitive patches of land with that same separation, Δs_{geo}) for both scenarios is presented in Fig. 5.28.



(a) "Scenario U" separation distribution.



(b) "Scenario P" separation distribution

Figure 5.28: The average fraction of Earth's surface area covered by population centers separated by Δs_{geo} at any given moment for two scenarios. The listed energies apply to individual (*e.g.*, nucleon or fragment) EASs, not the energy of their parent UHECR. See Eq. (5.31) and preceding paragraphs for why 0.23×10^X eV is shown. Top, "Scenario U" considers a 100% active Earth and represents the separation distances between all patches of land with sufficient population density to be sensitive to an EAS with energy given in the legend. For clarity, each EAS energy contour is scaled by a power of ten as shown on the left, also the 0.23×10^{15} eV contour has many "zero bins" whose vertical lines have been largely suppressed. Bottom, "Scenario P" considers the distribution for $\sim 10^6$ world-wide nighttime CRAYFIS users averaged over one year. Energy contour scaling is applied as well, as shown. Below 0.23×10^{19} eV, no pairs of geographic locations have sufficient population density (according to Center for International Earth Science Information Network (CIESIN)) to detect dual-EASs at night. The maximum separation distance of $\sim$20,000 km corresponds to half the circumference of the Earth.

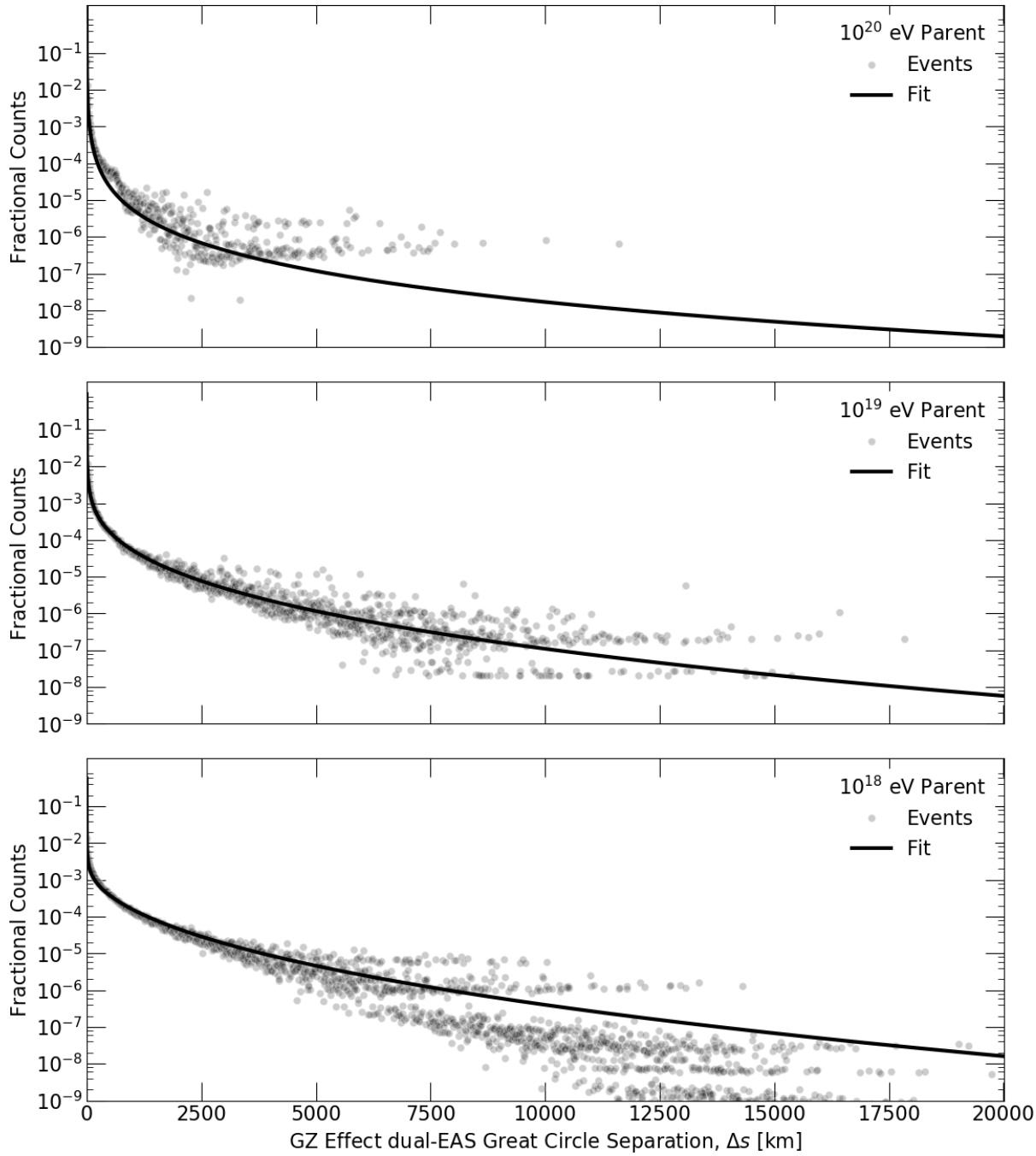


Figure 5.29: Relative likelihood for GZ Effect dual-EAS separations averaged over primary nucleus. Each simulated trajectory resulting in a dual-EAS is shown as a semi-transparent gray dot. The darkening of the dots occurs as events with similar separations pileup, and the solid line represents a fitted function. The banding that occurs at large separations is a feature of the discrete weighting function. See text for a discussion of the weighting function over nuclei, and details on the fitting function.

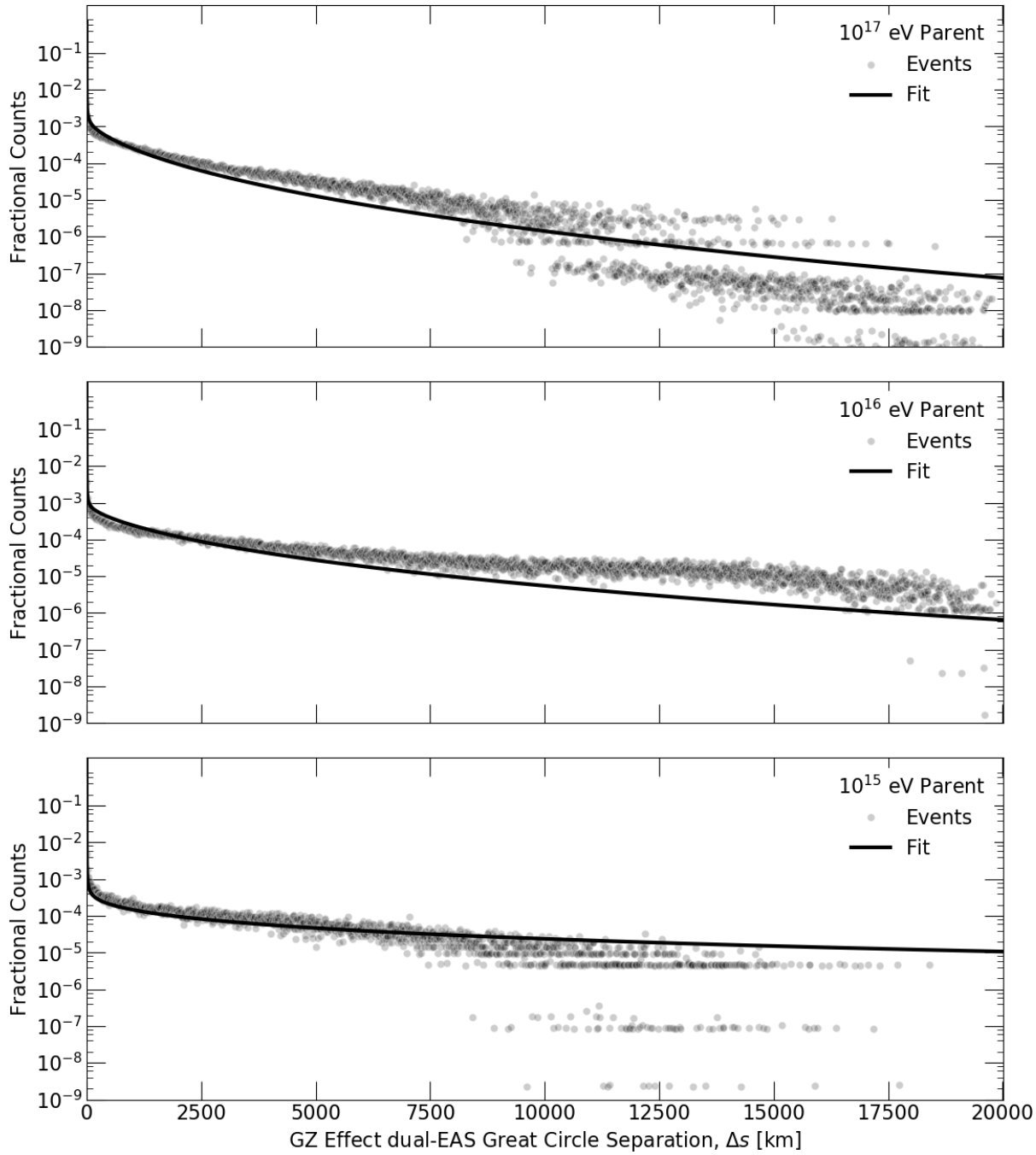


Figure 5.30: Relative likelihood for GZ Effect dual-EAS separations averaged over primary nucleus. Each simulated trajectory resulting in a dual-EAS is shown as a semi-transparent gray dot. The darkening of the dots occurs as events with similar separations pileup, and the solid line represents a fitted function. The banding that occurs at large separations is a feature of the discrete weighting function. See text for a discussion of the weighting function over nuclei, and details on the fitting function.

The simulated dual-EAS event-wise geographic separation distribution was shown in Figs. 5.21–5.23, and as a geographic average in Fig. 5.24 as a function of parent nuclei and energy. Averaging over parent nuclei (with weighting function $W(Z)$, Eq. (5.21)) and geographic location, the results of these figures are now presented on the per-event basis in Figs. 5.29 and 5.30 such that a model for the relative-likelihood of GZ Effect dual-EAS separations, $\langle\Gamma(\Delta s; E_0)\rangle$, can be constructed,

$$
\begin{aligned}
\langle\Gamma(\Delta s; E_0)\rangle &= A(\varepsilon) \times 10^{\boldsymbol{\vartheta}\cdot\boldsymbol{B}(\boldsymbol{\varepsilon})} \\
\boldsymbol{\varepsilon} &= \begin{bmatrix} 1 & \varepsilon & \varepsilon^2 & \varepsilon^3 & \varepsilon^4 \end{bmatrix} \\
\varepsilon &= \log_{10} E_0 \\
\boldsymbol{\vartheta} &= \begin{bmatrix} 1 & \vartheta & \vartheta^2 & \vartheta^3 & \vartheta^4 \end{bmatrix} \\
\vartheta &= \log_{10}(\Delta s + 1) \\
A(\varepsilon) &= \boldsymbol{\alpha} \cdot \boldsymbol{\varepsilon}^T \\
\boldsymbol{\alpha} &= \begin{bmatrix} \alpha_0 & \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \end{bmatrix} \\
\boldsymbol{B}(\boldsymbol{\varepsilon}) &= \boldsymbol{\beta} \cdot \boldsymbol{\varepsilon}^T \\
\boldsymbol{\beta} &= \begin{pmatrix} \beta_{0,0} & \beta_{0,1} & \beta_{0,2} & 0 & 0 \\ \beta_{1,0} & \beta_{1,1} & \beta_{1,2} & 0 & 0 \\ \beta_{2,0} & \beta_{2,1} & \beta_{2,2} & 0 & 0 \\ \beta_{3,0} & \beta_{3,1} & \beta_{3,2} & 0 & 0 \\ \beta_{4,0} & \beta_{4,1} & \beta_{4,2} & 0 & 0 \end{pmatrix}
\end{aligned}
\tag{5.28}
$$

where the 19 coefficients are,

$$\boldsymbol{\alpha} = \begin{bmatrix} -560.56 & 136.17 & -12.376 & 0.49940 & -0.00754 \end{bmatrix}$$
$$\boldsymbol{\beta} = \begin{pmatrix} 31.891 & -3.9160 & 0.11586 & 0 & 0 \\ -34.430 & 3.4332 & -0.08867 & 0 & 0 \\ 15.912 & -1.4996 & 0.03482 & 0 & 0 \\ -8.8789 & 0.96334 & -0.02590 & 0 & 0 \\ 1.6821 & -0.19090 & 0.00532 & 0 & 0 \end{pmatrix} \tag{5.29}$$

and $\int_0^{\pi R_E} \langle \Gamma(\Delta s; E_0) \rangle \, d(\Delta s) \simeq 1$ (within 10%, Fig. 5.31).

With Fig. 5.28 representing the average chance to strike a pair of CRAYFIS sub-arrays, $\gamma(\Delta s; E)$, and the model developed in Eq. (5.28) for dual-EAS separations, an expected average GZ Effect flux can be written following Eq. (5.20) (extending the results of Fig. 5.17),

$$\langle F_{\mathrm{GZ}}(E) \rangle = F(E) \left(\frac{\sum_{i=\text{nucleons}}^{\text{fragments}} f_i^c(E) W(Z_i) P_{\mathcal{S}}(Z_i, E)}{2 \sum_Z W(Z) \, N_{Z,E}} \right) \times \left(\frac{\int_0^{\pi R_E} \langle \Gamma(\Delta s; E) \rangle \, \gamma(\Delta s; E^*) \, d(\Delta s)}{\int_0^{\pi R_E} \langle \Gamma(\Delta s; E) \rangle \, d(\Delta s)} \right) \tag{5.30}$$

where E^* is the average (over Z) lower-energy (nucleon) EAS energy since $\gamma(\Delta s)$ is a function of actual EAS energy, not the UHECR parent. The nucleon energy is appropriate in this context as the fragment always carries at least half of the parent UHECR energy (Eq. (5.4)), and detection requires sensitivity to both EASs. This average (over Z) nucleon

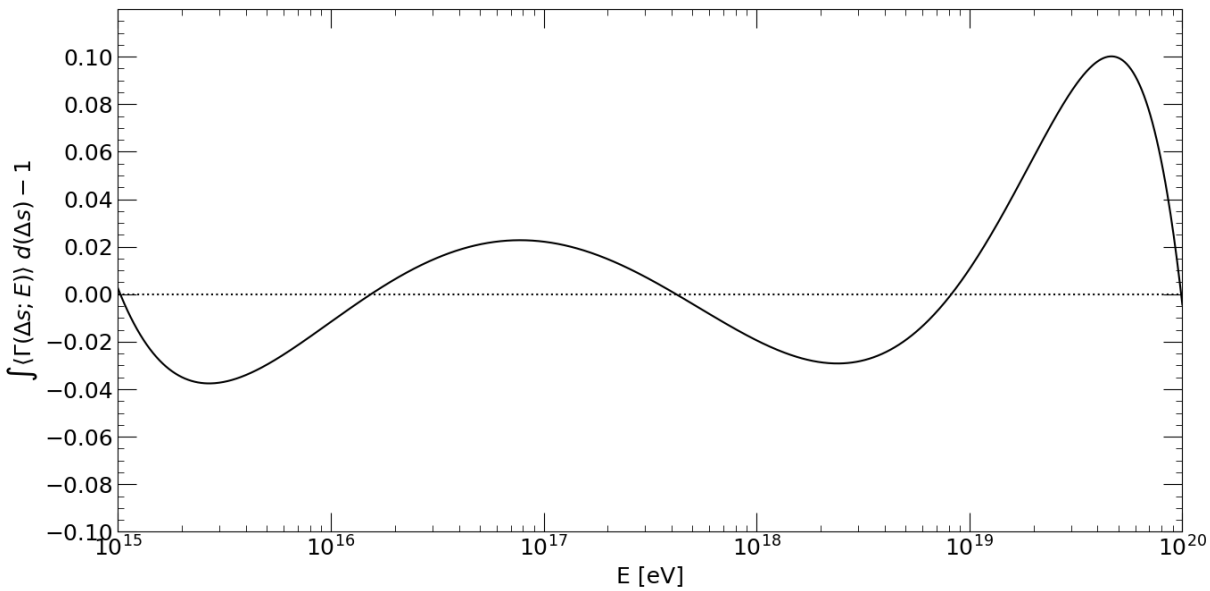


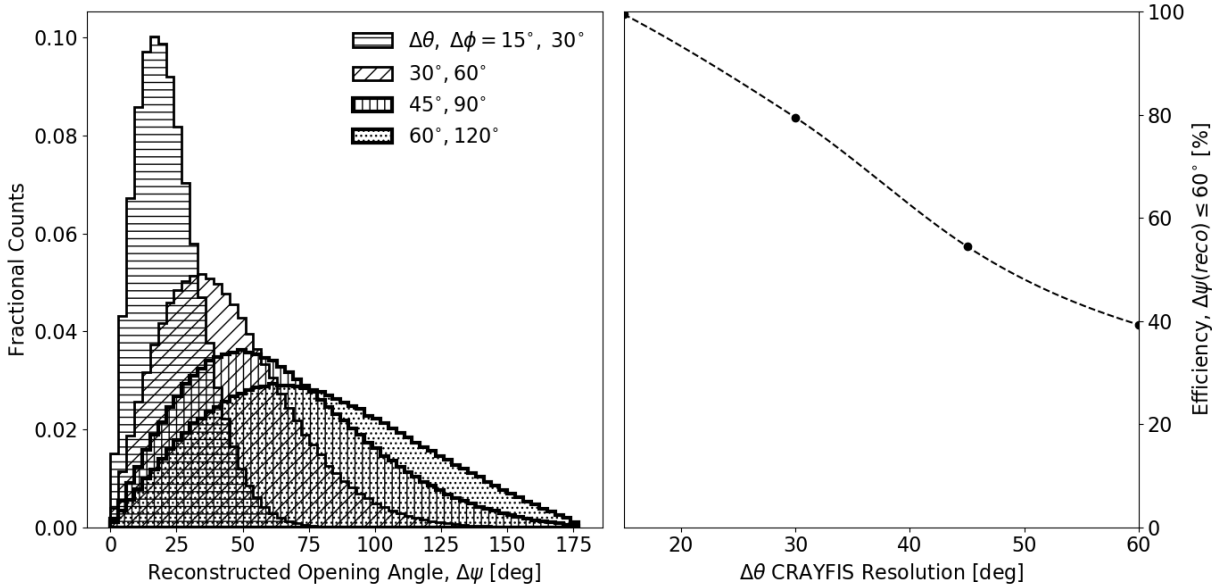
Figure 5.31: GZ Effect dual-EAS separation model normalization as a function of energy.

energy is computed as,

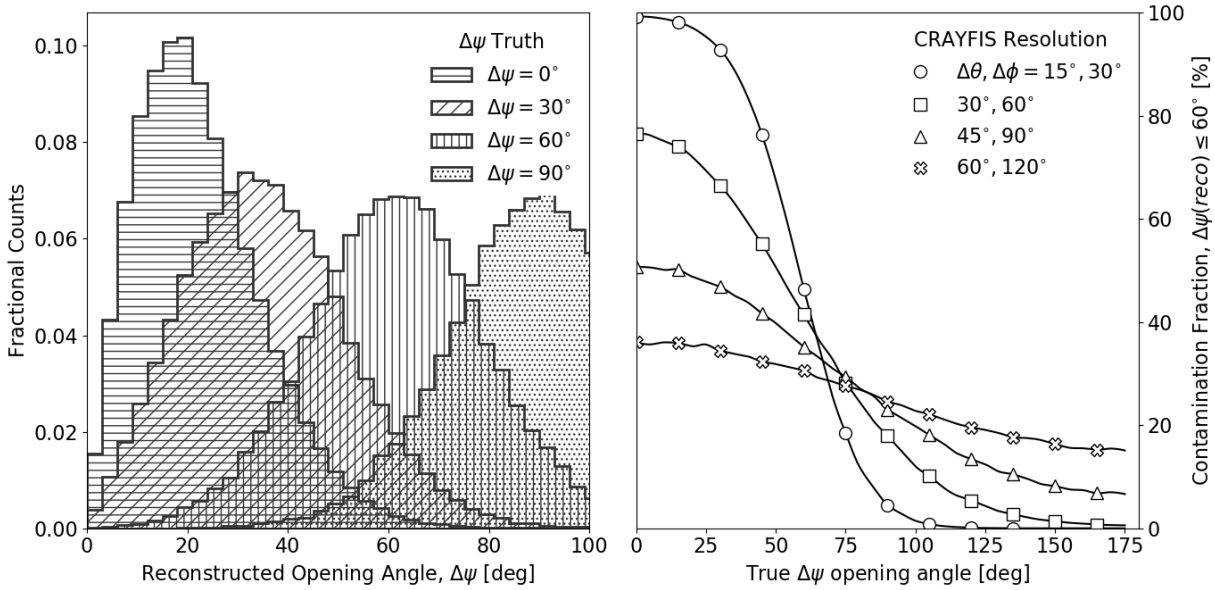
$$E^*(E) = \frac{\sum_Z W(Z) \frac{1}{A(Z)} E}{\sum_Z W(Z)} \simeq 0.230E \tag{5.31}$$

5.6.3 Temporal and Angular Resolution

To good approximation, UHECRs propagate at the speed of light (§5.4.3) as do their daughter fragments. For dual-EASs, the maximum fragment trajectory difference is approximately 1 Earth radii, corresponding to a worst-case time delay of ∼21 milliseconds. In our original paper (Whiteson et al. (2016)), it was found that individual smartphone performance limitations as well as clock variations between smartphones in an array limit practical observation time windows to ∼100 ms. In the same paper, the EAS angular reconstruction resolutions of a CRAYFIS array (zenith and azimuthal angle resolutions $\Delta\theta$ and $\Delta\phi$) were conservatively estimated to be on the order of $\Delta\theta \sim 30°$ and $\Delta\phi \sim 60°$ for



(a) CRAYFIS parallel EAS resolution and efficiency.



(b) Combinatorial contamination from non-parallel EASs.

Figure 5.32: Top left, the CRAYFIS-reconstructed distribution of apparent opening angle, $\Delta\psi$, for parallel ($\Delta\psi_{\text{truth}} = 0°$) dual-EASs as a function of zenith (azimuthal) resolution, $\Delta\theta$ ($\Delta\phi$). Bottom left, the CRAYFIS-reconstructed distribution of apparent opening angle for non-parallel (Combinatorial background) dual-EASs as a function of true opening angle (shown for angular resolution $\Delta\theta, \Delta\phi = 15°, 30°$). Top right, the fractional number (efficiency) of parallel events that are CRAYFIS-reconstructed within opening angle, $\Delta\psi \leq \Psi = 60°$. Bottom right, the fractional number (contamination efficiency) of non-parallel events that are reconstructed into the selection window of $\Delta\psi \leq 60°$.

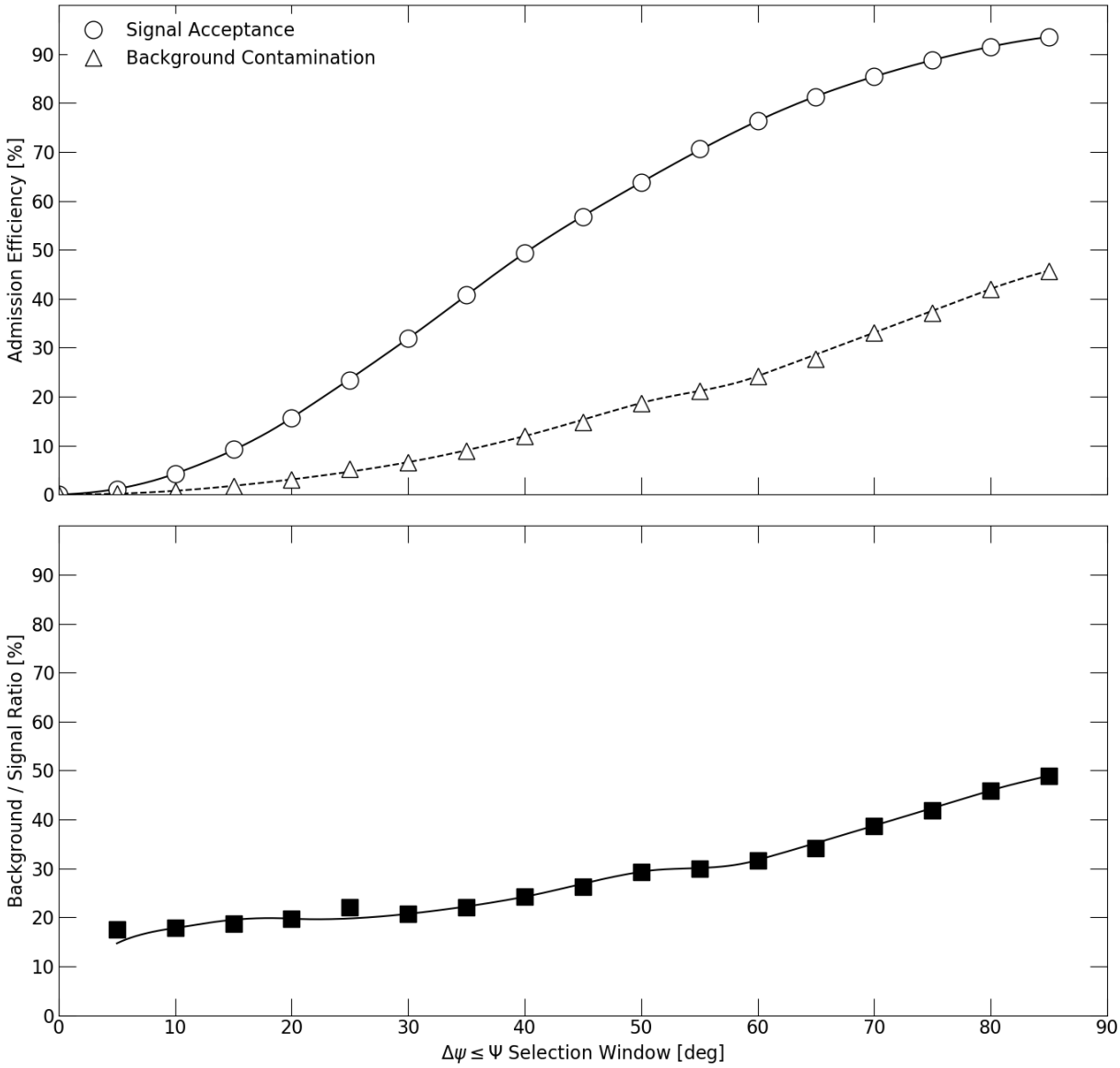


Figure 5.33: Top, expected signal acceptance (true $\Delta\psi = 0°$) and background (true $\Delta\psi > 0°$) contamination as a function of opening angle selection window limit, $\Delta\psi \leq \Psi$. The figure corresponds to a CRAYFIS angular resolution of $(\Delta\theta, \Delta\phi) = (30°, 60°)$, where $\Psi = 60°$ corresponds to the efficiency of 80% seen in Fig. 5.32a. The background follows a sinusoidal PDF in true $\Delta\psi$ (see Fig. 5.3). Bottom, the ratio of background contamination to signal acceptance.

many events, although it is noted that this result depends strongly on device density, total EAS energy and the angle of incidence.

Combinatorial background rejection in searches for GZ Effect dual-EASs, or any other parallel-EAS phenomena, depends on the restrictions placed on the opening angle between reconstructed EAS incident angles. The effect of various CRAYFIS angular resolutions on the opening angle for simulated parallel EASs are presented in Fig 5.32a. It can be seen from the right efficiency plot that for the estimated typical azimuthal resolution, $\Delta\theta = 30°$ ($\Delta\phi$ is taken as double $\Delta\theta$), about 80% of parallel-EAS events will pass the $\Delta\psi \leq 60°$ selection cut. On the other hand, for non-parallel combinatorial dual-EAS backgrounds in Fig. 5.32b, each contamination efficiency begins (at true $\Delta\psi = 0$) at the corresponding parallel-EAS efficiency of Fig. 5.32a with the same $\Delta\theta$ resolution, and then decreases with growing opening angle separation with a resolution-dependent broadness.

In Fig. 5.33, the implications for a $\Delta\psi \leq 60°$ window are shown assuming a typical CRAYFIS angular resolution. The optimal opening angle window is one where signal acceptance is maximized, and background contamination is minimized; however, the acceptance, contamination and background-to-signal ratios grow with an increasing selection window. Therefore, a choice of $\Delta\psi \leq 60°$ was selected to retain ∼80% of GZ Effect dual-EAS signal events with the expectation of ∼30% of random combinatorial events (non-GZ Effect, $\Delta\psi \geq 0°$) to fall within this selection cut.

5.6.4 Signal and Background

5.6.4.1 The Signal

At last, all pieces are in place to compute an expectation for the GZ Effect observation. As lone UHECR protons do no contribute to the GZ Effect signal, we consider the established UHECR flux, $F(E)$ (top of Fig. 4.16), to represent an upper-limit, maximal flux of incoming potential GZ Effect events. The fraction of this flux that becomes a possible

observation has been found to be,

$$\langle F_{\mathrm{GZ}}(E)\rangle = F(E)\left(\frac{\sum\limits_{i=\mathrm{nucleons}}^{\mathrm{fragments}} f_i^c(E)W(Z_i)P_{\mathcal{S}}(Z_i,E)}{2\sum\limits_{Z} W(Z)\ N_{Z,E}}\right) \times \left(\frac{\int\limits_0^{\pi R_E} \langle\Gamma(\Delta s;E)\rangle\ \gamma(\Delta s;0.23\ E)\ d(\Delta s)}{\int\limits_0^{\pi R_E} \langle\Gamma(\Delta s;E)\rangle\ d(\Delta s)}\right)\chi_{\mathrm{sig}}(60^\circ) \tag{5.32}$$

where the first fraction is from Eq. (5.20) with f_i^c the channel fractional contribution from the ith EAS, $W(Z)$ the atomic number (Z) weighting function (see Eq. (5.21)), $P_{\mathcal{S}}(Z,E)$ the trajectory-dependent probability to photodisintegrate via the Giant Dipole Resonance (see Eq. (5.8)), the factor of 2 in the denominator relates the sum over EASs to GZ Effect pairs, and the sum over $W(Z)\ N_{Z,E}$ normalizes the numerator sum and implicitly accounts for the fraction of photodisintegration events that do not produce dual-EASs. The second fraction is from Eq. (5.30) with $\langle\Gamma(\Delta s;E)\rangle$ the "almost-normalized" PDF model of dual-EAS separations, and $\gamma(\Delta s;0.23\ E)$ (see Fig. 5.28) the (scenario-dependent) average fraction of the Earth with CRAYFIS sub-array pairs separated by great circle distance Δs. R_E is the radius of the Earth and $\chi_{\mathrm{sig}}(\Psi)$ is the fraction (80%) of parallel EASs to be accepted following CRAYFIS event reconstruction and opening angle cut $\Delta\psi \leq \Psi$ (see Fig. 5.33).

Taken all together, for CRAYFIS observation windows of $\Delta t = 100$ ms, with a total integrated observation time of T, the average number of GZ Effect dual-EASs is,

$$\begin{aligned}\langle N_{\mathrm{sig}}(E,T;\Delta t)\rangle &= \langle F_{\mathrm{GZ}}(E)\rangle\ A\epsilon(0.23\ E)\ \Delta t\,(T/\Delta t)\\ &= \langle F_{\mathrm{GZ}}(E)\rangle\ A\epsilon(0.23\ E)\ T\end{aligned} \tag{5.33}$$

where the (scenario-dependent) effective area is (as was the case for $\gamma(\Delta s; E_{\text{nucleon}})$) made a function of average nucleon energy as a dual-EAS cannot be detected unless *both* lower and higher energy EASs are detected.

The flux results are plotted against the background in Figs. 5.34 and 5.35.

5.6.4.2 The Background

To estimate the corresponding background, we first find the expected fraction of random, everyday EASs to occur simultaneously at different locations. The average number of solo-UHECRs that are detectable by CRAYFIS as a function of energy and observation window is,

$$\langle N_{\text{solo}}(E, \Delta t)\rangle = F(E)\ A\epsilon(E)\Delta t \tag{5.34}$$

where $F(E)$ is the accepted UHECR flux once again.

In order to mimic a GZ Effect dual-EAS, two events must occur simultaneously. Additionally, these two events must occur within a hemisphere (or smaller region), which effectively reduces $A\epsilon$ by half (to first order). Assuming Poisson statistics, the probability to observe at least two events is,

$$\begin{aligned}\langle P_{\geq 2}(E, \Delta t)\rangle &= 1 - (1 + \langle N_{\text{solo}}(E, \Delta t)\rangle/2)\ e^{-\langle N_{\text{solo}}(E,\Delta t)\rangle/2} \\ &= 1 - (1 + F(E)A\epsilon(E)\Delta t/2)\ e^{-F(E)A\epsilon(E)\Delta t/2} \\ &= \frac{\text{Times seen } \geq 2 \text{ EASs in } \Delta\text{t}}{\text{Total EASs seen after } T/\Delta t \text{ observations}}\end{aligned} \tag{5.35}$$

where T is the total integrated observation time.

Although real GZ Effect dual-EASs will occur with differing energies in proportion to atomic mass numbers (Eq. (5.4)), an UHECR parent nuclei with energy E produces, on

average, a lower-energy EAS of energy $\sim$0.23 E (Eq. (5.31)). The conservative background is then tentatively,

$$\langle N_{\rm bkg}(E,T;\Delta t)\rangle = F(0.23\ E)A\epsilon(0.23\ E)\langle P_{\geq 2}(0.23\ E,\Delta t)\rangle\ T \tag{5.36}$$

However this is incomplete as the combinatorial background separation distribution of Eq. (5.3) must also be marginalized against the geographic separation distribution of Fig. 5.28,

$$\begin{aligned}\langle \Lambda(\Psi,E)\rangle &= \int_0^{\pi R_E} \mathrm{PDF}(\Delta s;\Delta\psi\leq\Psi)\gamma(\Delta s;0.23\ E)\ d(\Delta s)\\ &= \frac{1}{4R_E}\csc^2\left(\frac{\Psi}{2}\right)\\ &\quad\times\int_0^{\pi R_E}\sin\left(\frac{\Delta s}{R_E}\right)\left[1-\cos\Psi+\frac{3}{8}\sin^2\Psi\cos\left(\frac{\Delta s}{R_E}\right)\right]\ \gamma(\Delta s;0.23\ E)\ d(\Delta s)\end{aligned} \tag{5.37}$$

which yields an effective background flux,

$$\langle F_{bkg}(E,\Delta t)\rangle = F(0.23\ E)\ \langle P_{\geq 2}(0.23\ E,\Delta t)\rangle\ \langle\Lambda(60^\circ,0.23\ E)\rangle\ \chi_{\rm bkg}(60^\circ) \tag{5.38}$$

where $\chi_{\rm bkg}(\Psi)$ is the fraction (30%) of non-parallel EASs to be accepted following CRAYFIS event reconstruction and opening angle cut $\Delta\psi\leq\Psi$ (see Fig. 5.33).

The final expression for the GZ Effect dual-EAS background is then,

$$\langle N_{\rm bkg}(E,T;\Delta t)\rangle = \langle F_{\rm bkg}(E,\Delta t)\rangle A\epsilon(0.23\ E)\ T \tag{5.39}$$

The results of these calculations are presented in Figs. 5.34 and 5.35.

5.6.4.3 Results and Discussion

The fluxes of (GZ Effect) signal and background from the preceding two sections are naturally factored as,

$$\begin{aligned}\langle F_{\text{sig}}(E)\rangle &= F(E)\ \Xi_{\text{sig}}(E)\ \Upsilon_{\text{sig}}(E)\ \chi_{\text{sig}}(60^\circ)\\ \langle F_{\text{bkg}}(E)\rangle &= F(0.23\ E)\ \Xi_{\text{bkg}}(E)\ \Upsilon_{\text{bkg}}(E)\ \chi_{\text{bkg}}(60^\circ)\end{aligned} \tag{5.40}$$

where the probabilities for each respective process are,

$$\begin{aligned}\Xi_{\text{sig}}(E) &= \frac{\sum\limits_{i=\text{nucleons}}^{\text{fragments}} f_i^c(E)\ W(Z_i)\ P_{\mathcal{S}}(Z_i,E)}{2\sum\limits_{Z} W(Z)\ N_{Z,E}}\\ \Xi_{\text{bkg}}(E) &= 1-(1+F(0.23\ E)\ A\epsilon(0.23\ E)\ 0.1/2)\,e^{-F(0.23\ E)\ A\epsilon(0.23\ E)\ 0.1/2}\end{aligned} \tag{5.41}$$

(where Δt was set to 0.1 seconds), and the geographical probabilities to strike CRAYFIS detectors are,

$$\begin{aligned}\Upsilon_{\text{sig}}(E) &= \frac{\int\limits_0^{\pi R_E} \langle\Gamma(\Delta s;E)\rangle\ \gamma(\Delta s;0.23\ E)\ d(\Delta s)}{\int\limits_0^{\pi R_E} \langle\Gamma(\Delta s;E)\rangle\ d(\Delta s)}\\ \Upsilon_{\text{bkg}}(E) &= \frac{1}{4R_E}\csc^2\left(\frac{\pi}{6}\right)\\ &\quad\times \int\limits_0^{\pi R_E} \sin\left(\frac{\Delta s}{R_E}\right)\left[1-\cos\frac{\pi}{3}+\frac{3}{8}\sin^2\frac{\pi}{3}\cos\left(\frac{\Delta s}{R_E}\right)\right]\ \gamma(\Delta s;0.23\ E)\ d(\Delta s)\end{aligned} \tag{5.42}$$

(where Ψ was set to $\pi/3$ radians).

Each factor is illustrated separately in Fig.5.34, and then all together in Fig. 5.35.

In Fig. 5.34, for the case of the $\Xi_{\text{sig}}(E)$ factor, there is no dependence on the effective area, $A\epsilon$, or population distribution, $\gamma(\Delta s;E)$—specifically, this curve is nothing more than the atomic-number average of Fig. 5.17. The $\Xi_{\text{bkg}}(E)$ factor however is computed based off of

an expected number of single-EAS events, and therefore includes the scenario-dependent effective area, $A\epsilon$, which for "Scenario P" is zero for all but the highest energies. For the case of "Scenario U," it can be seen that (with all other detection considerations aside) the maximal CRAYFIS effective area spans enough of the planet that it is extremely likely to observe simultaneous EASs at any given moment.

On the other hand, where $\Xi(E)$ represented the GZ Effect and combinatorial dual-EAS probabilities, $\Upsilon(E)$ represents the geographical likelihood for a dual-EAS to strike two sensitive CRAYFIS sub-arrays. GZ Effect dual-EASs are more probably found closely-separated (Figs. 5.29 and 5.30), whereas the combinatorial background is most probably separated around a quarter of the Earth's circumference (Fig. 5.5). The CRAYFIS sub-array fractional surface area, Fig. 5.28 and symbolically $\gamma(\Delta s; E)$, is found to disfavor closely-separated EASs in such a way that the values of $\Upsilon(E)$ for signal and background are fairly comparable.

Which brings us at last to Fig. 5.35. This figure is the product of F, Ξ, Υ and χ as written in Eq. (5.40). The x-axis represents GZ Effect parent energies, however the flux from the single-(nucleon)EAS energy is shown for references as $F(0.23\ E)$ (since GZ Effect parents are not, by definition, directly observed).

On the one hand, it can be seen that the combinatorial background can substantially dominate GZ Effect dual-EAS events for a large CRAYFIS array ("Scenario U"). Yet, on the other hand, it can also be seen that the GZ Effect can dominate background for sufficiently small arrays ("Scenario P"). Specifically, Fig. 5.34 shows that $\Xi_{\text{sig}}(E)$—computed solely from phenomenology, Eq. (5.41)— creates an upper-limit on $A\epsilon$ (a tunable parameter in $\Xi_{\text{bkg}}(E)$). That is, the fraction of the Earth being considered for simultaneous EASs cannot be too large, lest the rate of random chance simultaneous events exceeds the phenomenological rate for signal. From Fig. 5.37 (a composite of Figs. 5.5, 5.29 and 5.30), it can be seen that a potential resolution for "Scenario U-like" arrays could be to search for

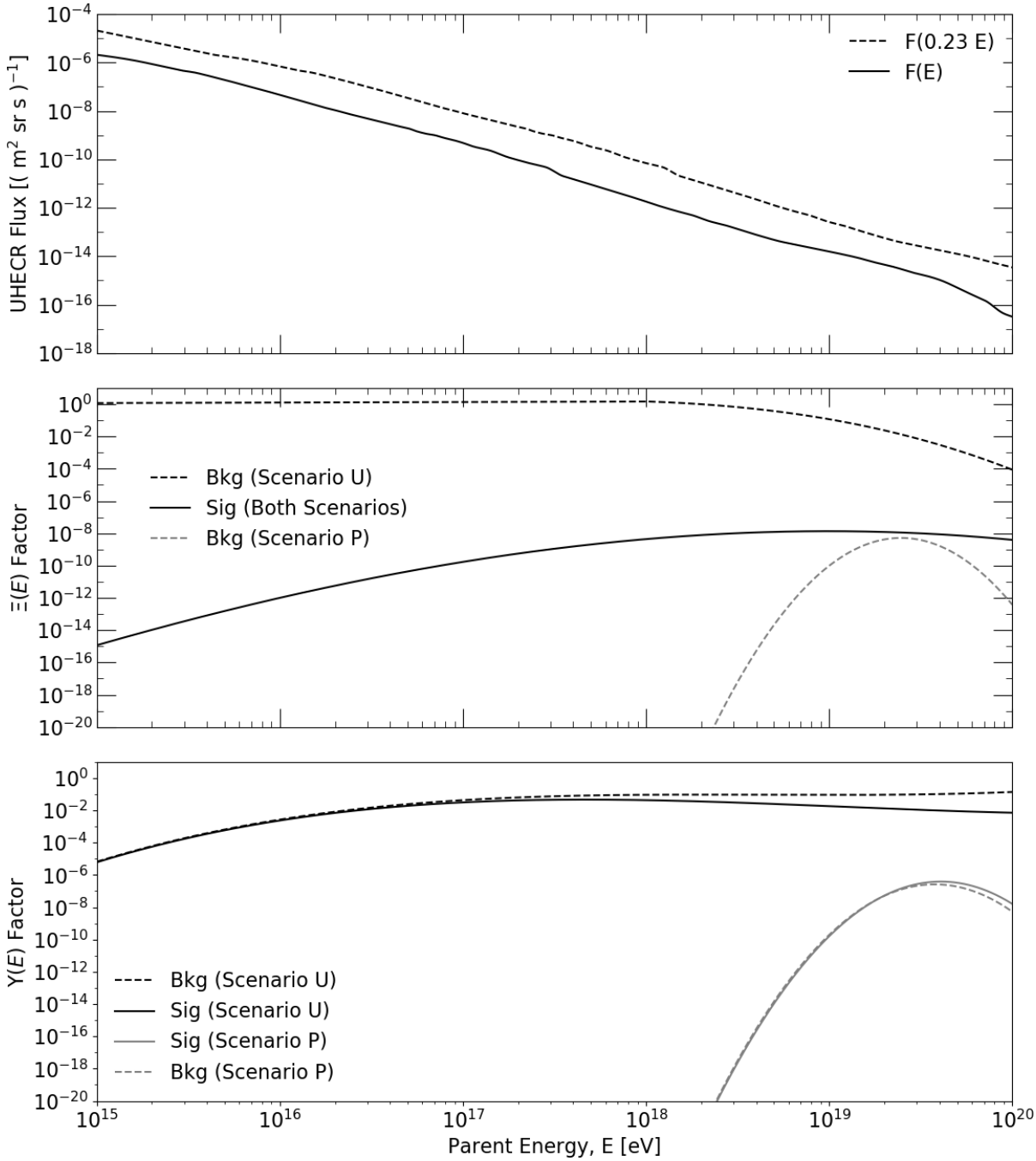


Figure 5.34: Factorized dual-EAS signal and background flux. Top, the established UHECR flux curve plotted as a function of GZ Effect parent energy, E, and for background purposes, as a function of the average nucleon EAS energy, 0.23 E. Middle, the $\Xi(E)$ factor for GZ Effect signal and combinatorial background for "Scenario U" and "Scenario P;" however, the signal curve is independent of the scenario. Bottom, the $\Upsilon(E)$ factor for signal and background for the two scenarios. See text for discussion.

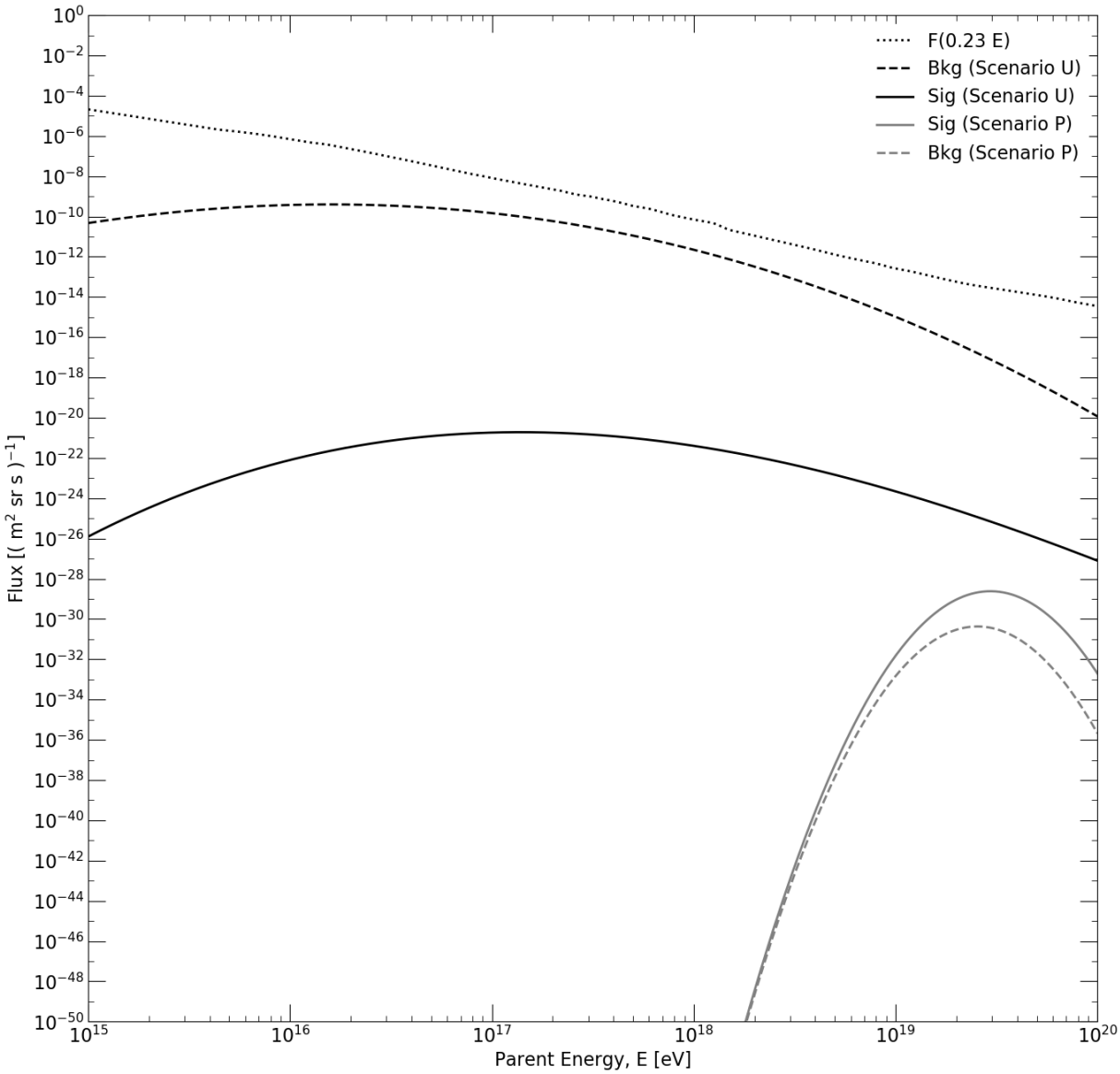


Figure 5.35: Expected GZ Effect (and combinatorial background) dual-EAS flux within 100 ms time, and 60° opening angle windows for "Scenario U" and "Scenario P." The established UHECR flux curve evaluated at the average nucleon EAS energy, $F(0.23\ E)$, is also shown as a comparison. See text for discussion.

dual-EASs occurring within a radius limit (*e.g.*, 500 km) of each other. Yet even so, the total GZ Effect flux of "Scenario U" ("Scenario P") is on the order of 10^{-21} (10^{-29}) $\mathrm{m}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{sec}^{-1}$, which equates to (summing over all energy bins, and applying each scenario- and energy-dependent effective area) $\sim$10 ($\sim 10^{-12}$) signal events over the course of a year on average. Therefore, even for a "Scenario U-like" CRAYFIS array with an optimized signal to background ratio, a GZ Effect discovery is still likely a decade-or-more endeavor, and GZ Effect detection with a "Scenario P-like" array is not reasonably feasible.

However, the GZ Effect is by no means the only way a dual-EAS might be created (§5.2). We therefore consider a hypothetical alternative dual-EAS mechanism wherein the physics of this alternative favors closely-separated EASs comparable to that of the GZ Effect (Figs. 5.29 and 5.30) such that the corresponding Υ would remain unchanged. As this alternative mechanism would produce parallel-incident EASs, χ too would go unchanged. In order to be consistent with experimental observation, F cannot be exceeded, leaving Ξ (the likelihood of the process) a tunable parameter. We therefore consider a boosted-Ξ scenario, $\Xi^B = B\ \Xi_{\mathrm{GZ}}$, such that $\langle F_{\mathrm{dual}}(E)\rangle = B\langle F_{\mathrm{GZ}}(E)\rangle$ (Fig. 5.36). This maximal boost-factor, B, such that $F(E) \geq \langle F_{\mathrm{dual}}(E)\rangle + \langle F_{\mathrm{bkg}}(E)\rangle$ is 2.9×10^9 and 7.3×10^{13} for "Scenario U" and "Scenario P" respectively. Such boosted scenarios are likely observable inside of a year as the boosted flux would imply an average of $\sim 10^{10}$ and $\sim$10 signal events per year for boosted-scenarios "U" and "P" respectively.

5.6.5 Statistical Analysis

The previous section has outlined the expected energy spectra for two GZ Effect scenarios (Fig. 5.35), and two maximally-boosted GZ Effect-adjacent scenarios (Fig. 5.36). However, potentially substantial backgrounds were also identified. Therefore, this section considers the statistical means, and the expected minimal integrated observation time needed to discover a dual-EAS signal of interest.

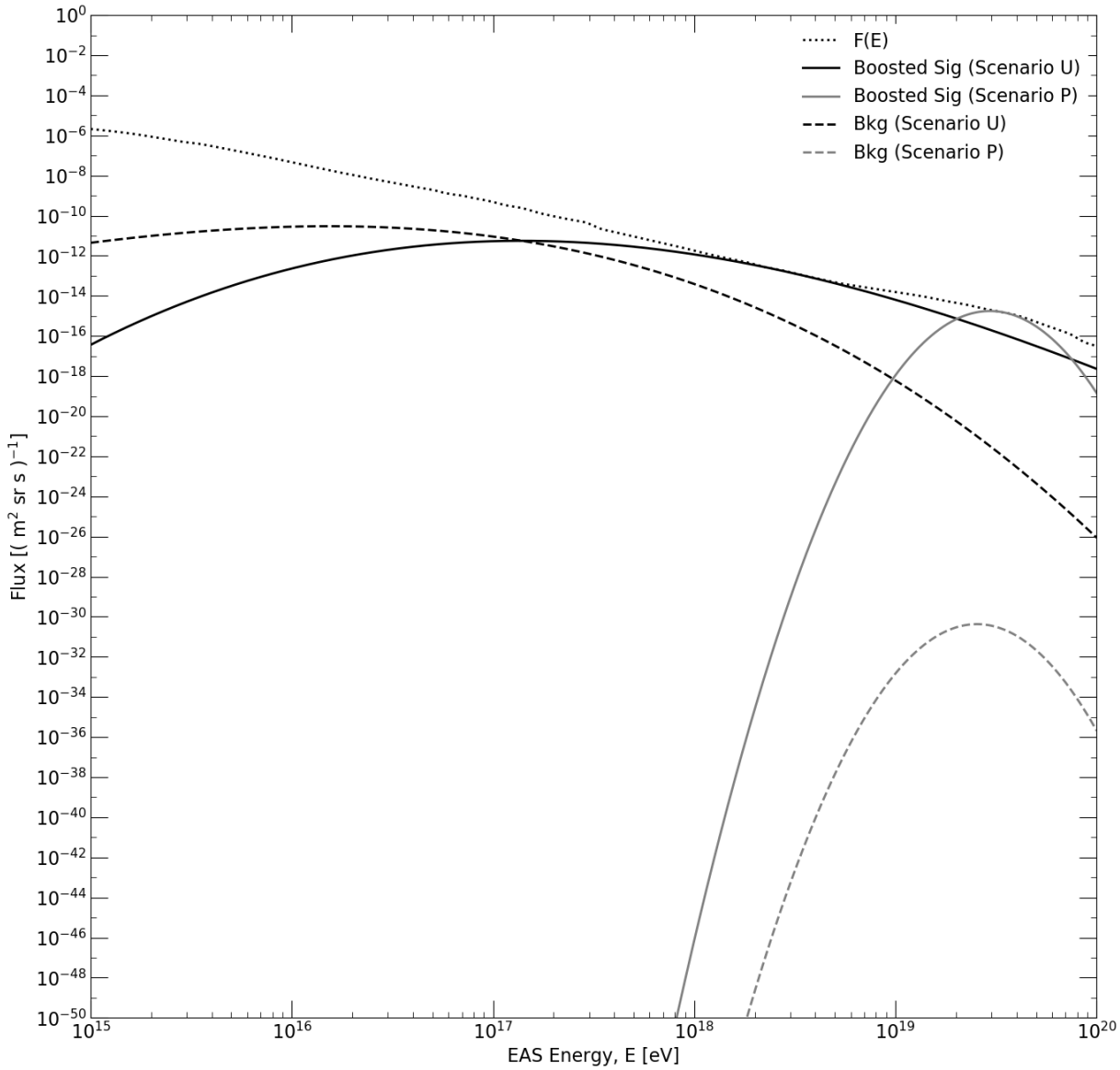
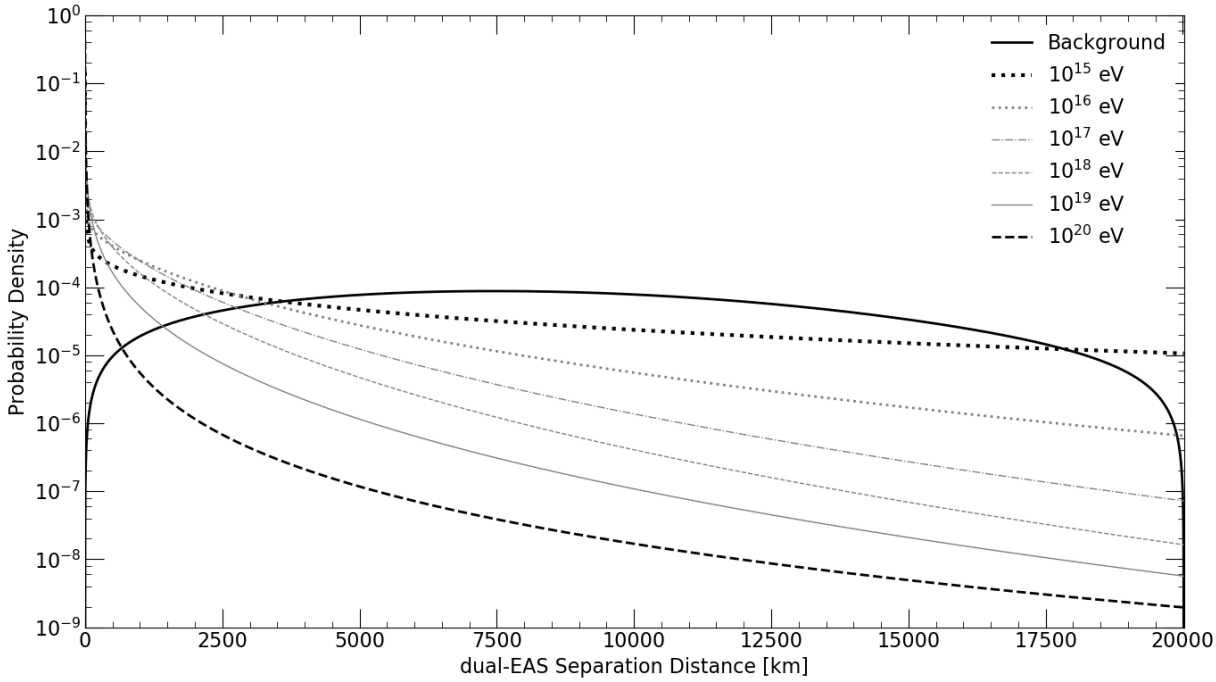
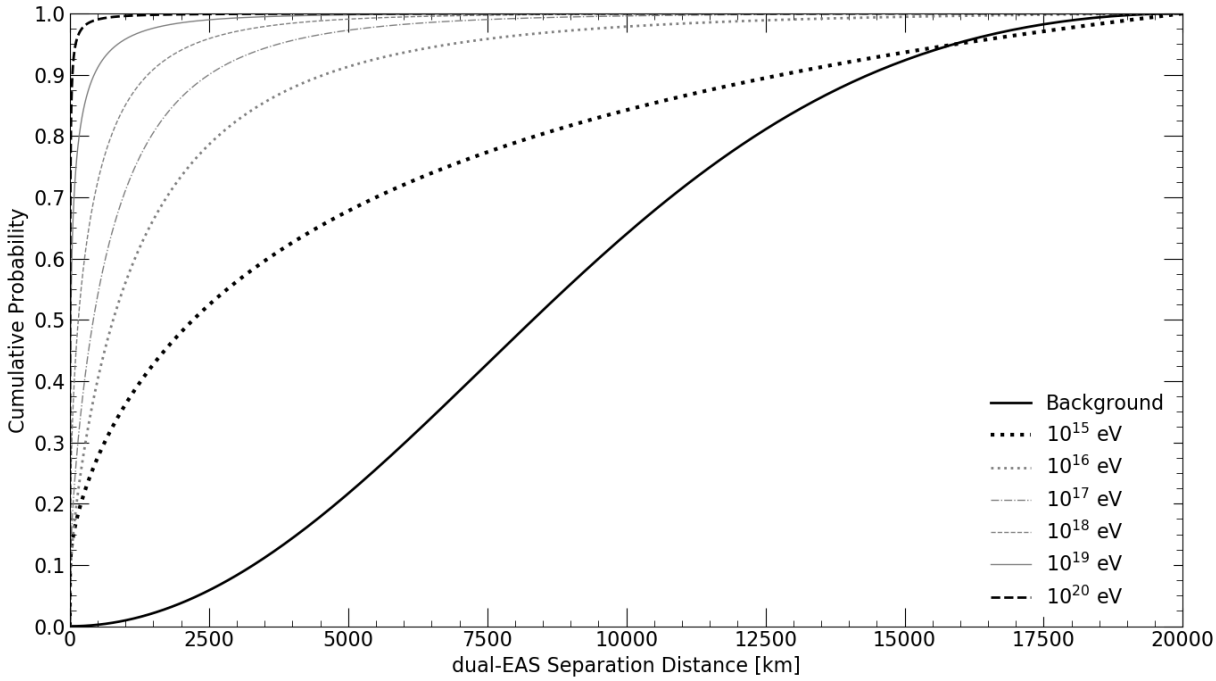


Figure 5.36: Signal and background flux for the boosted-Ξ scenarios—see text. Expected dual-EAS flux within 100 ms time, and 60° opening angle windows for "Scenario U" and "Scenario P" CRAYFIS arrays. The x-axis represents EAS shower energy, as the concept of an UHECR parent is not defined for this case. The established UHECR flux curve is also shown as a comparison.



(a) Dual-EAS Separation, Probability Density Function



(b) Dual-EAS Separation, Cumulative Distribution Function

Figure 5.37: Top, the dual-EAS separation PDF for GZ Effect-like signals (Eq. (5.28)) at various characteristic energies (see legend), and the combinatorial background (thick, solid) (Eq. (5.3)) where $\Psi = 60°$. Bottom, the corresponding CDF for the same curves.

On the one hand, the most general search for anomalous dual-EAS signals would be purely rate-based (*i.e.*, does the rate of dual-EASs exceed the expected Poisson background rate). However, for the GZ Effect or phenomena with similar signal and background models, the most orthogonal observable, and therefore the potentially strongest discriminating variable, is the likely separation distance, Δs, between dual-EAS events. Example likelihood analyses are now outlined for scenarios of interest.

Any collection of events, N_{tot}, is an undetermined mixture of signal and background events,

$$N_{\text{tot}} = N_{\text{sig}} + N_{\text{bkg}} \tag{5.43}$$

where N_{sig} events follow an Eq. (5.28) PDF,

$$\text{PDF}_{\text{sig}}(\Delta s; E) = \frac{\langle \Gamma(\Delta s; E) \rangle}{\int_0^{\pi R_E} \langle \Gamma(\Delta s; E) \rangle \, d(\Delta s)} \tag{5.44}$$

and N_{bkg} events follow an Eq. (5.3) PDF,

$$\text{PDF}_{\text{bkg}}(\Delta s; \Delta\psi \leq \Psi) = \frac{1}{4R_E} \csc^2\left(\frac{\Psi}{2}\right) \sin\left(\frac{\Delta s}{R_E}\right) \left[1 - \cos\Psi + \frac{3}{8}\sin^2\Psi \cos\left(\frac{\Delta s}{R_E}\right)\right] \tag{5.45}$$

These functions, and their corresponding CDFs are shown in Fig. 5.37.

It is assumed that observations cannot be precisely binned in energy, and therefore both PDFs are marginalized over each scenario's energy spectrum,

$$\text{PDF}_{\text{sig}}(\Delta s) = \frac{\int_{10^{15}}^{10^{20}} \langle \Gamma(\Delta s; E) \rangle \, \gamma(\Delta s; 0.23\ E)\ F(E)\ \Xi(E)\ \Upsilon(E)\ A\epsilon(0.23\ E)\ d(E)}{\int_{10^{15}}^{10^{20}} \int_0^{\pi R_E} \langle \Gamma(\Delta s; E) \rangle \, \gamma(\Delta s; 0.23\ E)\ F(E)\ \Xi(E)\ \Upsilon(E)\ A\epsilon(0.23\ E)\ d(\Delta s) d(E)} \tag{5.46}$$

Table 5.3: Expectation values for β for four scenarios and their expected yearly event rate

Scenario	Boost-Factor	$\langle\beta\rangle = \frac{N_{\text{sig}}}{N_{\text{sig}}+N_{\text{bkg}}}$	$\langle$Events / Year$\rangle$
"U"	1	2.47×10^{-8}	$\sim$10
"U-boosted"	2.9×10^{9}	0.986	$\sim 10^{10}$
"P"	1	0.965	$\sim 10^{-12}$
"P-boosted"	7.3×10^{13}	1.000	$\sim$10

and,

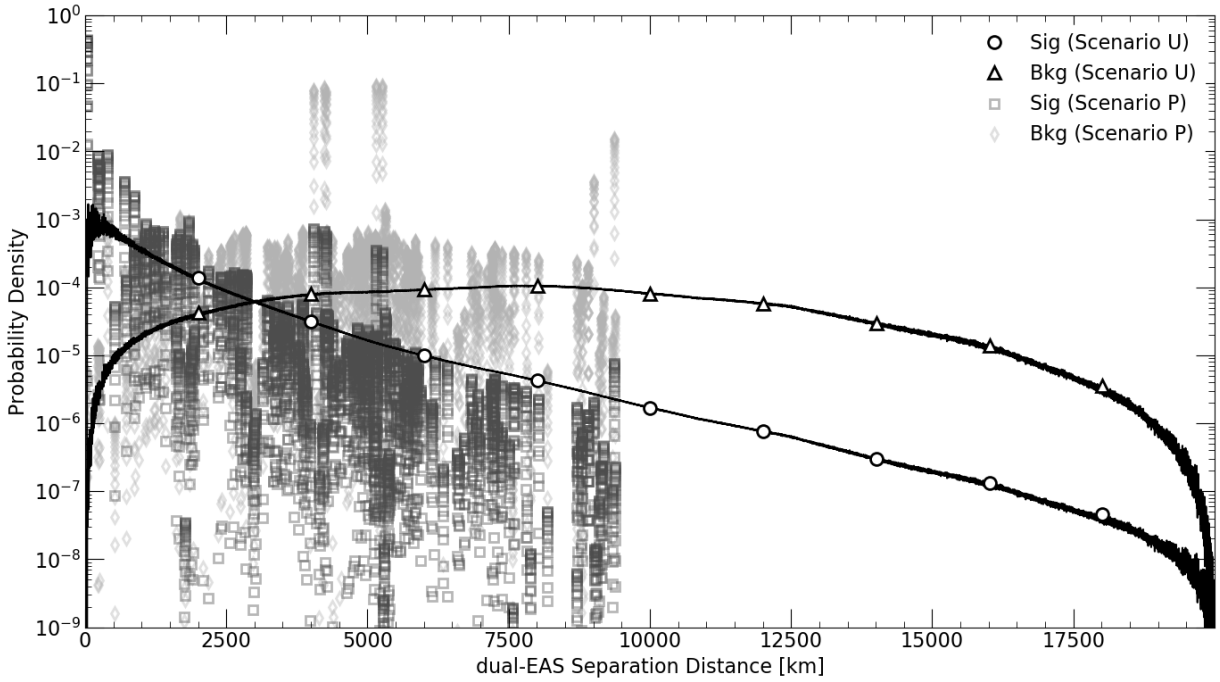
$$\begin{aligned}\text{PDF}_{\text{bkg}}(\Delta s) = \frac{1}{4R_E}\csc^2\left(\frac{\pi}{6}\right)\sin\left(\frac{\Delta s}{R_E}\right)\left[1-\cos\left(\frac{\pi}{3}\right)+\frac{3}{8}\sin^2\left(\frac{\pi}{3}\right)\cos\left(\frac{\Delta s}{R_E}\right)\right] \\ \times \frac{\int_{10^{15}}^{10^{20}} \gamma(\Delta s; 0.23\ E)\ F(0.23\ E)\ \Xi(E)\ \Upsilon(E)\ A\epsilon(0.23\ E)\ d(E)}{\int_{10^{15}}^{10^{20}}\int_{0}^{\pi R_E} \gamma(\Delta s; 0.23\ E)\ F(0.23\ E)\ \Xi(E)\ \Upsilon(E)\ A\epsilon(0.23\ E)\ d(\Delta s)d(E)}\end{aligned} \tag{5.47}$$

where the CRAYFIS array separation distribution, $\gamma(\Delta s; 0.23\ E)$ (§5.6.2), has been taken into consideration as well. Plots of these functions and their CDFs are provided in Fig. 5.38—note that the boosted scenarios follow the same separation distribution as their un-boosted scenario.

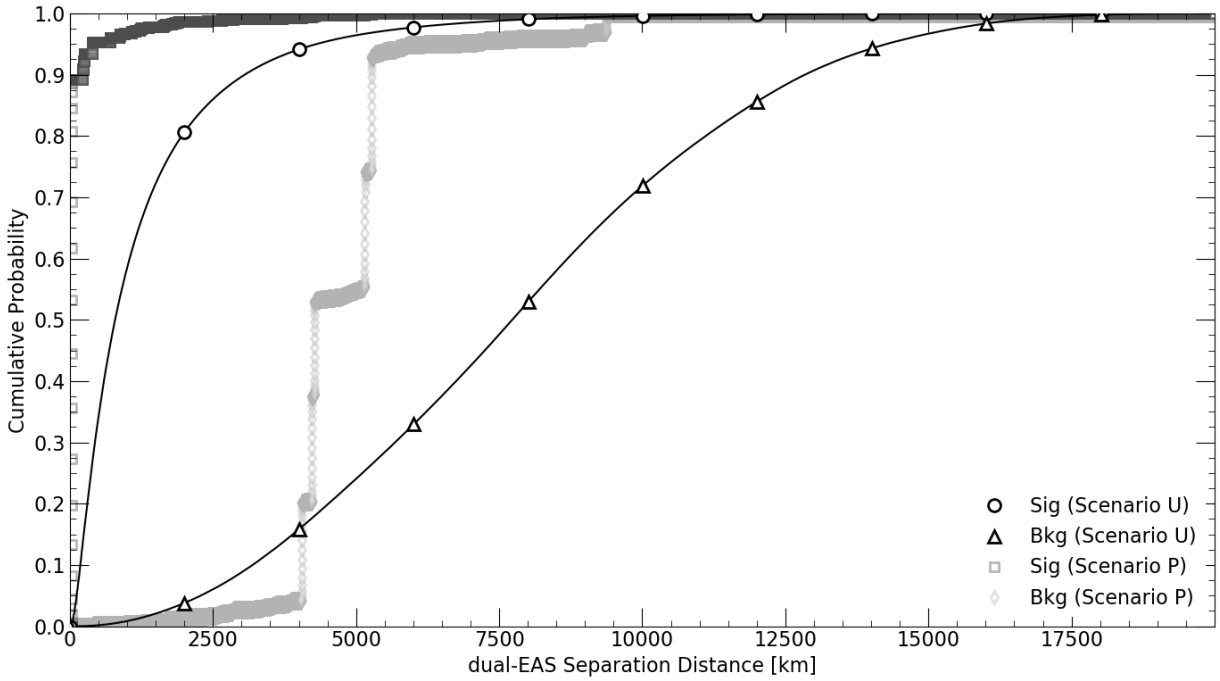
All together, the total separation distribution is,

$$\text{PDF}_{\text{tot}}(\Delta s \mid \beta) = \beta\ \text{PDF}_{\text{sig}}(\Delta s) + (1-\beta)\ \text{PDF}_{\text{bkg}}(\Delta s) \tag{5.48}$$

where $\beta = N_{\text{sig}}/N_{\text{tot}}$, and $1-\beta = N_{\text{bkg}}/N_{\text{tot}}$.



(a) Dual-EAS Separation, Probability Density Function



(b) Dual-EAS Separation, Cumulative Distribution Function

Figure 5.38: Top, the dual-EAS separation PDF for GZ Effect-like signals marginalized over energy for various scenarios (Eq. (5.46)), and corresponding backgrounds (Eq. (5.47)). Bottom, the corresponding CDFs for the same curves.

The expectation value of β is directly evaluable from Eq. (5.40) as $A\epsilon(0.23\ E)\ T$ is common to both signal and background,

$$\langle\beta\rangle = \frac{1}{10^{20}-10^{15}} \int_{10^{15}}^{10^{20}} \frac{F(E)\ \Xi_{\rm sig}(E)\ \Upsilon_{\rm sig}(E)\chi_{\rm sig}(60^\circ)\ d(E)}{F(E)\ \Xi_{\rm sig}(E)\ \Upsilon_{\rm sig}(E)\chi_{\rm sig}(60^\circ) + F(0.23\ E)\ \Xi_{\rm bkg}(E)\ \Upsilon_{\rm bkg}(E)\chi_{\rm bkg}(60^\circ)} \tag{5.49}$$

and the results are listed in Table 5.3. The mean number of events per year scales in direct proportion to the boost-factor, B,

$$\langle \text{Events / Year}\rangle = B\langle \text{Events / Year}\rangle_0 \tag{5.50}$$

whereas $\langle\beta\rangle$ scales as,

$$\langle\beta\rangle = \frac{B\ N^0_{\rm sig}}{B\ N^0_{\rm sig} + N_{\rm bkg}} \tag{5.51}$$

where naught denotes unboosted values.

An unbinned likelihood function can now be defined,

$$\ln \mathcal{L}(\beta \mid \Delta s) = \sum_{i=1}^{N_{\rm tot}} \ln \text{PDF}_{\rm tot}(\Delta s_i \mid \beta) \tag{5.52}$$

so that the undetermined signal fraction β, can be estimated from data by maximizing the likelihood function. The statistical significance (of rejecting $\beta = 0$) for the maximal likelihood estimation of $\hat{\beta}$ is then evaluated from the likelihood-ratio test statistic,

$$\text{TS} = 2\left(\ln \mathcal{L}(\hat{\beta} \mid \Delta s) - \ln \mathcal{L}(0 \mid \Delta s)\right) \tag{5.53}$$

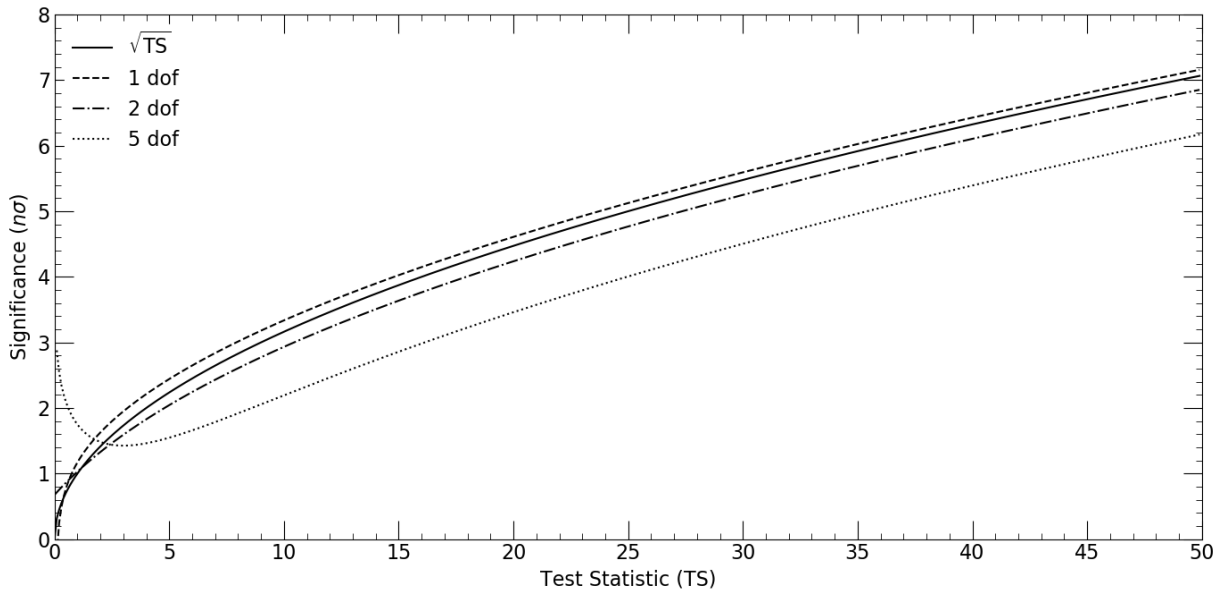


Figure 5.39: The exact (Eq. (5.56)) and approximate (Eq. (5.57)) relationship between a log-likelihood ratio test statistic and equivalent p-value significance threshold, $n\sigma$, for three example degrees of freedom (dof).

By Wilk's theorem (Wilks (1938)), this test statistic is expected to follow a $\chi^2(k=1)$ distribution,

$$\chi^2(x;k) = \frac{1}{2^{k/2}\Gamma(k/2)} x^{k/2-1} \exp(-x/2) \tag{5.54}$$

so that the corresponding significance (expressible as the standard deviation threshold, $n\sigma$, of a symmetric normal distribution p-value) is,

$$1 - \int_{-n\sigma}^{n\sigma} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\, d(x) = \chi^2(\text{TS};1) \tag{5.55}$$

which is solvable in terms of the Gauss error function,

$$n = \sqrt{2}\, \text{erf}^{-1}\left(1 - \chi^2(\text{TS};1)\right) \tag{5.56}$$

which for low degrees of freedom (*i.e.*, $k = 1$) can be well approximated by (Fig. 5.39),

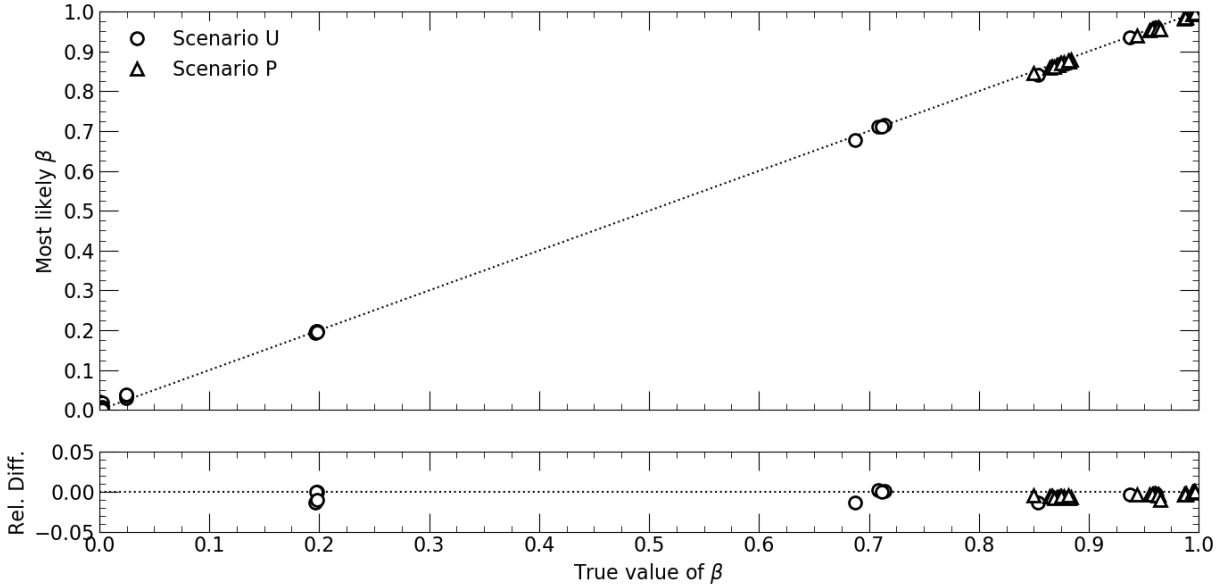
$$n \simeq \sqrt{\mathrm{TS}} \tag{5.57}$$

5.6.6 Monte Carlo Results

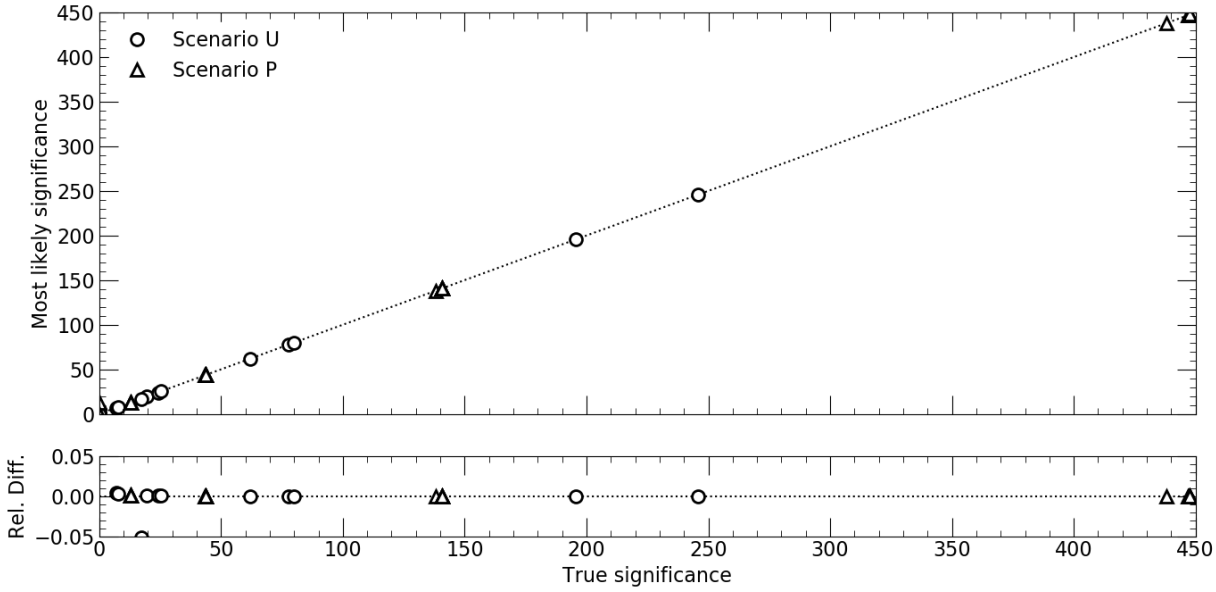
With the statistical machinery in place from the previous section, Monte Carlo pseudo-experiments are performed. The separation distances for each of N_{tot} simulated dual-EAS events are drawn from the combined signal and background model of Eq. (5.33) and Fig. 5.38a, where N_{tot} is stepped by powers of 10 from $N_{\mathrm{tot}} = 10^1$ to 10^4. For each combination of scenario and boost-factor, B, the β-truth, β_T, fraction can be computed directly from Eq. (5.51). Accordingly, for each N_{tot} and β_T fraction, an arbitrary-but-sufficient number (10^3) of hypothetical observation iterations are made with Poisson-distributed N_{sig} (and $N_{\mathrm{bkg}} = N_{\mathrm{tot}} - N_{\mathrm{sig}}$) generated events. The boost-factors for "Scenario U" range in powers of 10 from $B_{\mathrm{U}} = 10^0$ to 10^9, and for "Scenario P" from $B_{\mathrm{P}} = 10^0$ to 10^{13}.

The effectiveness of the likelihood method at extracting β from hypothetical observations, along with the corresponding statistical significance for doing so, is shown in Fig. 5.40. With the exception of only a handful of instances for "Scenario U" where β_T (truth) was very near zero, all other pseudo-experiments correctly estimated the true fraction of N_{tot} events attributable to GZ Effect-like dual-EAS phenomena to within 5% relative error.

The minimal observation time to reject the background-only hypothesis at 3σ significance is shown in Fig. 5.41. For "Scenario U," a minimal boosting of $\sim 10^6$ is needed to overcome the poor signal-to-background ratio (although this is possibly reducible through dual-EAS radius limits, or other effective area cuts, as discussed in §5.6.4.3). Additionally (and related to this poor ratio), more than 10 dual-EAS events are needed to statistically attribute a fraction of them to signal processes at 3σ significance or greater; however,



(a) Effectiveness of reconstructing β ("most likely β") from observations.



(b) Corresponding statistical significance (Eq. (5.57)) of rejecting $\beta = 0$.

Figure 5.40: For various N_{tot} dual-EAS events at various boost-factors, B (see text for details), the average results (from 10^3 Monte Carlo observations per N_{tot}, B and scenario combination) of likelihood analyses on hypothetical observations (statistical errors are too small to be shown). Top, β_T (truth) is given along the x-axis with the computed value of $\hat{\beta}$ that maximized the likelihood function $\ln \mathcal{L}(\beta \mid \Delta s)$ (Eq. (5.52)). The relative difference of $\hat{\beta}$ with respect to β_T is shown below (the dotted line illustrates zero relative difference in all plots). Bottom, the true statistical significance (of β_T rejecting $\beta = 0$) is given along the x-axis with the computed null-hypothesis (combinatorial background only) rejection significance along the y-axis. The relative difference of the rejection significance found from $\hat{\beta}$ with respect to β_T is shown below.

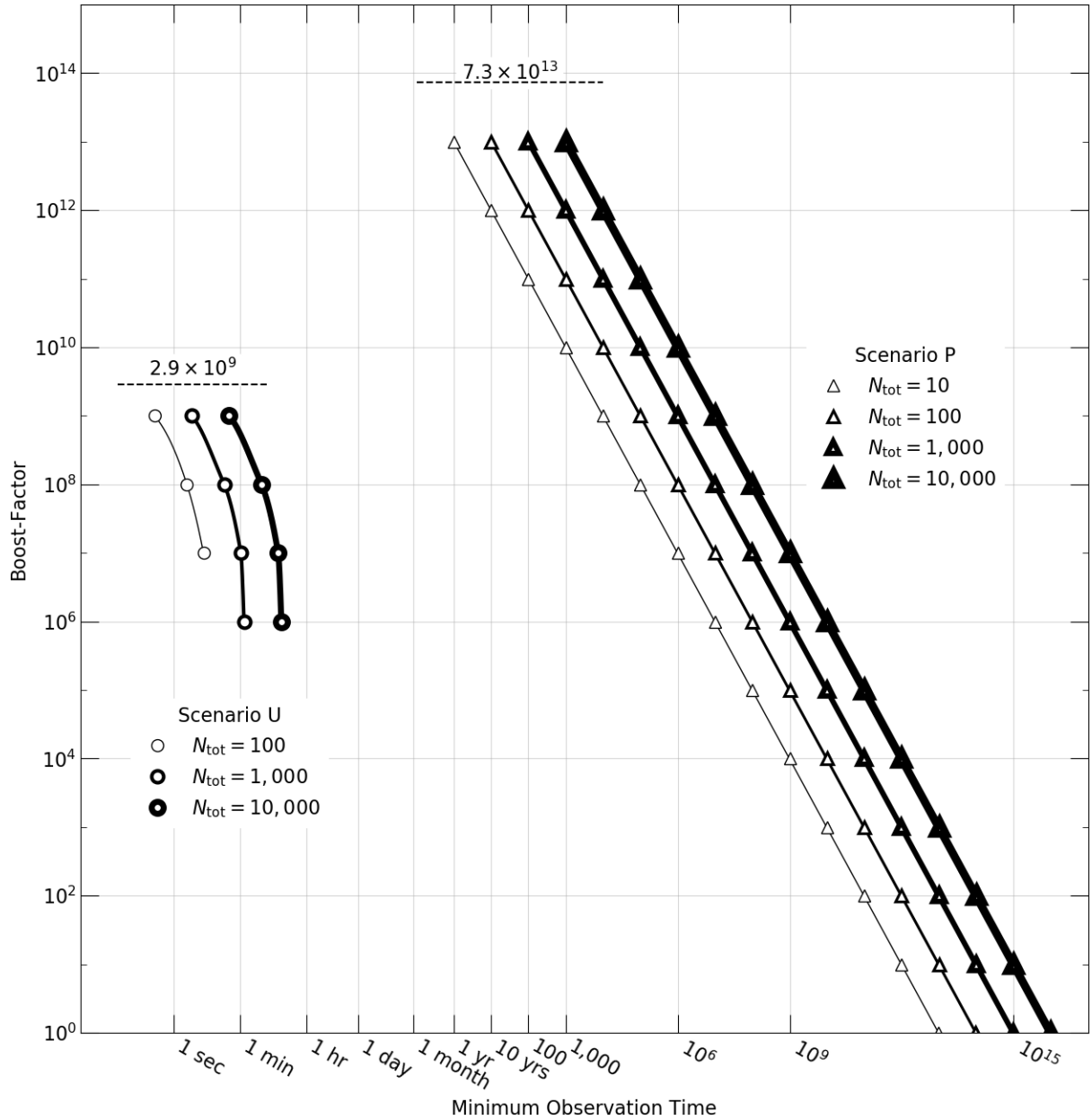


Figure 5.41: The minimum observation time needed to observe a GZ Effect-like dual-EAS signal at greater than 3σ significance as a function of $N_{\rm tot}$, the total number of dual-EAS events observed, and the boost-factor, B (y-axis). The maximum boost-factor to still be consistent with the established UHECR flux is shown above the dotted line above each scenario grouping—this point also corresponds to the shortest observational time needed to collect $N_{\rm tot}$ events. For "Scenario U," a minimal boost-factor of $\sim 10^6$ is needed to be detectable above its combinatorial background. Also for "Scenario U," $N_{\rm tot}$ of 10 is never a sufficient number of dual-EAS events to discriminate signal over background at greater than 3σ significance.

collecting events is not a problem for a "Scenario U-like" array as the collection area potentially accommodates 10,000 dual-EAS events every hour of integrated observation time. Which is to say, in the upper-limit of CRAYFIS user adoption, new or unexpected time-coincident EAS phenomena are in all likelihood readily detectable.

For the more pragmatic "Scenario P," the dramatically reduced effective area greatly suppresses the chances of a combinatorial dual-EAS background event, evidenced by the apparent ability of CRAYFIS to potentially detect new simultaneous EAS phenomena using only 10 data points. The downside to this effective area reduction however is that the chance of observing *any* simultaneous event at all is tremendously suppressed as well, and only phenomena with effective boost-factors in excess of 10^{12} are observable within a 10 year time frame. For this reason, smaller CRAYFIS array scenarios are probably only likely (under reasonable time frames) to detect "burst" phenomena where many simultaneous EASs occur at once, versus "continuous" phenomena like the GZ Effect.

Chapter 6

Conclusion

The study of extensive air showers (EASs) was introduced in Chapter 2, and the computational challenges (vis-à-vis hadronic interaction modeling) that afflict their numerical simulation were outlined. An effective model for EAS lateral particle density distributions was also developed. This proposed alternative model, Eq. (2.11), was found to fit simulation results better than traditional NKG-based models; although, the agreement between actual EAS data and these simulation results and models was not explored.

An overview of how smartphones become particle detectors was provided in Chapter 3 with a description of the Cosmic RAYs Found In Smartphones (CRAYFIS) application. Significant, and troublesome fluctuations in individual pixel responses were shown to vary in degree over example camera sensors. These performance variations were found to be dependent on camera hardware pre-processing and image format modes, as well as to changes in temperature and image exposure settings. Additionally, pixel response profiles were also shown to vary across smartphone models, identical or otherwise. The unexpected pixel fluctuations from troublesome pixels, which are known to mimic particle signatures

and miss-trigger a data acquisition cycle, must either be removed during a calibration cycle, or otherwise flagged further downstream.

Chapter 4 explores three means for profiling camera pixel performance in relation to this task. First, laboratory testing of a subset of smartphones with radioactive sources and accelerator muon beams produced the preliminary conservative estimates for typical camera sensor photon and muon effective areas of 10^{-5} and 0.05 cm^2 respectively. Consequentially, it was estimated in Fig. 4.11 that a CRAYFIS array made up of 1% of households in a residential area is potentially sensitive to individual EASs with total energy greater than 10^{17} eV. Secondly, a means for *in situ* validation of individual smartphones was proposed by Eq. (4.3). However, a case study of two smartphones at different altitudes found that significant miss-triggered noise is likely present in CRAYFIS-beta tester data. Still, a tantalizing proof of concept for the prospects of CRAYFIS is demonstrated in Fig. 4.12 where it seems likely that CRAYFIS is largely performing how it should be. Lastly, a cross-calibration method was proposed for a test array of CRAYFIS smartphones at the Telescope Array Observatory in Millard County, Utah. Such an experiment is shown to have the ability to validate the effective areas of camera sensors, uncover systematic issues with data quality, and establish the effectiveness (efficiency and resolution) of CRAYFIS EAS reconstruction algorithms.

In Chapter 5, the potential sensitivity of a global detector network of consumer smartphones to time-coincident EAS phenomena was considered. The Gerizimosa-Zatsepin (GZ) Effect was taken as a prototypical phenomenological model for two scenarios, one of order 10^6 worldwide CRAYFIS users, and an upper limit case of order 10^9 users. For the GZ Effect specifically, geographic asymmetries in flux and EAS separation distances were identified in Figs. 5.18–5.23. The CRAYFIS network effective area was then estimated in Fig. 5.27 and found to exceed that of the currently largest UHECR observatories (for the scenarios considered). A model for dual-EAS phenomena separation distances was

developed as Eq. (5.28), and following additional considerations of the combinatorial background and reconstruction resolutions of CRAYFIS sub-arrays, estimates for GZ Effect dual-EAS flux were made in Fig. 5.35. To generalize to unexpected phenomena, a maximal boost-factor consistent with total observed UHECR flux was illustrated in Fig. 5.36. At last, following a statistical treatment of hypothetical observations, minimum observation times given phenomenological boost-factors are presented in Fig. 5.41 where it was demonstrated that a global array of CRAYFIS smartphones is suited to detect time-coincident phenomena.

In summary, CRAYFIS is ultimately a low-stakes, high-payoff experiment. Its operational advantages notably feature an unparalleled minimal overhead of support personnel and equipment, paired with the potential of turning the populated planet into an UHECR observatory. CRAYFIS does however face a number of technical and sociopolitical challenges regarding the significant variability in consumer camera sensor pixel responses, and widespread user adoption respectively. Nonetheless, plans are in place to address technological difficulties, and initial (small) CRAYFIS networks are still sensitive to "burst" phenomena. Like any technology, CRAYFIS does not perform equally well at all tasks. As such, existing UHECR observatories are still better equipped and optimized to study phenomena (like individual EASs) that have already been documented and studied for some time. On the other hand, this dissertation has outlined in detail how a global network of CRAYFIS-enabled smartphones can excel at probing for new physics and rare phenomena at the highest energy frontier.

Bibliography

Aab, A. et al. (2015). The Pierre Auger Cosmic Ray Observatory. *Nucl. Instrum. Meth.*, A798:172–213.

Aartsen, M. G. et al. (2013). Measurement of the cosmic ray energy spectrum with IceTop-73. *Phys. Rev.*, D88(4):042004.

Aartsen, M. G. et al. (2018). Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science*, 361(6398):eaat1378.

Abraham, J. et al. (2004). Properties and performance of the prototype instrument for the Pierre Auger Observatory. *Nucl. Instrum. Meth.*, A523:50–95.

Abramovsky, V. A., Gribov, V. N., and Kancheli, O. V. (1973). Character of Inclusive Spectra and Fluctuations Produced in Inelastic Processes by Multi - Pomeron Exchange. *Yad. Fiz.*, 18:595–616. [Sov. J. Nucl. Phys.18,308(1974)].

Agostinelli, S. et al. (2003). GEANT4: A Simulation toolkit. *Nucl. Instrum. Meth.*, A506:250–303.

Akasofu, S.-I., Gray, P., and Lee, L. (1980). A model of the heliospheric magnetic field configuration. *Planetary and Space Science*, 28(6):609 – 615.

Apel, W. D. et al. (2010). The KASCADE-Grande experiment. *Nucl. Instrum. Meth.*, A620:202–216.

Auger, P., Ehrenfest, P., Maze, R., Daudin, J., and Fréon, R. A. (1939). Extensive cosmic-ray showers. *Rev. Mod. Phys.*, 11:288–291.

Barnhill, D. et al. (2005). Measurement of the lateral distribution function of UHECR air showers with the Pierre Auger Observatory. In *Proceedings, 29th International Cosmic Ray Conference (ICRC 2005) - by Forschungszentrum Karlsruhe, Institute for Nuclear Physics, and University Karlsruhe, Institute for Experimental Nuclear Physics: Pune, India, August 3-11, 2005*, volume 7, pages 291–294.

Berezinsky, V. and Vilenkin, A. (1997). Cosmic necklaces and ultrahigh-energy cosmic rays. *Phys. Rev. Lett.*, 79:5202–5205.

Berezinsky, V. S. and Zatsepin, G. T. (1969). Cosmic rays at ultrahigh-energies (neutrino?). *Phys. Lett.*, 28B:423–424.

Bhattacharjee, P. (1989). Cosmic strings and ultrahigh-energy cosmic rays. *Phys. Rev. D*, 40:3968–3975.

Bhattacharjee, P. and Rana, N. (1990). Ultrahigh-energy particle flux from cosmic strings. *Physics Letters B*, 246(3):365 – 370.

Bhattacharjee, P. and Sigl, G. (1995). Monopole annihilation and highest energy cosmic rays. *Phys. Rev.*, D51:4079–4091.

Boezio, M. et al. (2003). Energy spectra of atmospheric muons measured with the caprice98 balloon experiment. *Phys. Rev.*, D67:072003.

Brandenberger, R. H. (1994). Topological defects and structure formation. *Int. J. Mod. Phys.*, A9:2117–2190.

Breit, G. and Wigner, E. (1936). Capture of slow neutrons. *Phys. Rev.*, 49:519–531.

Brun, R., Bruyant, F., Maire, M., McPherson, A. C., and Zanarini, P. (1987). GEANT3.

Capella, A. and Krzywicki, A. (1978). Theoretical model of soft hadron-nucleus collisions at high energies. *Phys. Rev. D*, 18:3357–3370.

Carrel, O. and Martin, M. (1994). Observation of time correlations in cosmic rays. *Physics Letters B*, 325:526–530.

Center for International Earth Science Information Network (CIESIN), C. U. The Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets, 2018. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC), `http://dx.doi.org/10.7927/H45Q4T5F`.

Chung, D. J. H., Kolb, E. W., and Riotto, A. (1998). Superheavy dark matter. *Phys. Rev.*, D59:023501.

Dave, P. and Taboada, I. (2019). Neutrinos from Primordial Black Hole Evaporation. In *HAWC Contributions to the 36th International Cosmic Ray Conference (ICRC2019)*.

Davoudiasl, H., Hewett, J. L., and Rizzo, T. G. (2002). Gravi burst: Super GZK cosmic rays from localized gravity. *Phys. Lett.*, B549:267–272.

Dhital, N., Homola, P., Jarvis, J. F., Poznanski, P., Almeida Cheminant, K., Bratek, Ł., Bretz, T., Gora, D., Jagoda, P., Jałocha, J., Kopanski, K., Lemanski, D., Magrys, M., Nazari, V., Niedzwiedzki, J., Nocun, M., Noga, W., Ozieblo, A., Smelcerz, K., Smolek, K., Stasielak, J., Stuglik, S., Sułek, M., Sushchov, O., and Zamora-Saa, J. (2017). We are all the Cosmic-Ray Extremely Distributed Observatory. *arXiv e-prints*, page arXiv:1709.05196.

Dormand, J. and Prince, P. (1980). A family of embedded runge-kutta formulae. *Journal of Computational and Applied Mathematics*, 6(1):19 – 26.

Durand, L. and Hong, P. (1987). QCD and Rising Total Cross-Sections. *Phys. Rev. Lett.*, 58:303–306.

Epele, L. N., Mollerach, S., and Roulet, E. (1999). On the disintegration of cosmic ray nuclei by solar photons. *JHEP*, 03:017.

Epstein, R. I. (1980). The acceleration of interstellar grains and the composition of the cosmic rays. *Monthly Notices of the Royal Astronomical Society*, 193(4):723–729.

Falcke, H. D. et al. (2007). A very brief description of LOFAR the Low Frequency Array. *Highlights Astron.*, 14:386–387.

Fargion, D., Mele, B., and Salis, A. (1999). Ultrahigh-energy neutrino scattering onto relic light neutrinos in galactic halo as a possible source of highest energy extragalactic cosmic rays. *Astrophys. J.*, 517:725–733.

Fegan, D. J., Mcbreen, B., and O'Sullivan, C. (1983). OBSERVATION OF A BURST OF COSMIC RAYS AT ENERGIES ABOVE 7 X 10**13-EV. *Phys. Rev. Lett.*, 51:2341–2344.

Fenu, F. (2017). The cosmic ray energy spectrum measured using the Pierre Auger Observatory. pages 9–16. [PoSICRC2017,486(2018)].

Fesefeldt, H. (1985). The Simulation of Hadronic Showers: Physics and Applications.

Fletcher, R. S., Gaisser, T. K., Lipari, P., and Stanev, T. (1994). SIBYLL: An Event generator for simulation of high-energy cosmic ray cascades. *Phys. Rev.*, D50:5710–5731.

Gaisser, T. K. and Halzen, F. (1985). "soft" hard scattering in the teraelectronvolt range. *Phys. Rev. Lett.*, 54:1754–1756.

Gerasimova, N. and Zatsepin, G. (1960). Disintegration of cosmic ray nuclei by solar photons. *Soviet Phys., JETP*, 11:899.

Giani, S., Leroy, C., and Rancoita, P. G., editors (2011). *Cosmic rays for particle and astroparticle physics. Proceedings, 12th ICATPP Conference, Como, Italy, October 7-8, 2010*, volume 6 of *Astroparticle, Particle, Space Physics, Radiation Interaction, Detectors and Medical Physics Applications*, Hackensack. WSP, WSP.

Goldreich, P. and Morrison, P. (1964). On the absorption of gamma rays in intergalactic space. *JETP*, 18(1):239.

Gould, R. J. and Schréder, G. P. (1967). Opacity of the universe to high-energy photons. *Phys. Rev.*, 155:1408–1411.

Gribov, V. N. (1968). A REGGEON DIAGRAM TECHNIQUE. *Sov. Phys. JETP*, 26:414–422. [Zh. Eksp. Teor. Fiz.53,654(1967)].

Gribov, V. N. (1969). Glauber corrections and the interaction between high-energy hadrons and nuclei. *Sov. Phys. JETP*, 29:483–487. [Zh. Eksp. Teor. Fiz.56,892(1969)].

Habs, D., Guenther, M. M., Jentschel, M., and Thirolf, P. G. (2012). Nuclear Photonics. *AIP Conf. Proc.*, 1462(1):177–184.

Haungs, A., Rebel, H., and Roth, M. (2003). Energy spectrum and mass composition of high-energy cosmic rays. *Reports on Progress in Physics*, 66(7):1145–1206.

Hawking, S. W. (1974). Black hole explosions. *Nature*, 248:30–31.

Heck, D., Knapp, J., Capdevielle, J. N., Schatz, G., and Thouw, T. (1998). *CORSIKA: a Monte Carlo code to simulate extensive air showers.*

Hess, V. (2018). On the Observations of the Penetrating Radiation during Seven Balloon Flights.

Hill, C. T. (1983). Monopolonium. *Nuclear Physics B*, 224(3):469 – 490.

Hill, C. T., Schramm, D. N., and Walker, T. P. (1987). Ultra-high-energy cosmic rays from superconducting cosmic strings. *Phys. Rev. D*, 36:1007–1016.

Hillas, A. M. (1984). The Origin of Ultrahigh-Energy Cosmic Rays. *Ann. Rev. Astron. Astrophys.*, 22:425–444.

Hindmarsh, M. B. and Kibble, T. W. B. (1995). Cosmic strings. *Rept. Prog. Phys.*, 58:477–562.

Jelley, J. V. (1966). High-energy gamma-ray absorption in space by a 3.5 degree k microwave field. *Phys. Rev. Lett.*, 16:479–481.

Kalmykov, N. N., Ostapchenko, S. S., and Pavlov, A. I. (1994). EAS and a quark - gluon string model with jets. *Bull. Russ. Acad. Sci. Phys.*, 58:1966–1969. [Izv. Ross. Akad. Nauk Ser. Fiz.58N12,21(1994)].

Kampert, K. H., Hainzelmann, G., Spiering, C., Simon, M., Lorenz, E., Pohl, M., Droege, W., Kunow, H., and Scholer, M., editors (2001). *Proceedings, 27th International Cosmic Ray Conference (ICRC) : Contributed Papers*, Germany. Copernicus Gesellschaft e.V., Katlenburg-Lindau, University of Wuppertal.

Karakula, S. and Tkaczyk, W. (1993). The formation of the cosmic ray energy spectrum by a photon field. *Astroparticle Physics*, 1(2):229–237.

Kawai, H., Yoshida, S., Yoshii, H., Tanaka, K., Cohen, F., Fukushima, M., Hayashida, N., Hiyama, K., Ikeda, D., Kido, E., Kondo, Y., Nonaka, T., Ohnishi, M., Ohoka, H., Ozawa, S., Sagawa, H., Sakurai, N., Shibata, T., Shimodaira, H., Takeda, M., Taketa, A., Takita, M., Tokuno, H., Torii, R., Udo, S., Yamakawa, Y., Fujii, H., Matsuda, T., Tanaka, M., Yamaoka, H., Hibino, K., Benno, T., Doura, K., Chikawa, M., Nakamura, T., Teshima, M., Kadota, K., Uchihori, Y., Hayashi, K., Hayashi, Y., Kawakami, S., Matsuyama, T., Minamino, M., Ogio, S., Ohshima, A., Okuda, T., Shimizu, N., Tanaka, H., Bergman, D., Hughes, G., Stratton, S., Thomson, G., Endo, A., Inoue, N., Kawana, S., Wada, Y., Kasahara, K., Azuma, R., Iguchi, T., Kakimoto, F., Machida, S., Misumi, K., Murano,

Y., Tameda, Y., Tsunesada, Y., Chiba, J., Miyata, K., Abu-Zayyad, T., Belz, J., Cady, R., Cao, Z., Huentemeyer, P., Jui, C., Martens, K., Matthews, J., Mostofa, M., Smith, J., Sokolsky, P., Springer, R., Thomas, J., Thomas, S., Wiencke, L., Doyle, T., Taylor, M., Wickwar, V., Wilkerson, T., Hashimoto, K., Honda, K., Ikuta, K., Ishii, T., Kanbe, T., and Tomida, T. (2008). Telescope array experiment. *Nuclear Physics B - Proceedings Supplements*, 175-176:221 – 226. Proceedings of the XIV International Symposium on Very High Energy Cosmic Ray Interactions.

Kibble, T. W. B. (1976). Topology of cosmic domains and strings. *Journal of Physics A: Mathematical and General*, 9(8):1387–1398.

Kieda, D., Salamon, M., and Dingus, B., editors (1999). *Proceedings, 26th International Cosmic Ray Conference (ICRC) : Contributed Papers*, Stanford. Stanford University, Stanford University.

Kitamura, T., Ohara, S., Konishi, T., Tsuji, K., Chikawa, M., Unno, W., Masaki, I., Urata, K., and Kato, Y. (1997). Chaos in cosmic ray air showers. *Astroparticle Physics*, 6(3):279 – 291.

Knapp, J., Heck, D., and Schatz, G. (1996). Comparison of hadronic interaction models used in air shower simulations and of their influence on shower development and observables.

Knapp, J., Heck, D., and Schatz, G. (1997). Comparison of hadronic interaction models used in EAS simulations. *Nucl. Phys. Proc. Suppl.*, 52B:136–138. [,136(1997)].

Lafebre, S., Falcke, H., Horandel, J., and Kuijpers, J. (2008). Prospects for direct cosmic ray mass measurements through the Gerasimova-Zatsepin effect. *Astron. Astrophys.*, 485:1.

M. Tanabashi, e. a. (2018). Review of particle physics. *Phys. Rev. D*, 98:030001.

Masperi, L. and Orsaria, M. (2002). Hard component of ultrahigh-energy cosmic rays and vortons. *Astropart. Phys.*, 16:411–423.

Masperi, L. and Silva, G. A. (1998). Cosmic rays from decaying vortons. *Astropart. Phys.*, 8:173–177.

Medina-Tanco, G. A. and Watson, A. A. (1999). The Photodisintegration of cosmic ray nuclei by solar photons: The Gerasimova-Zatsepin effect revisited. *Astropart. Phys.*, 10:157–164.

Nikishov, A. I. (1962). Absorption of High-Energy Photons in the Universe. *JETP*, 14(2):393.

Ochi, N. et al. (2001). LAAS network observation of air showers. *Nucl. Phys. Proc. Suppl.*, 97:165–168. [,165(1999)].

Ochi, N. et al. (2003). The LAAS network observation for studying time correlations in extensive air showers. *Proc. SPIE Int. Soc. Opt. Eng.*, 4858:14–25.

Ostapchenko, S. (2006). QGSJET-II: Towards reliable description of very high energy hadronic interactions. *Nucl. Phys. Proc. Suppl.*, 151:143–146.

Potgieter, M. S., Raubenheimer, B. C., and van der Walt, D. J., editors (1998). *Cosmic ray. Proceedings, 25th International Conference, Durban, South Africa, July 30-August 6, 1997. Vol. 8: Invited, rapporteur, and highlight papers.*

Prager, H. (2018). *Phenomenology of extra quarks at the LHC*. PhD thesis, Southampton U.

Randall, L. and Sundrum, R. (1999). A Large mass hierarchy from a small extra dimension. *Phys. Rev. Lett.*, 83:3370–3373.

Regge, T. (1959). Introduction to complex orbital momenta. *Nuovo Cim.*, 14:951.

Roesler, S., Engel, R., and Ranft, J. (2000). The Monte Carlo event generator DPMJET-III. In *Advanced Monte Carlo for radiation physics, particle transport simulation and applications. Proceedings, Conference, MC2000, Lisbon, Portugal, October 23-26, 2000*, pages 1033–1038.

Roulet, E. (1993). Ultrahigh energy neutrino absorption by neutrino dark matter. *Phys. Rev. D*, 47:5247–5252.

Spitzer, L. (1949). On the origin of heavy cosmic-ray particles. *Phys. Rev.*, 76:583–583.

Stecker, F. W. (1969). The Cosmic Gamma-Ray Spectrum from Secondary-Particle Production in the Metagalaxy. *apj*, 157:507.

Tsunesada, Y., Abuzayyad, T., Ivanov, D., Thomson, G., Fujii, T., and Ikeda, D. (2018). Energy Spectrum of Ultra-High-Energy Cosmic Rays Measured by The Telescope Array. *PoS*, ICRC2017:535.

Unno, W., Kitamura, T., Konishi, T., Tsuji, K., Chikawa, M., Kato, Y., Ohara, S., Urata, K., and Masaki, I. (1997). Chaotic behavior in arrival times of cosmic ray air showers. *Europhys. Lett.*, 39:465–468.

Vandenbroucke, J., Bravo, S., Karn, P., Meehan, M., Plewa, M., Ruggles, T., Schultz, D., Peacock, J., and Simons, A. L. (2016). Detecting particles with cell phones: the Distributed Electronic Cosmic-ray Observatory. *PoS*, ICRC2015:691.

Vilenkin, A. (1985). Cosmic strings and domain walls. *Physics Reports*, 121(5):263 – 315.

Weiler, T. (1982). Resonant absorption of cosmic-ray neutrinos by the relic-neutrino background. *Phys. Rev. Lett.*, 49:234–237.

Werner, K. (1993). Strings, pomerons, and the venus model of hadronic interactions at ultrarelativistic energies. *Phys. Rept.*, 232:87–299.

Whiteson, D., Mulhearn, M., Shimmin, C., Cranmer, K., Brodie, K., and Burns, D. (2016). Searching for ultra-high energy cosmic rays with smartphones. *Astropart. Phys.*, 79:1–9.

Wickramasinghe, N. C. (1972). On the Injection of Grains into Interstellar Clouds. *Monthly Notices of the Royal Astronomical Society*, 159(3):269–287.

Wickramasinghe, N. C. (1974). Electric charge and acceleration of suprathermal grains. *Astrophysics and Space Science*, 28(2):L25–L29.

Wilks, S. S. (1938). The large-sample distribution of the likelihood ratio for testing composite hypotheses. *Ann. Math. Statist.*, 9(1):60–62.

Zatsepin, G. (1951). *Dokl. Akad. Nauk SSSR*, 80:577.

Appendix A

The Standard Model of Particle Physics

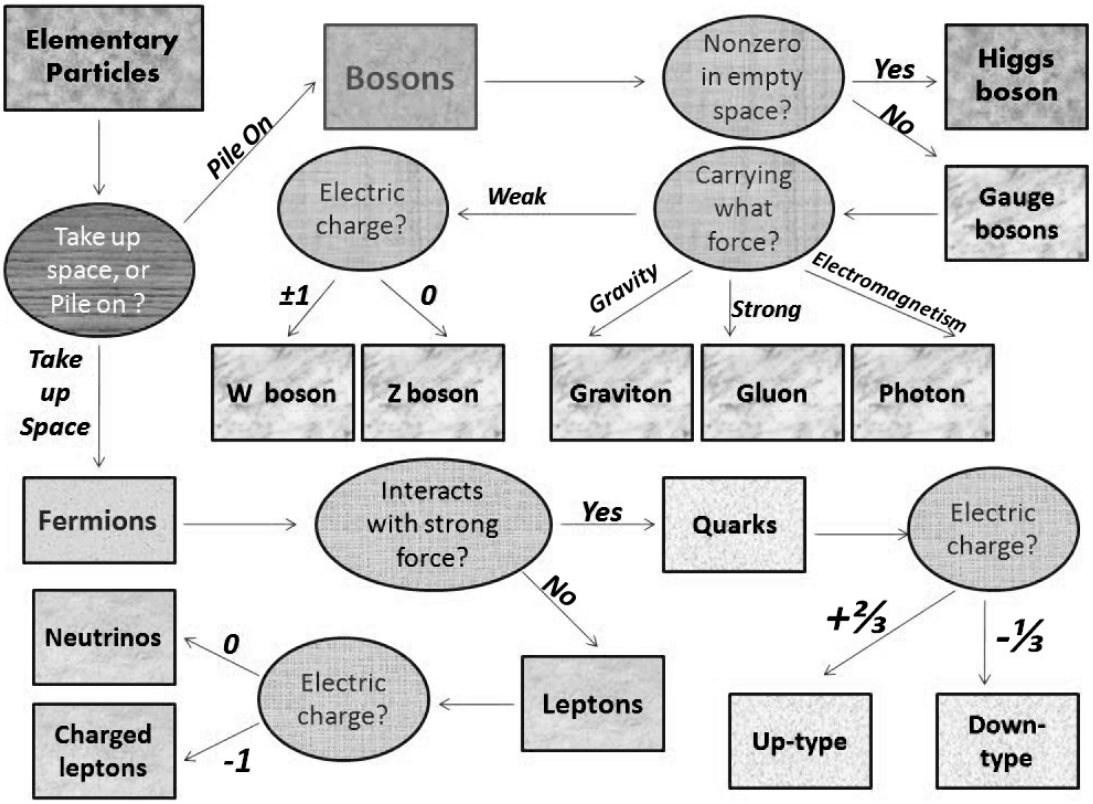


Figure A.1: Some distinguishing characteristics of the elementary particles of the Standard Model (image courtesy of `https://en.wikipedia.org/wiki/Standard_Model`).

> If we lived on a planet where nothing ever changed, there would be little to do. There would be nothing to figure out. There would be no impetus for science. And if we lived in an unpredictable world, where things changed in random or very complex ways, we would not be able to figure things out. But we live in an in-between universe, where things change, but according to patterns, rules, or as we call them, laws of nature. If I throw a stick up in the air, it always falls down. If the sun sets in the west, it always rises again the next morning in the east. And so it becomes possible to figure things out. We can do science, and with it we can improve our lives.
>
> (Carl Sagan, *Cosmos*, 1980)

The Standard Model of Particle Physics (SM) represents an extremely compact and effective encapsulation of over 100 years of subatomic experimental results. However, a more semantically-descriptive title could have been, the Quantized Field-Operator Model for the Dynamical Evolution of Discrete Sets of Intrinsic Properties of Spacetime[†]. This is because the "particles" usually associated with the SM (Fig. A.1) are not *particles* in the usual granular, object-permanence meaning of the word. The measurable quantities usually associated with SM particles (*e.g.*, electric charge, mass, etc) are not fixed onto a single, corporeal subatomic object occupying a finite volume of space; rather, these quantities describe a *localization* in space were the interplay of the "real" fundamental constituents of Nature (the *quantum fields*) are exhibiting those qualities (a *state*) as a net result of their interaction.

Yet, the corporal idea of a particle is certainly not unreasonable. Experimentally, it has been observed over and over again that measurable (time-persisting, *i.e.*, conserved) quantities like electric charge, mass, and intrinsic angular momentum (spin) never exist in totally random, totally independent concoctions—to the contrary, they have always come lumped together, without exception, in very specific combinations. By seeking out the master list of all allowed intrinsic quantity combinations of Nature (to wit, in accelerator experiments[‡]), a minimalist sub-set of such quantity combinations needed to reproduce the entire list was found; the short-list are what the particles of the SM in Fig. A.1 represent.

[†]Descriptive... but awful.

[‡]Particle listings, `http://pdg.lbl.gov/2019/listings/contents_listings.html`

But how do these particles move about? The *Lagrangian* (density) of the SM is compactly summarized by J. A. Shifflett on the following two pages, and contained neatly in Eq. (1) are all the "...patterns, rules, or as we call them, laws of nature" that govern how Nature evolves over time and space at the subatomic level (with the description of gravitation, dark matter and dark energy notoriously absent). All subsequent equations simply unpack and define the symbols used in Eq. (1).

A major take-away; however, is to notice that the Lagrangian is written entirely in terms of quantum fields[†], and their derivatives. An immediate consequence of this is that there is no unique way to write Eq. (1), or more precisely, there is no unique way to symbolically *unpack* Eq. (1). These freedoms in how one chooses to combine fields together turn out to have a profound importance. The algebraic prescription that allows for the altering of field definitions such that there are no numerical changes propagated to the results of calculations is what is referred to as a *symmetry*. And a physical consequence of a symmetry is a conservation law; *e.g.*, the conservation of (prior to electroweak symmetry breaking) $\mathrm{U}(1)_Y \leftrightarrow$hypercharge, $\mathrm{SU}(2)_L \leftrightarrow$weak isospin, and $\mathrm{SU}(3)_c \leftrightarrow$color charge. Further, the symmetry is only possible if the dynamical interaction (D_μ) between a vector gauge boson field (B_μ, $\boldsymbol{W}_{\mu\nu}$, and $\boldsymbol{G}_{\mu\nu}$) and a corresponding fermion field ($\nu_{L,R}$, $e_{L,R}$, $u_{L,R}$, and $d_{L,R}$) is exactly as prescribed in Eqs. (2) and (3). Eq. (4) applies as well, however the non-zero vacuum expectation value of the Higgs field breaks the electroweak symmetry of $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ into just $\mathrm{U}(1)_{e.m}$, giving the $W^\pm$ and Z^0 bosons their mass (*i.e.*, Eq. (13) with numerical results in Eq. (14)).

[†]A *field* in physics is the word for "some function which assigns a numeric value, a set of values, or in this case, a set of things not unlike functions themselves called *operators* (which then 'create' the physical states of Nature) to every point in space and time." A *quantum* field is a field of field operators at every point in space and time, each of which encapsulates a state of Nature that evolves or changes in some quantized (non-continuous) manner (*e.g.*, as described by commutation relations between field and conjugate momenta density operators).

Standard Model Lagrangian (including neutrino mass terms)
From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,
W. N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,
Extracted by J.A. Shifflett, updated from Particle Data Group tables at pdg.lbl.gov, 2 Feb 2015.

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)}\\
& +(\bar{\nu}_L,\bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu\nu_R + \text{(h.c.)} && \text{(lepton dynamical term)}\\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L,\bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)}\\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L,\bar{\nu}_L)\,\phi^* M^\nu\nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)}\\
& +(\bar{u}_L,\bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)}\\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L,\bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)}\\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L,\bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)}\\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \qquad (1)
\end{aligned}
$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar{\psi}=\text{(h.c.)}\psi=\psi^\dagger=\psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}=\left[\partial_\mu-\frac{ig_1}{2}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix},\quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix}=\left[\partial_\mu+\frac{ig_1}{6}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu+ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \tag{2}$$

$$D_\mu\nu_R=\partial_\mu\nu_R,\quad D_\mu e_R=[\partial_\mu-ig_1B_\mu]\,e_R,\quad D_\mu u_R=\left[\partial_\mu+\frac{i2g_1}{3}B_\mu+ig\mathbf{G}_\mu\right]u_R,\quad D_\mu d_R=\left[\partial_\mu-\frac{ig_1}{3}B_\mu+ig\mathbf{G}_\mu\right]d_R, \tag{3}$$

$$D_\mu\phi=\left[\partial_\mu+\frac{ig_1}{2}B_\mu+\frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \tag{4}$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T=(0,v+h)/\sqrt{2}\,,\qquad <\phi>_0^T=\text{(expectation value of }\phi)=(0,v)/\sqrt{2}\,, \tag{5}$$

where v is a real constant such that $\mathcal{L}_\phi=\overline{(\partial_\mu\phi)}\partial^\mu\phi-m_h^2[\bar{\phi}\phi-v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu,\quad \mathbf{W}_{\mu\nu}=\partial_\mu\mathbf{W}_\nu-\partial_\nu\mathbf{W}_\mu+ig_2(\mathbf{W}_\mu\mathbf{W}_\nu-\mathbf{W}_\nu\mathbf{W}_\mu)/2,\quad \mathbf{G}_{\mu\nu}=\partial_\mu\mathbf{G}_\nu-\partial_\nu\mathbf{G}_\mu+ig(\mathbf{G}_\mu\mathbf{G}_\nu-\mathbf{G}_\nu\mathbf{G}_\mu). \tag{6}$$

The non-matrix $A_\mu, Z_\mu, W_\mu^\pm$ bosons are mixtures of $\mathbf{W}_\mu$ and B_μ components, according to the weak mixing angle θ_w,

$$A_\mu=W_{11\mu}sin\theta_w+B_\mu cos\theta_w,\qquad Z_\mu=W_{11\mu}cos\theta_w-B_\mu sin\theta_w,\qquad W_\mu^+=W_\mu^{-*}=W_{12\mu}/\sqrt{2}, \tag{7}$$

$$B_\mu=A_\mu cos\theta_w-Z_\mu sin\theta_w,\quad W_{11\mu}=-W_{22\mu}=A_\mu sin\theta_w+Z_\mu cos\theta_w,\quad W_{12\mu}=W_{21\mu}^*=\sqrt{2}\,W_\mu^+,\quad sin^2\theta_w=.2315(4). \tag{8}$$

The fermions include the leptons e_R, e_L, ν_R, ν_L and quarks u_R, u_L, d_R, d_L. They all have implicit 3-component generation indices, $e_i=(e,\mu,\tau)$, $\nu_i=(\nu_e,\nu_\mu,\nu_\tau)$, $u_i=(u,c,t)$, $d_i=(d,s,b)$, which contract into the fermion mass matrices $M^e_{ij}, M^\nu_{ij}, M^u_{ij}, M^d_{ij}$, and implicit 2-component indices which contract into the Pauli matrices,

$$\sigma^\mu=\left[\begin{pmatrix}1&0\\0&1\end{pmatrix},\begin{pmatrix}0&1\\1&0\end{pmatrix},\begin{pmatrix}0&-i\\i&0\end{pmatrix},\begin{pmatrix}1&0\\0&-1\end{pmatrix}\right],\quad \tilde{\sigma}^\mu=[\sigma^0,-\sigma^1,-\sigma^2,-\sigma^3],\quad tr(\sigma^i)=0,\quad \sigma^{\mu\dagger}=\sigma^\mu,\quad tr(\sigma^\mu\sigma^\nu)=2\delta^{\mu\nu}. \tag{9}$$

The quarks also have implicit 3-component color indices which contract into $\mathbf{G}_\mu$. So $\mathcal{L}$ really has implicit sums over 3-component generation indices, 2-component Pauli indices, 3-component color indices in the quark terms, and 2-component $SU(2)$ indices in $(\bar{\nu}_L,\bar{e}_L), (\bar{u}_L,\bar{d}_L), (-\bar{e}_L,\bar{\nu}_L), (-\bar{d}_L,\bar{u}_L), \bar{\phi}$, $\mathbf{W}_\mu$, $\binom{\nu_L}{e_L}, \binom{u_L}{d_L}, \binom{-e_L}{\nu_L}, \binom{-d_L}{u_L}, \phi$.

Overview of the Standard Model Lagrangian courtesy of J. A. Shifflett,

`http://einstein-schrodinger.com/Standard_Model.pdf`

The electroweak and strong coupling constants, Higgs vacuum expectation value (VEV), and Higgs mass are,

$$g_1 = e/cos\theta_w, \quad g_2 = e/sin\theta_w, \quad g > 6.5e = g(m_\tau^2), \quad v = 246GeV(PDG) \approx \sqrt{2}\cdot 180\,GeV(CG), \quad m_h = 125.02(30)GeV \tag{10}$$

where $e = \sqrt{4\pi\alpha\hbar c} = \sqrt{4\pi/137}$ in natural units. Using (4,5) and rewriting some things gives the mass of $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\mathcal{W}^-_{\mu\nu}\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \tag{11}$$

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \quad \mathcal{W}^\pm_{\mu\nu} = D_\mu W^\pm_\nu - D_\nu W^\pm_\mu, \quad D_\mu W^\pm_\nu = [\,\partial_\mu \pm ieA_\mu]W^\pm_\nu, \tag{12}$$

$$D_\mu <\phi>_0 = \frac{iv}{\sqrt{2}}\begin{pmatrix} g_2W_{12\mu}/2 \\ g_1B_\mu/2 + g_2W_{22\mu}/2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix} W_{12\mu}/\sqrt{2} \\ (B_\mu sin\theta_w/cos\theta_w + W_{22\mu})/\sqrt{2}\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix} W^+_\mu \\ -Z_\mu/\sqrt{2}\,cos\theta_w\end{pmatrix}, \tag{13}$$

$$\Rightarrow \quad m_A = 0, \qquad m_{W^\pm} = g_2v/2 = 80.425(38)GeV, \qquad m_Z = g_2v/2cos\theta_w = 91.1876(21)GeV. \tag{14}$$

Ordinary 4-component Dirac fermions are composed of the left and right handed 2-component fields,

$$e = \begin{pmatrix} e_{L1} \\ e_{R1}\end{pmatrix},\ \nu_e = \begin{pmatrix} \nu_{L1} \\ \nu_{R1}\end{pmatrix},\ u = \begin{pmatrix} u_{L1} \\ u_{R1}\end{pmatrix},\ d = \begin{pmatrix} d_{L1} \\ d_{R1}\end{pmatrix}, \quad \text{(electron, electron neutrino, up and down quark)} \tag{15}$$

$$\mu = \begin{pmatrix} e_{L2} \\ e_{R2}\end{pmatrix},\ \nu_\mu = \begin{pmatrix} \nu_{L2} \\ \nu_{R2}\end{pmatrix},\ c = \begin{pmatrix} u_{L2} \\ u_{R2}\end{pmatrix},\ s = \begin{pmatrix} d_{L2} \\ d_{R2}\end{pmatrix}, \quad \text{(muon, muon neutrino, charmed and strange quark)} \tag{16}$$

$$\tau = \begin{pmatrix} e_{L3} \\ e_{R3}\end{pmatrix},\ \nu_\tau = \begin{pmatrix} \nu_{L3} \\ \nu_{R3}\end{pmatrix},\ t = \begin{pmatrix} u_{L3} \\ u_{R3}\end{pmatrix},\ b = \begin{pmatrix} d_{L3} \\ d_{R3}\end{pmatrix}, \quad \text{(tauon, tauon neutrino, top and bottom quark)} \tag{17}$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \tilde{\sigma}^\mu & 0\end{pmatrix} \qquad \text{where } \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2Ig^{\mu\nu}. \quad \text{(Dirac gamma matrices in chiral representation)} \tag{18}$$

The corresponding antiparticles are related to the particles according to $\psi^c = -i\gamma^2\psi^*$ or $\psi^c_L = -i\sigma^2\psi^*_R$, $\psi^c_R = i\sigma^2\psi^*_L$. The fermion charges are the coefficients of A_μ when (8,10) are substituted into either the left or right handed derivative operators (2-4). The fermion masses are the singular values of the 3×3 fermion mass matrices M^ν, M^e, M^u, M^d,

$$M^e = \mathbf{U}^{e\dagger}_L\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau\end{pmatrix}\mathbf{U}^e_R, \quad M^\nu = \mathbf{U}^{\nu\dagger}_L\begin{pmatrix} m_{\nu_e} & 0 & 0 \\ 0 & m_{\nu_\mu} & 0 \\ 0 & 0 & m_{\nu_\tau}\end{pmatrix}\mathbf{U}^\nu_R, \quad M^u = \mathbf{U}^{u\dagger}_L\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t\end{pmatrix}\mathbf{U}^u_R, \quad M^d = \mathbf{U}^{d\dagger}_L\begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b\end{pmatrix}\mathbf{U}^d_R, \tag{19}$$

$$m_e = .510998910(13)MeV, \quad m_{\nu_e} \sim .001 - 2eV, \quad m_u = 1.7 - 3.1MeV, \quad m_d = 4.1 - 5.7MeV, \tag{20}$$

$$m_\mu = 105.658367(4)MeV, \quad m_{\nu_\mu} \sim .001 - 2eV, \quad m_c = 1.18 - 1.34GeV, \quad m_s = 80 - 130MeV, \tag{21}$$

$$m_\tau = 1776.84(17)MeV, \quad m_{\nu_\tau} \sim .001 - 2eV, \quad m_t = 171.4 - 174.4GeV, \quad m_b = 4.13 - 4.37GeV, \tag{22}$$

where the $\mathbf{U}$s are 3×3 unitary matrices ($\mathbf{U}^{-1} = \mathbf{U}^\dagger$). Consequently the "true fermions" with definite masses are actually linear combinations of those in $\mathcal{L}$, or conversely the fermions in $\mathcal{L}$ are linear combinations of the true fermions,

$$e'_L = \mathbf{U}^e_L e_L, \quad e'_R = \mathbf{U}^e_R e_R, \quad \nu'_L = \mathbf{U}^\nu_L \nu_L, \quad \nu'_R = \mathbf{U}^\nu_R \nu_R, \quad u'_L = \mathbf{U}^u_L u_L, \quad u'_R = \mathbf{U}^u_R u_R, \quad d'_L = \mathbf{U}^d_L d_L, \quad d'_R = \mathbf{U}^d_R d_R, \tag{23}$$

$$e_L = \mathbf{U}^{e\dagger}_L e'_L, \quad e_R = \mathbf{U}^{e\dagger}_R e'_R, \quad \nu_L = \mathbf{U}^{\nu\dagger}_L \nu'_L, \quad \nu_R = \mathbf{U}^{\nu\dagger}_R \nu'_R, \quad u_L = \mathbf{U}^{u\dagger}_L u'_L, \quad u_R = \mathbf{U}^{u\dagger}_R u'_R, \quad d_L = \mathbf{U}^{d\dagger}_L d'_L, \quad d_R = \mathbf{U}^{d\dagger}_R d'_R. \tag{24}$$

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar{u}'_L\mathbf{U}^u_L\tilde{\sigma}^\mu W^\pm_\mu \mathbf{U}^{d\dagger}_L d'_L$ and $\bar{\nu}'_L\mathbf{U}^\nu_L\tilde{\sigma}^\mu W^\pm_\mu \mathbf{U}^{e\dagger}_L e'_L$. Because of this, and some absorption of constants into the fermion fields, all the parameters in the $\mathbf{U}$s are contained in only four components of the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}^q = \mathbf{U}^u_L\mathbf{U}^{d\dagger}_L$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l = \mathbf{U}^\nu_L\mathbf{U}^{e\dagger}_L$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} e^{-i\delta/2} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta/2}\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13}\end{pmatrix}\begin{pmatrix} e^{i\delta/2} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta/2}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1\end{pmatrix}, \quad c_j = \sqrt{1 - s_j^2}, \tag{25}$$

$$\delta^q = 69(4)\,\text{deg}, \quad s^q_{12} = 0.2253(7), \quad s^q_{23} = 0.041(1), \quad s^q_{13} = 0.0035(2), \tag{26}$$

$$\delta^l = ?, \quad s^l_{12} = 0.560(16), \quad s^l_{23} = 0.7(1), \quad s^l_{13} = 0.153(28). \tag{27}$$

$\mathcal{L}$ is invariant under a $U(1)\otimes SU(2)$ gauge transformation with $U^{-1} = U^\dagger$, $detU = 1$, θ real,

$$\mathbf{W}_\mu \to U\mathbf{W}_\mu U^\dagger - (2i/g_2)U\partial_\mu U^\dagger, \quad \mathbf{W}_{\mu\nu} \to U\mathbf{W}_{\mu\nu}U^\dagger, \quad B_\mu \to B_\mu + (2/g_1)\partial_\mu\theta, \quad B_{\mu\nu} \to B_{\mu\nu}, \quad \phi \to e^{-i\theta}U\phi, \tag{28}$$

$$\begin{pmatrix} \nu_L \\ e_L\end{pmatrix} \to e^{i\theta}U\begin{pmatrix} \nu_L \\ e_L\end{pmatrix}, \quad \begin{pmatrix} u_L \\ d_L\end{pmatrix} \to e^{-i\theta/3}U\begin{pmatrix} u_L \\ d_L\end{pmatrix}, \quad \begin{matrix} \nu_R \to \nu_R, & u_R \to e^{-4i\theta/3}u_R, \\ e_R \to e^{2i\theta}e_R, & d_R \to e^{2i\theta/3}d_R, \end{matrix} \tag{29}$$

and under an $SU(3)$ gauge transformation with $V^{-1} = V^\dagger$, $detV = 1$,

$$\mathbf{G}_\mu \to V\mathbf{G}_\mu V^\dagger - (i/g)V\partial_\mu V^\dagger, \quad \mathbf{G}_{\mu\nu} \to V\mathbf{G}_{\mu\nu}V^\dagger, \quad u_L \to Vu_L, \quad d_L \to Vd_L, \quad u_R \to Vu_R, \quad d_R \to Vd_R. \tag{30}$$

Overview of the Standard Model Lagrangian courtesy of J. A. Shifflett,

`http://einstein-schrodinger.com/Standard_Model.pdf`

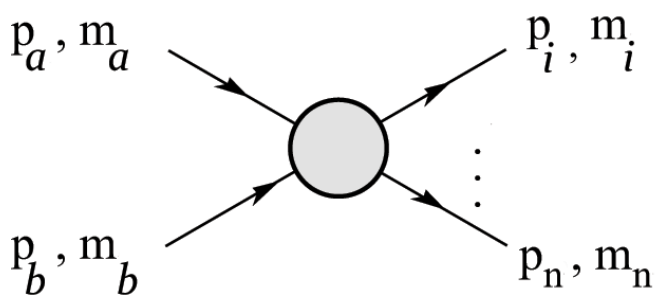


Figure A.2: Definitions of variables for production of an n-body final state. Image credit: Fig. 47.5 of M. Tanabashi (2018).

Although algebraic transformation symmetries "explain" why particle fields interact and evolve the ways they do, 25 numerical values (12 fermion masses, 4 CKM parameters, 4 PMNS parameters, 3 gauge coupling constants, the Higgs mass and vacuum expectation value) cannot be computed from the Lagrangian itself, and must be experimentally measured.

Still, with the Lagrangian in place, all that remains then is to compute quantities of interest. For high-energy collider experiments (and extensive air showers!), the practical quantity of interest is the interaction cross section, σ, given here for 2 incident particles with n-particles in the final state (Fig. A.2),

$$\begin{aligned}\sigma =& \frac{1}{(2E_a)(2E_b)|\boldsymbol{v}_a - \boldsymbol{v}_b|} \\ &\times \int \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3\, 2E_i} (2\pi)^4 \delta^4 \left(p_a^\mu + p_b^\mu - \sum_{i=1}^{n} p_i^\mu \right) \left| \mathcal{M}\left(\boldsymbol{p}_a, \boldsymbol{p}_b \to \{\boldsymbol{p}_i\}\right) \right|^2\end{aligned} \tag{A.1}$$

where E and $\boldsymbol{p}$ represent energies and momenta respectively, $|\boldsymbol{v}_a - \boldsymbol{v}_b|$ represents the longitudinal momenta divided by energy as seen in the laboratory frame of reference, and $p^\mu = (E, \boldsymbol{p})$ are 4-momenta. The invariant scattering amplitude, $\mathcal{M}$, is computed from the

scattering (S-)matrix,

$$\begin{aligned}\langle\phi_i|S|\phi_a\phi_b\rangle &= I - i(2\pi)^4\delta^4\left(p_a^\mu + p_b^\mu - \sum_{i=1}^{n} p_i^\mu\right)\mathcal{M}_{a,b\to n} \\ &= \frac{\int \mathcal{D}\phi \prod_i \phi_a\phi_b\phi_i \exp\left[i\int_{-\infty}^{\infty} d^4x\mathcal{L}\right]}{\int \mathcal{D}\phi \exp\left[i\int_{-\infty}^{\infty} d^4x\mathcal{L}\right]}\end{aligned} \tag{A.2}$$

where the second line is a Feynman path integral over all possible intermediate field configurations over spacetime, and $\mathcal{L}$ is the SM Lagrangian. No one actually knows how to solve this analytically, so perturbative or numerical methods are used to evaluate this expression out to arbitrary precision.

On the other hand, the cross section is measured experimentally simply by counting the number of times a process occurs, N, after colliding beams of particles at a rate, f, with particle densities of n_i/A_i^* for $i = 1, 2$ where A^* represents the effective cross sectional area of each beam,

$$\sigma = \frac{N}{\int dt f \frac{n_1 n_2}{A_1^* A_2^*}} \tag{A.3}$$

A comparison of data and theory for several SM cross sections are provided in Fig. A.3.

A cross section carries units of area called barns [b] (10^{-28} m^2), where 1 b is approximately the cross sectional area of a heavy atomic nucleus. For a particle traversing material with a number density, ρ, of "targets", the inverse mean interaction length, λ^{-1}, for a process to occur with cross section, σ, is,

$$\lambda^{-1} = \sigma\rho \tag{A.4}$$

and the probability for interaction after traversing a distance, s is,

$$P = 1 - e^{-s/\lambda} \tag{A.5}$$

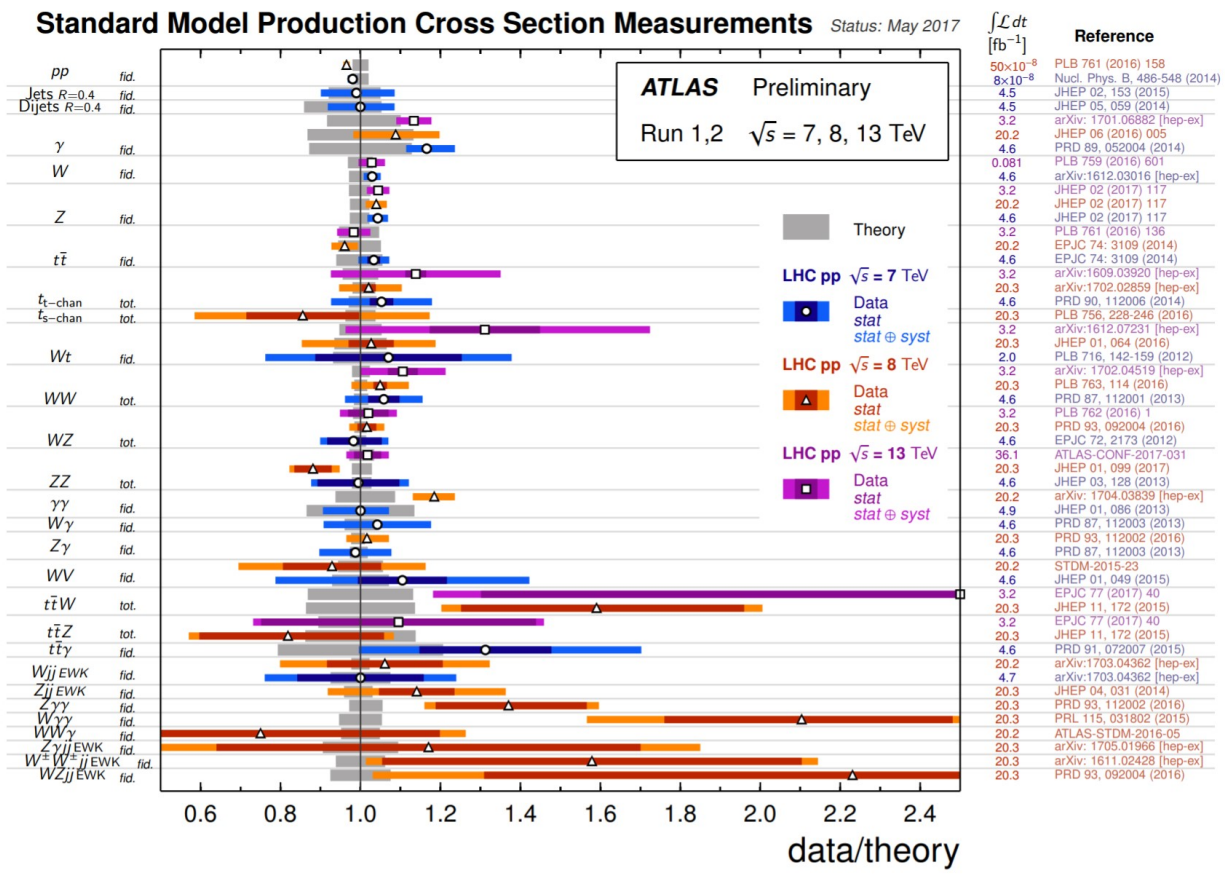


Figure A.3: The data/theory ratio for several Standard Model total and fiducial production cross section measurements, corrected for leptonic branching fractions. The dark-colour error bar represents the statistical uncertainly. The lighter-colour error bar represents the full uncertainty, including systematics and luminosity uncertainties. Not all measurements are statistically significant yet.
Image credit: Fig. 1.2 of Prager (2018).

Appendix B

CORSIKA Simulations

Ready-to-go CORSIKA and ROOT can be installed by cloning repositories `https://github.com/ealbin/corsika7` and `https://github.com/ealbin/root` respectively.

A CORSIKA input file template is provided in §B.1 for reference (it is also included in the github repository above). Supplemental example EAS lateral density and energy spectral results are provided in §B.2.

B.1 Example CORSIKA Input File

Listing B.1: Example CORSIKA input file (`input.txt`)

```
c
c Lines beginning with "c" are comment lines, additionally comments can
c directly follow parameter listings as shown.
c
RUNNR      1                       Number identifying the run
EVTNR      1                       Number of the first shower event
NSHOW      1                       Number of showers to simulate
c
c                                  Full path to output directory
DIRECT /full/output/path/but/upper/case/paths/could/be/trouble/NO/SPACES
c
c                                  A note about the seeds:
c                                      1st value: is the "seed", which can
c                                          optionally become the seed-for-a-
c                                          seed if values 2 and 3 are non-zero.
c                                      2nd and 3rd value: the number of times
c                                          a seed generator is called based
c                                          off of the first value, such that
c                                          the number of times,
c                                          N = 2nd + (3rd * 10^9).
c                                  The seeds are assigned to the various parts
c                                      below in the order they appear.
c      ==> v <==                   In short, replace this ("v") column's
c          v                           numbers, and leave the other two as
c          v                           zeros.
SEED       12  0  0                Seed for hadronic part
SEED       34  0  0                Seed for EGS4 part
SEED       56  0  0                Seed for Cherenkov photons (CERENKOV option)
SEED       78  0  0                Seed for Cherenkov telescope offsets
SEED       90  0  0                Seed for HERWIG for NUPRIM option
SEED       23  0  0                Seed for PARALLEL option
SEED       45  0  0                Seed for CONEX option
c
PRMPAR     5626                    Primary particle code (iron)
c                                      ref: CORSIKA_GUIDE7.6900.pdf, pp. 116-117
c
ERANGE     1.E6  1.E6              Energy range of primary [GeV]
```

```
c                                       (same values fix the energy)
c
ESLOPE     -2.7                     Slope of energy spectrum
c                                       (applies if a range is specified above)
c
ECUTS      .05  .01  .001  .001     Energy cuts for particles [GeV]
c                                            hadrons, muons, electrons, photons
c                                   minimums:     .05    .01     .00005   .00005
c
ECTMAP     .001                     Cut on gamma-factor (or energy in GeV for
c                                       em/neutrino particles), saved/tracked if
c                                       above this level (min: .00005)
c
THETAP     0.  0.                   Range of zenith angle [deg]
c                                       (same values fix the angle)
c
PHIP       0.  0.                   Range of azimuth angle [deg]
c                                       (same values fix the angle)
c
c                                   Observation level above sea level
c                                       (up to 10 can be specified) [cm]
OBSLEV     0.
OBSLEV     500.E2
OBSLEV     1000.E2
OBSLEV     1400.E2 ... ... ... ... (Telescope Array Project, UT)
OBSLEV     2000.E2
OBSLEV     5000.E2
OBSLEV     10000.E2
OBSLEV     20000.E2
OBSLEV     50000.E2
OBSLEV     100000.E2
c
FIXCHI     0.                       Starting altitude overburden [g/cm**2],
c                                       0 = top of atmosphere
c
ATMOD      1                        U.S. std atmosphere (Linsley parameters)
c
MAGNET     21.82  45.51             Local magnetic field value [uT] for
c                                       Telescope Array, UT
c                                       Lat: 39d 17m 49s N, Lon: 112d 54m 31s,
c                                       Alt: 1400m, Sept 20 2019,
```

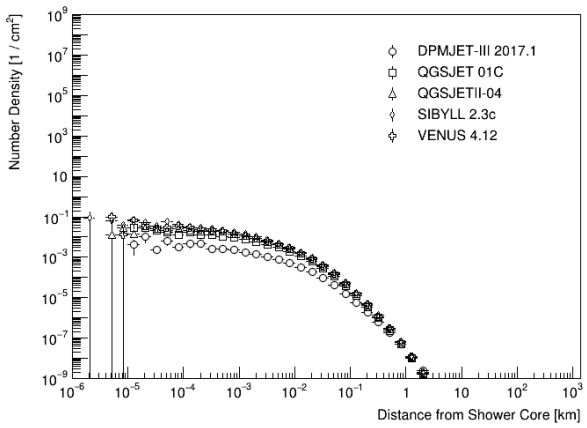
```
c                                       Model: IGRF/WMM/EMM average
c                                       (ref: https://www.ngdc.noaa.gov/geomag/)
c
c ** comment out if not using THIN
THIN       1.E-6  1.E30  0.E0      Useful/essential for primary
c                                       energies > 10^16 [eV].
c                                       Multiplying stored particles by
c                                       their thinning "weight" has been found
c                                       to produce excellent reproductions of
c                                       spectra comprable to non-thinned
c                                       simulations.
c                                   1st value: thinning level, all particles
c                                       with energy below (primary * this) are
c                                       "thinned" i.e. only one of the
c                                       particles in an interaction are
c                                       followed (and weighted)
c                                   2nd value: weight threshold, any thinned
c                                       particles that would have a weight
c                                       above this threshold are cut
c                                   3rd value: distance from core threshold,
c                                       any particles within this distance
c                                       from the shower core are further
c                                       thinned by selecting at random with a
c                                       probability proportional to
c                                       (r / this)^4, and are weighted by the
c                                       inverse of that probability
c
c ** uncomment for cluster (parallel) computing **
c PARALLEL 1000.  100000.  1  F    Only works if compiled with the PARALLEL
c                                       option, otherwise comment this out.
c                                   1st value: particles with energies above
c                                       this [GeV] get drawn from the 6th seed
c                                       above
c                                   2nd value: maximum energy [GeV] for a
c                                       complete subshower before splitting
c                                       the task
c                                   3rd value: MPI identification number
c                                   4th value: particles above the 1st value
c                                       are written to a .cut file
c
ELMFLG     T  T                     Electromagnetic interaction flags
```

```
c                                   1st value: use NKG T/F  -- it's analytical,
c                                       fast and approximate
c                                   2nd value: use EGS4 T/F -- it's monte carlo,
c                                       slow and increasingly accurate with
c                                       energy, also, it uses the SEED #2 above
c
RADNKG     20000.E2                 Outer radius for NKG treatment of the
c                                       electromagnetic component if enabled
c                                       above [cm]
c
STEPFC     1.                       Electron multiple scatter length factor
c                                       (for EGS4).
c                                       If = 10 speeds up computation ~2x,
c                                       If = .1 slows down ~5x
c
MUMULT     T                        Use Moliere theory and Coulomb scattering
c                                       for muon multiple scattering
c                                       (if F, do a Gauss approx)
c
HADFLG     0  1  0  1  0  2         Hadronic interaction flags
c                                       1st value:
c                                         = 0 and the number of interactions
c                                             fluctuates,
c                                         > 0 and an average is used
c                                       2nd value:
c                                         = 0 and no diffractive interactions
c                                             allowed,
c                                         > 0 and they are possible
c                                       3rd value:
c                                         = 0 and use collider data for pi0
c                                             rapidity,
c                                         > 0 and treat them like charged pions
c                                       4th value:
c                                         = 0 and the number of pi0 fluctuates
c                                             like charged pions,
c                                         > 1 and use collider data
c                                       5th value:
c                                         = 0 and charge exchange reactions
c                                             allowed,
c                                         > 0 and they're inhibited
c                                       6th value:
```

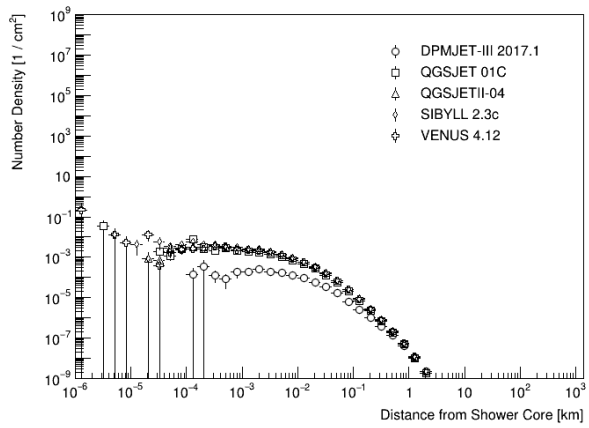
```
c                                        = 0 and primary nucleus fragments at
c                                            first interaction completely into
c                                            free nucleons,
c                                        = 1 and fragments successively
c                                            assuming non-interacting nucleons
c                                            proceed as one new nucleus,
c                                        = 2 and new nucleus may evaporate
c                                            with an experimental data driven
c                                            distribution,
c                                        = 3 and evaporate according to
c                                            Goldhaber theory,
c                                        = 4 and identical fragments as 2 or 3,
c                                            but without transverse momenta
c
MAXPRT     1                       Max number of events to print in detail in log
c
EXIT
```

B.2 Supplemental CORSIKA Results

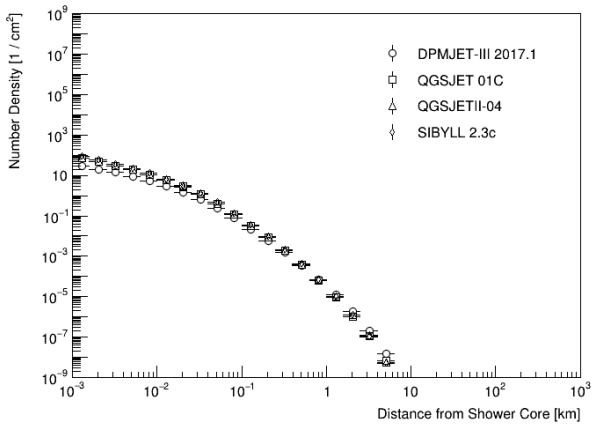
The following figures supplement those shown in Chapter 2.



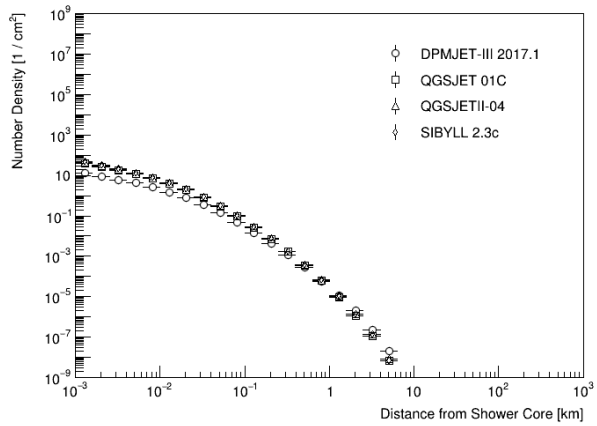
(a) 10^{15} eV Helium



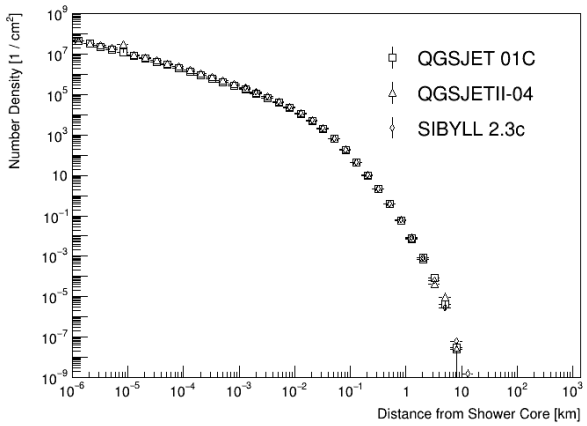
(b) 10^{15} eV Iron



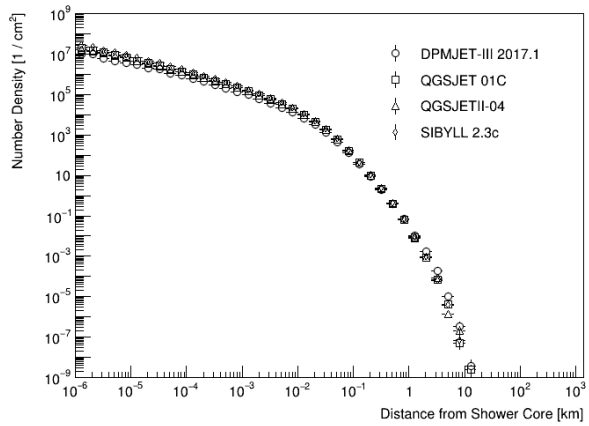
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

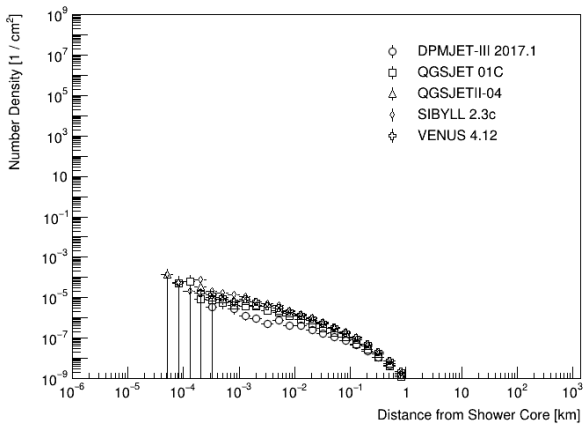


(e) 10^{21} eV Helium

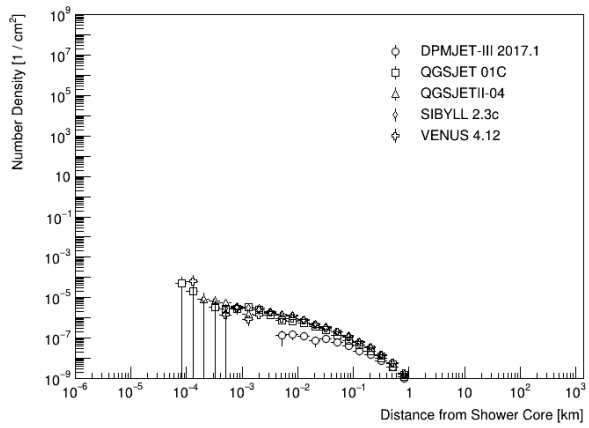


(f) 10^{21} eV Iron

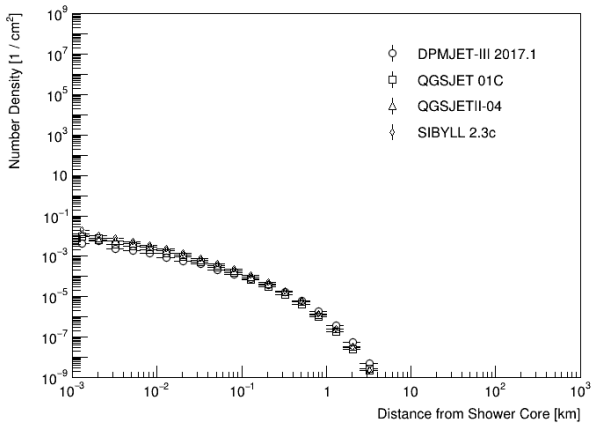
Figure B.1: The lateral density distribution of the electrons in Fig. 2.2.



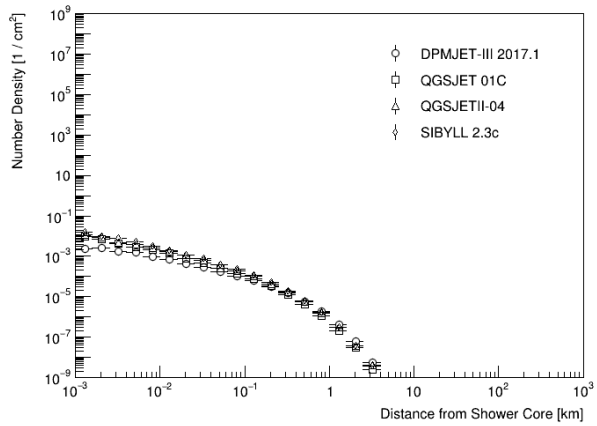
(a) 10^{15} eV Helium



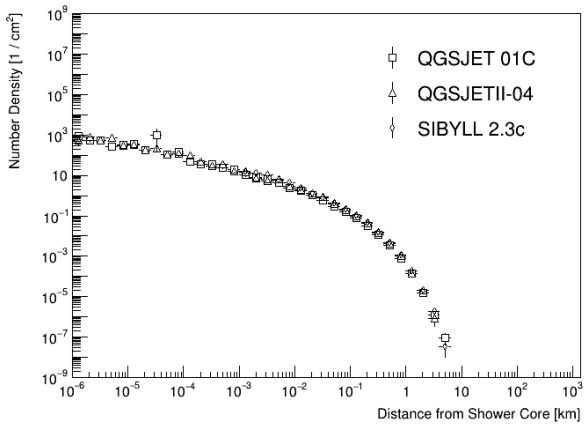
(b) 10^{15} eV Iron



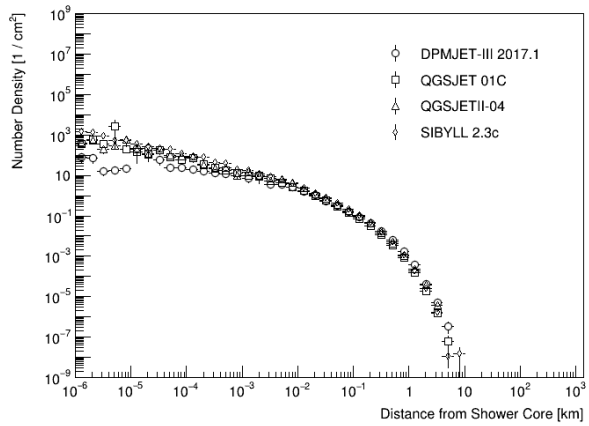
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

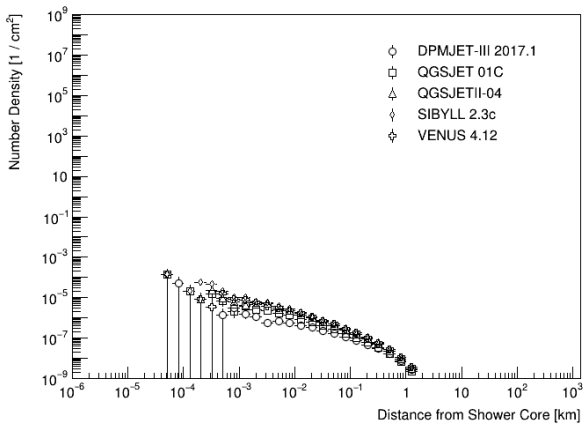


(e) 10^{21} eV Helium

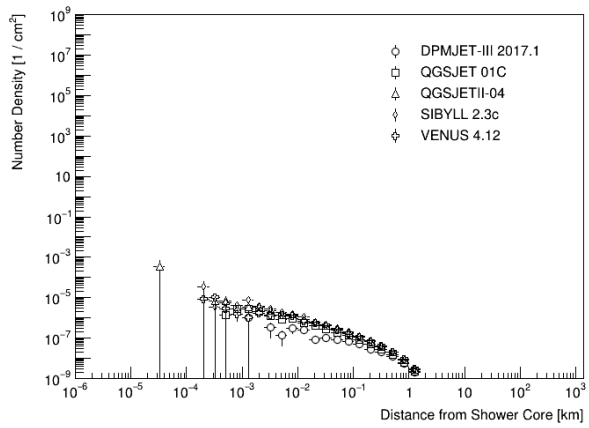


(f) 10^{21} eV Iron

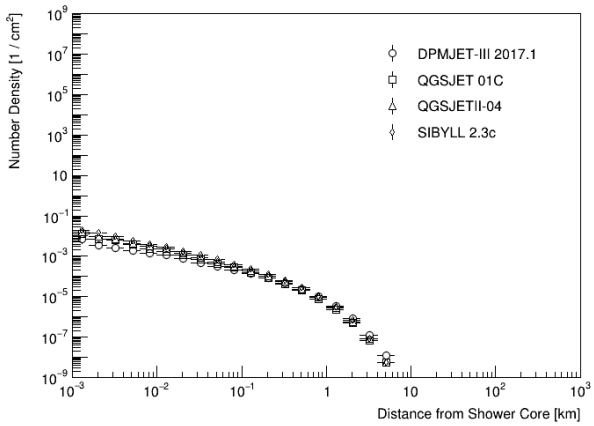
Figure B.2: The lateral density distribution of the protons in Fig. 2.2.



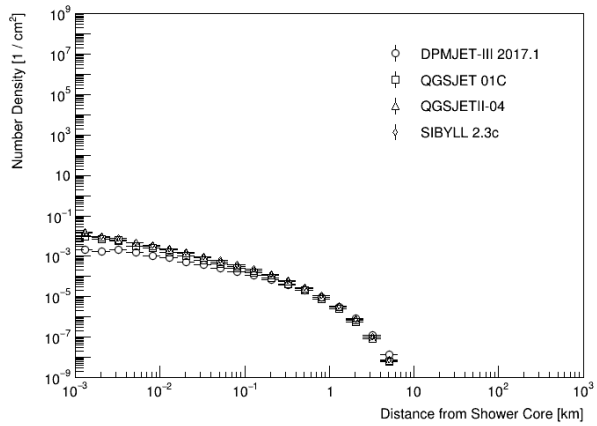
(a) 10^{15} eV Helium



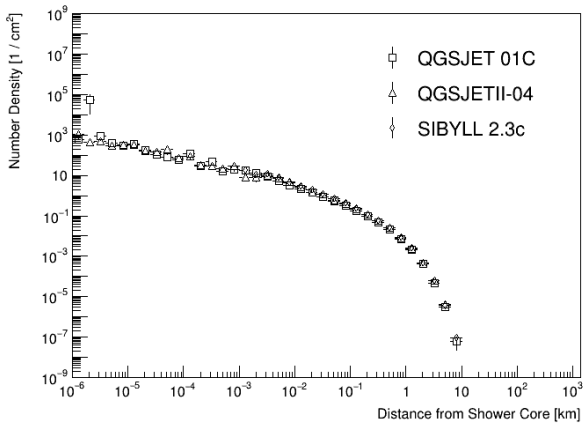
(b) 10^{15} eV Iron



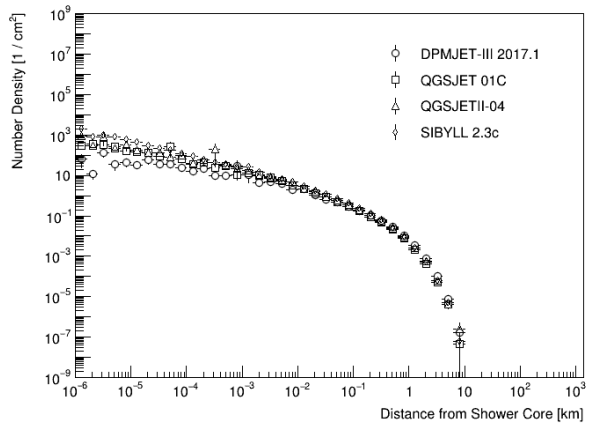
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

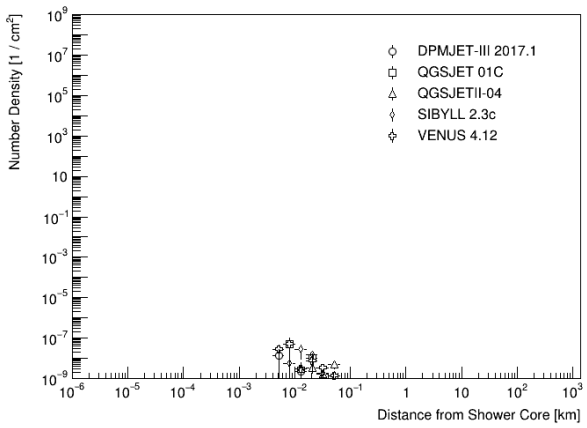


(e) 10^{21} eV Helium

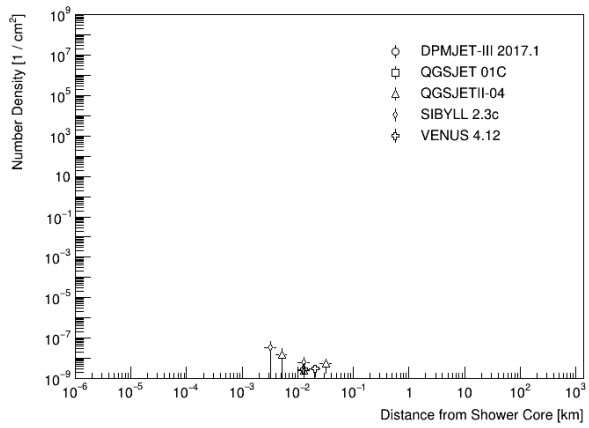


(f) 10^{21} eV Iron

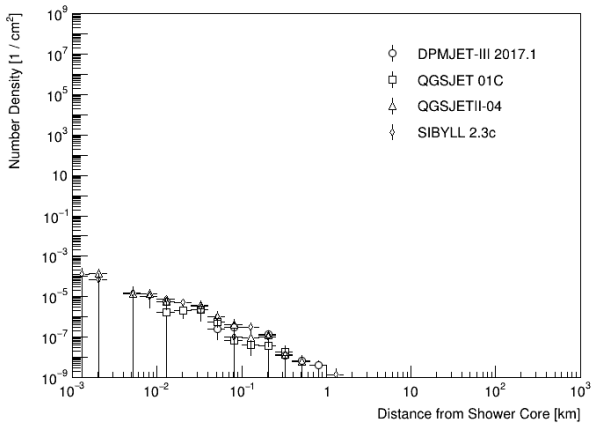
Figure B.3: The lateral density distribution of the neutrons in Fig. 2.2.



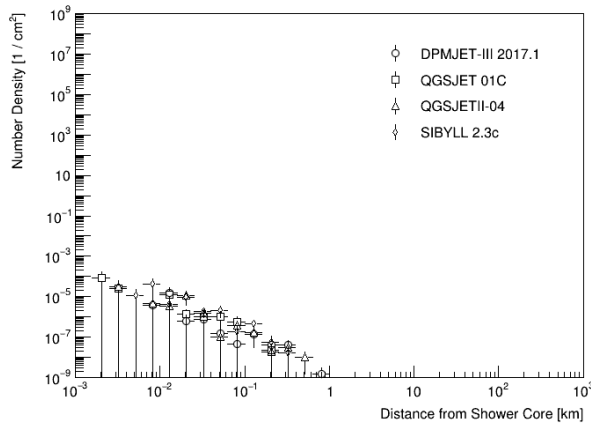
(a) 10^{15} eV Helium



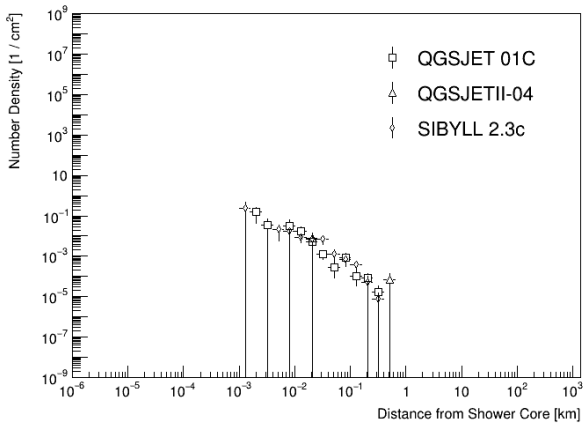
(b) 10^{15} eV Iron



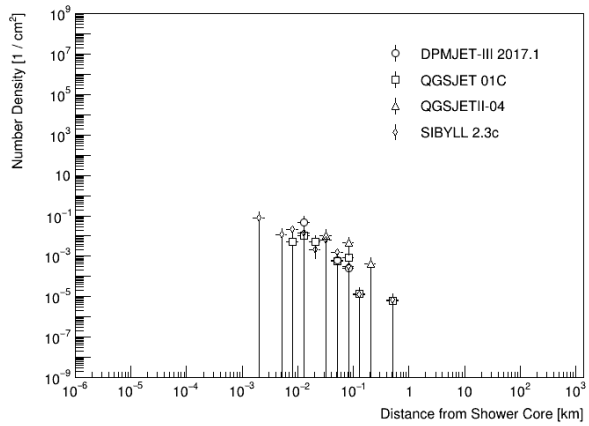
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

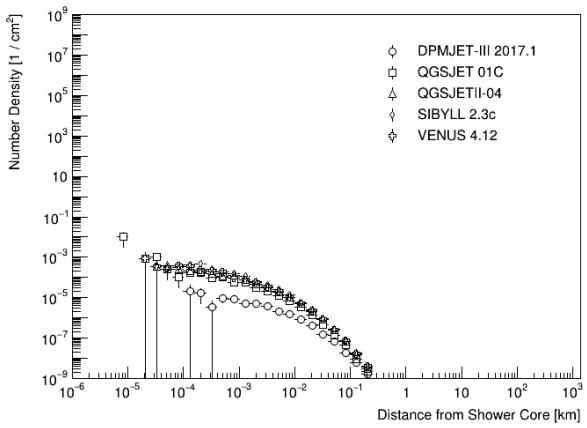


(e) 10^{21} eV Helium

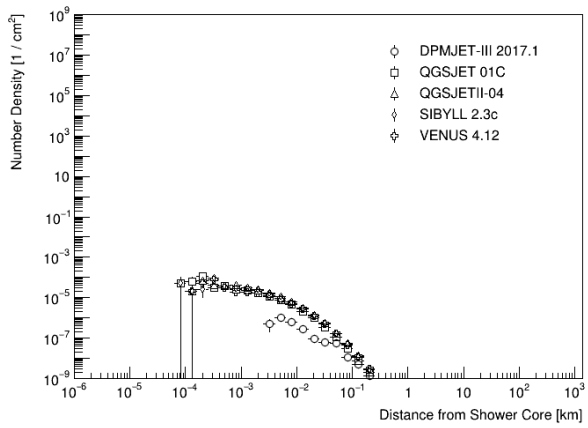


(f) 10^{21} eV Iron

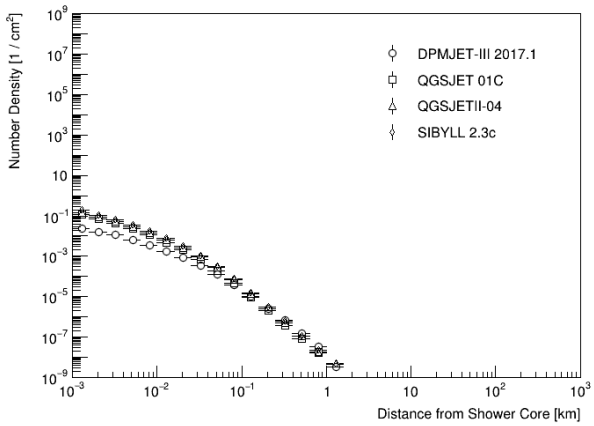
Figure B.4: The lateral density distribution of the nuclei in Fig. 2.2.



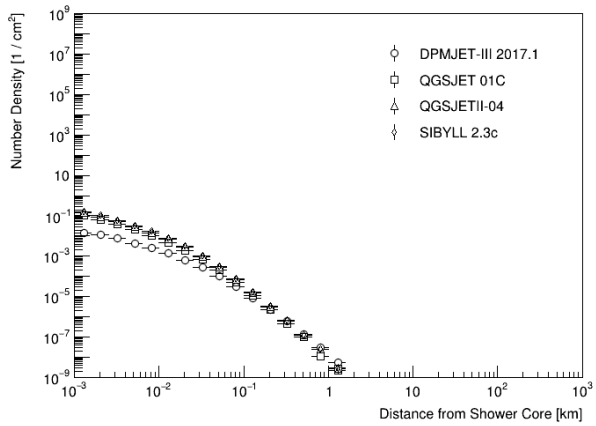
(a) 10^{15} eV Helium



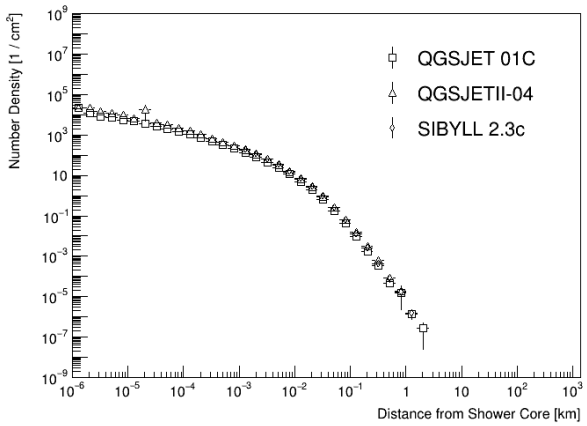
(b) 10^{15} eV Iron



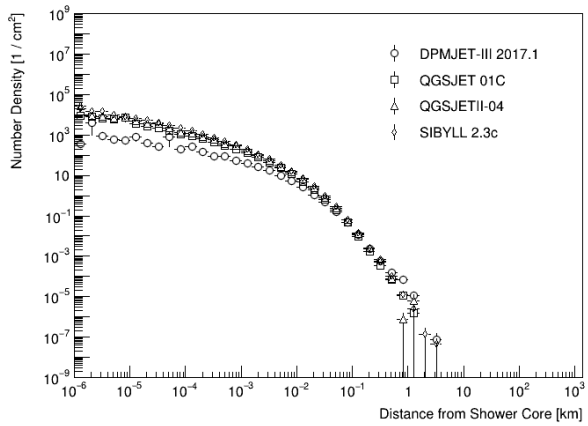
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

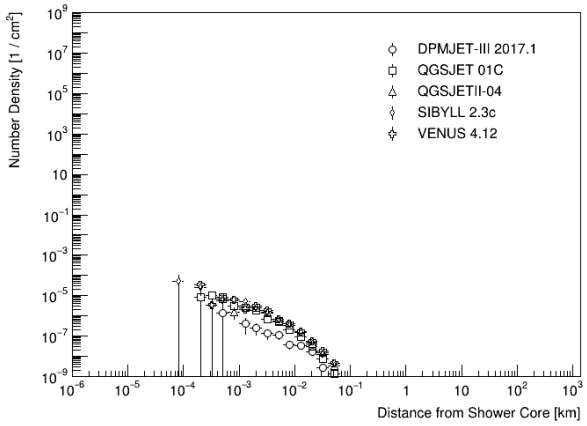


(e) 10^{21} eV Helium

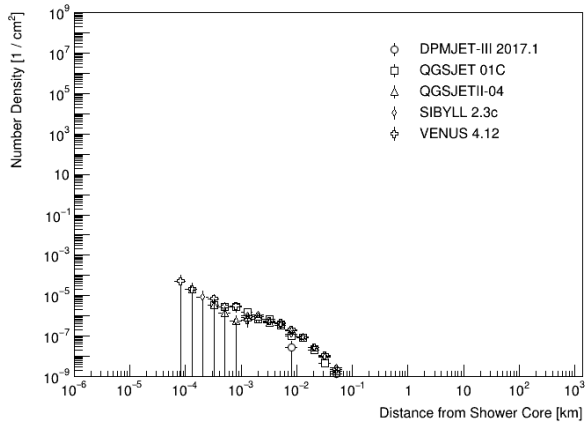


(f) 10^{21} eV Iron

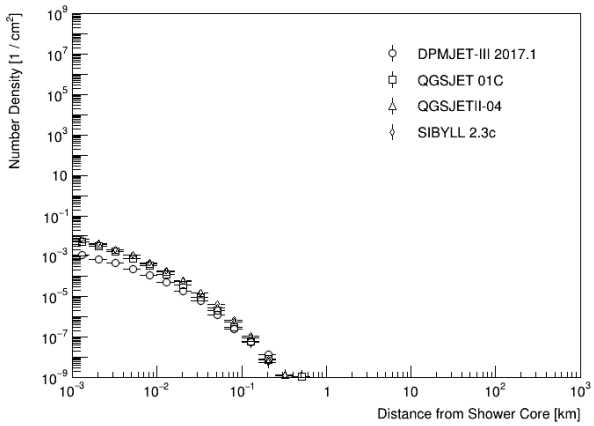
Figure B.5: The lateral density distribution of the "other-charged" in Fig. 2.2.



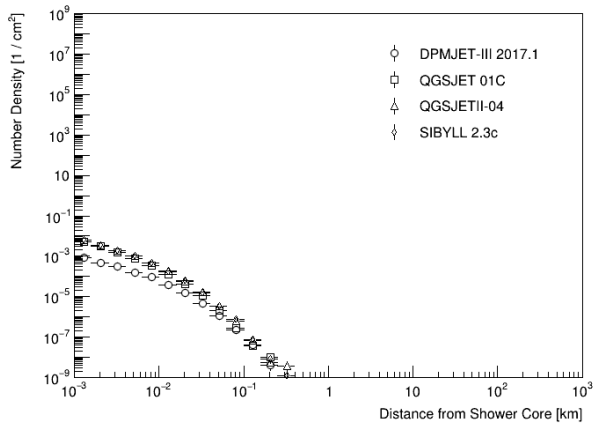
(a) 10^{15} eV Helium



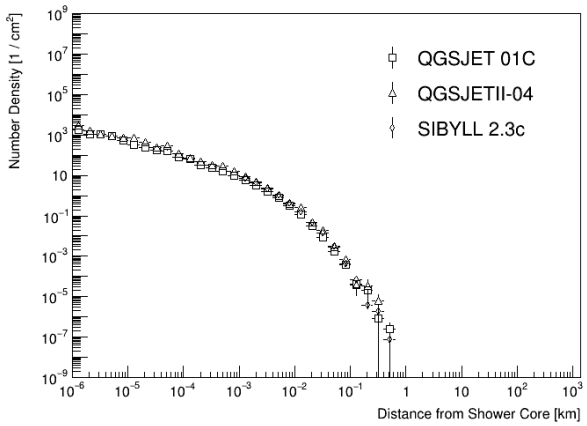
(b) 10^{15} eV Iron



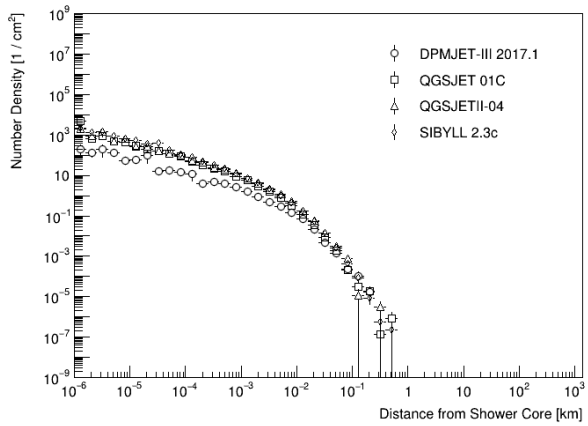
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

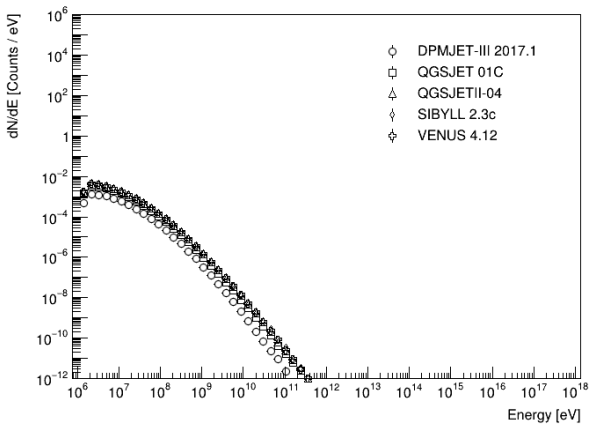


(e) 10^{21} eV Helium

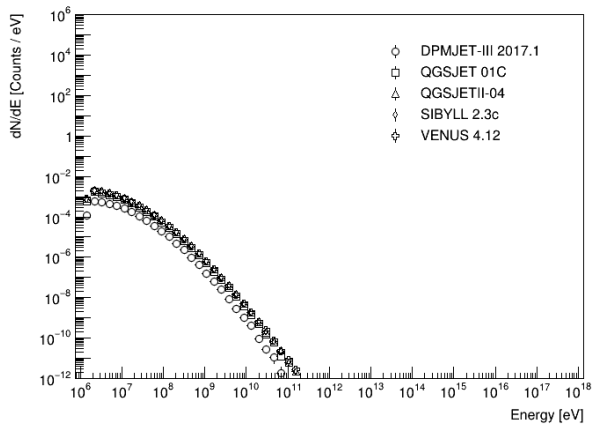


(f) 10^{21} eV Iron

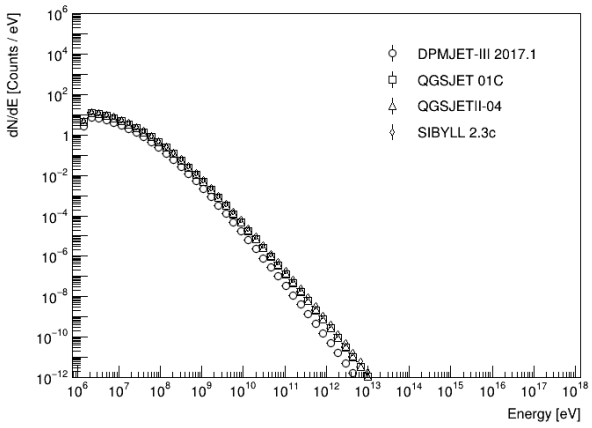
Figure B.6: The lateral density distribution of the "other-neutral" in Fig. 2.2.



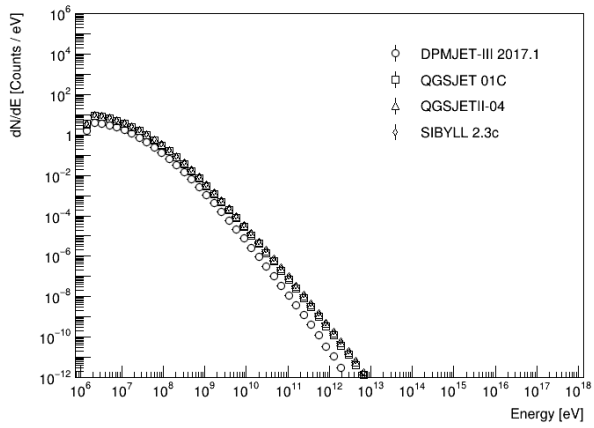
(a) 10^{15} eV Helium



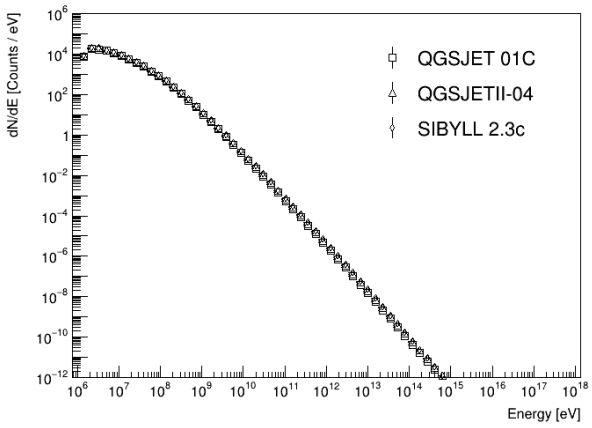
(b) 10^{15} eV Iron



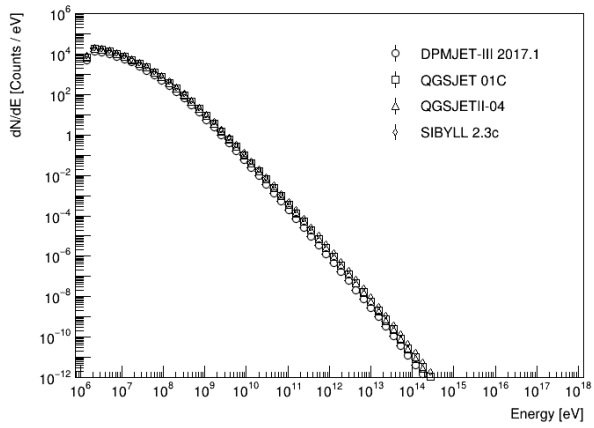
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

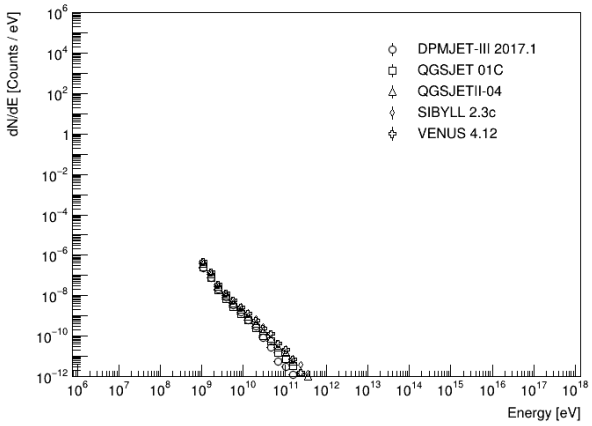


(e) 10^{21} eV Helium

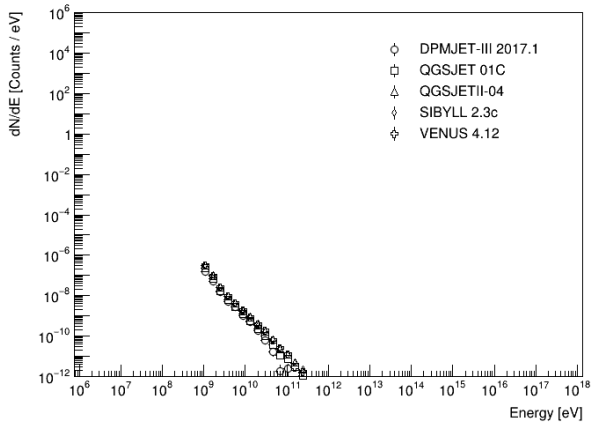


(f) 10^{21} eV Iron

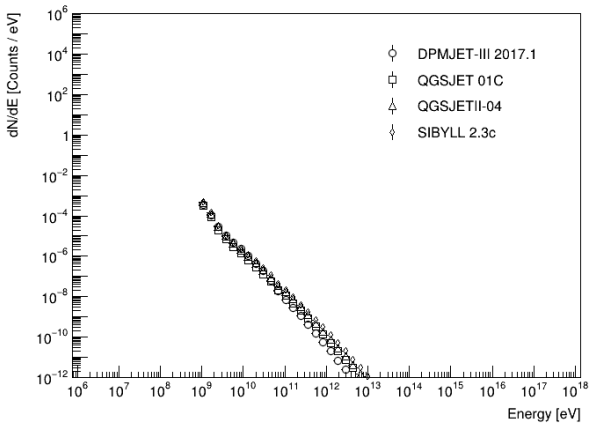
Figure B.7: The energy spectrum of the electrons in Fig. 2.2.



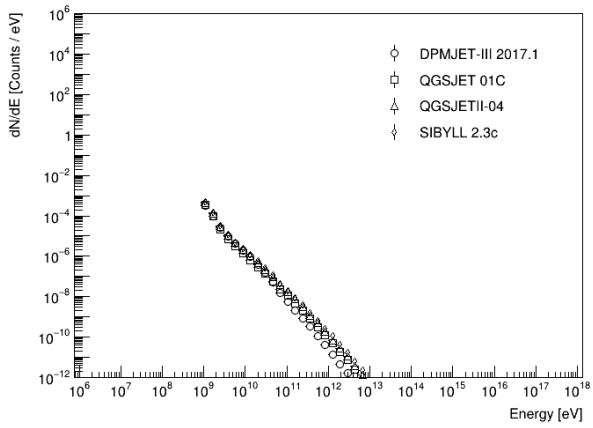
(a) 10^{15} eV Helium



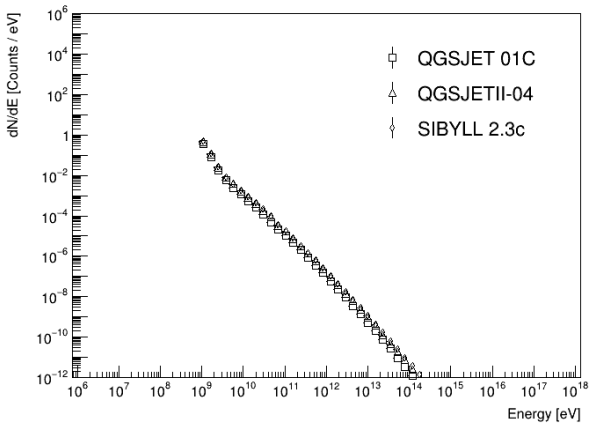
(b) 10^{15} eV Iron



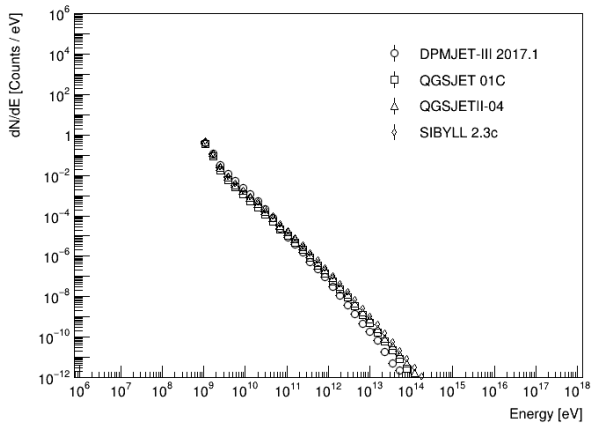
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

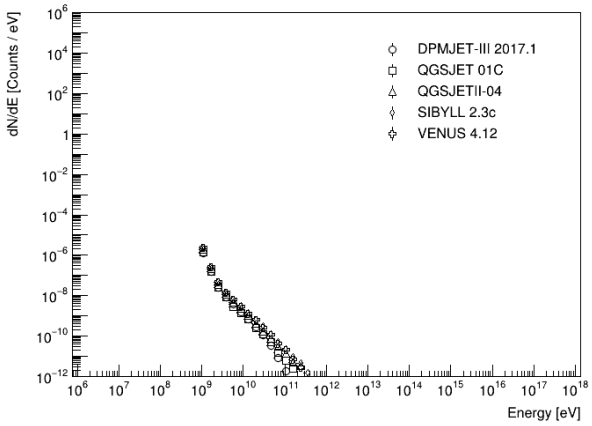


(e) 10^{21} eV Helium

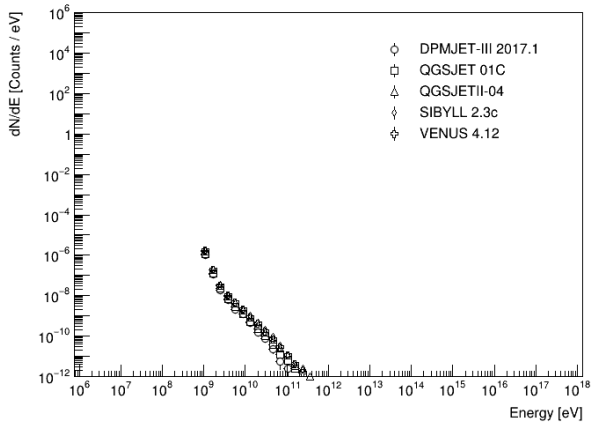


(f) 10^{21} eV Iron

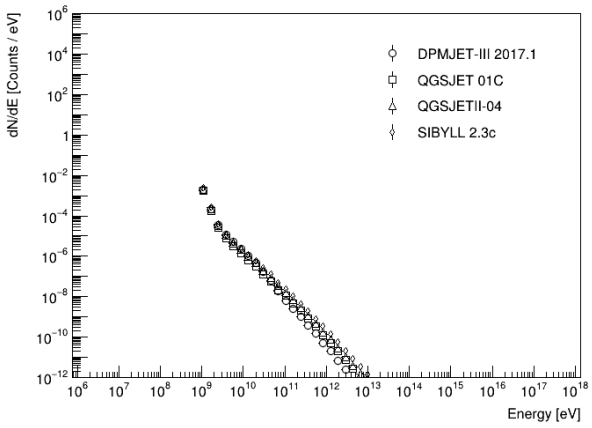
Figure B.8: The energy spectrum of the protons in Fig. 2.2. The abrupt start of the spectrum is due to the proton rest mass of 0.938×10^9 eV.



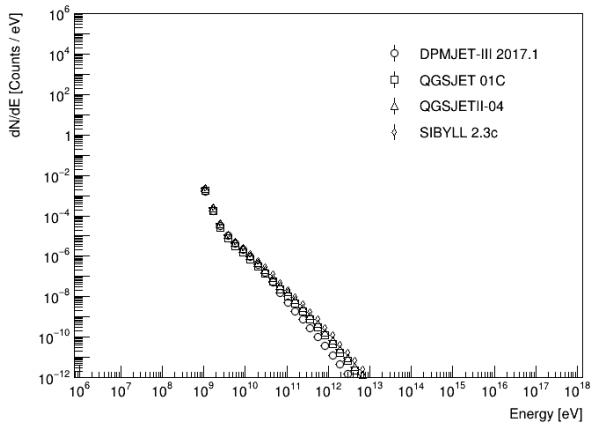
(a) 10^{15} eV Helium



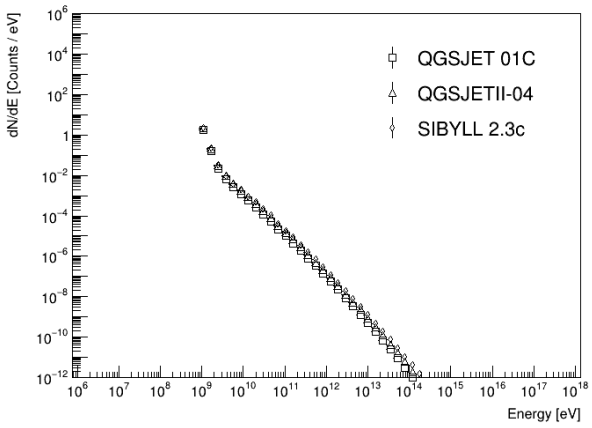
(b) 10^{15} eV Iron



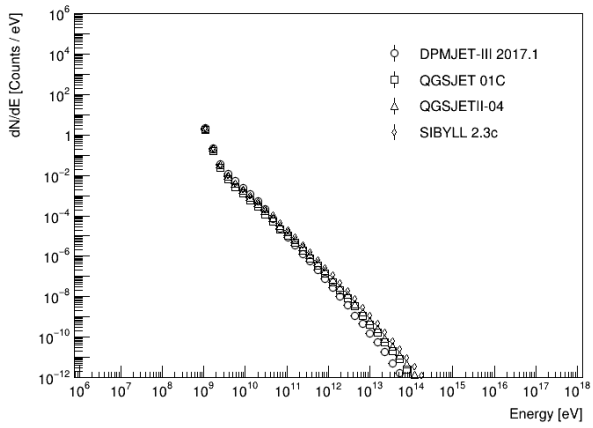
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

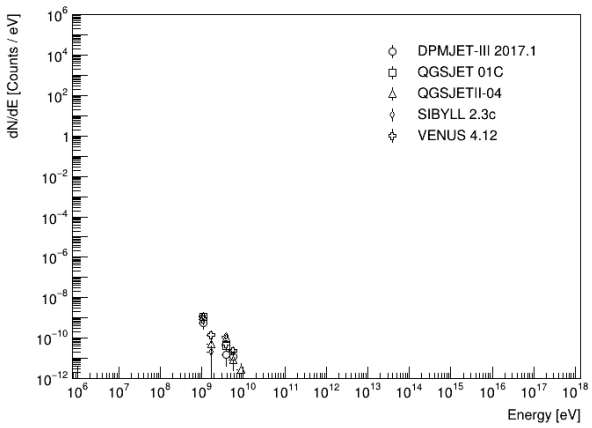


(e) 10^{21} eV Helium

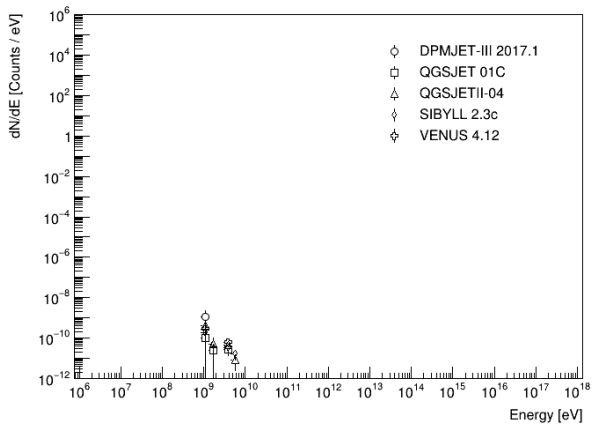


(f) 10^{21} eV Iron

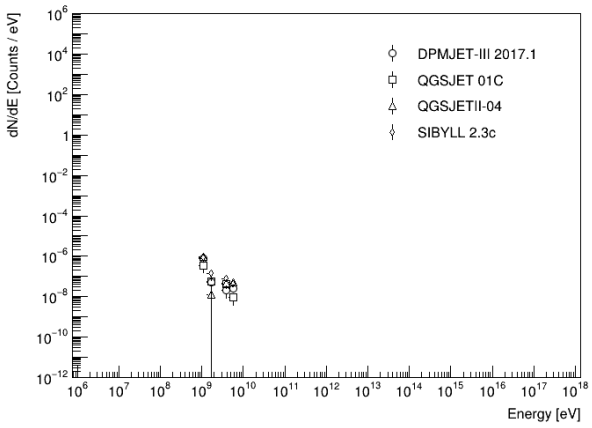
Figure B.9: The energy spectrum of the neutrons in Fig. 2.2. The abrupt start of the spectrum is due to the neutron rest mass of 0.940×10^9 eV.



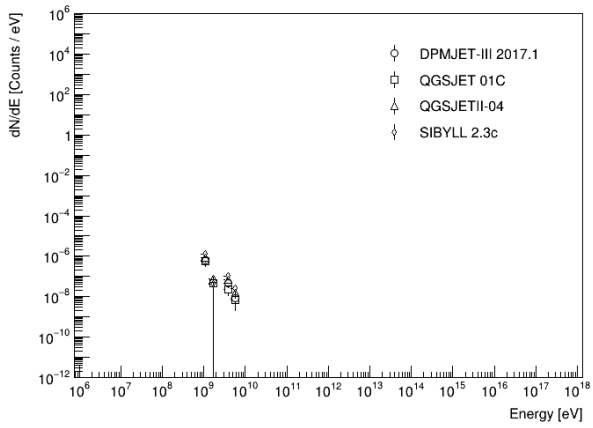
(a) 10^{15} eV Helium



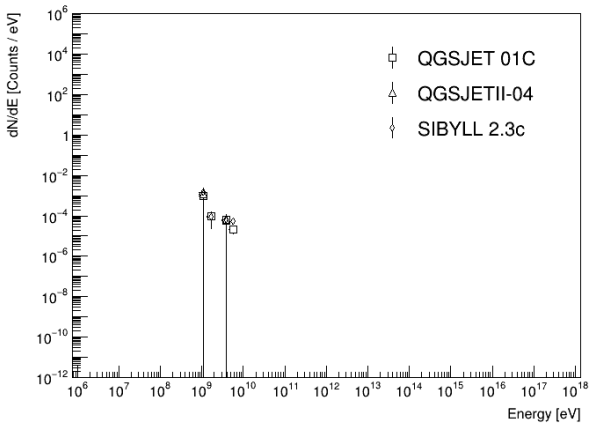
(b) 10^{15} eV Iron



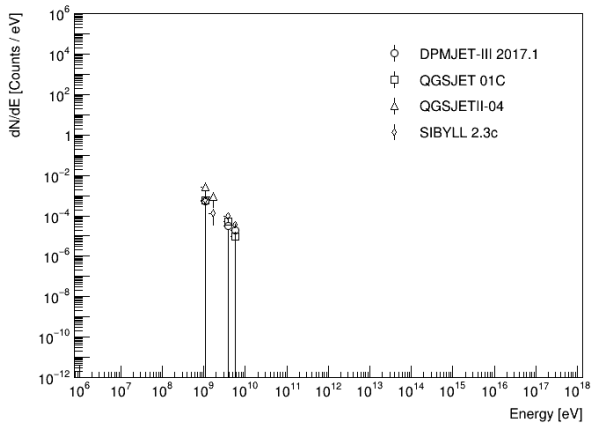
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

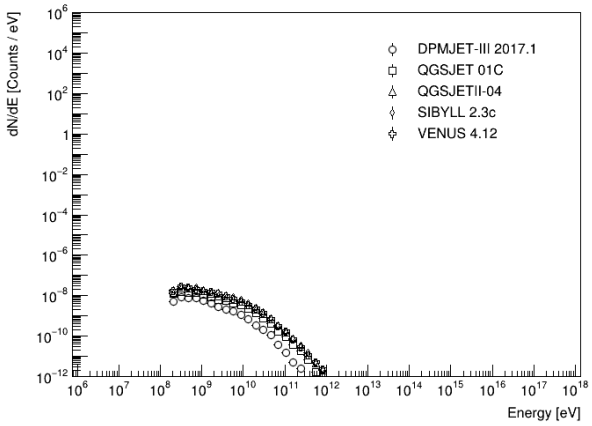


(e) 10^{21} eV Helium

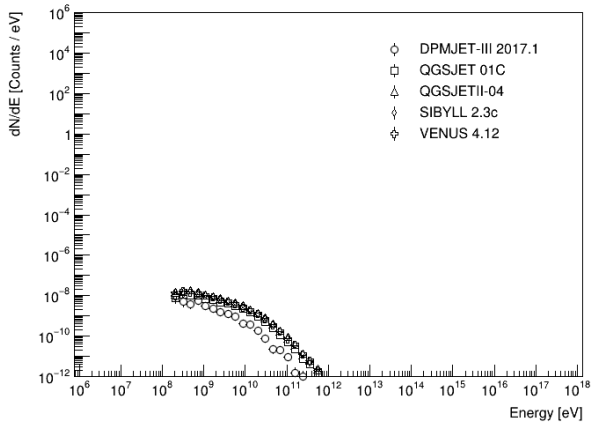


(f) 10^{21} eV Iron

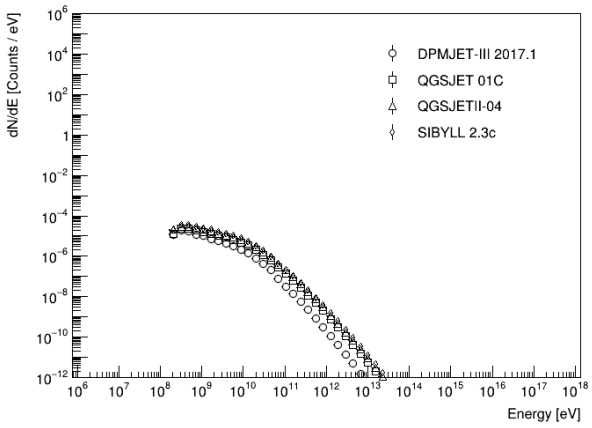
Figure B.10: The energy spectrum of the nuclei in Fig. 2.2. The abrupt start of the spectrum is due to the proton rest mass of 0.938×10^9 eV (a proton labeled by CORSIKA as Hydrogen).



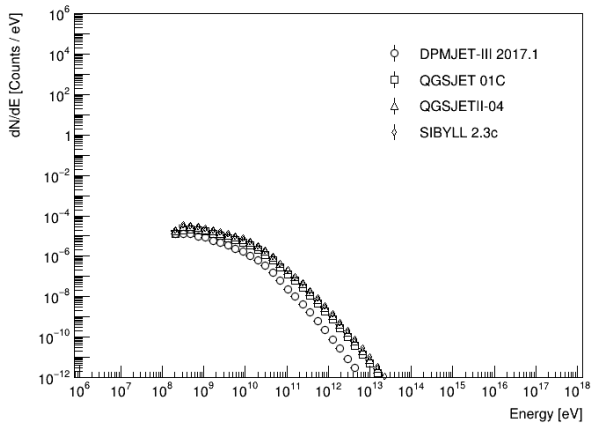
(a) 10^{15} eV Helium



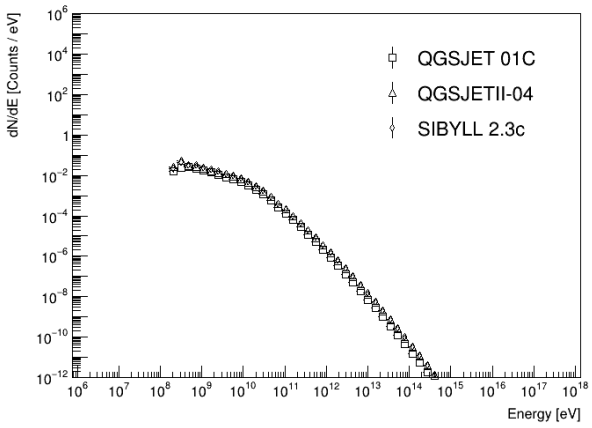
(b) 10^{15} eV Iron



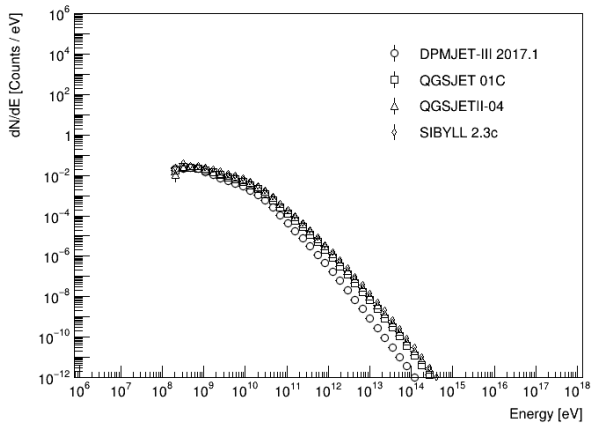
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron

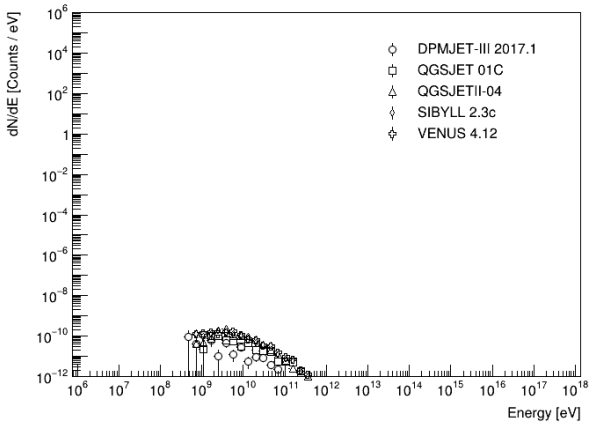


(e) 10^{21} eV Helium

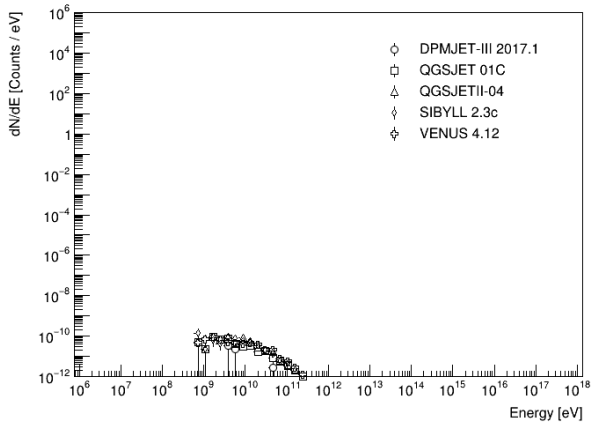


(f) 10^{21} eV Iron

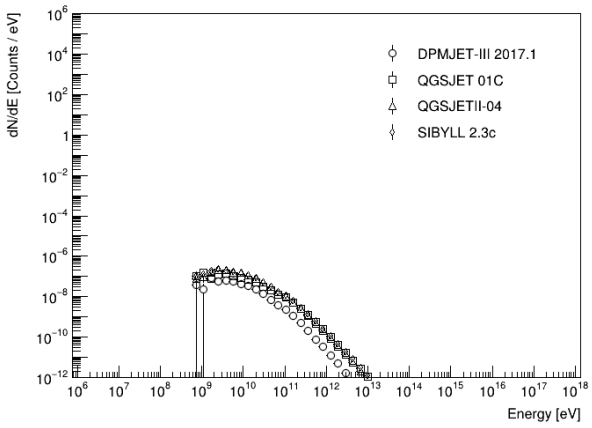
Figure B.11: The energy spectrum of the "other-charged" in Fig. 2.2. The abrupt start of the spectrum is due to the charged pion rest mass of 1.40×10^8 eV.



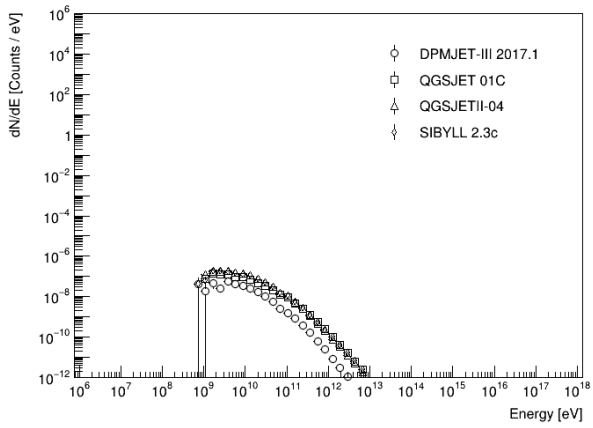
(a) 10^{15} eV Helium



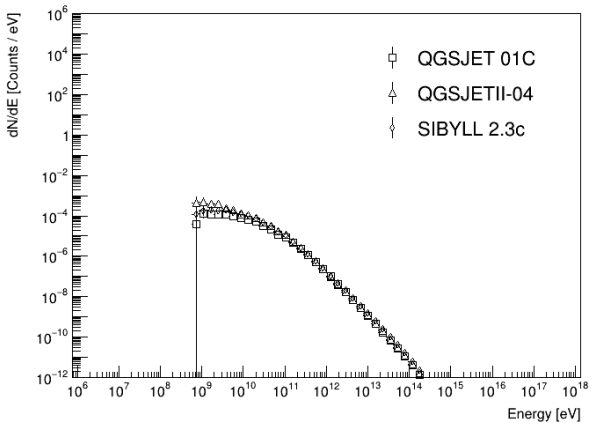
(b) 10^{15} eV Iron



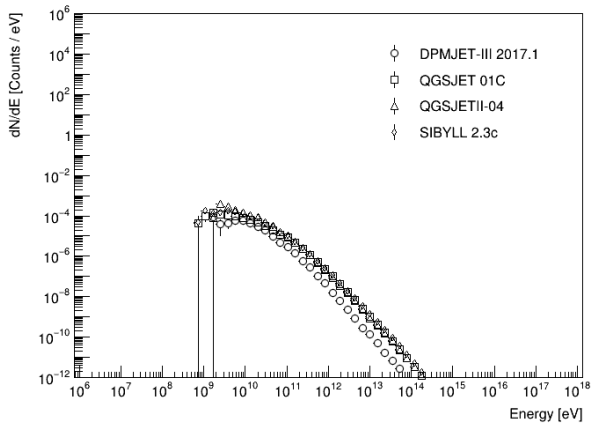
(c) 10^{18} eV Helium



(d) 10^{18} eV Iron



(e) 10^{21} eV Helium



(f) 10^{21} eV Iron

Figure B.12: The energy spectrum of the "other-neutral" in Fig. 2.2. The abrupt start of the spectrum is due to relativistic neutral kaons (K_L^0) with rest mass of 4.98×10^8 eV.

Appendix C

CRAYFIS Database

The following code listings were developed for unpacking, checking, storing and fetching CRAYFIS data. The complete listing can be downloaded from `https://github.com/ealbin/cassandra`.

Listing C.1: Example Cassandra access (`jumpstart.py`)

```
#!/bin/env python

# an example to accessing Cassandra from python
# you can run this file e.g. python jumpstart.py
# check out the TL;DR at the bottom..
#-----------------------------------------------

# (1) get the IP address of the Cassandra server
# ref: https://docker-py.readthedocs.io/en/stable/
import docker
client = docker.from_env()
# below will error if the container is not already running
# kick it off as needed: bash /home/crayfis-data/cassandra/bin/cmd.sh
server = client.containers.get('crayvault')
ipaddr = server.attrs['NetworkSettings']['IPAddress']


# (2) connect with the Cassandra server
# ref: https://datastax.github.io/python-driver/index.html
from cassandra.cluster import Cluster
cluster = Cluster([ipaddr])
session = cluster.connect()
#help(session) # to wit: default_timeout and row_factory


# (3) explore the current keyspaces and tables
# ref: https://datastax.github.io/python-driver/api/cassandra/metadata.html
meta = cluster.metadata
keyspaces = meta.keyspaces
# raw: where raw data goes, right now that's the only data keyspace
# system_xxxx: cluster info
raw = keyspaces['raw']
tables = raw.tables
# etc, e.g.
events = raw.tables['events']
columns = events.columns
#columns.keys()
# etc..


```

```
41 # (4) submit CQL searches to the database
42 # ref: https://docs.datastax.com/en/cql/3.1/cql/cql_reference/cqlCommandsTOC.html
43 # e.g. get all events and all info
44 results = session.execute( 'select * from raw.events' )
45 #while results.has_more_pages:
46 #    for event in results.current_rows:
47 #        pass # process your data
48 #    results.fetch_next_page()
49
50 # e.g. get only device_id and pixels
51 results = session.execute( 'select device_id, pixels from raw.events' )
52
53
54 # (5) disconnect from the server
55 cluster.shutdown()
56
57
58 # TL;DR / Boiler-plate
59 #-----------------------------------------------
60 import docker
61 ipaddr = docker.from_env().containers.get('crayvault').attrs['NetworkSettings']['IPAddress']
62 from cassandra.cluster import Cluster
63 cluster = Cluster([ipaddr])
64 session = cluster.connect()
65 #...
66 meta = cluster.metadata
67 print 'keyspaces:  {0}'.format(meta.keyspaces.keys())
68 print 'raw tables: {0}'.format(meta.keyspaces['raw'].tables.keys())
69 print
70 print 'raw.events columns: {0}'.format(session.execute('select * from raw.events').
    ↪ column_names)
71 print
72 print 'device_ids in events: {0}'.format([ row.device_id for row in session.execute('select
    ↪ distinct device_id from raw.events').current_rows ])
73 #...
74 cluster.shutdown()
```

Listing C.2: Cassandra database commands (`bin/cmd.sh`)

```
#!/bin/env bash

# Variables
CASSANDRA_IMAGE="cassandra:latest"
CLUSTER_NAME="crayvault"
HOST_CASSANDRA_DIR="/data/cassandra"
HOST_IMAGE="ubuntu:daq"
HOST_NAME="craydata"
HOST_DATA="/data/daq.crayfis.io/raw"
HOST_SRC="$PWD/src"

update() {
    check=`docker ps | egrep -c "${HOST_NAME}"`
    if [ $check -gt 0 ]; then docker kill ${HOST_NAME}; docker rm ${HOST_NAME}; fi
    cmd="docker build -t ${HOST_IMAGE} ."
    echo
    echo $cmd
    eval $cmd
    exit_code=$?
    echo
    if [[ $exit_code != 0 ]]; then break; fi
    data_map="${HOST_DATA}:/data/daq.crayfis.io/raw"
    src_map="${HOST_SRC}:/home/${HOST_NAME}/src"
    ingested_map="${HOST_SRC}/ingested"
    cmd="docker run --rm --name ${HOST_NAME} -v ${data_map} -v ${src_map} -v ${ingested_map}
        ↪  --link ${CLUSTER_NAME}:cassandra -dt ${HOST_IMAGE}"
    echo $cmd
    eval $cmd
    echo
    cmd="docker exec ${HOST_NAME} python /home/${HOST_NAME}/src/update.py"
    echo $cmd
    eval $cmd
    echo
    docker kill ${HOST_NAME}
}

if [ $# -eq 1 ]; then
    if [ "$1" = "update" ]; then
        update
    else
```

```
40          echo 'invalid option'
41          exit
42      fi
43  fi
44
45  prompt[0]="Boot up ${CASSANDRA_IMAGE}"
46  prompt[1]="Build and Boot ${HOST_IMAGE} (debug)"
47  prompt[2]="Update Cassandra with latest data"
48  prompt[3]="csql> ${CLUSTER_NAME}"
49  prompt[4]="bash ${CLUSTER_NAME}"
50  prompt[5]="kill all"
51  prompt[6]="Cleanup docker images"
52  prompt[7]="Make environment"
53
54  PS3="Select Command: "
55  select opt in "${prompt[@]}"
56  do
57      case $opt in ${prompt[0]}) # boot up cassandra image
58              check=`docker ps | egrep -c "${CLUSTER_NAME}"`
59              if [ $check -gt 0 ]; then echo "instance of ${CLUSTER_NAME} already running...";
                    ↪  break; fi
60              eval "docker rm ${CLUSTER_NAME}"
61              cmd="docker run --rm --name ${CLUSTER_NAME} -v $PWD/config/cassandra:/etc/
                    ↪ cassandra -v ${HOST_CASSANDRA_DIR}:/var/lib/cassandra -d ${
                    ↪ CASSANDRA_IMAGE}"
62              echo
63              echo $cmd
64              eval $cmd
65              echo
66              break
67              ;;
68
69          ${prompt[1]}) # build and boot host image for debug
70              check=`docker ps | egrep -c "${HOST_NAME}"`
71              if [ $check -gt 0 ]; then docker kill ${HOST_NAME}; docker rm ${HOST_NAME}; fi
72              cmd="docker build -t ${HOST_IMAGE} ."
73              echo
74              echo $cmd
75              eval $cmd
76              exit_code=$?
77              echo
```

```
78              if [[ $exit_code != 0 ]]; then break; fi
79              data_map="${HOST_DATA}:/data/daq.crayfis.io/raw"
80              src_map="${HOST_SRC}:/home/${HOST_NAME}/src"
81              ingested_map="${HOST_SRC}/ingested"
82              cmd="docker run --rm --name ${HOST_NAME} -v ${data_map} -v ${src_map} -v ${
                    ↪ ingested_map} --link ${CLUSTER_NAME}:cassandra -it ${HOST_IMAGE}"
83              echo $cmd
84              eval $cmd
85              echo
86              break
87              ;;
88
89          ${prompt[2]}) # update cassandra with latest data
90              update
91              break
92              ;;
93
94          ${prompt[3]}) # csql cassandra
95              cmd="docker run -it --link ${CLUSTER_NAME}:cassandra --rm cassandra cqlsh
                    ↪ cassandra"
96              echo
97              echo $cmd
98              eval $cmd
99              echo
100             break
101             ;;
102
103         ${prompt[4]}) # bash cassandra
104             cmd="docker run -it -v $PWD:/home -v $PWD/config/cassandra:/etc/cassandra --link
                    ↪  ${CLUSTER_NAME}:cassandra --rm cassandra bash"
105             echo
106             echo $cmd
107             eval $cmd
108             echo
109             break
110             ;;
111
112         ${prompt[5]}) # kill all
113             check=`docker ps | egrep -c "${CLUSTER_NAME}"`
114             if [ $check -gt 0 ]; then docker kill $CLUSTER_NAME; fi
115
```

```
116                 check=`docker ps | egrep -c "${HOST_NAME}"`
117                 if [ $check -gt 0 ]; then docker kill $HOST_NAME; fi
118                 break
119                 ;;
120
121             ${prompt[6]}) # cleanup docker images
122                 for id in `docker images | egrep "^<none>" | awk '{print $3}'`; do docker rmi
                        ↪ $id; done
123                 break
124                 ;;
125
126             ${prompt[7]}) # make environment
127                 export CASSANDRA_IMAGE=$CASSANDRA_IMAGE
128                 export CLUSTER_NAME=$CLUSTER_NAME
129                 export HOST_CASSANDRA_DIR=$HOST_CASSANDRA_DIR
130                 export HOST_IMAGE=$HOST_IMAGE
131                 export HOST_NAME=$HOST_NAME
132                 export HOST_DATA=$HOST_DATA
133                 export HOST_SRC=$HOST_SRC
134                 break
135                 ;;
136
137             *) echo invalid option;;
138         esac
139     done
```

Listing C.3: Cassandra database updater (`src/update.py`)

```
#!/bin/env python

# updates cassandra with current data
# keeps track of data that's been processed in the `ingested` directory

import ingest
import os
import sys
import time

data_dir = '/data/daq.crayfis.io/raw/'
ingested_dir = './ingested'

print '>> starting...'
sys.stdout.flush()

tarfiles = []
for path, directories, files in os.walk( data_dir ):
    if '_old/' in path: continue

    for filename in files:
        if filename.endswith('.tar.gz'):
            tarfiles.append( os.path.join(path,filename) )
tarfiles = sorted( tarfiles, key=lambda k: k.lower(), reverse=True ) # most recent first

print '>> found {0} tarfiles in {1}'.format( len(tarfiles), data_dir )

target = 0.
n = float(len(tarfiles))
elapsed = 0.
absolute_start = time.time()
n_skipped = 0.
n_completed = 0.
for i, file in enumerate(tarfiles):

    # Don't repeat what's done already
    if os.path.isfile( os.path.join( ingested_dir, file.replace('/','_') ) ):
        print '    skipping {0}, already ingested'.format(file)
        n_skipped += 1.
        continue
```

```
    start = time.time()
    did_it_work = ingest.from_tarfile(file)

    if did_it_work == True:
        elapsed += time.time() - start
        open( os.path.join( ingested_dir, file.replace('/','_') ), 'a' ).close()
        n_completed += 1.
    else:
        print '\nfail: {0}'.format(file)
        n_skipped += 1.
        continue

#    if (n_completed > 0) and ( (i+1.)/n > (target/100.) or n_completed < 48 ):
    total_minutes = ( time.time() - absolute_start ) / 60.
    rate = n_completed / elapsed # files / second
    hours_remaining = (n - n_skipped - n_completed) / rate / 3600.
    print '\r>> working... {0}%, current file: {1}, ave time/file: {2:.3} s, elapsed time: {3:.3} m, eta: {4:.5} hrs        '.format( target, file, 1./rate, total_minutes, hours_remaining),
    sys.stdout.flush()
    if (i+1.)/n > (target/100.):
        if target < 1:
            target += .1
        elif target < 10:
            target += 1.
        elif target < 90:
            target += 5.
        elif target < 99:
            target += 1.
        else:
            target += .1
```

Listing C.4: Data ingestion module (`src/ingest/__init__.py`)

```
"""Cassandra data ingestion module

intended use:
-------------

    ingest.from_tarfile( filepath )
        Ingest CrayonMessages from file.tar.gz into Cassandra
"""

import ingest

def from_tarfile( filepath ):
    """Ingest a Crayfis tarfile into Cassandra.

    Parameters
    ----------
    filepath : string
        Full system filepath locating data tarfile,
        e.g. /data/daq.crayfis.io/raw/YYYY/MM/HOST/HH.tar.gz

    Returns
    -------
    boolean
        Writes data contained in filepath to Cassandra and returns True.
        Returns False if a non-recoverable error occurs
    """
    return ingest.from_tarfile( filepath )
```

Listing C.5: Data ingester (`src/ingest/ingest.py`)

```
"""Cassandra data ingestion module

intended use:
-------------

    ingest.from_tarfile( filepath )
        Ingest CrayonMessages from file.tar.gz into Cassandra
"""

import os
import tarfile
import CrayonMessage
import Cassandra


def from_tarfile( filepath ):
    """Ingest a Crayfis tarfile into Cassandra.

    Parameters
    ----------
    filepath : string
        Full system filepath locating data tarfile,
        e.g. /data/daq.crayfis.io/raw/YYYY/MM/HOST/HH.tar.gz

    Returns
    -------
    boolean
        Writes data contained in filepath to Cassandra and returns true.
        If there was a problem that couldn't be dealt with, returns false.
    """
    __debug_mode = False
    __debug_N    = 100

    # load tarfile into memory
    try:
        crayfile = tarfile.open( filepath, 'r:gz' )
        if __debug_mode: print 'LOADED tarfile successfully: {0}'.format(crayfile.name)
    except Exception as e:
        print 'terminal error: {0} cannot be found/opened.'.format(filepath)
        return False
```

```
41
42      craymsgs = [ m for m in crayfile.getmembers() if m.name.endswith('.msg') ]
43      if __debug_mode: print 'FOUND {0} messages'.format(len(craymsgs))
44
45      host = os.uname()
46      football = Cassandra.get_football()
47      for msg_i, message in enumerate(craymsgs):
48          football.clear()
49          # save metadata
50          if not football.set_metadata(host=host, tarfile=filepath, tarmember=message.name):
51              football.add_error( '[ingest] metadata failure, check attribute names ingest/
                    ↪ Cassandra/[keyspace]/[table].py' )
52              football.insert_misfit()
53              continue # abort this one, go to next message
54
55          msg = crayfile.extractfile( message )
56          # save message to Cassandra
57          CrayonMessage.from_msg( msg, football )
58          msg.close()
59
60          if __debug_mode and msg_i == __debug_N - 1 : print 'DEBUG break after {0} messages'.
                ↪ format(__debug_N); break
61      crayfile.close()
62      return True
```

Listing C.6: Crayon message module (`src/ingest/CrayonMessage/__init__.py`)

```
"""CrayonMessage
deserialization, format enforcement and error checking.

intended use:
-------------

    from_msg( tarfile.ExFileObject serialized message, Cassandra football  )
        Ingest crayon message (and update the football).
"""

import CrayonMessage

def from_msg( serialized_msg, football ):
    """Ingest extracted message.

    Parameters
    ----------
    serialized_msg : tarfile.ExFileObject
        Serialized raw object from tarfile.extractfile( message ).

    football : Cassandra football object
        The interface to Cassandra that gets passed around.

    Returns
    -------
    None
        Updates Cassandra through the football, then passes it.
    """
    CrayonMessage.from_msg( serialized_msg, football )
```

Listing C.7: Crayon message processor

(src/ingest/CrayonMessage/CrayonMessage.py)

```
"""CrayonMessage
deserialization, format enforcement and error checking.

intended use:
-------------

    from_msg( tarfile.ExFileObject serialized message, Cassandra football  )
        Ingest crayon message (and update the football).
"""

from .. import crayfis_data_pb2
import DataChunk

def from_msg( serialized_msg, football ):
    """Ingest extracted message.

    Parameters
    ----------
    serialized_msg : tarfile.ExFileObject
        Serialized raw object from tarfile.extractfile( message ).

    football : Cassandra football object
        The interface to Cassandra that gets passed around.

    Returns
    -------
    None
        Updates Cassandra through the football, then passes it.
    """
    __debug_mode = False

    # deserialize protobuf CrayonMessage
    protobuf_msg = None
    try:
        serialized_msg.seek(0)
        serialized_string = serialized_msg.read()
        if not football.set_serialized( serialized_string ):
            football.add_error( '[CrayonMessage] could not save serialized message' )
```

```
39                football.insert_misfit()
40                return
41            protobuf_msg = crayfis_data_pb2.CrayonMessage.FromString( serialized_string )
42            if __debug_mode: print '[CrayonMessage] DESERIALIZED protobuf string successfully'
43        except Exception as e:
44            football.add_error( '[CrayonMessage] deserialization failure' )
45            football.insert_misfit()
46            return
47
48        # break out members by type-category
49        manifest = [ {'field':f, 'value':v} for [f,v] in protobuf_msg.ListFields() ]
50        bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
51        messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
52        enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
53        basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
54                                                                 m['field'].TYPE_FLOAT, m['field
                                                                     ↪ '].TYPE_DOUBLE,
55                                                                 m['field'].TYPE_INT32, m['field
                                                                     ↪ '].TYPE_SINT32, m['field
                                                                     ↪ '].TYPE_UINT32,
56                                                                 m['field'].TYPE_INT64, m['field
                                                                     ↪ '].TYPE_SINT64, m['field
                                                                     ↪ '].TYPE_UINT64,
57                                                                 m['field'].TYPE_STRING ] ]
58        if __debug_mode: print '[CrayonMessage] FOUND {0} bytes, {1} messages, {2} enums and {3}
              ↪  basics'.format( len(bytes), len(messages), len(enums), len(basics) )
59
60        # enforce expected structure
61        if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
62            football.add_error( '[CrayonMessage] len(all) - len(expected) = {0} [!= 0]'.format(
                  ↪ len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
63        if not len( messages ) == 0:
64            football.add_error( '[CrayonMessage] len(messages) = {0} [!= 0]'.format(len(messages
                  ↪ )) )
65        if not len( enums ) == 0:
66            football.add_error( '[CrayonMessage] len(enums) = {0} [!= 0]'.format(len(enums)) )
67        if not len( bytes ) == 1:
68            football.add_error( '[CrayonMessage] len(bytes) = {0} [!= 1]'.format(len(bytes)) )
69        if not bytes[0]['field'].name == 'payload':
70            football.add_error( '[CrayonMessage] bytes[0]["field"].name = {0} [!= "payload"]'.
                  ↪ format(bytes[0]['field'].name) )
```

```
71
72      if not football.get_n_errors() == 0:
73          football.insert_misfit()
74          return
75
76      # save current headers
77      if not football.set_headers( basics ):
78          football.add_error( '[CrayonMessage] field name missmatch: {0}'.format([b['field'].
                ↪ name for b in basics]) )
79          football.insert_misfit()
80          return
81
82      # deserialize protobuf datachunk
83      DataChunk.from_string( bytes[0]['value'], football )
```

Listing C.8: DataChunk module

(src/ingest/CrayonMessage/DataChunk/__init__.py)

```
"""DataChunk
deserialization, format enforcement and error checking.

intended use:
-------------

    from_string( string serialized message, Cassandra football )
        Ingest serialized datachunk (update Cassandra via the football).
"""

import DataChunk

def from_string( serialized_chunk, football ):
    """Ingest serialized datachunk.

    Parameters
    ----------
    serialized_chunk : string
        Serialized protobuf DataChunk object

    football : Cassandra football object
        Interface to Cassandra that gets passed around.

    Returns
    -------
    None
        Updates Cassandra via the football, and then passes it.
    """
    DataChunk.from_string( serialized_chunk, football )
```

Listing C.9: DataChunk processor

(src/ingest/CrayonMessage/DataChunk/DataChunk.py)

```
"""DataChunk
deserialization, format enforcement and error checking.

intended use:
-------------

    from_string( string serialized message, Cassandra football )
        Ingest serialized datachunk (update Cassandra via the football).
"""

from ... import crayfis_data_pb2

import ExposureBlock
import RunConfig
import CalibrationResult
import PreCalibrationResult

def from_string( serialized_chunk, football ):
    """Ingest serialized datachunk.

    Parameters
    ----------
    serialized_chunk : string
        Serialized protobuf DataChunk object

    football : Cassandra football object
        Interface to Cassandra that gets passed around.

    Returns
    -------
    None
        Updates Cassandra via the football, and then passes it.
    """
    __debug_mode = False

    # deserialize protobuf DataChunk
    chunk = None
    try:
```

```
39          chunk = crayfis_data_pb2.DataChunk.FromString( serialized_chunk )
40          if __debug_mode: print '[DataChunk] DESERIALIZED protobuf string successfully'
41      except Exception as e:
42          football.add_error( '[DataChunk] deserialization failure' )
43          football.insert_misfit()
44          return
45
46      # break out members by type-category
47      manifest = [ {'field':f, 'value':v} for [f,v] in chunk.ListFields() ]
48      bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
49      messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
50      enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
51      basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
52                                                               m['field'].TYPE_FLOAT, m['field
                                                                     ↪ '].TYPE_DOUBLE,
53                                                               m['field'].TYPE_INT32, m['field
                                                                     ↪ '].TYPE_SINT32, m['field
                                                                     ↪ '].TYPE_UINT32,
54                                                               m['field'].TYPE_INT64, m['field
                                                                     ↪ '].TYPE_SINT64, m['field
                                                                     ↪ '].TYPE_UINT64,
55                                                               m['field'].TYPE_STRING ] ]
56      if __debug_mode: print '[DataChunk] FOUND {0} bytes, {1} messages, {2} enums and {3}
            ↪ basics'.format( len(bytes), len(messages), len(enums), len(basics) )
57
58      # enforce expected structure
59      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
60          football.add_error( '[DataChunk] len(all) - len(expected) = {0} [!= 0]; '.format(len
                ↪ (manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
61      if not len( basics ) == 0:
62          football.add_error( '[DataChunk] len(basics) = {0} [!= 0]; '.format(len(basics)) )
63      if not len( bytes ) == 0:
64          football.add_error( '[DataChunk] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
65      if not len( enums ) == 0:
66          football.add_error( '[DataChunk] len(enums) = {0} [!= 0]; '.format(len(enums)) )
67      if len( messages ) == 0:
68          football.add_error( '[DataChunk] len(messages) = {0} [> 0]; '.format(len(messages))
                ↪ )
69
70      if not football.get_n_errors() == 0:
71          football.insert_misfit()
```

```
72          return
73
74      # save DataChunks to Cassandra
75      for message in messages:
76          if message['field'].name == 'exposure_blocks':
77              if __debug_mode: print '[DataChunk] exposure_block'
78              for block in message['value']:
79                  if not ExposureBlock.ingest(block, football):
80                      football.add_error( '[DataChunk] bad exposure_block' )
81                      football.insert_misfit()
82                      return
83
84          elif message['field'].name == 'run_configs':
85              if __debug_mode: print '[DataChunk] run_config'
86              for config in message['value']:
87                  if not RunConfig.ingest(config, football):
88                      football.add_error( '[DataChunk] bad run_config' )
89                      football.insert_misfit()
90                      return
91
92          elif message['field'].name == 'calibration_results':
93              if __debug_mode: print '[DataChunk] calibration_result'
94              for result in message['value']:
95                  if not CalibrationResult.ingest(result, football):
96                      football.add_error( '[DataChunk] bad calibration_result' )
97                      football.insert_misfit()
98                      return
99
100         elif message['field'].name == 'precalibration_results':
101             if __debug_mode: print '[DataChunk] precalibration_result'
102             for result in message['value']:
103                 if not PreCalibrationResult.ingest(result, football):
104                     football.add_error( '[DataChunk] bad precalibration_result' )
105                     football.insert_misfit()
106                     return
107
108         else:
109             football.add_error( '[DataChunk] message["field"].name = {0} [!= {
                    ↪ exposure_blocks, run_configs, calibration_results, precalibration_results
                    ↪ }]; '.format(message['field'].name) )
110             football.insert_misfit()
```

```
111                 return
```

Listing C.10: RunConfig processor

(src/ingest/CrayonMessage/DataChunk/RunConfig.py)

```
"""RunConfig
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf RunConfig object, Cassandra football )
        Ingest protobuf object (update the football).
"""

def ingest( runconfig, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    runconfig : google protobuf RunConfig
        RunConfig to be read

    football : Cassandra football object
        Interface to Cassandra.

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in runconfig.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
36                                                                  m['field'].TYPE_INT32, m['field
                                                                        ↪ '].TYPE_SINT32, m['field
                                                                        ↪ '].TYPE_UINT32,
37                                                                  m['field'].TYPE_INT64, m['field
                                                                        ↪ '].TYPE_SINT64, m['field
                                                                        ↪ '].TYPE_UINT64,
38                                                                  m['field'].TYPE_STRING ] ]
39      if __debug_mode: print '[RunConfig] FOUND {0} bytes, {1} messages, {2} enums and {3}
            ↪ basics'.format( len(bytes), len(messages), len(enums), len(basics) )
40
41      # enforce expected structure
42      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
43          football.add_error( '[RunConfig] len(all) - len(expected) = {0} [!= 0]; '.format(len
                ↪ (manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
44      if not len( bytes ) == 0:
45          football.add_error( '[RunConfig] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
46      if not len( enums ) == 0:
47          football.add_error( '[RunConfig] len(enums) = {0} [!= 0]; '.format(len(enums)) )
48      if not len( messages ) == 0:
49          football.add_error( '[RunConfig] len(messages) = {0} [!= 0]; '.format(len(messages))
                ↪  )
50
51      if not football.get_n_errors() == 0:
52          return False
53
54      # save run_config to Cassandra
55      if not football.insert_run_config( basics ):
56          football.add_error( '[RunConfig] field name missmatch: {0}'.format([b['field'].name
                ↪ for b in basics]) )
57
58      if not football.get_n_errors() == 0:
59          return False
60      return True
```

Listing C.11: PreCalibrationResult processor

(src/ingest/CrayonMessage/DataChunk/PreCalibrationResult.py)

```
"""PreCalibrationResult
deserialization, format enforcement and error checking.

intended use:
-------------

    ingest( google protobuf PreCalibrationResult object, Cassandra football )
        Ingest protobuf object (update the football).
"""

def ingest( result, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    result : google protobuf PreCalibrationResult
        PreCalibration to be read

    football : Cassandra football object
        Interface to Cassandra.

    Returns
    -------
    boolean
        True if sucessful, False if mifit behavior.
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in result.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
36                                                                  m['field'].TYPE_INT32, m['field
                                                                        ↪ '].TYPE_SINT32, m['field
                                                                        ↪ '].TYPE_UINT32,
37                                                                  m['field'].TYPE_INT64, m['field
                                                                        ↪ '].TYPE_SINT64, m['field
                                                                        ↪ '].TYPE_UINT64,
38                                                                  m['field'].TYPE_STRING ] ]
39      if __debug_mode: print '[PreCalibrationResult] FOUND {0} bytes, {1} messages, {2} enums
            ↪ and {3} basics'.format( len(bytes), len(messages), len(enums), len(basics) )
40
41      # enforce expected structure
42      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
43          football.add_error( '[PreCalibrationResult] len(all) - len(expected) = {0} [!= 0]; '
                ↪ .format(len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
44      if not len( bytes ) == 1:
45          football.add_error( '[PreCalibrationResult] len(bytes) = {0} [!= 1]; '.format(len(
                ↪ bytes)) )
46      if not len( enums ) == 0:
47          football.add_error( '[PreCalibrationResult] len(enums) = {0} [!= 0]; '.format(len(
                ↪ enums)) )
48      if not len( messages ) == 0:
49          football.add_error( '[PreCalibrationResult] len(messages) = {0} [!= 0]; '.format(len
                ↪ (messages)) )
50
51      if not football.get_n_errors() == 0:
52          return False
53
54      # save precalibration_result to Cassandra
55      if not football.insert_precalibration_result( basics, compressed_weights=bytes ):
56          football.add_error( '[PreCalibrationResult] field name missmatch: {0}'.format([b['
                ↪ field'].name for b in basics]) )
57
58      if not football.get_n_errors() == 0:
59          return False
60      return True
```

Listing C.12: CalibrationResult processor

(src/ingest/CrayonMessage/DataChunk/CalibrationResult.py)

```
"""CalibrationResult
deserialization, format enforcement and error checking.

intended use:
-------------

    ingest( google protobuf CalibrationResult object, Cassandra football )
        Ingest protobuf object (update the football).
"""

def ingest( result, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    result : google protobuf CalibrationResult
        Calibration to be read

    football : Cassandra football object
        Interface to Cassandra.

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior.
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in result.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
36                                                                  m['field'].TYPE_INT32, m['field
                                                                        ↪ '].TYPE_SINT32, m['field
                                                                        ↪ '].TYPE_UINT32,
37                                                                  m['field'].TYPE_INT64, m['field
                                                                        ↪ '].TYPE_SINT64, m['field
                                                                        ↪ '].TYPE_UINT64,
38                                                                  m['field'].TYPE_STRING ] ]
39      if __debug_mode: print '[CalibrationResult] FOUND {0} bytes, {1} messages, {2} enums and
            ↪  {3} basics'.format( len(bytes), len(messages), len(enums), len(basics) )
40
41      # enforce expected structure
42      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
43          football.add_error( '[CalibrationResult] len(all) - len(expected) = {0} [!= 0]; '.
                ↪ format(len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
44      if not len( bytes ) == 0:
45          football.add_error( '[CalibrationResult] len(bytes) = {0} [!= 0]; '.format(len(bytes
                ↪ )) )
46      if not len( enums ) == 0:
47          football.add_error( '[CalibrationResult] len(enums) = {0} [!= 0]; '.format(len(enums
                ↪ )) )
48      if not len( messages ) == 0:
49          football.add_error( '[CalibrationResult] len(messages) = {0} [!= 0]; '.format(len(
                ↪ messages)) )
50
51      if not football.get_n_errors() == 0:
52          return False
53
54      # save calibration_result to Cassandra
55      if not football.insert_calibration_result( basics ):
56          football.add_error( '[CalibrationResult] field name missmatch: {0}'.format([b['field
                ↪ '].name for b in basics]) )
57
58      if not football.get_n_errors() == 0:
59          return False
60      return True
```

Listing C.13: ExposureBlock module

(src/ingest/CrayonMessage/DataChunk/ExposureBlock/__init__.py)

```
"""ExposureBlock
deserialization, format enforcement and error checking.

intended use:
-------------

    ingest( google protobuf ExposureBlock object, Cassandra football )
        Ingest protobuf object (update the football).
"""

import ExposureBlock

def ingest( block, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    block : google protobuf ExposureBlock
        ExposureBlock to be read

    football : Cassandra football object
        Interface to Cassandra

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior.
    """
    return ExposureBlock.ingest( block, football )
```

Listing C.14: ExposureBlock processor

(src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock.py)

```
"""ExposureBlock
deserialization, format enforcement and error checking.

intended use:
-------------

    ingest( google protobuf ExposureBlock object, Cassandra football )
        Ingest protobuf object (update the football).
"""

import uuid
import Event

def ingest( block, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    block : google protobuf ExposureBlock
        ExposureBlock to be read

    football : Cassandra football object
        Interface to Cassandra

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior.
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in block.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
```

```
                                                                    m['field'].TYPE_FLOAT, m['field'].TYPE_DOUBLE,
                                                                    m['field'].TYPE_INT32, m['field'].TYPE_SINT32, m['field'].TYPE_UINT32,
                                                                    m['field'].TYPE_INT64, m['field'].TYPE_SINT64, m['field'].TYPE_UINT64,
                                                                    m['field'].TYPE_STRING ] ]
    if __debug_mode: print '[ExposureBlock] FOUND {0} bytes, {1} messages, {2} enums and {3} basics'.format( len(bytes), len(messages), len(enums), len(basics) )

    # enforce expected structure
    if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
        football.add_error( '[ExposureBlock] len(all) - len(expected) = {0} [!= 0]; '.format (len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
    if not len( bytes ) == 0:
        football.add_error( '[ExposureBlock] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
    if not len( enums ) == 1:
        football.add_error( '[ExposureBlock] len(enums) = {0} [!= 1]; '.format(len(enums)) )
    if not enums[0]['field'].name == 'daq_state':
        football.add_error( '[ExposureBlock] enums[0]["field"].name = {0} [!= "daq_state"]; '.format(enums[0]['field'].name) )

    # translate enum into string
    state = ''
    if   enums[0]['value'] == 0:
        state = 'INIT'
    elif enums[0]['value'] == 1:
        state = 'CALIBRATION'
    elif enums[0]['value'] == 2:
        state = 'DATA'
    elif enums[0]['value'] == 3:
        state = 'PRECALIBRATION'
    else:
        football.add_error( '[ExposureBlock] daq_state = {0} [!= {0,1,2,3}]; '.format(enums [0]['value']) )

    if not football.get_n_errors() == 0:
        return False

```

```
    # compute block_uuid
    # SHA1 hash of start_time and end_time
    # (in the DNS namespace, because I had to give it one..)
    start_time = None
    end_time   = None
    for basic in basics:
        if basic['field'].name == 'start_time':
            start_time = str( basic['value'] )
        elif basic['field'].name == 'end_time':
            end_time = str( basic['value'] )
    if start_time is None or end_time is None:
        football.add_error( '[ExposureBlock] could not find start_time and/or end_time' )
        return False
    block_uuid = uuid.uuid5( uuid.NAMESPACE_DNS, start_time + end_time )

    n_events = 0
    for message in messages:
        if message['field'].name == 'events':
            for event in message['value']:
                # save event to Cassandra
                n_events += 1
                if __debug_mode:
                    print '[ExposureBlock] basics:'
                    for basic in basics:
                        print '\t{0} : {1}'.format( basic['field'].name, str(basic['value'])[:30])
                    print '-------------------'
                if not Event.ingest( event, football, block_basics=basics, daq_state=state, block_uuid=block_uuid ):
                    football.add_error( '[ExposureBlock] bad event' )
                    continue
        else:
            football.add_error( '[ExposureBlock] message["field"].name = {0} [!= {events, byteblocks, zerobiassquares}]; '.format(message['field'].name) )

    if not football.get_n_errors() == 0:
        return False

    # save exposure_block to Cassandra
    if not football.insert_exposure_block( basics, daq_state=state, block_uuid=block_uuid, n_events=n_events ):
```

```
107            football.add_error( '[ExposureBlock] field name missmatch: {0}'.format([b['field'].
                ↪ name for b in basics]) )
108
109        if not football.get_n_errors() == 0:
110            return False
111        return True
```

Listing C.15: Event module (`src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock/Event/__init__.py`)

```
"""Event
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf Event object, Cassandra football )
        Ingest protobuf object (updates the football).
"""

import Event

def ingest( event, football, block_basics=None, daq_state=None, block_uuid=None ):
    """Ingest protobuf object.

    Parameters
    ----------
    event : google protobuf Event
        Event to be read

    football : Cassandra football object
        Cassandra interface.

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior.
    """
    return Event.ingest( event, football, block_basics=block_basics, daq_state=daq_state,
        ↪ block_uuid=block_uuid )
```

Listing C.16: Event processor (`src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock/Event/Event.py`)

```
"""Event
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf Event object, Cassandra football )
        Ingest protobuf object (updates the football).
"""

import ByteBlock
import Pixel
import ZeroBiasSquare

def ingest( event, football, block_basics=None, daq_state=None, block_uuid=None ):
    """Ingest protobuf object.

    Parameters
    ----------
    event : google protobuf Event
        Event to be read

    football : Cassandra football object
        Cassandra interface.

    Returns
    -------
    boolean
        True if sucessful, False if misfit behavior.
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in event.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
```

```
                                                                    m['field'].TYPE_FLOAT, m['field'].TYPE_DOUBLE,
                                                                    m['field'].TYPE_INT32, m['field'].TYPE_SINT32, m['field'].TYPE_UINT32,
                                                                    m['field'].TYPE_INT64, m['field'].TYPE_SINT64, m['field'].TYPE_UINT64,
                                                                    m['field'].TYPE_STRING ] ]
    if __debug_mode: print '[Event] FOUND {0} bytes, {1} messages, {2} enums and {3} basics'.format( len(bytes), len(messages), len(enums), len(basics) )

    # enforce expected structure
    if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
        football.add_error( '[Event] len(all) - len(expected) = {0} [!= 0]; '.format(len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
    if not len( bytes ) == 0:
        football.add_error( '[Event] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
    if not len( enums ) == 0:
        football.add_error( '[Event] len(enums) = {0} [!= 0]; '.format(len(enums)) )

    pixels    = []
    byteblock = None
    zerobias  = None
    for message in messages:
        if message['field'].name == 'pixels':
            for pixel in message['value']:
                pixels.append( Pixel.ingest(pixel, football) )

        elif message['field'].name == 'byteblocks':
            #football.add_error( '[Event] too many byteblocks' )
            byteblock = ByteBlock.ingest(message['value'], football)

        elif message['field'].name == 'zero_bias':
            #football.add_error( '[Event] too many zero-bias squares' )
            zerobias = ZeroBiasSquare.ingest(message['value'], football)

        else:
            football.add_error( '[Event] message["field"].name = {0} [!= {{pixels, byteblocks, zero_bias}}]; '.format(message['field'].name) )

```

```
    if not football.get_n_errors() == 0:
        return False

    # save event to Cassandra
    if not football.insert_event( basics, block_basics=block_basics, daq_state=daq_state,
        ↪ block_uuid=block_uuid, pixels=pixels, byteblock=byteblock, zerobias=zerobias ):
        football.add_error( '[Event] field name missmatch: {0}'.format([b['field'].name for
            ↪ b in basics]) )

    if not football.get_n_errors() == 0:
        return False
    return True
```

Listing C.17: ByteBlock processor (`src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock/Event/ByteBlock.py`)

```
"""ByteBlock
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf ByteBlock object, Cassandra football )
        Ingest protobuf object (updates the football).
"""

def ingest( block, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    block : google protobuf ByteBlock
        Calibration to be read

    football : Cassandra football object
        Interface to Cassandra.

    Returns
    -------
    python dictionary
        name : value pairs of block
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in block.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
36                                                                  m['field'].TYPE_INT32, m['field
                                                                        ↪ '].TYPE_SINT32, m['field
                                                                        ↪ '].TYPE_UINT32,
37                                                                  m['field'].TYPE_INT64, m['field
                                                                        ↪ '].TYPE_SINT64, m['field
                                                                        ↪ '].TYPE_UINT64,
38                                                                  m['field'].TYPE_STRING ] ]
39      if __debug_mode: print '[ByteBlock] FOUND {0} bytes, {1} messages, {2} enums and {3}
            ↪ basics'.format( len(bytes), len(messages), len(enums), len(basics) )
40
41      # enforce expected structure
42      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
43          football.add_error( '[ByteBlock] len(all) - len(expected) = {0} [!= 0]; '.format(len
                ↪ (manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
44      if not len( bytes ) == 0:
45          football.add_error( '[ByteBlock] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
46      if not len( enums ) == 0:
47          football.add_error( '[ByteBlock] len(enums) = {0} [!= 0]; '.format(len(enums)) )
48      if not len( messages ) == 0:
49          football.add_error( '[ByteBlock] len(messages) = {0} [!= 0]; '.format(len(messages))
                ↪ )
50
51      # build dictionary
52      bbdict = { 'x':None, 'y':None, 'val':None, 'side_length':None }
53      for basic in basics:
54          if basic['field'].name not in bbdict.keys():
55              football.add_error( '[ByteBlock] unknown attribute: {0}'.format(basic['field'].
                    ↪ name) )
56              continue
57          bbdict[ basic['field'].name ] = basic['value']
58
59      return bbdict
```

Listing C.18: Pixel processor (`src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock/Event/Pixel.py`)

```
"""Pixel
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf Pixel object, Cassandra football )
        Ingest protobuf object (updates the football).
"""

def ingest( pixel, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    pixel : google protobuf Pixel
        Pixel to be read

    football : Cassandra football object
        Cassandra interface.

    Returns
    -------
    python dictionary
        name : value pairs of pixel
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in pixel.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
36                                                                  m['field'].TYPE_INT32, m['field
                                                                        ↪ '].TYPE_SINT32, m['field
                                                                        ↪ '].TYPE_UINT32,
37                                                                  m['field'].TYPE_INT64, m['field
                                                                        ↪ '].TYPE_SINT64, m['field
                                                                        ↪ '].TYPE_UINT64,
38                                                                  m['field'].TYPE_STRING ] ]
39      if __debug_mode: print '[Pixel] FOUND {0} bytes, {1} messages, {2} enums and {3} basics'
            ↪ .format( len(bytes), len(messages), len(enums), len(basics) )
40
41      # enforce expected structure
42      if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
43          football.add_error( '[Pixel] len(all) - len(expected) = {0} [!= 0]; '.format(len(
                ↪ manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
44      if not len( bytes ) == 0:
45          football.add_error( '[Pixel] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
46      if not len( enums ) == 0:
47          football.add_error( '[Pixel] len(enums) = {0} [!= 0]; '.format(len(enums)) )
48      if not len( messages ) == 0:
49          football.add_error( '[Pixel] len(messages) = {0} [!= 0]; '.format(len(messages)) )
50
51      # build dictionary
52      pdict = { 'x':None, 'y':None, 'val':None, 'adjusted_val':None, 'near_max':None, 'avg_3':
            ↪ None, 'avg_5':None }
53      for basic in basics:
54          if basic['field'].name not in pdict.keys():
55              football.add_error( '[Pixel] unknown attribute: {0}'.format(basic['field'].name)
                    ↪  )
56              continue
57          pdict[ basic['field'].name ] = basic['value']
58
59      return pdict
```

Listing C.19: Zero-Biased Square processor (`src/ingest/CrayonMessage/DataChunk/ExposureBlock/ExposureBlock/Event/ZeroBiasSquare.py`)

```
"""ZeroBiasSquare
deserialization, format enforcement and error checking.

inteded use:
------------

    ingest( google protobuf ZeroBiasSquare object, Cassandra football )
        Ingest protobuf object (updates the football).
"""

def ingest( square, football ):
    """Ingest protobuf object.

    Parameters
    ----------
    square : google protobuf ZeroBiasSquare
        Calibration to be read

    football : Cassandra football object
        Interface to Cassandra.

    Returns
    -------
    python dictionary
        name : value pairs of square
    """
    __debug_mode = False

    # break out members by type-category
    manifest = [ {'field':f, 'value':v} for [f,v] in square.ListFields() ]
    bytes    = [ m for m in manifest if m['field'].type == m['field'].TYPE_BYTES   ]
    messages = [ m for m in manifest if m['field'].type == m['field'].TYPE_MESSAGE ]
    enums    = [ m for m in manifest if m['field'].type == m['field'].TYPE_ENUM    ]
    basics   = [ m for m in manifest if m['field'].type in [ m['field'].TYPE_BOOL,
                                                             m['field'].TYPE_FLOAT, m['field
                                                                 ↪ '].TYPE_DOUBLE,
```

```
                                                                    m['field'].TYPE_INT32, m['field'].TYPE_SINT32, m['field'].TYPE_UINT32,
                                                                    m['field'].TYPE_INT64, m['field'].TYPE_SINT64, m['field'].TYPE_UINT64,
                                                                    m['field'].TYPE_STRING ] ]
    if __debug_mode: print '[ZeroBiasSquare] FOUND {0} bytes, {1} messages, {2} enums and {3} basics'.format( len(bytes), len(messages), len(enums), len(basics) )

    # enforce expected structure
    if not len(manifest) - len(bytes) - len(messages) - len(enums) - len(basics) == 0:
        football.add_error( '[ZeroBiasSquare] len(all) - len(expected) = {0} [!= 0]; '.format(len(manifest)-len(bytes)-len(messages)-len(enums)-len(basics)) )
    if not len( bytes ) == 0:
        football.add_error( '[ZeroBiasSquare] len(bytes) = {0} [!= 0]; '.format(len(bytes)) )
    if not len( enums ) == 0:
        football.add_error( '[ZeroBiasSquare] len(enums) = {0} [!= 0]; '.format(len(enums)) )
    if not len( messages ) == 0:
        football.add_error( '[ZeroBiasSquare] len(messages) = {0} [!= 0]; '.format(len( messages)) )

    # build dictionary
    zbsdict = { 'x_min':None, 'y_min':None, 'val':None, 'frame_number':None }
    for basic in basics:
        if basic['field'].name not in zbsdict.keys():
            football.add_error( '[ZeroBiasSquare] unknown attribute: {0}'.format(basic['field'].name) )
            continue
        zbsdict[ basic['field'].name ] = basic['value']

    return zbsdict
```

Listing C.20: Cassandra interface module (`src/ingest/Cassandra/__init__.py`)

```
"""Cassandra interface

inteded use:
------------

    get_football()
        The football interfaces the back-end of
        how and what to write to Cassandra across
        tables across keyspaces.  Pass it around,
        and ask it to write for you.
        *note, once written to Cassandra, data is
        purged from the football automatically.

        intended use:
            football = get_football()
            football.clear() # to reset at any time
            e.g.
                football.insert_run_config( basics )
                (run_config object is written to Cassandra,
                then cleared automatically)
"""

import Cassandra

def get_football():
    """Returns football.
    The football interfaces the back-end of
    how and what to write to Cassandra across
    tables across keyspaces.  Pass it around,
    and ask it to write for you.

    intended use:
        football = get_football()
        football.clear() # to reset at any time
        e.g.
            football.insert_run_config( basics )
    """
    return Cassandra.get_football()
```

Listing C.21: Cassandra interface (`src/ingest/Cassandra/Cassandra.py`)

```
"""Cassandra interface

inteded use:
------------

    get_football()
        The football interfaces the back-end of
        how and what to write to Cassandra across
        tables across keyspaces.  Pass it around,
        and ask it to write for you.
        *note, once written to Cassandra, data is
        purged from the football automatically.

        intended use:
            football = get_football()
            football.clear() # to reset at any time
            e.g.
                football.insert_run_config( basics )
                (run_config object is written to Cassandra,
                then cleared automatically)
"""
__debug_mode = False

import raw_keyspace
import writer

#########################
# initialize Cassandra #
#########################
#writer.init_raw.clear()  # comment out to save database
writer.init_raw.do_it()  # tells Cassandra the structure

class __BallBag:
    """private class to isolate the user
    from multiple keyspace footballs...
    If there are multiple keyspaces..
    """
    def __init__(self):
        """create new ballbag with footballs
        from each keyspace
```

```
41          """
42          self.clear()
43
44      def clear(self):
45          """clear all footballs of data
46          """
47          raw_keyspace.clear()
48
49      # Errors and shared data
50      #----------------------
51      def add_error(self, error):
52          """log an error message
53          """
54          raw_keyspace.add_error( error )
55
56      def get_n_errors(self):
57          """return N errors logged
58          """
59          return raw_keyspace.get_n_errors()
60
61      def set_metadata(self, host='', tarfile='', tarmember=''):
62          """log metadata
63          """
64          host = repr(host)
65          is_sucessful = raw_keyspace.set_metadata( host=host, tarfile=tarfile, tarmember=
                ↪ tarmember )
66          return is_sucessful
67
68      def set_serialized(self, serialized_string ):
69          """log raw, serialized CrayonMessage
70          """
71          is_sucessful = raw_keyspace.set_serialized( serialized_string )
72          return is_sucessful
73
74      def set_headers(self, basics):
75          """log CrayonMessage headers
76          """
77          is_sucessful = raw_keyspace.set_headers( basics )
78          return is_sucessful
79
80      # Specific insertions
```

```
    #-------------------
    def insert_misfit(self):
        """INSERT misfit object into Cassandra
        """
        is_sucessful = raw_keyspace.insert_misfit()
        return is_sucessful

    def insert_run_config(self, basics):
        """INSERT runconfig object into Cassandra
           Parameters:
               basics : Google protobuf field descriptor object and value
        """
        is_sucessful = raw_keyspace.insert_run_config( basics )
        return is_sucessful

    def insert_calibration_result(self, basics):
        """INSERT calibration_result object into Cassandra
           Parameters:
               basics : Google protobuf field descriptor object and value
        """
        is_sucessful = raw_keyspace.insert_calibration_result( basics )
        return is_sucessful

    def insert_precalibration_result(self, basics, compressed_weights=''):
        """INSERT precalibration_result object into Cassandra
           Parameters:
               basics : Google protobuf field descriptor object and value

               compressed_weights : string
                                    Serialized weights
        """
        is_sucessful = raw_keyspace.insert_precalibration_result( basics, compressed_weights
            ↪ =compressed_weights )
        return is_sucessful

    def insert_exposure_block(self, basics, daq_state='', block_uuid=None, n_events=0):
        """INSERT exposure_block object into Cassandra
           Parameters:
               basics     : Google protobuf field descriptor object and value
                            Collection of basic data types (no objects).

```

```
121                 daq_state   : string
122                               Decoded daq_state enum string.
123
124                 block_uuid : uuid.uuid5( uuid.NAMESPACE_DNS, string )
125                               SHA1 hash UUID composed of a string: start_time+end_time to
                                      ↪ identify this block.
126
127                 n_events    : int
128                               Number of events in this exposure block
129           """
130           is_sucessful = raw_keyspace.insert_exposure_block( basics, daq_state=daq_state,
                  ↪ block_uuid=block_uuid, n_events=n_events )
131           return is_sucessful
132
133       def insert_event(self, basics, block_basics=None, daq_state='', block_uuid=None, pixels
              ↪ =[], byteblock={}, zerobias={}):
134           """INSERT event object into Cassandra
135              Parameters:
136                 basics       : Google protobuf field descriptor object and value
137
138                 block_basics : Google protobuf field descriptor object and value
139                                from cooresponding exposure block for denormalization
140
141                 daq_state    : string, decoded daq_state enum string
142
143                 block_uuid   : unique identifier to parent exposure block
144
145                 pixels       : array of name-value attribute pairs for pixels
146
147                 byteblock    : name-value attribute pairs for byteblock
148
149                 zerobias     : name-value attribute pairs for zero bias square
150           """
151           is_sucessful = raw_keyspace.insert_event( basics, block_basics=block_basics,
                  ↪ daq_state=daq_state, block_uuid=block_uuid, pixels=pixels, byteblock=
                  ↪ byteblock, zerobias=zerobias )
152           return is_sucessful
153
154   #------------------------------------------------------------------------------
155
156   __football = __BallBag()
```

```
if __debug_mode: print '[Cassandra] football is ready'

def get_football():
    """Returns football.
    The football interfaces the back-end of
    how and what to write to Cassandra across
    tables across keyspaces.  Pass it around,
    and ask it to write for you.

    intended use:
        football = get_football()
        football.clear() # to reset at any time
        e.g.
            football.insert_run_config( basics )
    """
    if __debug_mode: print '[Cassandra] passing football'
    return __football
```

Listing C.22: Cassandra Keyspace module

(src/ingest/Cassandra/raw_keyspace/__init__.py)

```
"""Cassandra keyspace: ‘raw‘

intended use:
-------------
    Internals of the Cassandra football.
    Handles neuances unique to the ‘raw‘ keyspace.

    Tables:
        misfits
        exposure_blocks
        events
        runconfigs
        calibration_results
        precalibration_results
"""

import raw_keyspace

def clear():
    raw_keyspace.clear()

# Errors and shared data
#-----------------------
def add_error( error_string ):
    raw_keyspace.add_error( error_string )

def get_n_errors():
    return raw_keyspace.get_n_errors()

def set_metadata(host='', tarfile='', tarmember=''):
    return raw_keyspace.set_metadata(host=host, tarfile=tarfile, tarmember=tarmember)

def set_serialized( serialized_string ):
    return raw_keyspace.set_serialized( serialized_string )

def set_headers( basics ):
    return raw_keyspace.set_headers( basics )

```

```
# Specific insertions
#-------------------
def insert_misfit():
    return raw_keyspace.insert_misfit()

def insert_run_config( basics ):
    return raw_keyspace.insert_run_config( basics )

def insert_calibration_result( basics ):
    return raw_keyspace.insert_calibration_result( basics )

def insert_precalibration_result( basics, compressed_weights='' ):
    return raw_keyspace.insert_precalibration_result( basics, compressed_weights=
        ↪ compressed_weights )

def insert_exposure_block( basics, daq_state='', block_uuid=None, n_events=0 ):
    return raw_keyspace.insert_exposure_block( basics, daq_state=daq_state, block_uuid=
        ↪ block_uuid, n_events=n_events )

def insert_event( basics, block_basics=None, daq_state='', block_uuid=None, pixels=[],
    ↪ byteblock={}, zerobias={} ):
    return raw_keyspace.insert_event( basics, block_basics=block_basics, daq_state=daq_state
        ↪ , block_uuid=block_uuid, pixels=pixels, byteblock=byteblock, zerobias=zerobias )
```

Listing C.23: Cassandra Keyspace

(src/ingest/Cassandra/raw_keyspace/raw_keyspace.py)

```
"""Cassandra keyspace: ‘raw‘

intended use:
————————————
    Internals of the Cassandra football.
    Handles neuances unique to the ‘raw‘ keyspace.

    Tables:
        misfits
        exposure_blocks
        events
        runconfigs
        calibration_results
        precalibration_results
"""
__debug_mode = False

import Misfit
import ExposureBlock
import Event
import RunConfig
import CalibrationResult
import PreCalibrationResult

from .. import writer

misfit                = Misfit.Football()
exposure_block        = ExposureBlock.Football()
event                 = Event.Football()
run_config            = RunConfig.Football()
calibration_result    = CalibrationResult.Football()
precalibration_result = PreCalibrationResult.Football()
n_errors = 0

def clear():
    global n_errors
    n_errors = 0
    misfit               .clear()
```

```
    exposure_block       .clear()
    event                .clear()
    run_config           .clear()
    calibration_result   .clear()
    precalibration_result.clear()
    if __debug_mode: print '[raw_keyspace] football cleared'

# Errors and shared data
#----------------------
def add_error( error_string ):
    global n_errors
    n_errors += 1
    misfit.add_error( error_string )
    if __debug_mode: print '[raw_keyspace] error added'

def get_n_errors():
    return n_errors

def set_metadata(host='', tarfile='', tarmember=''):
    is_sucessful  = misfit               .set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    is_sucessful &= exposure_block       .set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    is_sucessful &= event                .set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    is_sucessful &= run_config           .set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    is_sucessful &= calibration_result   .set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    is_sucessful &= precalibration_result.set_metadata( host=host, tarfile=tarfile, tarmember=tarmember )
    if __debug_mode: print '[raw_keyspace] metadata set: ' + host[:20] + '...' + tarfile[-20:] + ' ' + tarmember
    return is_sucessful

def set_serialized( serialized_string ):
    is_sucessful = misfit.set_serialized( serialized_string )
    if __debug_mode: print '[raw_keyspace] serialized message set'
    return is_sucessful

def set_headers( basics ):
```

```
    is_sucessful  = misfit                .set_attributes( basics )
    is_sucessful &= exposure_block        .set_attributes( basics )
    is_sucessful &= event                 .set_attributes( basics )
    is_sucessful &= run_config            .set_attributes( basics )
    is_sucessful &= calibration_result    .set_attributes( basics )
    is_sucessful &= precalibration_result.set_attributes( basics )
    if __debug_mode: print '[raw_keyspace] headers set'
    return is_sucessful

# Specific insertions
#-------------------
def insert_misfit():
    is_sucessful = writer.insert( table='raw.misfits', names=misfit.get_names(), values=
        ↪ misfit.get_values() )
    if not is_sucessful:
        print '[WARNING] FAILURE TO LOG MISFIT'
        print '          errors: {0}'.format(misfit.errors)
        print '          file: {0}'.format(misfit.tarfile)
        print '          member: {0}'.format(misfit.tarmember)
    clear()
    return is_sucessful

def insert_run_config( basics ):
    run_config.set_attributes( basics )
    is_sucessful = writer.insert( table='raw.run_configs', names=run_config.get_names(),
        ↪ values=run_config.get_values() )
    if not is_sucessful:
        print '[ISSUE] run config'
        print '      errors: {0}'.format(misfit.errors)
        print '      file: {0}'.format(misfit.tarfile)
        print '      member: {0}'.format(misfit.tarmember)
    run_config.reset()
    return is_sucessful

def insert_calibration_result( basics ):
    calibration_result.set_attributes( basics )
    is_sucessful = writer.insert( table='raw.calibration_results', names=calibration_result.
        ↪ get_names(), values=calibration_result.get_values() )
    if not is_sucessful:
        print '[ISSUE] calibration result'
        print '      errors: {0}'.format(misfit.errors)
```

```
111         print '      file: {0}'.format(misfit.tarfile)
112         print '      member: {0}'.format(misfit.tarmember)
113     calibration_result.reset()
114     return is_sucessful
115 
116 def insert_precalibration_result( basics, compressed_weights='' ):
117     precalibration_result.set_attributes( basics, compressed_weights=compressed_weights )
118     is_sucessful = writer.insert( table='raw.precalibration_results', names=
        ↪ precalibration_result.get_names(), values=precalibration_result.get_values() )
119     if not is_sucessful:
120         print '[ISSUE] precalibration result'
121         print '      errors: {0}'.format(misfit.errors)
122         print '      file: {0}'.format(misfit.tarfile)
123         print '      member: {0}'.format(misfit.tarmember)
124     precalibration_result.reset()
125     return is_sucessful
126 
127 def insert_exposure_block( basics, daq_state='', block_uuid=None, n_events=0 ):
128     exposure_block.set_attributes( basics, daq_state=daq_state, block_uuid=block_uuid,
        ↪ n_events=n_events )
129     is_sucessful = writer.insert( table='raw.exposure_blocks', names=exposure_block.
        ↪ get_names(), values=exposure_block.get_values() )
130     if not is_sucessful:
131         print '[ISSUE] exposure_block'
132         print '      errors: {0}'.format(misfit.errors)
133         print '      file: {0}'.format(misfit.tarfile)
134         print '      member: {0}'.format(misfit.tarmember)
135     exposure_block.reset()
136     return is_sucessful
137 
138 def insert_event( basics, block_basics=None, daq_state='', block_uuid=None, pixels=[],
    ↪ byteblock={}, zerobias={} ):
139     event.set_attributes( basics )
140     event.set_block_attributes( block_basics, daq_state=daq_state )
141     event.set_block_uuid( block_uuid )
142     event.set_pixels( pixels )
143     event.set_byteblock( byteblock )
144     event.set_zerobias( zerobias )
145     is_sucessful = writer.insert( table='raw.events', names=event.get_names(), values=event.
        ↪ get_values() )
146     if not is_sucessful:
```

```
147            print '[ISSUE] event'
148            print '      errors: {0}'.format(misfit.errors)
149            print '      file: {0}'.format(misfit.tarfile)
150            print '      member: {0}'.format(misfit.tarmember)
151        event.reset()
152        return is_sucessful
```

Listing C.24: Cassandra Keyspace RunConfig

(src/ingest/Cassandra/raw_keyspace/RunConfig.py)

```
"""`run_configs` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def clear(self):
        self.device_id     = None # varchar
        self.submit_time   = None # varint
        self.tarfile       = None # varchar
        self.tarmember     = None # varchar
        self.host          = None # varchar
        self.user_id       = None # varint
        self.app_code      = None # varchar
        self.remote_addr   = None # inet
        self.reset()

    def reset(self):
        # appears as id / id_hi in Google protobuf
        # appears as run_id / run_id_hi in Cassandra
        self.id            = None # varint
        self.id_hi         = None # varint

        self.start_time    = None # varint
        self.crayfis_build = None # varchar
        self.hw_params     = None # varchar
        self.os_params     = None # varchar
```

```
        self.camera_params = None # varchar
        self.camera_id     = None # varint
        if self.__debug_mode: print '[raw.run_config] reset'

    def get_names(self):
        # must be in same order as get_values()
        names = ''
        if self.device_id     is not None: names += 'device_id, '
        if self.submit_time   is not None: names += 'submit_time, '
        if self.tarfile       is not None: names += 'tarfile, '
        if self.tarmember     is not None: names += 'tarmember, '
        if self.host          is not None: names += 'host, '
        if self.user_id       is not None: names += 'user_id, '
        if self.app_code      is not None: names += 'app_code, '
        if self.remote_addr   is not None: names += 'remote_addr, '
        if self.id            is not None: names += 'run_id, '
        if self.id_hi         is not None: names += 'run_id_hi, '
        if self.start_time    is not None: names += 'start_time, '
        if self.crayfis_build is not None: names += 'crayfis_build, '
        if self.hw_params     is not None: names += 'hw_params, '
        if self.os_params     is not None: names += 'os_params, '
        if self.camera_params is not None: names += 'camera_params, '
        if self.camera_id     is not None: names += 'camera_id, '
        if names != '': names = names[:-2]
        if self.__debug_mode: print '[raw.run_config] names: ' + names
        return names

    def get_values(self):
        # must be in same order as get_names()
        values = ''
        if self.device_id     is not None: values += compose.varchar(self.device_id)     + ', '
        if self.submit_time   is not None: values += str(self.submit_time)              + ', '
        if self.tarfile       is not None: values += compose.varchar(self.tarfile)       + ', '
        if self.tarmember     is not None: values += compose.varchar(self.tarmember)     + ', '
        if self.host          is not None: values += compose.varchar(self.host)          + ', '
```

```
        if self.user_id       is not None: values += str(self.user_id)                 + ',
            ↪  '
        if self.app_code      is not None: values += compose.varchar(self.app_code)      + '
            ↪ , '
        if self.remote_addr   is not None: values += compose.inet(self.remote_addr)      + '
            ↪ , '
        if self.id            is not None: values += str(self.id)                      + ',
            ↪  '
        if self.id_hi         is not None: values += str(self.id_hi)                   + ',
            ↪  '
        if self.start_time    is not None: values += str(self.start_time)              + ',
            ↪  '
        if self.crayfis_build is not None: values += compose.varchar(self.crayfis_build) + '
            ↪ , '
        if self.hw_params     is not None: values += compose.varchar(self.hw_params)     + '
            ↪ , '
        if self.os_params     is not None: values += compose.varchar(self.os_params)     + '
            ↪ , '
        if self.camera_params is not None: values += compose.varchar(self.camera_params) + '
            ↪ , '
        if self.camera_id     is not None: values += str(self.camera_id)               + ',
            ↪  '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.run_config] values[:100]: ' + values[:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.run_config] metadata set'
        return True

    def set_attributes(self, basics):
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
            except Exception as e:
                print '[raw.run_config] attribute unknown: ' + basic['field'].name
                return False
        if self.__debug_mode: print '[raw.run_config] basics set'
```

```
        return True
```

Listing C.25: Cassandra Keyspace PreCalibrationResult

(src/ingest/Cassandra/raw_keyspace/PreCalibrationResult.py)

```
"""`precalibration_results` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def clear(self):
        self.device_id          = None # varchar
        self.submit_time        = None # varint
        self.tarfile            = None # varchar
        self.tarmember          = None # varchar
        self.host               = None # varchar
        self.user_id            = None # varint
        self.app_code           = None # varchar
        self.remote_addr        = None # inet
        self.reset()

    def reset(self):
        self.run_id             = None # varint
        self.run_id_hi          = None # varint
        self.precal_id          = None # varint
        self.precal_id_hi       = None # varint

        self.start_time         = None # varint
        self.end_time           = None # varint

        self.weights            = None # set<double>
```

```
39
40          self.sample_res_x       = None # varint
41          self.sample_res_y       = None # varint
42          self.interpolation      = None # varint
43          self.battery_temp       = None # varint
44
45          self.compressed_weights = None # varchar
46          self.compressed_format  = None # varchar
47
48          self.second_hist        = None # set<varint>
49          self.hotcell            = None # set<varint>
50          self.res_x              = None # varint
51          if self.__debug_mode: print '[raw.precalibration_result] reset'
52
53      def get_names(self):
54          # must be same order as get_values()
55          names = ''
56          if self.device_id          is not None: names += 'device_id, '
57          if self.submit_time        is not None: names += 'submit_time, '
58          if self.tarfile            is not None: names += 'tarfile, '
59          if self.tarmember          is not None: names += 'tarmember, '
60          if self.host               is not None: names += 'host, '
61          if self.user_id            is not None: names += 'user_id, '
62          if self.app_code           is not None: names += 'app_code, '
63          if self.remote_addr        is not None: names += 'remote_addr, '
64          if self.run_id             is not None: names += 'run_id, '
65          if self.run_id_hi          is not None: names += 'run_id_hi, '
66          if self.precal_id          is not None: names += 'precal_id, '
67          if self.precal_id_hi       is not None: names += 'precal_id_hi, '
68          if self.start_time         is not None: names += 'start_time, '
69          if self.end_time           is not None: names += 'end_time, '
70          if self.weights            is not None: names += 'weights, '
71          if self.sample_res_x       is not None: names += 'sample_res_x, '
72          if self.sample_res_y       is not None: names += 'sample_res_y, '
73          if self.interpolation      is not None: names += 'interpolation, '
74          if self.battery_temp       is not None: names += 'battery_temp, '
75          if self.compressed_weights is not None: names += 'compressed_weights, '
76          if self.compressed_format  is not None: names += 'compressed_format, '
77          if self.second_hist        is not None: names += 'second_hist, '
78          if self.hotcell            is not None: names += 'hotcell, '
79          if self.res_x              is not None: names += 'res_x, '
```

```
        if names != '': names = names[:-2]
        if self.__debug_mode: print '[raw.precalibration_result] names: ' + names
        return names

    def get_values(self):
        # must be same order as get_names()
        values = ''
        if self.device_id          is not None: values += compose.varchar(self.device_id) + ', '
        if self.submit_time        is not None: values += str(self.submit_time) + ', '
        if self.tarfile            is not None: values += compose.varchar(self.tarfile) + ', '
        if self.tarmember          is not None: values += compose.varchar(self.tarmember) + ', '
        if self.host               is not None: values += compose.varchar(self.host) + ', '
        if self.user_id            is not None: values += str(self.user_id) + ', '
        if self.app_code           is not None: values += compose.varchar(self.app_code) + ', '
        if self.remote_addr        is not None: values += compose.inet(self.remote_addr) + ', '
        if self.run_id             is not None: values += str(self.run_id) + ', '
        if self.run_id_hi          is not None: values += str(self.run_id_hi) + ', '
        if self.precal_id          is not None: values += str(self.precal_id) + ', '
        if self.precal_id_hi       is not None: values += str(self.precal_id_hi) + ', '
        if self.start_time         is not None: values += str(self.start_time) + ', '
        if self.end_time           is not None: values += str(self.end_time) + ', '
        if self.weights            is not None: values += compose.set_numeric(self.weights) + ', '
        if self.sample_res_x       is not None: values += str(self.sample_res_x) + ', '
        if self.sample_res_y       is not None: values += str(self.sample_res_y) + ', '
```

```
        if self.interpolation      is not None: values += str(self.interpolation)
            ↪                 + ', '
        if self.battery_temp       is not None: values += str(self.battery_temp)
            ↪                  + ', '
        if self.compressed_weights is not None: values += compose.varchar(self.
            ↪ compressed_weights) + ', '
        if self.compressed_format  is not None: values += compose.varchar(self.
            ↪ compressed_format)  + ', '
        if self.second_hist        is not None: values += compose.set_numeric(self.
            ↪ second_hist)    + ', '
        if self.hotcell            is not None: values += compose.set_numeric(self.hotcell)
            ↪        + ', '
        if self.res_x              is not None: values += str(self.res_x)
            ↪                          + ', '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.precalibration_result] values[:100]: ' + values
            ↪ [:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.precalibration_result] metadata set'
        return True

    def set_attributes(self, basics, compressed_weights=None ):
        self.compressed_weights = compressed_weights
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
            except Exception as e:
                print '[raw.precalibration_result] attribute unknown: ' + basic['field'].
                    ↪ name
                return False
        if self.__debug_mode: print '[raw.precalibration_result] basics set'
        return True
```

Listing C.26: Cassandra Keyspace CalibrationResult

(src/ingest/Cassandra/raw_keyspace/CalibrationResult.py)

```
"""`calibration_results` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def clear(self):
        self.device_id     = None # varchar
        self.submit_time   = None # varint
        self.tarfile       = None # varchar
        self.tarmember     = None # varchar
        self.host          = None # varchar
        self.user_id       = None # varint
        self.app_code      = None # varchar
        self.remote_addr   = None # inet
        self.reset()

    def reset(self):
        self.run_id        = None # varchar (usually arrives as a UUID..?)
        self.run_id_hi     = None # varint

        self.start_time    = None # varint
        self.end_time      = None # varint

        self.hist_pixel    = None # set<varint>
        self.hist_l2pixel  = None # set<varint>
        self.hist_maxpixel = None # set<varint>
```

```
        self.hist_numpixel = None # set<varint>
        if self.__debug_mode: print '[raw.calibration_result] reset'

    def get_names(self):
        # must be same order as get_values()
        names = ''
        if self.device_id     is not None: names += 'device_id, '
        if self.submit_time   is not None: names += 'submit_time, '
        if self.tarfile       is not None: names += 'tarfile, '
        if self.tarmember     is not None: names += 'tarmember, '
        if self.host          is not None: names += 'host, '
        if self.user_id       is not None: names += 'user_id, '
        if self.app_code      is not None: names += 'app_code, '
        if self.remote_addr   is not None: names += 'remote_addr, '
        if self.run_id        is not None: names += 'run_id, '
        if self.run_id_hi     is not None: names += 'run_id_hi, '
        if self.start_time    is not None: names += 'start_time, '
        if self.end_time      is not None: names += 'end_time, '
        if self.hist_pixel    is not None: names += 'hist_pixel, '
        if self.hist_l2pixel  is not None: names += 'hist_l2pixel, '
        if self.hist_maxpixel is not None: names += 'hist_maxpixel, '
        if self.hist_numpixel is not None: names += 'hist_numpixel, '
        if names != '': names = names[:-2]
        if self.__debug_mode: print '[raw.calibration_result] names: ' + names
        return names

    def get_values(self):
        # must be same order as get_names()
        values = ''
        if self.device_id     is not None: values += compose.varchar(self.device_id)
            ↪          + ', '
        if self.submit_time   is not None: values += str(self.submit_time)
            ↪ + ', '
        if self.tarfile       is not None: values += compose.varchar(self.tarfile)
            ↪            + ', '
        if self.tarmember     is not None: values += compose.varchar(self.tarmember)
            ↪          + ', '
        if self.host          is not None: values += compose.varchar(self.host)
            ↪               + ', '
        if self.user_id       is not None: values += str(self.user_id)
            ↪ + ', '
```

```
        if self.app_code      is not None: values += compose.varchar(self.app_code)
            ↪          + ', '
        if self.remote_addr   is not None: values += compose.inet(self.remote_addr)
            ↪          + ', '
        if self.run_id        is not None: values += compose.varchar(self.run_id)
            ↪            + ', '
        if self.run_id_hi     is not None: values += str(self.run_id_hi)
            ↪ + ', '
        if self.start_time    is not None: values += str(self.start_time)
            ↪ + ', '
        if self.end_time      is not None: values += str(self.end_time)
            ↪ + ', '
        if self.hist_pixel    is not None: values += compose.set_numeric(self.hist_pixel)
            ↪    + ', '
        if self.hist_l2pixel  is not None: values += compose.set_numeric(self.hist_l2pixel)
            ↪  + ', '
        if self.hist_maxpixel is not None: values += compose.set_numeric(self.hist_maxpixel)
            ↪  + ', '
        if self.hist_numpixel is not None: values += compose.set_numeric(self.hist_numpixel)
            ↪  + ', '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.calibration_result] values[:100]: ' + values[:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.calibration_result] metadata set'
        return True

    def set_attributes(self, basics):
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
            except Exception as e:
                print '[raw.calibration_result] attribute unknown: ' + basic['field'].name
                return False
        if self.__debug_mode: print '[raw.calibration_result] basics set'
        return True
```

Listing C.27: Cassandra Keyspace ExposureBlock

(src/ingest/Cassandra/raw_keyspace/ExposureBlock.py)

```
"""`exposure_blocks` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def clear(self):
        self.device_id        = None # varchar
        self.submit_time      = None # varint
        self.tarfile          = None # varchar
        self.tarmember        = None # varchar
        self.host             = None # varchar
        self.user_id          = None # varint
        self.app_code         = None # varchar
        self.remote_addr      = None # inet
        self.reset()

    def reset(self):
        self.precal_id        = None # varint
        self.precal_id_hi     = None # varint

        self.start_time       = None # varint
        self.end_time         = None # varint
        self.start_time_nano  = None # varint
        self.end_time_nano    = None # varint
        self.start_time_ntp   = None # varint
        self.end_time_ntp     = None # varint
```

```
39
40          self.gps_lat          = None # double
41          self.gps_lon          = None # double
42          self.gps_altitude     = None # double
43          self.gps_accuracy     = None # double
44          self.gps_fixtime      = None # varint
45          self.gps_fixtime_nano = None # varint
46
47          self.battery_temp     = None # varint
48          self.battery_end_temp = None # varint
49          self.daq_state        = None # varchar
50          self.res_x            = None # varint
51          self.res_y            = None # varint
52
53          self.L1_thresh        = None # varint
54          self.L2_thresh        = None # varint
55          self.L0_conf          = None # varchar
56          self.L1_conf          = None # varchar
57          self.L2_conf          = None # varchar
58          self.L0_processed     = None # varint
59          self.L1_processed     = None # varint
60          self.L2_processed     = None # varint
61          self.L0_pass          = None # varint
62          self.L1_pass          = None # varint
63          self.L2_pass          = None # varint
64          self.L0_skip          = None # varint
65          self.L1_skip          = None # varint
66          self.L2_skip          = None # varint
67          self.frames_dropped   = None # varint
68
69          self.hist             = None # set<varint>
70          self.xbn              = None # varint
71          self.aborted          = None # boolean
72
73          self.block_uuid       = None # varchar
74          self.n_events         = None # varint
75          if self.__debug_mode: print '[raw.exposure_block] reset'
76
77      def get_names(self):
78          # must be in same order as get_values()
79          names = ''
```

```
        if self.device_id        is not None: names += 'device_id, '
        if self.submit_time      is not None: names += 'submit_time, '
        if self.tarfile          is not None: names += 'tarfile, '
        if self.tarmember        is not None: names += 'tarmember, '
        if self.host             is not None: names += 'host, '
        if self.user_id          is not None: names += 'user_id, '
        if self.app_code         is not None: names += 'app_code, '
        if self.remote_addr      is not None: names += 'remote_addr, '
        if self.precal_id        is not None: names += 'precal_id, '
        if self.precal_id_hi     is not None: names += 'precal_id_hi, '
        if self.start_time       is not None: names += 'start_time, '
        if self.end_time         is not None: names += 'end_time, '
        if self.start_time_nano  is not None: names += 'start_time_nano, '
        if self.end_time_nano    is not None: names += 'end_time_nano, '
        if self.start_time_ntp   is not None: names += 'start_time_ntp, '
        if self.end_time_ntp     is not None: names += 'end_time_ntp, '
        #if self.gps_lat          is not None: names += 'gps_lat, '
        #if self.gps_lon          is not None: names += 'gps_lon, '
        #if self.gps_altitude     is not None: names += 'gps_altitude, '
        names += 'gps_lat, '
        names += 'gps_lon, '
        names += 'gps_altitude, '
        if self.gps_accuracy     is not None: names += 'gps_accuracy, '
        if self.gps_fixtime      is not None: names += 'gps_fixtime, '
        if self.gps_fixtime_nano is not None: names += 'gps_fixtime_nano, '
        if self.battery_temp     is not None: names += 'battery_temp, '
        if self.battery_end_temp is not None: names += 'battery_end_temp, '
        if self.daq_state        is not None: names += 'daq_state, '
        if self.res_x            is not None: names += 'res_x, '
        if self.res_y            is not None: names += 'res_y, '
        if self.L1_thresh        is not None: names += 'L1_thresh, '
        if self.L2_thresh        is not None: names += 'L2_thresh, '
        if self.L0_conf          is not None: names += 'L0_conf, '
        if self.L1_conf          is not None: names += 'L1_conf, '
        if self.L2_conf          is not None: names += 'L2_conf, '
        if self.L0_processed     is not None: names += 'L0_processed, '
        if self.L1_processed     is not None: names += 'L1_processed, '
        if self.L2_processed     is not None: names += 'L2_processed, '
        if self.L0_pass          is not None: names += 'L0_pass, '
        if self.L1_pass          is not None: names += 'L1_pass, '
        if self.L2_pass          is not None: names += 'L2_pass, '
```

```
        if self.L0_skip          is not None: names += 'L0_skip, '
        if self.L1_skip          is not None: names += 'L1_skip, '
        if self.L2_skip          is not None: names += 'L2_skip, '
        if self.frames_dropped   is not None: names += 'frames_dropped, '
        if self.hist             is not None: names += 'hist, '
        if self.xbn              is not None: names += 'xbn, '
        if self.aborted          is not None: names += 'aborted, '
        if self.block_uuid       is not None: names += 'block_uuid, '
        if self.n_events         is not None: names += 'n_events, '
        if names != '': names = names[:-2]
        if self.__debug_mode: print '[raw.exposure_block] names: ' + names
        return names

    def get_values(self):
        # must be in same order as get_names()
        values = ''
        if self.device_id        is not None: values += compose.varchar(self.device_id) + ', '
        if self.submit_time      is not None: values += str(self.submit_time)           + ', '
        if self.tarfile          is not None: values += compose.varchar(self.tarfile) + ', '
        if self.tarmember        is not None: values += compose.varchar(self.tarmember) + ', '
        if self.host             is not None: values += compose.varchar(self.host) + ', '
        if self.user_id          is not None: values += str(self.user_id)               + ', '
        if self.app_code         is not None: values += compose.varchar(self.app_code) + ', '
        if self.remote_addr      is not None: values += compose.inet(self.remote_addr) + ', '
        if self.precal_id        is not None: values += str(self.precal_id)             + ', '
        if self.precal_id_hi     is not None: values += str(self.precal_id_hi)          + ', '
        if self.start_time       is not None: values += str(self.start_time)            + ', '
        if self.end_time         is not None: values += str(self.end_time)              + ', '
```

```
149         if self.start_time_nano  is not None: values += str(self.start_time_nano)          +
            ↪  ', '
150         if self.end_time_nano    is not None: values += str(self.end_time_nano)            +
            ↪  ', '
151         if self.start_time_ntp   is not None: values += str(self.start_time_ntp)           +
            ↪  ', '
152         if self.end_time_ntp     is not None: values += str(self.end_time_ntp)             +
            ↪  ', '
153         if self.gps_lat          is not None: values += str(self.gps_lat)                  +
            ↪  ', '
154         else: values += '-1, ' # used as primary key so needs to be present
155         if self.gps_lon          is not None: values += str(self.gps_lon)                  +
            ↪  ', '
156         else: values += '-1, '
157         if self.gps_altitude     is not None: values += str(self.gps_altitude)             +
            ↪  ', '
158         else: values += '-1, '
159         if self.gps_accuracy     is not None: values += str(self.gps_accuracy)             +
            ↪  ', '
160         if self.gps_fixtime      is not None: values += str(self.gps_fixtime)              +
            ↪  ', '
161         if self.gps_fixtime_nano is not None: values += str(self.gps_fixtime_nano)         +
            ↪  ', '
162         if self.battery_temp     is not None: values += str(self.battery_temp)             +
            ↪  ', '
163         if self.battery_end_temp is not None: values += str(self.battery_end_temp)         +
            ↪  ', '
164         if self.daq_state        is not None: values += compose.varchar(self.daq_state)
            ↪ + ', '
165         if self.res_x            is not None: values += str(self.res_x)                    +
            ↪  ', '
166         if self.res_y            is not None: values += str(self.res_y)                    +
            ↪  ', '
167         if self.L1_thresh        is not None: values += str(self.L1_thresh)                +
            ↪  ', '
168         if self.L2_thresh        is not None: values += str(self.L2_thresh)                +
            ↪  ', '
169         if self.L0_conf          is not None: values += compose.varchar(self.L0_conf)
            ↪ + ', '
170         if self.L1_conf          is not None: values += compose.varchar(self.L1_conf)
            ↪ + ', '
```

```
        if self.L2_conf          is not None: values += compose.varchar(self.L2_conf) + ', '
        if self.L0_processed     is not None: values += str(self.L0_processed)        + ', '
        if self.L1_processed     is not None: values += str(self.L1_processed)        + ', '
        if self.L2_processed     is not None: values += str(self.L2_processed)        + ', '
        if self.L0_pass          is not None: values += str(self.L0_pass)             + ', '
        if self.L1_pass          is not None: values += str(self.L1_pass)             + ', '
        if self.L2_pass          is not None: values += str(self.L2_pass)             + ', '
        if self.L0_skip          is not None: values += str(self.L0_skip)             + ', '
        if self.L1_skip          is not None: values += str(self.L1_skip)             + ', '
        if self.L2_skip          is not None: values += str(self.L2_skip)             + ', '
        if self.frames_dropped   is not None: values += str(self.frames_dropped)      + ', '
        if self.hist             is not None: values += compose.set_numeric(self.hist) + ', '
        if self.xbn              is not None: values += str(self.xbn)                 + ', '
        if self.aborted          is not None: values += compose.boolean(self.aborted) + ', '
        if self.block_uuid       is not None: values += str(self.block_uuid)          + ', '
        if self.n_events         is not None: values += str(self.n_events)            + ', '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.exposure_block] values[:100]: ' + values[:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.exposure_block] metadata set'
```

```
        return True

    def set_attributes(self, basics, daq_state='', block_uuid=None, n_events=0 ):
        self.daq_state  = daq_state
        self.block_uuid = block_uuid
        self.n_events   = n_events
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
            except Exception as e:
                print '[raw.exposure_block] attribute unknown: ' + basic['field'].name
                return False
        if self.__debug_mode: print '[raw.exposure_block] basics set'
        return True
```

Listing C.28: Cassandra Keyspace Event

(src/ingest/Cassandra/raw_keyspace/Event.py)

```
"""`events` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def load(self):
        pass

    def clear(self):
        self.device_id          = None # varchar
        self.submit_time        = None # varint
        self.tarfile            = None # varchar
        self.tarmember          = None # varchar
        self.host               = None # varchar
        self.user_id            = None # varint
        self.app_code           = None # varchar
        self.remote_addr        = None # inet
        self.reset()

    def reset(self):
        self.run_id             = None # varint
        self.run_id_hi          = None # varint
        self.precal_id          = None # varint
        self.precal_id_hi       = None # varint

        self.start_time         = None # varint
```

```
39          self.end_time           = None # varint
40          self.start_time_nano    = None # varint
41          self.end_time_nano      = None # varint
42          self.start_time_ntp     = None # varint
43          self.end_time_ntp       = None # varint
44
45          self.daq_state          = None # varchar
46          self.res_x              = None # varint
47          self.res_y              = None # varint
48
49          self.L1_thresh          = None # varint
50          self.L2_thresh          = None # varint
51          self.L0_conf            = None # varchar
52          self.L1_conf            = None # varchar
53          self.L2_conf            = None # varchar
54          self.L0_processed       = None # varint
55          self.L1_processed       = None # varint
56          self.L2_processed       = None # varint
57          self.L0_pass            = None # varint
58          self.L1_pass            = None # varint
59          self.L2_pass            = None # varint
60          self.L0_skip            = None # varint
61          self.L1_skip            = None # varint
62          self.L2_skip            = None # varint
63          self.frames_dropped     = None # varint
64          self.aborted            = None # boolean
65
66          self.timestamp          = None # varint
67          self.timestamp_nano     = None # varint
68          self.timestamp_ntp      = None # varint
69          self.timestamp_target   = None # varint
70
71          self.gps_lat            = None # double
72          self.gps_lon            = None # double
73          self.gps_altitude       = None # double
74          self.gps_accuracy       = None # double
75          self.gps_fixtime        = None # varint
76          self.gps_fixtime_nano   = None # varint
77
78          self.battery_start_temp = None # varint
79          self.battery_temp       = None # varint
```

```
80          self.battery_end_temp   = None # varint
81          self.pressure           = None # double
82          self.orient_x           = None # double
83          self.orient_y           = None # double
84          self.orient_z           = None # double
85
86          self.avg                = None # double
87          self.std                = None # double
88
89          self.hist               = None # set<varint>
90          self.xbn                = None # varint
91
92          self.block_uuid         = None # varchar
93          self.byte_block         = None # frozen <byteblock>
94          self.pixels             = None # set<frozen <pixel>>
95          self.zero_bias          = None # frozen <square>
96          if self.__debug_mode: print '[raw.event] cleared'
97
98      def get_names(self):
99          # must be in same order as get_values()
100         names = ''
101         if self.device_id          is not None: names += 'device_id, '
102         if self.submit_time        is not None: names += 'submit_time, '
103         if self.tarfile            is not None: names += 'tarfile, '
104         if self.tarmember          is not None: names += 'tarmember, '
105         if self.host               is not None: names += 'host, '
106         if self.user_id            is not None: names += 'user_id, '
107         if self.app_code           is not None: names += 'app_code, '
108         if self.remote_addr        is not None: names += 'remote_addr, '
109         if self.run_id             is not None: names += 'run_id, '
110         if self.run_id_hi          is not None: names += 'run_id_hi, '
111         if self.precal_id          is not None: names += 'precal_id, '
112         if self.precal_id_hi       is not None: names += 'precal_id_hi, '
113         if self.start_time         is not None: names += 'start_time, '
114         if self.end_time           is not None: names += 'end_time, '
115         if self.start_time_nano    is not None: names += 'start_time_nano, '
116         if self.end_time_nano      is not None: names += 'end_time_nano, '
117         if self.start_time_ntp     is not None: names += 'start_time_ntp, '
118         if self.end_time_ntp       is not None: names += 'end_time_ntp, '
119         if self.daq_state          is not None: names += 'daq_state, '
120         if self.res_x              is not None: names += 'res_x, '
```

```
121         if self.res_y              is not None: names += 'res_y, '
122         if self.L1_thresh          is not None: names += 'L1_thresh, '
123         if self.L2_thresh          is not None: names += 'L2_thresh, '
124         if self.L0_conf            is not None: names += 'L0_conf, '
125         if self.L1_conf            is not None: names += 'L1_conf, '
126         if self.L2_conf            is not None: names += 'L2_conf, '
127         if self.L0_processed       is not None: names += 'L0_processed, '
128         if self.L1_processed       is not None: names += 'L1_processed, '
129         if self.L2_processed       is not None: names += 'L2_processed, '
130         if self.L0_pass            is not None: names += 'L0_pass, '
131         if self.L1_pass            is not None: names += 'L1_pass, '
132         if self.L2_pass            is not None: names += 'L2_pass, '
133         if self.L0_skip            is not None: names += 'L0_skip, '
134         if self.L1_skip            is not None: names += 'L1_skip, '
135         if self.L2_skip            is not None: names += 'L2_skip, '
136         if self.frames_dropped     is not None: names += 'frames_dropped, '
137         if self.aborted            is not None: names += 'aborted, '
138         if self.timestamp          is not None: names += 'timestamp, '
139         if self.timestamp_nano     is not None: names += 'timestamp_nano, '
140         if self.timestamp_ntp      is not None: names += 'timestamp_ntp, '
141         if self.timestamp_target   is not None: names += 'timestamp_target, '
142         #if self.gps_lat            is not None: names += 'gps_lat, '
143         #if self.gps_lon            is not None: names += 'gps_lon, '
144         #if self.gps_altitude       is not None: names += 'gps_altitude, '
145         names += 'gps_lat, ' # used as primary key, must be present
146         names += 'gps_lon, '
147         names += 'gps_altitude, '
148         if self.gps_accuracy       is not None: names += 'gps_accuracy, '
149         if self.gps_fixtime        is not None: names += 'gps_fixtime, '
150         if self.gps_fixtime_nano   is not None: names += 'gps_fixtime_nano, '
151         if self.battery_start_temp is not None: names += 'battery_start_temp, '
152         if self.battery_temp       is not None: names += 'battery_temp, '
153         if self.battery_end_temp   is not None: names += 'battery_end_temp, '
154         if self.pressure           is not None: names += 'pressure, '
155         if self.orient_x           is not None: names += 'orient_x, '
156         if self.orient_y           is not None: names += 'orient_y, '
157         if self.orient_z           is not None: names += 'orient_z, '
158         if self.avg                is not None: names += 'avg, '
159         if self.std                is not None: names += 'std, '
160         if self.hist               is not None: names += 'hist, '
161         if self.xbn                is not None: names += 'xbn, '
```

```
162         if self.block_uuid          is not None: names += 'block_uuid, '
163         if self.byte_block          is not None: names += 'byte_block, '
164         if self.pixels              is not None and len(self.pixels) > 0: names += 'pixels, '
165         if self.zero_bias           is not None: names += 'zero_bias, '
166         if names != '': names = names[:-2]
167         if self.__debug_mode: print '[raw.event] names: ' + names
168         return names
169
170     def get_values(self):
171         # must be in same order as get_names()
172         values = ''
173         if self.device_id           is not None: values += compose.varchar(self.device_id)
            ↪       + ', '
174         if self.submit_time         is not None: values += str(self.submit_time)
            ↪                + ', '
175         if self.tarfile             is not None: values += compose.varchar(self.tarfile)
            ↪         + ', '
176         if self.tarmember           is not None: values += compose.varchar(self.tarmember)
            ↪       + ', '
177         if self.host                is not None: values += compose.varchar(self.host)
            ↪            + ', '
178         if self.user_id             is not None: values += str(self.user_id)
            ↪                    + ', '
179         if self.app_code            is not None: values += compose.varchar(self.app_code)
            ↪        + ', '
180         if self.remote_addr         is not None: values += compose.inet(self.remote_addr)
            ↪        + ', '
181         if self.run_id              is not None: values += str(self.run_id)
            ↪                    + ', '
182         if self.run_id_hi           is not None: values += str(self.run_id_hi)
            ↪                 + ', '
183         if self.precal_id           is not None: values += str(self.precal_id)
            ↪                 + ', '
184         if self.precal_id_hi        is not None: values += str(self.precal_id_hi)
            ↪                + ', '
185         if self.start_time          is not None: values += str(self.start_time)
            ↪                 + ', '
186         if self.end_time            is not None: values += str(self.end_time)
            ↪                   + ', '
187         if self.start_time_nano     is not None: values += str(self.start_time_nano)
            ↪            + ', '
```

```
        if self.end_time_nano      is not None: values += str(self.end_time_nano)
        ↪              + ', '
        if self.start_time_ntp     is not None: values += str(self.start_time_ntp)
        ↪             + ', '
        if self.end_time_ntp       is not None: values += str(self.end_time_ntp)
        ↪               + ', '
        if self.daq_state          is not None: values += compose.varchar(self.daq_state)
        ↪       + ', '
        if self.res_x              is not None: values += str(self.res_x)
        ↪                       + ', '
        if self.res_y              is not None: values += str(self.res_y)
        ↪                       + ', '
        if self.L1_thresh          is not None: values += str(self.L1_thresh)
        ↪                  + ', '
        if self.L2_thresh          is not None: values += str(self.L2_thresh)
        ↪                  + ', '
        if self.L0_conf            is not None: values += compose.varchar(self.L0_conf)
        ↪         + ', '
        if self.L1_conf            is not None: values += compose.varchar(self.L1_conf)
        ↪         + ', '
        if self.L2_conf            is not None: values += compose.varchar(self.L2_conf)
        ↪         + ', '
        if self.L0_processed       is not None: values += str(self.L0_processed)
        ↪               + ', '
        if self.L1_processed       is not None: values += str(self.L1_processed)
        ↪               + ', '
        if self.L2_processed       is not None: values += str(self.L2_processed)
        ↪               + ', '
        if self.L0_pass            is not None: values += str(self.L0_pass)
        ↪                    + ', '
        if self.L1_pass            is not None: values += str(self.L1_pass)
        ↪                    + ', '
        if self.L2_pass            is not None: values += str(self.L2_pass)
        ↪                    + ', '
        if self.L0_skip            is not None: values += str(self.L0_skip)
        ↪                    + ', '
        if self.L1_skip            is not None: values += str(self.L1_skip)
        ↪                    + ', '
        if self.L2_skip            is not None: values += str(self.L2_skip)
        ↪                    + ', '
```

```
208         if self.frames_dropped     is not None: values += str(self.frames_dropped)
            ↪             + ', '
209         if self.aborted            is not None: values += compose.boolean(self.aborted)
            ↪         + ', '
210         if self.timestamp          is not None: values += str(self.timestamp)
            ↪                  + ', '
211         if self.timestamp_nano     is not None: values += str(self.timestamp_nano)
            ↪             + ', '
212         if self.timestamp_ntp      is not None: values += str(self.timestamp_ntp)
            ↪              + ', '
213         if self.timestamp_target   is not None: values += str(self.timestamp_target)
            ↪           + ', '
214         if self.gps_lat            is not None: values += str(self.gps_lat)
            ↪                    + ', '
215         else: values += '-1, ' # used as primary key, must be present
216         if self.gps_lon            is not None: values += str(self.gps_lon)
            ↪                    + ', '
217         else: values += '-1, '
218         if self.gps_altitude       is not None: values += str(self.gps_altitude)
            ↪               + ', '
219         else: values += '-1, '
220         if self.gps_accuracy       is not None: values += str(self.gps_accuracy)
            ↪               + ', '
221         if self.gps_fixtime        is not None: values += str(self.gps_fixtime)
            ↪                + ', '
222         if self.gps_fixtime_nano   is not None: values += str(self.gps_fixtime_nano)
            ↪           + ', '
223         if self.battery_start_temp is not None: values += str(self.battery_start_temp)
            ↪         + ', '
224         if self.battery_temp       is not None: values += str(self.battery_temp)
            ↪               + ', '
225         if self.battery_end_temp   is not None: values += str(self.battery_end_temp)
            ↪           + ', '
226         if self.pressure           is not None: values += str(self.pressure)
            ↪                   + ', '
227         if self.orient_x           is not None: values += str(self.orient_x)
            ↪                   + ', '
228         if self.orient_y           is not None: values += str(self.orient_y)
            ↪                   + ', '
229         if self.orient_z           is not None: values += str(self.orient_z)
            ↪                   + ', '
```

```
        if self.avg                 is not None: values += str(self.avg)
            ↪                          + ', '
        if self.std                 is not None: values += str(self.std)
            ↪                          + ', '
        if self.hist                is not None: values += compose.set_numeric(self.hist)
            ↪        + ', '
        if self.xbn                 is not None: values += str(self.xbn)
            ↪                          + ', '
        if self.block_uuid          is not None: values += str(self.block_uuid)
            ↪                 + ', '
        if self.byte_block          is not None: values += compose.byte_block(self.byte_block
            ↪ )   + ', '
        if self.pixels              is not None and len(self.pixels) > 0: values += compose.
            ↪ pixels(self.pixels)           + ', '
        if self.zero_bias           is not None: values += compose.zero_bias(self.zero_bias)
            ↪      + ', '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.event] values[:100]: ' + values[:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.event] metadata set'
        return True

    def set_attributes(self, basics):
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
            except Exception as e:
                print '[raw.event] attribute unknown: ' + basic['field'].name
                return False
        if self.__debug_mode: print '[raw.event] basics set'
        return True

    def set_block_attributes(self, block_basics, daq_state=''):
        for basic in block_basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
```

```
            except Exception as e:
                # it's ok not to denormalize everything
                pass
        self.daq_state = daq_state
        if self.__debug_mode: print '[raw.event] block_basics set'
        return True


    def set_block_uuid(self, block_uuid):
        self.block_uuid = block_uuid

    def set_pixels(self, pixels):
        self.pixels = pixels

    def set_byteblock(self, byte_block):
        self.byte_block = byte_block

    def set_zerobias(self, zero_bias):
        self.zero_bias = zero_bias
```

Listing C.29: Cassandra Keyspace Misfit

(src/ingest/Cassandra/raw_keyspace/Misfit.py)

```
"""`misfits` Cassandra Football

Acts as the interface between Google protobuf
and Cassandra.  Updated by set_() functions.
Cassandra-compatable strings are returned by
get_() functions.

"""

from ..writer import compose as compose

class Football:

    def __init__(self):
        self.__debug_mode = False
        self.clear()

    def add_error(self, error_string):
        if self.errors is not None:
            self.errors += '; ' + error_string
        else:
            self.errors = error_string
        if self.__debug_mode: print '[raw.misfit] error added: "' + error_string + '"'

    def clear(self):
        self.errors       = None # varchar
        self.device_id    = None # varchar
        self.submit_time  = None # varint
        self.tarfile      = None # varchar
        self.tarmember    = None # varchar
        self.host         = None # varchar
        self.message      = None # blob
        if self.__debug_mode: print '[raw.misfit] cleared'

    def get_names(self):
        # must be same order as get_values()
        names = ''
        if self.errors      is not None: names += 'errors, '
```

```
        if self.device_id   is not None: names += 'device_id, '
        if self.submit_time is not None: names += 'submit_time, '
        if self.tarfile     is not None: names += 'tarfile, '
        if self.tarmember   is not None: names += 'tarmember, '
        if self.host        is not None: names += 'host, '
        if self.message     is not None: names += 'message, '
        if names != '': names = names[:-2]
        if self.__debug_mode: print '[raw.misfit] names: ' + names
        return names

    def get_values(self):
        # must be same order as get_names()
        values = ''
        if self.errors      is not None: values += compose.varchar(self.errors)     + ', '
        if self.device_id   is not None: values += compose.varchar(self.device_id)  + ', '
        if self.submit_time is not None: values += str(self.submit_time)           + ', '
        if self.tarfile     is not None: values += compose.varchar(self.tarfile)    + ', '
        if self.tarmember   is not None: values += compose.varchar(self.tarmember)  + ', '
        if self.host        is not None: values += compose.varchar(self.host)       + ', '
        if self.message     is not None: values += compose.blob(self.message)       + ', '
        if values != '': values = values[:-2]
        if self.__debug_mode: print '[raw.misfit] values[:100]: ' + values[:100]
        return values

    def set_metadata(self, host='', tarfile='', tarmember=''):
        self.host      = host
        self.tarfile   = tarfile
        self.tarmember = tarmember
        if self.__debug_mode: print '[raw.misfit] metadata set'
        return True

    def set_serialized(self, serialized_string):
        self.message = serialized_string
        if self.__debug_mode: print '[raw.misfit] serialized message[:100]: ' + repr(
            ↪ serialized_string)[1:101]
        return True

    def set_attributes(self, basics ):
        for basic in basics:
            try:
                setattr( self, basic['field'].name, basic['value'] )
```

```
            except Exception as e:
                print '[raw.misfit] attribute unknown: ' + basic['field'].name
                return False
        if self.__debug_mode: print '[raw.misfit] basics set'
        return True
```

Listing C.30: Cassandra writer module (`src/ingest/Cassandra/writer/__init__.py`)

```
"""Access interface to Cassandra
"""

import writer

def insert( table='', names='', values='' ):
    return writer.insert( table=table, names=names, values=values )
```

Listing C.31: Cassandra writer (`src/ingest/Cassandra/writer/writer.py`)

```
"""Access interface to Cassandra

return True if write sucessful
return False if there is a problem
"""

import crayvault
import init_raw
import compose

import time

__session = None

try:
    __session = crayvault.get_session()
except Exception as e:
    print
    print 'ERROR: failed to connect with crayvault'

def insert( table='', names='', values='' ):
    starttime = time.time()
#    print 'Writing: {0}'.format(table)
#    print '\t{0}...{1}  <=>  {2}...{3}'.format(names[:20], names[-20:], values[:20], values[-20:])
    command  = """INSERT INTO {0} ( {1} ) VALUES ( {2} ) IF NOT EXISTS;""".format( table, names, values )
    try:
        __session.execute( command )
#        print '\tinsertion time: {0:.3} ms'.format( (time.time() - starttime) * 1000. )
    except Exception as e:
        print
        print 'ERROR: {0}'.format(e)
#        print values
#        print
#        print '     INSERT into ' + table + ' ( ' + names + ' )'
#        print '     VALUES ( ' + values + ' ) '
#        print
        return False
    return True
```

Listing C.32: Cassandra writer init (`src/ingest/Cassandra/writer/init_raw.py`)

```
from crayvault import get_session
import sys

__session = get_session()

#-----------------------------------------------------------------------
# KEYSPACE: raw

def clear():
    progress = [ '|', '\\', '--', '/' ]
    i = 0
    print '>> WARNING clearing Cassandra, starting fresh...'
    while (True):
        try:
            __session.execute( 'DROP KEYSPACE IF EXISTS raw' ) #!! clean start
        except Exception as e:
            print '\r>> waiting on Cassandra...{0}'.format(progress[i % 4]),
            sys.stdout.flush()
            i += 1
            continue
        print '\r>> waiting on Cassandra... done.'
        sys.stdout.flush()
        break

#-----------------------------------------------------------------------

def do_it():
    __session.execute( """CREATE KEYSPACE IF NOT EXISTS raw
                        WITH replication = {'class':'SimpleStrategy','replication_factor
                            ↪ ':1};""" )


    # type definitions
    #----------------

    # pixel type def
    __session.execute( """CREATE TYPE IF NOT EXISTS raw.pixel (
                        x               varint,
                        y               varint,
                        val             varint,
```

```
                        adjusted_val     varint,
                        near_max         varint,
                        ave_3            double,
                        ave_5            double );""" )

    # square type def
    __session.execute( """CREATE TYPE IF NOT EXISTS raw.square (
                        x_min            varint,
                        y_min            varint,
                        val              set<varint>,
                        frame_number     varint ); """ )

    # byteblock type def
    __session.execute( """CREATE TYPE IF NOT EXISTS raw.byteblock (
                        x                set<varint>,
                        y                set<varint>,
                        val              set<varint>,
                        side_length      varint );""" )



    # table definitions
    #-----------------


    # misfits table
    __session.execute( """CREATE TABLE IF NOT EXISTS raw.misfits (
                        errors       varchar,
                        device_id    varchar,
                        submit_time  varint,
                        tarfile      varchar,
                        tarmember    varchar,
                        host         varchar,
                        message      blob,
                        PRIMARY KEY ( device_id, submit_time ) );""" )

    # exposure_blocks table
    __session.execute( """CREATE TABLE IF NOT EXISTS raw.exposure_blocks (
                        device_id            varchar,
                        submit_time          varint,
                        tarfile              varchar,
```

```
                    tarmember           varchar,
                    host                varchar,
                    user_id             varint,
                    app_code            varchar,
                    remote_addr         inet,

                    precal_id           varint,
                    precal_id_hi        varint,

                    start_time          varint,
                    end_time            varint,
                    start_time_nano     varint,
                    end_time_nano       varint,
                    start_time_ntp      varint,
                    end_time_ntp        varint,

                    gps_lat             double,
                    gps_lon             double,
                    gps_altitude        double,
                    gps_accuracy        double,
                    gps_fixtime         varint,
                    gps_fixtime_nano    varint,

                    battery_temp        varint,
                    battery_end_temp    varint,
                    daq_state           varchar,
                    res_x               varint,
                    res_y               varint,

                    L1_thresh           varint,
                    L2_thresh           varint,
                    L0_conf             varchar,
                    L1_conf             varchar,
                    L2_conf             varchar,
                    L0_processed        varint,
                    L1_processed        varint,
                    L2_processed        varint,
                    L0_pass             varint,
                    L1_pass             varint,
                    L2_pass             varint,
                    L0_skip             varint,
```

```
                        L1_skip             varint,
                        L2_skip             varint,
                        frames_dropped      varint,

                        hist                set<varint>,
                        xbn                 varint,
                        aborted             boolean,

                        block_uuid          uuid,
                        n_events            varint,

                        PRIMARY KEY ( device_id, block_uuid, start_time, gps_altitude,
                            ↪ gps_lat, gps_lon ) );""" )

    # events table
    __session.execute( """CREATE TABLE IF NOT EXISTS raw.events (
                        device_id           varchar,
                        submit_time         varint,
                        tarfile             varchar,
                        tarmember           varchar,
                        host                varchar,
                        user_id             varint,
                        app_code            varchar,
                        remote_addr         inet,

                        run_id              varint,
                        run_id_hi           varint,
                        precal_id           varint,
                        precal_id_hi        varint,

                        start_time          varint,
                        end_time            varint,
                        start_time_nano     varint,
                        end_time_nano       varint,
                        start_time_ntp      varint,
                        end_time_ntp        varint,

                        timestamp           varint,
                        timestamp_nano      varint,
                        timestamp_ntp       varint,
                        timestamp_target    varint,
```

```
162
163                     gps_lat             double,
164                     gps_lon             double,
165                     gps_altitude        double,
166                     gps_accuracy        double,
167                     gps_fixtime         varint,
168                     gps_fixtime_nano    varint,
169
170                     battery_temp        varint,
171                     pressure            double,
172                     orient_x            double,
173                     orient_y            double,
174                     orient_z            double,
175
176                     daq_state           varchar,
177                     res_x               varint,
178                     res_y               varint,
179                     L1_thresh           varint,
180                     L2_thresh           varint,
181                     L0_conf             varchar,
182                     L1_conf             varchar,
183                     L2_conf             varchar,
184                     L0_processed        varint,
185                     L1_processed        varint,
186                     L2_processed        varint,
187                     L0_pass             varint,
188                     L1_pass             varint,
189                     L2_pass             varint,
190                     L0_skip             varint,
191                     L1_skip             varint,
192                     L2_skip             varint,
193                     frames_dropped      varint,
194                     aborted             boolean,
195                     battery_start_temp  varint,
196                     battery_end_temp    varint,
197
198                     avg                 double,
199                     std                 double,
200
201                     hist                set<varint>,
202                     xbn                 varint,
```

```
203
204                         block_uuid          uuid,
205                         byte_block          frozen <byteblock>,
206                         pixels              set<frozen <pixel>>,
207                         zero_bias           frozen <square>,
208                         PRIMARY KEY ( device_id, block_uuid, timestamp, gps_altitude,
                                ↪ gps_lat, gps_lon ) );""" )
209
210     # run_configs table
211     __session.execute( """CREATE TABLE IF NOT EXISTS raw.run_configs (
212                         device_id           varchar,
213                         submit_time         varint,
214                         tarfile             varchar,
215                         tarmember           varchar,
216                         host                varchar,
217                         user_id             varint,
218                         app_code            varchar,
219                         remote_addr         inet,
220
221                         run_id_hi           varint,
222                         run_id              varint,
223
224                         start_time          varint,
225                         crayfis_build       varchar,
226                         hw_params           varchar,
227                         os_params           varchar,
228                         camera_params       varchar,
229                         camera_id           varint,
230                         PRIMARY KEY ( device_id ) );""" )
231
232     # calibration_results table
233     __session.execute( """CREATE TABLE IF NOT EXISTS raw.calibration_results (
234                         device_id           varchar,
235                         submit_time         varint,
236                         tarfile             varchar,
237                         tarmember           varchar,
238                         host                varchar,
239                         user_id             varint,
240                         app_code            varchar,
241                         remote_addr         inet,
242
```

```
                        run_id              varchar,
                        run_id_hi           varint,

                        start_time          varint,
                        end_time            varint,

                        hist_pixel          set<varint>,
                        hist_l2pixel        set<varint>,
                        hist_maxpixel       set<varint>,
                        hist_numpixel       set<varint>,
                        PRIMARY KEY ( device_id ) );""" ) # (run_id anomalously arrives as
                            ↪ UUID?)

    # precalibration_results table
    __session.execute( """CREATE TABLE IF NOT EXISTS raw.precalibration_results (
                        device_id           varchar,
                        submit_time         varint,
                        tarfile             varchar,
                        tarmember           varchar,
                        host                varchar,
                        user_id             varint,
                        app_code            varchar,
                        remote_addr         inet,

                        run_id              varint,
                        run_id_hi           varint,
                        precal_id           varint,
                        precal_id_hi        varint,

                        start_time          varint,
                        end_time            varint,

                        weights             set<double>,

                        sample_res_x        varint,
                        sample_res_y        varint,
                        interpolation       varint,
                        battery_temp        varint,

                        compressed_weights  varchar,
                        compressed_format   varchar,
```

```
283
284                                 second_hist          set<varint>,
285                                 hotcell              set<varint>,
286                                 res_x                varint,
287                                 PRIMARY KEY ( device_id ) );""" )
```

Listing C.33: Cassandra writer compose (`src/ingest/Cassandra/writer/compose.py`)

```
"""Format conversion for Cassandra data types
"""

def varchar( varchar ):
    string = repr(varchar)
    if string[0].lower() == 'u':
        string = string[2:-1]
    else:
        string = string[1:-1]
    return "'{0}'".format( string.replace("'","''") )

def inet( inet ):
    return varchar( inet )

def blob( blob ):
    return 'textAsBlob({0})'.format( varchar( blob ) )

def boolean( boolean ):
    return str(boolean).lower()

def set_numeric( array ):
    string = '{ '
    for a in array:
        string += str(a) + ', '
    string = string[:-2] + ' }'
    return string

def byte_block( block ):
    string  = '{ '
    if 'x'           in block: string += 'x: {0}, '.format( set_numeric( block['x'] ) )
    if 'y'           in block: string += 'y: {0}, '.format( set_numeric( block['y'] ) )
    if 'val'         in block: string += 'val: {0}, '.format( set_numeric( block['val'] ) )
    if 'side_length' in block: string += 'side_length: {0}, '.format( block['side_length'] )
    string = string[:-2] + ' }'
    return string

def zero_bias( square ):
    if square['x_min'] == None: square['x_min'] = -1
    if square['y_min'] == None: square['y_min'] = -1
    if square['frame_number'] == None: square['frame_number'] = -1
```

```
    string  = '{ '
    if 'x_min'        in square: string += 'x_min: {0}, '.format( square['x_min'] )
    if 'y_min'        in square: string += 'y_min: {0}, '.format( square['y_min'] )
    if 'val'          in square: string += 'val: {0}, '.format( set_numeric( square['val'] ) )
    if 'frame_number' in square: string += 'frame_number: {0}, '.format( square['frame_number'] )
    string = string[:-2] + ' }'
    return string

def pixels( pixels ):
    string = '{ '
    for n, pixel in enumerate(pixels):
        string += '{ '

        if 'x'            in pixel: string += 'x: {0}, '.format( pixel['x'] )
        if 'y'            in pixel: string += 'y: {0}, '.format( pixel['y'] )
        if 'val'          in pixel: string += 'val: {0}, '.format( pixel['val'] )
        if 'adjusted_val' in pixel  and pixel['adjusted_val'] is not None: string += 'adjusted_val: {0}, '.format( pixel['adjusted_val'] )
        if 'near_max'     in pixel: string += 'near_max: {0}, '.format( pixel['near_max'] )
        if 'ave_3'        in pixel: string += 'ave_3: {0}, '.format( pixel['ave_3'] )
        if 'ave_5'        in pixel: string += 'ave_5: {0}, '.format( pixel['ave_5'] )
        string = string[:-2] + ' }, '
    string = string[:-2] + ' }'
    return string
```

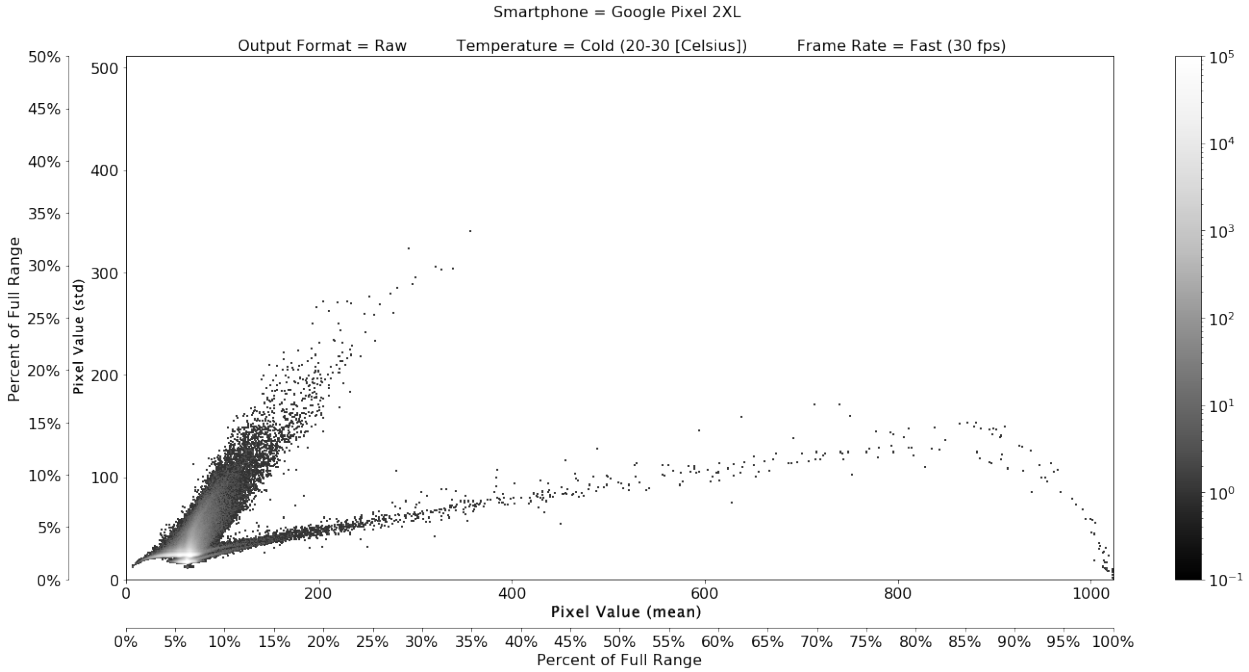
Listing C.34: Cassandra writer access (`src/ingest/Cassandra/writer/crayvault.py`)

```
"""CRAYFIS Cassandra Database
"""

# get server IP address
import docker
__client = docker.from_env()
__server = __client.containers.get('crayvault')
__ipaddr = __server.attrs['NetworkSettings']['IPAddress']

# connect to the server
from cassandra.cluster import Cluster

__cluster = Cluster([__ipaddr])

def get_session():
    return __cluster.connect()
```

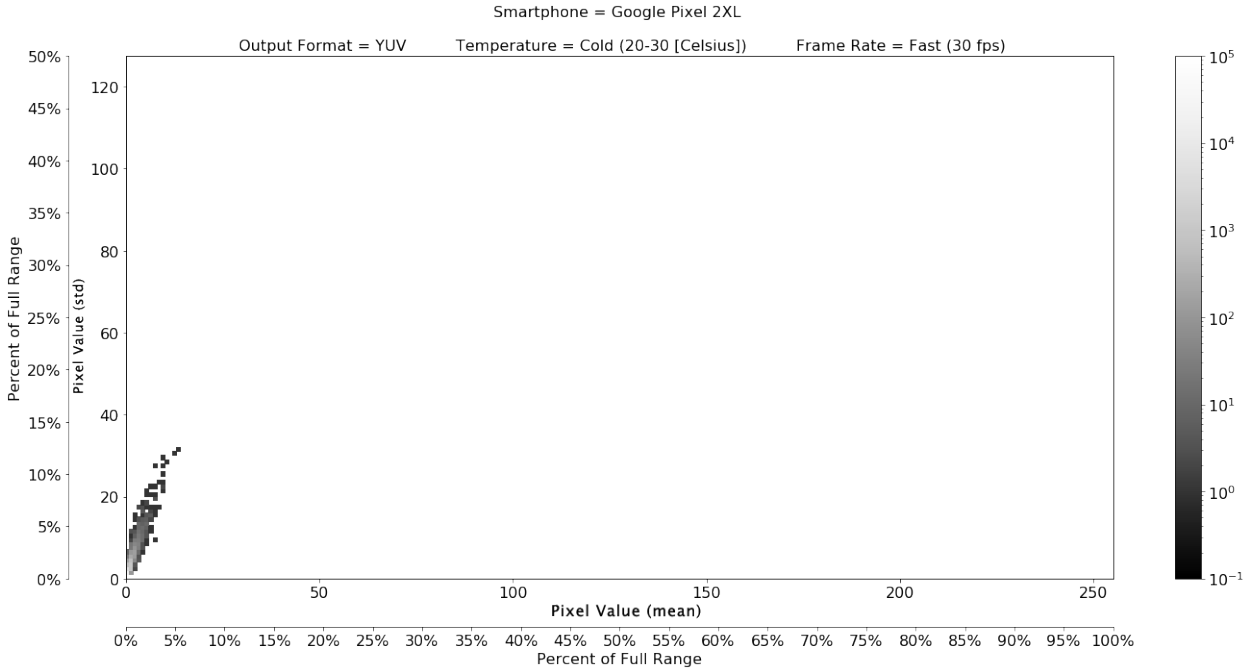
Appendix D

CRAYFIS Supplementary Figures

The following supplementary figures demonstrate the variability of pixel responses in camera sensors across variation in temperature, exposure settings, image format, and smartphone models.

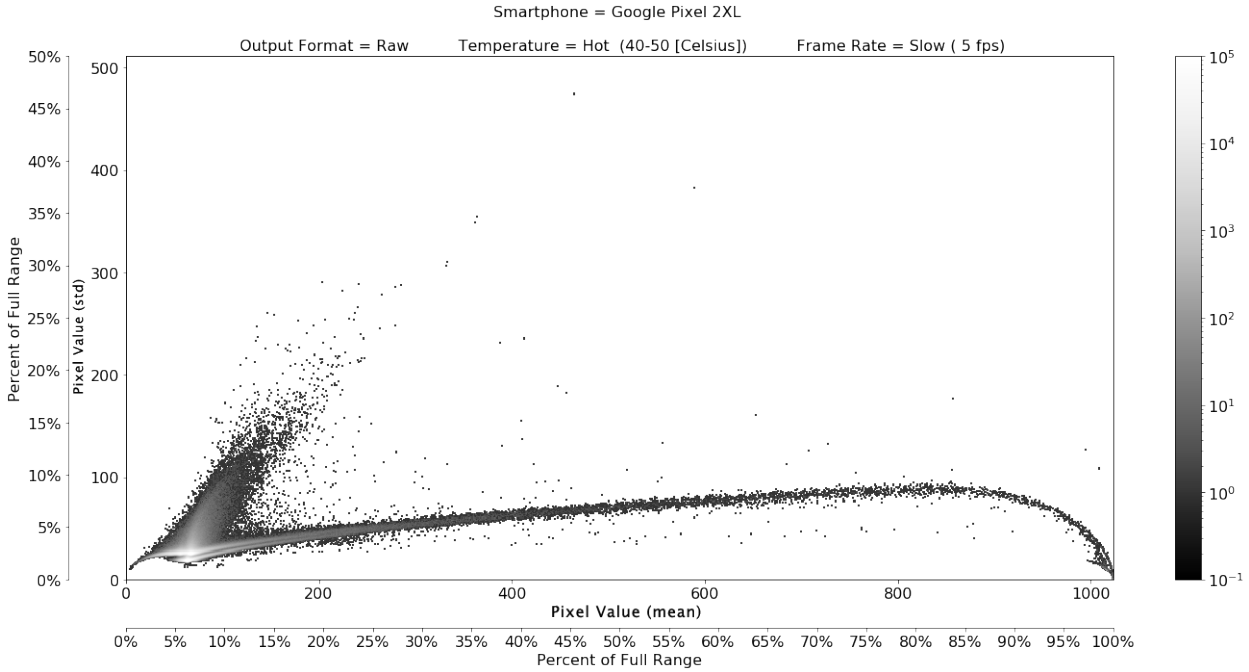


(a) Google Pixel 2XL RAW image format, cold bath, short exposure

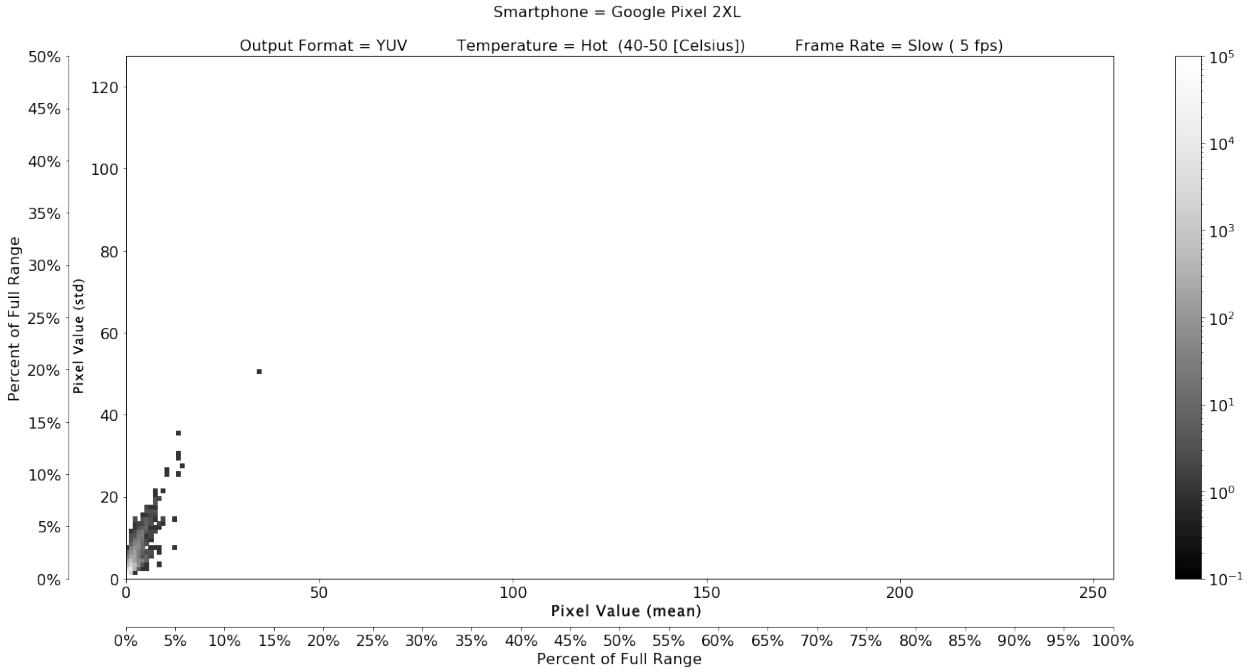


(b) Google Pixel 2XL YUV image format, cold bath, short exposure

Figure D.1: Reference corresponding Fig. 4.1 and Chapter 4.1 for discussion.

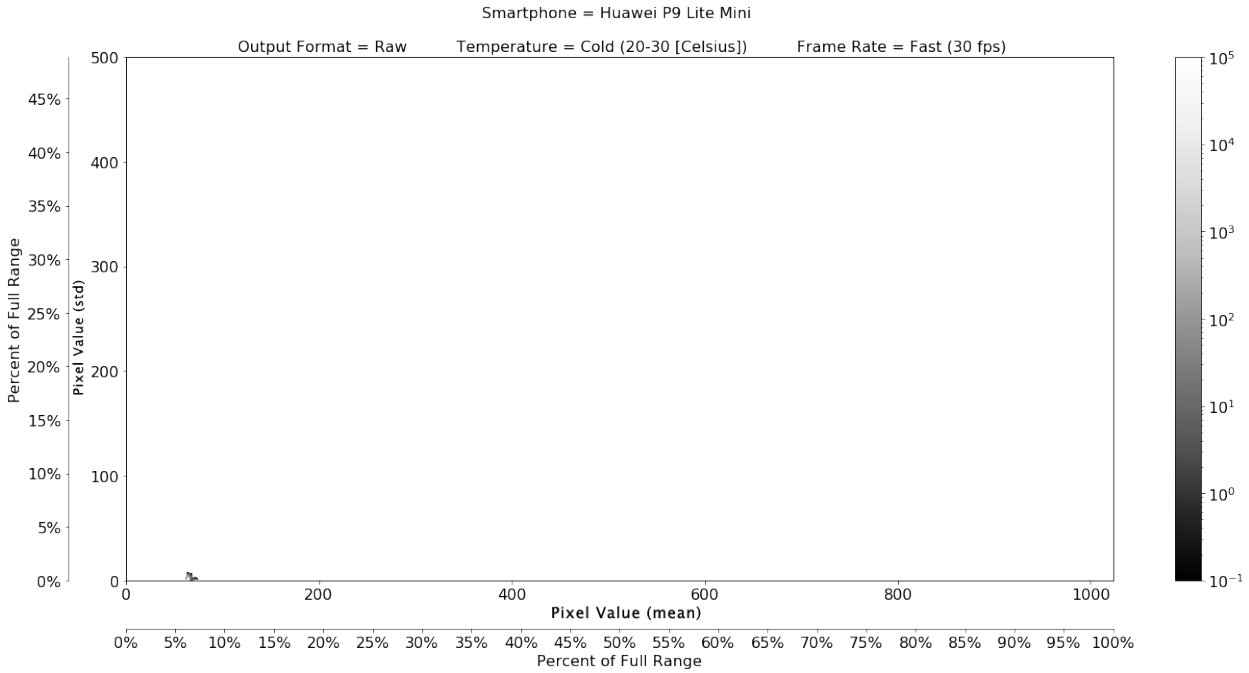


(a) Google Pixel 2XL RAW image format, hot bath, long exposure

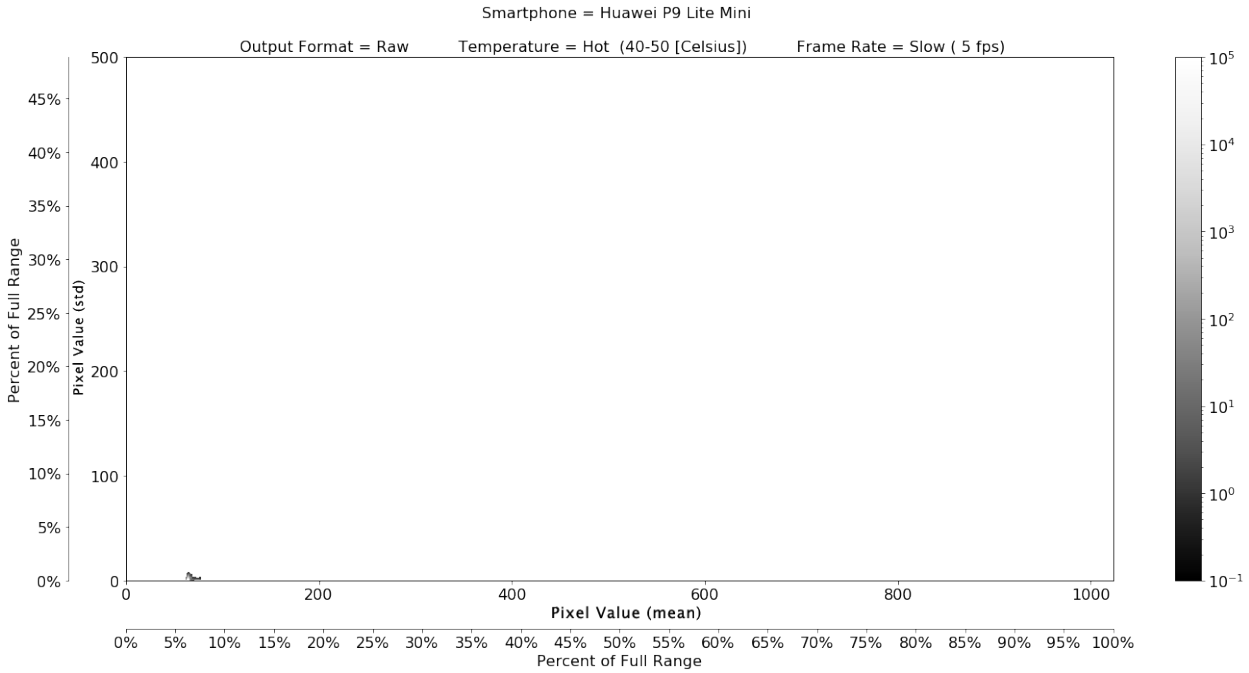


(b) Google Pixel 2XL YUV image format, hot bath, long exposure

Figure D.2: Reference corresponding Fig. 4.2 and Chapter 4.1 for discussion.



(a) Huawei P9 Lite Mini RAW image format, cold bath, short exposure



(b) Huawei P9 Lite Mini RAW image format, hot bath, long exposure

Figure D.3: Some devices, such as the Huawei P9 Lite Mini, perform some sort of extensive pre-processing of the pixel response even in RAW format (all pixels are somehow mapped to a mean of ∼7% with very low noise—the small lump on the bottom of the plots). Additional pre-processing in the YUV versions of these two RAW pixel response profiles somehow map all pixels to the (0, 0) coordinate on these mean versus standard deviation plots (and are therefore not shown).

Appendix E

Shower-Reconstructing Application for Mobile Phones

The following code listings were developed for the CRAYFIS at TA (CRAYTAR) Project. The complete listing can be downloaded from `https://github.com/ealbin/ShRAMP_Android`.

Listing E.1: Global Settings (`GlobalSettings.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp;

import android.annotation.TargetApi;
import android.os.Process;
import android.renderscript.RenderScript;

import sci.crayfis.shramp.camera2.CameraController;

/**
 * Settings that effect all aspects of this application
 *
 * TODO: A general app todo-note, passing image metadata isn't technically necessary anymore, in the future
 * TODO: consider removing DataQueue and updating ImageProcessor.  However, leaving it in does not
 * TODO: seem to effect performance.
 */
@TargetApi(21)
abstract public class GlobalSettings {

    // Feature Locks
    //::::::::::::::::::::::

```

```
38      // Force device to use YUV_420_888 output format, and/or automatic exposure/white
            ↪ balance/focus
39      // FYI, max effective fps for RAW_SENSOR is normally around 15 fps depending on the
            ↪ phone (hardware limited),
40      //      max effective fps for YUV_420_888 is normal around 20 fps (buffering limited)
41      //      also FYI, RenderScript runs around 15 fps or so for both
42      public static final Boolean DISABLE_RAW_OUTPUT        = false;
43      public static final Boolean FORCE_CONTROL_MODE_AUTO   = false;
44
45      // Does not override above settings, however enables lens shading and other enhancement
46      // algorithms that would otherwise be disabled under normal conditions
47      public static final Boolean FORCE_WORST_CONFIGURATION = false;
48
49
50      // ShRAMP data folder
51      //::::::::::::::::::::::
52
53      // Erases everything at start if true
54      public static final boolean START_FROM_SCRATCH = false;
55
56
57      // Useful Definitions
58      //::::::::::::::::::::::
59
60      // Convenient exposure times in nanoseconds
61      public static final Long FPS_30 =   33333333L;
62      public static final Long FPS_20 =   50000000L;
63      public static final Long FPS_15 =   66666666L;
64      public static final Long FPS_10 =  100000000L;
65      public static final Long FPS_05 =  200000000L;
66      public static final Long FPS_01 = 1000000000L;
67
68      // Convenient temperatures in Celsius
69      public static final Double TEMPERATURE_LOW    = 20.;
70      public static final Double TEMPERATURE_GOAL   = 30.;
71      public static final Double TEMPERATURE_HIGH   = 40.;
72      public static       Double TEMPERATURE_START; // set on app start by MasterController
73
74
75      // Optimization
76      //::::::::::::::::::::::
```

```
77
78      // Threshold used in fps optimization
79      public static final Double OPTIMAL_DUTY_THRESHOLD = 0.999;
80
81
82      // Camera Preference
83      //:::::::::::::::::::::::
84
85      public static final CameraController.Select PREFERRED_CAMERA = CameraController.Select.
            ↪ BACK;
86      public static final CameraController.Select SECONDARY_CAMERA = CameraController.Select.
            ↪ FRONT;
87
88
89      // Output Surface Use
90      //:::::::::::::::::::::::
91
92      // Enable live preview on screen by setting TEXTURE_VIEW_SURFACE_ENABLED to true
93      public static final Boolean TEXTURE_VIEW_SURFACE_ENABLED = false;
94      public static final Boolean IMAGE_READER_SURFACE_ENABLED = true;  // always true, never
            ↪ false
95
96
97      // Resource Limits
98      //:::::::::::::::::::::::
99
100     // Memory and ImageReader buffer limits
101     public static final Long    AMPLE_MEMORY_MiB        = 200L;
102     public static final Long    LOW_MEMORY_MiB          = 100L;
103     public static final Integer MAX_SIMULTANEOUS_IMAGES = 1;
104
105     // RenderScript
106     //:::::::::::::::::::::::
107
108     // RenderScript can be run in "low power" mode and "low" priority without sacrificing
            ↪ performance
109     public static final Integer RENDER_SCRIPT_FLAGS = RenderScript.CREATE_FLAG_LOW_LATENCY &
            ↪  RenderScript.CREATE_FLAG_LOW_POWER;
110     public static final RenderScript.Priority RENDER_SCRIPT_PRIORITY = RenderScript.Priority
            ↪ .LOW;
111
```

```
112
113     // Thread Priorities
114     //::::::::::::::::::::::
115
116     // Priorities of all co-running threads of the app, optimized for best performance
117     public static final Integer CAPTURE_MANAGER_THREAD_PRIORITY   = Process.
            ↪ THREAD_PRIORITY_URGENT_AUDIO;
118     public static final Integer CAMERA_CONTROLLER_THREAD_PRIORITY = Process.
            ↪ THREAD_PRIORITY_LESS_FAVORABLE;
119     public static final Integer DATA_QUEUE_THREAD_PRIORITY        = Process.
            ↪ THREAD_PRIORITY_AUDIO;
120     public static final Integer IMAGE_READER_THREAD_PRIORITY      = Process.
            ↪ THREAD_PRIORITY_URGENT_AUDIO;
121     public static final Integer IMAGE_PROCESSOR_THREAD_PRIORITY   = Process.
            ↪ THREAD_PRIORITY_LESS_FAVORABLE;
122     public static final Integer STORAGE_MEDIA_THREAD_PRIORITY     = Process.
            ↪ THREAD_PRIORITY_LESS_FAVORABLE;
123
124     // Delays
125     //::::::::::::::::::::::
126
127     // Default wait time for wait() calls, 20 milliseconds
128     public static final Long DEFAULT_WAIT_MS = FPS_05 / 1000000;
129
130     // Long wait time for wait() calls, 1 minute
131     public static final Long DEFAULT_LONG_WAIT = 60 * 1000L;
132
133
134     // Time-Codes
135     //::::::::::::::::::::::
136
137     // If true, time-code characters are chosen to allow a chance at the occasional
            ↪ vulgarity
138     public static final boolean ENABLE_VULGARITY = true;
139
140
141     // FPS Range (only effective for auto exposure/white-balance/focus mode)
142     //::::::::::::::::::::::
143
144     // Maximum FPS this app will support
145     public static final int MAX_FPS = 30;
```

```
146
147     // Maximum FPS range acceptable for this app, e.g. FPS range [10,12] has a range of 2
148     public static final int MAX_FPS_DIFF = 2;
149
150
151     // File extensions
152     //:::::::::::::::::::::::
153
154     public static final String MEAN_FILE      = ".mean";
155     public static final String STDDEV_FILE    = ".stddev";
156     public static final String STDERR_FILE    = ".stderr";
157     public static final String MASK_FILE      = ".mask";
158     public static final String HISTOGRAM_FILE = ".hist";
159     public static final String SIGNIF_FILE    = ".signif";
160     public static final String IMAGE_FILE     = ".frame";
161
162
163     // Debugging
164     //:::::::::::::::::::::::
165
166     // Prevent queuing anything (all image data and metadata are dropped instantly).
167     // False for normal operation.
168     public static final Boolean DEBUG_DISABLE_QUEUE = false;
169
170     // Prevent image processing with RenderScript from occurring.
171     // False for normal operation.
172     public static final Boolean DEBUG_DISABLE_PROCESSING = false;
173
174     // Prevent any and all file saving.
175     // False for normal operation.
176     public static final Boolean DEBUG_DISABLE_ALL_SAVING = false;
177
178     // Save full image data every INTERVAL (provided DISABLE_ALL_SAVING isn't true).
179     // False for normal operation.
180     public static final Boolean DEBUG_ENABLE_IMAGE_SAVING   = false;
181     public static final Integer DEBUG_IMAGE_SAVING_INTERVAL = 10;
182
183     // Save a frame's pixel significance every INTERVAL (provided DISABLE_ALL_SAVING isn't
        ↪ true).
184     // False for normal operation.
185     public static final Boolean DEBUG_SAVE_SIGNIFICANCE           = true;
```

```
186     public static final Integer DEBUG_SIGNIFICANCE_SAVING_INTERVAL = 100;
187
188     // Save a frame's pixel significance as a histogram to save space at
            ↪ SIGNIFICANCE_SAVING_INTERVAL
189     public static final Boolean DEBUG_SAVE_SIGNIF_HIST = false;
190
191     // Save new statistics (provided DISABLE_ALL_SAVING isn't true).
192     // True for normal operation.
193     public static final Boolean DEBUG_SAVE_MEAN   = true;
194     public static final Boolean DEBUG_SAVE_STDDEV = true;
195
196     // Allow significance threshold to increase.
197     // TODO: threshold and its increase are still under investigation
198     //public static final Boolean DEBUG_ENABLE_THRESHOLD_INCREASE = false;
199
200 }
```

Listing E.2: Flightplan (`FlightPlan.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp;

import android.annotation.TargetApi;
import android.support.annotation.Nullable;
import android.util.Log;

import java.util.ArrayList;
import java.util.List;

import sci.crayfis.shramp.analysis.AnalysisController;
import sci.crayfis.shramp.camera2.capture.CaptureConfiguration;
import sci.crayfis.shramp.camera2.capture.CaptureController;
import sci.crayfis.shramp.util.StorageMedia;

/**
 * The device will run the operations listed in FlightPlan()
 */
@TargetApi(21)
public final class FlightPlan {

    // TODO: in the future, this will be a state machine
    private static final List<CaptureConfiguration> mFlightPlan = new ArrayList<>();

    ////////////////////////////
```

```
41      //::::::::::::::::::::::: > >     EDIT FlightPlan()     < <::::::::::::::::::::
42      //vvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvv
43      /**
44       * The device will run the operations listed.
45       * e.g. mFlightPlan.add( CaptureConfiguration.newXXX() )
46       *      where XXX can be "CoolDownSession", "WarmUpSession", "DataSession", etc...
47       *      See CaptureConfiguration for what's available
48       */
49      public FlightPlan() {
50
51          // Example cycle - turn off by setting if(false)
52          if (true) {
53              // Calibrate if needed (if mean/stddev/mask files cannot be found)
54              if (AnalysisController.needsCalibration()) {
55                  addCalibrationCycle();
56              }
57
58              // Optimize FPS if needed (part of the calibration cycle if it's run)
59              if (!CaptureController.isOptimalExposureSet()) {
60                  mFlightPlan.add(CaptureConfiguration.newOptimizationSession(null));
61              }
62
63              // Take a data run (see sci.crayfis.shramp.camera2.capture.CaptureConfiguration
                    ↪ for more)
64              mFlightPlan.add(CaptureConfiguration.newDataSession(1000,
65                      null, null, 1, true));
66          }
67
68          // TESTING / WORK IN PROGRESS
69          //-----------------------------
70          //mFlightPlan.add(CaptureConfiguration.newColdFastCalibration());
71          //mFlightPlan.add(CaptureConfiguration.newColdSlowCalibration());
72
73          //mFlightPlan.add(CaptureConfiguration.newHotFastCalibration());
74          //mFlightPlan.add(CaptureConfiguration.newHotSlowCalibration());
75
76          /*
77          // Compute mask and import calibration
78          Runnable task = new Runnable() {
79              @Override
80              public void run() {
```

```
81                  AnalysisController.makePixelMask();
82
83                  // Wait for writing to finish
84                  synchronized (this) {
85                      while (StorageMedia.isBusy()) {
86                          try {
87                              Log.e(Thread.currentThread().getName(), "Waiting for writing to
                                    ↪ finish..");
88                              this.wait(5 * GlobalSettings.DEFAULT_WAIT_MS);
89                          }
90                          catch (InterruptedException e) {
91                              // TODO: error
92                          }
93                      }
94                  }
95                  AnalysisController.importLatestCalibration();
96              }
97          };
98          mFlightPlan.add(CaptureConfiguration.newTaskSession(task));
99          */
100     }
101     //^^^
```

```
121         int heatUpTime   = 10; // minutes
122         int coolDownTime = 15; // minutes
123
124         double temperature_low = Math.min(GlobalSettings.TEMPERATURE_START, GlobalSettings.
            ↪ TEMPERATURE_GOAL);
125         temperature_low = Math.max(GlobalSettings.TEMPERATURE_LOW, temperature_low);
126
127         // Warm up if the phone is too cold
128         mFlightPlan.add(CaptureConfiguration.newWarmUpSession(temperature_low, heatUpTime,
            ↪ 1000));
129
130         // Cool down if the phone is too hot
131         mFlightPlan.add(CaptureConfiguration.newCoolDownSession(temperature_low,
            ↪ coolDownTime));
132
133         // Calibrate Cold-Fast/Slow
134         mFlightPlan.add(CaptureConfiguration.newColdFastCalibration());
135         mFlightPlan.add(CaptureConfiguration.newColdSlowCalibration());
136
137         // Warm up to Hot
138         mFlightPlan.add(CaptureConfiguration.newWarmUpSession(GlobalSettings.
            ↪ TEMPERATURE_HIGH, heatUpTime, 1000));
139
140         // Calibrate Hot-Fast/Slow
141         mFlightPlan.add(CaptureConfiguration.newHotFastCalibration());
142         mFlightPlan.add(CaptureConfiguration.newHotSlowCalibration());
143
144         // Cool down to data taking temperature
145         mFlightPlan.add(CaptureConfiguration.newCoolDownSession(GlobalSettings.
            ↪ TEMPERATURE_GOAL, coolDownTime));
146
147         // Compute mask and import calibration
148         Runnable task = new Runnable() {
149             @Override
150             public void run() {
151                 AnalysisController.makePixelMask();
152
153                 // Wait for writing to finish
154                 synchronized (this) {
155                     while (StorageMedia.isBusy()) {
156                         try {
```

```
157                                 Log.e(Thread.currentThread().getName(), "Waiting for writing to
                                        ↪ finish..");
158                                 this.wait(5 * GlobalSettings.DEFAULT_WAIT_MS);
159                             }
160                             catch (InterruptedException e) {
161                                 // TODO: error
162                             }
163                         }
164                     }
165                     AnalysisController.importLatestCalibration();
166                 }
167             };
168             mFlightPlan.add(CaptureConfiguration.newTaskSession(task));
169 
170             // Discover optimal frame rate for data taking
171             mFlightPlan.add(CaptureConfiguration.newOptimizationSession(null));
172         }
173 
174     }
```

Listing E.3: Main (`MaineShRAMP.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp;

import android.Manifest;
import android.annotation.TargetApi;
import android.app.Activity;
import android.content.Intent;
import android.content.pm.PackageManager;
import android.os.Build;
import android.support.annotation.NonNull;
import android.os.Bundle;
import android.system.Os;
import android.system.StructUtsname;
import android.util.Log;

import sci.crayfis.shramp.util.BuildString;
import sci.crayfis.shramp.error.FailManager;
import sci.crayfis.shramp.util.Datestamp;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Right now, this doesn't do much..
// The app starts with onCreate(), and this class logs basic device metadata and asks
    ↪ permissions
```

```
40  // before handing full control over to MasterController.
41  // For the future, I haven't decided exactly what else I want this to do, or if it should
        ↪ just
42  // be part of MasterController..
43
44  /**
45   * Entry point for the ShRAMP app
46   * Checks permissions then hands control over to MasterController
47   * AsyncResponse is for SSH data transfer, currently disabled and probably going to be moved
48   * out of this class.
49   */
50  @TargetApi(21)
51  public final class MaineShRAMP extends Activity { //implements AsyncResponse {
52
53      // Public Class Fields
54      //::::::::::::::::::::::::
55
56      // PERMISSIONS and PERMISSION_CODE...............
57      // The list of device permissions needed for this app to operate.
58      // Consider moving this over to GlobalSettings..
59      public static final String[] PERMISSIONS = {
60              Manifest.permission.INTERNET,
61              Manifest.permission.CAMERA,
62              Manifest.permission.WRITE_EXTERNAL_STORAGE
63      };
64      public static final int PERMISSION_CODE = 0; // could be anything >= 0
65
66      // Private Instance Fields
67      //::::::::::::::::::::::::
68
69      // mNextActivity and mFailActivity...............
70      // Where to pass control of the app over to.  Set in onCreate()
71      private Intent mNextActivity;
72      private Intent mFailActivity;
73
74      ///////////////////////////
75      //::::::::::::::::::::::::
76      ///////////////////////////
77
78      // Public Overriding Instance Methods
79      //::::::::::::::::::::::::
```

```
80
81      // onCreate...............
82      /**
83       * Entry point for the app at start.
84       * @param savedInstanceState passed in by Android OS for returning from a suspended
            ↪ state
85       *                          (not used)
86       */
87      @Override
88      public void onCreate(Bundle savedInstanceState) {
89          super.onCreate(savedInstanceState);
90
91          mNextActivity = new Intent(this, MasterController.class);
92          mFailActivity = new Intent(this, FailManager.class);
93
94          // Setting this flag destroys MaineShRAMP after passing control over to one of these
               ↪  new
95          // intents
96          mNextActivity.addFlags(Intent.FLAG_ACTIVITY_CLEAR_TOP);
97          mFailActivity.addFlags(Intent.FLAG_ACTIVITY_CLEAR_TOP);
98
99          Log.e(Thread.currentThread().getName(), "Welcome to the Shower Reconstruction
               ↪ Application for Mobile Phones");
100         Log.e(Thread.currentThread().getName(), "or \"ShRAMP\" for short");
101
102         // Log date
103         Datestamp.logStartDate();
104
105         // Log build info
106         String buildString = BuildString.get();
107         Log.e(Thread.currentThread().getName(), buildString);
108
109         // Log device info
110         StructUtsname uname = Os.uname();
111         String unameString = " \n\n"
112                 + "Machine:   " + uname.machine  + "\n"
113                 + "Node name: " + uname.nodename + "\n"
114                 + "Release:   " + uname.release  + "\n"
115                 + "Sysname:   " + uname.sysname  + "\n"
116                 + "Version:   " + uname.version  + "\n ";
117         Log.e(Thread.currentThread().getName(), unameString);
```

```
118
119         // Log hardware info
120         String buildDetails = " \n\n"
121                 + "Underlying board:        " + Build.BOARD               + "\n"
122                 + "Bootloader version:      " + Build.BOOTLOADER          + "\n"
123                 + "Brand:                   " + Build.BRAND               + "\n"
124                 + "Industrial device:       " + Build.DEVICE              + "\n"
125                 + "Build fingerprint:       " + Build.FINGERPRINT         + "\n"
126                 + "Hardware:                " + Build.HARDWARE            + "\n"
127                 + "Host:                    " + Build.HOST                + "\n"
128                 + "Changelist label/number: " + Build.ID                  + "\n"
129                 + "Hardware manufacturer:   " + Build.MANUFACTURER        + "\n"
130                 + "Model:                   " + Build.MODEL               + "\n"
131                 + "Product name:            " + Build.PRODUCT             + "\n"
132                 + "Radio firmware version:  " + Build.getRadioVersion()   + "\n"
133                 + "Build tags:              " + Build.TAGS                + "\n"
134                 + "Build time:              " + Long.toString(Build.TIME) + "\n"
135                 + "Build type:              " + Build.TYPE                + "\n"
136                 + "User:                    " + Build.USER                + "\n ";
137         Log.e(Thread.currentThread().getName(), buildDetails);
138
139         // if the API was 22 or below, the user would have granted permissions on start
140         if (Build.VERSION.SDK_INT < Build.VERSION_CODES.M) {
141             Log.e(Thread.currentThread().getName(), "API 22 or below, permissions granted on
                    ↪  start");
142             Log.e(Thread.currentThread().getName(), "Starting MasterController");
143             super.startActivity(this.mNextActivity);
144         }
145         else {
146             // if API > 22
147             if (permissionsGranted()) {
148                 super.startActivity(this.mNextActivity);
149             }
150             else {
151                 // Execution resumes with onRequestPermissionResult() below
152                 super.requestPermissions(PERMISSIONS, PERMISSION_CODE);
153             }
154         }
155     }
156
157     // Private Instance Methods
```

```
158     //::::::::::::::::::::::
159
160     // permissionsGranted..............
161     /**
162      * Check if permissions have been granted
163      * @return true if all permissions have been granted, false if not
164      */
165     @TargetApi(23)
166     private boolean permissionsGranted() {
167         boolean allGranted = true;
168
169         for (String permission : MaineShRAMP.PERMISSIONS) {
170             int permission_value = checkSelfPermission(permission);
171
172             if (permission_value == PackageManager.PERMISSION_DENIED) {
173                 Log.e(Thread.currentThread().getName(), permission + ": " + "DENIED");
174                 allGranted = false;
175             }
176             else {
177                 Log.e(Thread.currentThread().getName(), permission + ": " + "GRANTED");
178             }
179         }
180
181         if (allGranted) {
182             Log.e(Thread.currentThread().getName(), "All permissions granted");
183         }
184         else {
185             Log.e(Thread.currentThread().getName(), "Some or all permissions denied");
186         }
187
188         return allGranted;
189     }
190
191     // onRequestPermissions..............
192     /**
193      * After user responds to permission request, this routine is called.
194      * @param requestCode permission code, ref. PERMISSION_CODE field
195      * @param permissions permissions requested
196      * @param grantResults user's response
197      */
198     @TargetApi(23)
```

```
    @Override
    public void onRequestPermissionsResult(int requestCode, @NonNull String[] permissions,
                                           @NonNull int[] grantResults) {
        super.onRequestPermissionsResult(requestCode, permissions, grantResults);
        if (this.permissionsGranted()) {
            Log.e(Thread.currentThread().getName(), "Permissions asked and granted");
            super.startActivity(mNextActivity);
        }
        else {
            Log.e(Thread.currentThread().getName(), "Permissions were not granted");
            super.startActivity(mFailActivity);
        }
    }


    // TODO: SSH stuff works, but isn't used at this moment as I work on getting stats and
        ↪ cuts working right
    // Also, probably going to to move this out of MaineShRAMP..
    //::::::::::::::::::::::::

    // SSHrampSession is an AsyncTask, holding this reference allows main to
    // see the result when it finishes.
    // It's linked to this main activity in onCreate below.
    //public static SSHrampSession SSHrampSession_reference = new SSHrampSession();

    /*
    public void upload() {

        TextView textOut = (TextView) findViewById(R.id.textOut);
        textOut.append("Uploading to craydata.ps.uci.edu..  \n");

        if (haveSSHKey()) {
            SSHrampSession_reference.execute(filename);
        }
        else {
            textOut.append("\t shit, ssh fail.");
        }
    }
    */

    /**
```

```
239         * Tests if .ssh folder exists and can read it.
240         * @return true (yes) or false (no)
241         */
242        //public boolean haveSSHKey() {
243        //     String ssh_path = Environment.getExternalStorageDirectory() + "/.ssh";
244        //     File file_obj = new File(ssh_path);
245        //     return file_obj.canRead();
246        //}
247
248        /**
249         * Implements the AsyncResponse interface.
250         * Called after an SSHrampSession operation is completed as an AsyncTask.
251         * @param status a string of information to give back to the Activity.
252         */
253        //@Override
254        //public void processFinish(String status){
255        //     TextView textOut = (TextView) findViewById(R.id.textOut);
256        //     textOut.append(status);
257        //}
258
259    }
```

Listing E.4: Master Controller (`MasterController.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp;

import android.annotation.TargetApi;
import android.app.Activity;
import android.content.Context;
import android.hardware.camera2.CameraManager;
import android.os.Bundle;
import android.os.Handler;
import android.support.annotation.Nullable;
import android.util.Log;

import sci.crayfis.shramp.analysis.AnalysisController;
import sci.crayfis.shramp.battery.BatteryController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.capture.CaptureController;
import sci.crayfis.shramp.sensor.SensorController;
import sci.crayfis.shramp.surfaces.SurfaceController;
import sci.crayfis.shramp.util.StorageMedia;
import sci.crayfis.shramp.util.HandlerManager;
import sci.crayfis.shramp.util.HeapMemory;

/**
 * Oversees the setup of surfaces, cameras and capture session
 */
```

```
41  @TargetApi(21)
42  public final class MasterController extends Activity {
43
44      // Private Class Fields
45      //::::::::::::::::::::::
46
47      // mHandler..............
48      // Reference to this Activity's thread Handler
49      private static Handler mHandler;
50
51      // mInstance..............
52      // Static reference to single instance of this class.
53      private static MasterController mInstance;
54
55      // Execution-Routing Runnables
56      //::::::::::::::::::::::
57      // Devices and surfaces are prepared asynchronously, so these runnables enable execution
        ↪ to
58      // pause until everything is ready
59
60      // GoTo_prepareSurfaces..............
61      // Called after the camera is initialized
62      private final static Runnable GoTo_prepareSurfaces = new Runnable() {
63          @Override
64          public void run() {
65              prepareSurfaces();
66          }
67      };
68
69      // GoTo_prepareAnalysis..............
70      // Called after the output surfaces are initialized
71      private final static Runnable GoTo_prepareAnalysis = new Runnable() {
72          @Override
73          public void run() {
74              prepareAnalysis();
75          }
76      };
77
78      ////////////////////////////
79      //::::::::::::::::::::::
80      ////////////////////////////
```

```
81
82      // Public Overriding Instance Methods
83      //:::::::::::::::::::::::
84
85      // onCreate..............
86      /**
87       * Entry point for this activity after MaineShRAMP hands control over to it.
88       * Starts the chain of events that leads to data capture (configuring camera, surfaces,
            ↪ etc)
89       * @param savedInstanceState passed in by Android OS for returning from a suspended
            ↪ state
90       *                           (not used)
91       */
92      @Override
93      public void onCreate(@Nullable Bundle savedInstanceState) {
94          super.onCreate(savedInstanceState);
95
96          // For access to this instance from static methods
97          mInstance = this;
98
99          // Activity thread Handler
100         mHandler = new Handler(getMainLooper());
101
102         // In the future, this will be removed.  For now, just start clean for simplicity.
103         if (GlobalSettings.START_FROM_SCRATCH) {
104             Log.e(Thread.currentThread().getName(), "Clearing ShRAMP data directory,
                    ↪ starting from scratch");
105             StorageMedia.cleanSlate();
106         }
107
108         // Set up ShRAMP data directory
109         StorageMedia.setUpShrampDirectory();
110
111         // In the future, sensors will be initialized here
112         //Log.e(Thread.currentThread().getName(), "Loading sensor package");
113         //SensorController.initializeTemperature(mInstance, false);
114
115         // Initialized battery information
116         Log.e(Thread.currentThread().getName(), "Battery Info:");
117         BatteryController.initialize(mInstance);
118         GlobalSettings.TEMPERATURE_START = BatteryController.getCurrentTemperature();
```

```
119         Log.e(Thread.currentThread().getName(), " \n" + BatteryController.getString() + " \n
            ↪ ");
120
121         // Get system camera manager
122         CameraManager cameraManager = (CameraManager) getSystemService(Context.
            ↪ CAMERA_SERVICE);
123         if (cameraManager == null) {
124             // TODO: error
125             Log.e(Thread.currentThread().getName(), "Camera manager cannot be null");
126             MasterController.quitSafely();
127             return;
128         }
129
130         // Discover abilities of detectable cameras
131         CameraController.discoverCameras(cameraManager);
132         CameraController.writeCameraCharacteristics();
133
134         // Open the preferred camera and ready it for capture.
135         // The camera opens asynchronously, so whenever it finishes, it will run
            ↪ GoTo_prepareSurfaces
136         // to continue execution in prepareSurfaces() below.
137         if (!CameraController.openCamera(GlobalSettings.PREFERRED_CAMERA,
            ↪ GoTo_prepareSurfaces, mHandler)) {
138             CameraController.openCamera(GlobalSettings.SECONDARY_CAMERA,
                ↪ GoTo_prepareSurfaces, mHandler);
139         }
140     }
141
142     // Public Class Methods
143     //:::::::::::::::::::::::
144
145     // prepareSurfaces..............
146     /**
147      * Initialize all output surfaces.  This happens asynchronously, so whenever it finishes
            ↪ , it
148      * will run GoTo_prepareAnalysis to continue execution in prepareAnalysis() below.
149      */
150     public static void prepareSurfaces() {
151         SurfaceController.openSurfaces(mInstance, GoTo_prepareAnalysis, mHandler);
152     }
153
```

```
154     // prepareAnalysis...............
155     /**
156      * Initialize analysis Allocations and RenderScripts.  This happens synchronously as
            ↪ there is
157      * no hardware setup directly involved unlike surfaces and cameras.  When finished
            ↪ continue with
158      * startCaptureSequence() below.
159      */
160     public static void prepareAnalysis() {
161         AnalysisController.initialize(mInstance);
162         startCaptureSession();
163     }
164
165     // startCaptureSequence...............
166     /**
167      * This is essentially the end of the line for MasterController.
168      * If there is enough memory left over after setup to support capture, pass execution
            ↪ control
169      * over to the CaptureController and associates.
170      */
171     public static void startCaptureSession() {
172         if (HeapMemory.getAvailableMiB() < GlobalSettings.AMPLE_MEMORY_MiB) {
173             // TODO: error
174             Log.e("LOW MEMORY " + Long.toString(HeapMemory.getAvailableMiB()) + " MiB", "
                    ↪ CANNOT START");
175             quitSafely();
176             return;
177         }
178
179         Log.e(Thread.currentThread().getName(), "
                ↪ ::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                ↪ ::::::::::::::::::::::::::::::::::::::::::::::::::::::::");
180         HeapMemory.logAvailableMiB();
181
182         CaptureController.startCaptureSequence();
183     }
184
185     // quitSafely...............
186     /**
187      * This method can be called by any class at any time to shut everything down, close all
188      * cameras, surfaces etc, end all running threads and exit the app completely.
```

```
189         */
190     public static void quitSafely() {
191         Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> MasterController quitSafely
            ↪ <<\n ");
192         CameraController.closeCamera();
193         BatteryController.shutdown();
194         HandlerManager.finish();
195         mInstance.finish();
196     }
197 
198     // Public Overriding Instance Methods
199     //::::::::::::::::::::::::
200 
201     // finish ..............
202     /**
203      * Final action to completely close the app.
204      */
205     @Override
206     public void finish() {
207         finishAffinity();
208         Log.e(Thread.currentThread().getName(), "MasterController finished");
209     }
210 
211     // onPause ..............
212     /**
213      * Release resources on pause (app is not in foreground)
214      */
215     @Override
216     public void onPause() {
217         super.onPause();
218         SensorController.onPause();
219     }
220 
221     // onResume ..............
222     /**
223      * Regain resources on resume
224      */
225     @Override
226     public void onResume() {
227         super.onResume();
228         SensorController.onResume();
```

```
229         }
230
231     }
```

Listing E.5: Analysis Controller (`analysis/AnalysisController.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.app.Activity;
import android.graphics.ImageFormat;
import android.renderscript.Allocation;
import android.renderscript.Element;
import android.renderscript.RenderScript;
import android.renderscript.Type;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Size;

import org.apache.commons.math3.special.Erf;
import org.jetbrains.annotations.Contract;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.ScriptC_PostProcessing;
import sci.crayfis.shramp.ScriptC_LiveProcessing;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.util.NumToString;
import sci.crayfis.shramp.util.StorageMedia;
```

```
41
42  /**
43   * Public interface to the analysis (ImageProcessor) code
44   * TODO: char is 16 bits in Java and 8 bits in RenderScript!  Double check stuff.. checks
       ↪ out
45   * TODO: triple check it
46   */
47  @TargetApi(21)
48  public abstract class AnalysisController {
49
50      // Private Class Constants
51      //::::::::::::::::::::::::
52
53      // WAIT...............
54      // Dummy object for calling wait()
55      private final static Object WAIT = new Object();
56
57      // Private Class Fields
58      //::::::::::::::::::::::::
59
60      // mRS...............
61      // System RenderScript object
62      private static RenderScript mRS;
63
64      // mLiveProcessing...............
65      // Reference to LiveProcessing.rs RenderScript
66      private static ScriptC_LiveProcessing mLiveProcessing;
67
68      // mPostProcessing...............
69      // Reference to PostProcessing.rs RenderScript
70      private static ScriptC_PostProcessing mPostProcessing;
71
72      // mUCharType...............
73      // RenderScript Allocation unsigned char type [width x height pixels]
74      private static Type mUCharType;
75
76      // mUShortType...............
77      // RenderScript Allocation unsigned short type [width x height pixels]
78      private static Type mUShortType;
79
80      // mUIntType...............
```

```
81      // RenderScript Allocation unsigned int type [width x height pixels]
82      private static Type mUIntType;
83
84      // mFloatType...............
85      // RenderScript Allocation float type [width x height pixels]
86      private static Type mFloatType;
87
88      // mDoubleType..............
89      // RenderScript Allocation double type [width x height pixels]
90      private static Type mDoubleType;
91
92      // mSimpleLongType..............
93      // RenderScript Allocation signed long type [1 x 1]
94      private static Type mSimpleLongType;
95
96      // mNpixels...............
97      // Total number of pixels [width * height pixels]
98      private static int mNpixels;
99
100     // mNeedsCalibration...............
101     // TODO: probably remove in the future, a switch for doing calibration
102     private static boolean mNeedsCalibration;
103
104     // mThresholdOffset...............
105     // TODO: probably remove in the future, a fudge factor for controlling the significance
            ↪ rate
106     private static double mThresholdOffset = 0.;
107
108     ///////////////////////////
109     //:::::::::::::::::::::::
110     ///////////////////////////
111
112     // Public Class Methods
113     //:::::::::::::::::::::::
114
115     // initialize...............
116     /**
117      * Set up RenderScript things
118      * @param activity Reference to main activity
119      */
120     public static void initialize(@NonNull Activity activity) {
```

```
121
122         mRS = RenderScript.create(activity, RenderScript.ContextType.NORMAL,
123                                           GlobalSettings.RENDER_SCRIPT_FLAGS);
124         mRS.setPriority(GlobalSettings.RENDER_SCRIPT_PRIORITY);
125
126         mLiveProcessing = new ScriptC_LiveProcessing(mRS);
127         mPostProcessing = new ScriptC_PostProcessing(mRS);
128         ImageProcessor.setLiveProcessor(mLiveProcessing);
129         ImageProcessor.setPostProcessor(mPostProcessing);
130
131         Element ucharElement  = Element.U8(mRS);
132         Element ushortElement = Element.U16(mRS);
133         Element uintElement   = Element.U32(mRS);
134         Element ulongElement  = Element.U64(mRS);
135         Element floatElement  = Element.F32(mRS);
136         Element doubleElement = Element.F64(mRS);
137
138         Size outputSize = CameraController.getOutputSize();
139         if (outputSize == null) {
140             // TODO: error
141             Log.e(Thread.currentThread().getName(), "Output size cannot be null");
142             MasterController.quitSafely();
143             return;
144         }
145         int width  = outputSize.getWidth();
146         int height = outputSize.getHeight();
147         mNpixels = width * height;
148
149         ImageWrapper.setRowsCols(height, width);
150
151         // TODO: remove
152         PrintAllocations.setNpixels(mNpixels);
153
154         mUCharType  = new Type.Builder(mRS, ucharElement ).setX(width).setY(height).create()
                ↪ ;
155         mUShortType = new Type.Builder(mRS, ushortElement).setX(width).setY(height).create()
                ↪ ;
156         mUIntType   = new Type.Builder(mRS, uintElement  ).setX(width).setY(height).create()
                ↪ ;
157         mFloatType  = new Type.Builder(mRS, floatElement ).setX(width).setY(height).create()
                ↪ ;
```

```
158         mDoubleType = new Type.Builder(mRS, doubleElement).setX(width).setY(height).create()
                ↪ ;
159
160         mSimpleLongType = new Type.Builder(mRS, ulongElement).setX(1).setY(1).create();
161
162         Integer outputFormat = CameraController.getOutputFormat();
163         if (outputFormat == null) {
164             // TODO: error
165             Log.e(Thread.currentThread().getName(), "Output format cannot be null");
166             MasterController.quitSafely();
167             return;
168         }
169         switch (outputFormat) {
170             case (ImageFormat.YUV_420_888): {
171                 ImageWrapper.setAs8bitData();
172                 ImageProcessor.setImageAllocation(newUCharAllocation());
173                 break;
174             }
175             case (ImageFormat.RAW_SENSOR): {
176                 ImageWrapper.setAs16bitData();
177                 ImageProcessor.setImageAllocation(newUShortAllocation());
178                 break;
179             }
180             default: {
181                 // TODO: error
182                 Log.e(Thread.currentThread().getName(), "Output format is neither
                        ↪ YUV_420_888 or RAW_SENSOR");
183                 MasterController.quitSafely();
184                 return;
185             }
186         }
187
188         // Must happen after ImageWrapper is set up (above)
189         // TODO: maybe make it so it can be set at the same time?
190         OutputWrapper.configure();
191
192         importLatestCalibration();
193
194         if (GlobalSettings.DEBUG_SAVE_SIGNIF_HIST) {
195             ImageProcessor.enableSignificanceHistogram(mNpixels);
196         }
```

```
197
198         ImageProcessor.setSignificanceAllocation(newFloatAllocation());
199         ImageProcessor.setCountAboveThresholdAllocation(newSimpleLongAllocation());
200         ImageProcessor.setAnomalousStdDevAllocation(newSimpleLongAllocation());
201         ImageProcessor.disableSignificance();
202         ImageProcessor.resetTotals();
203     }
204
205     // importLatestCalibration..............
206     /**
207      * Check for existing calibration data and import it
208      */
209     public static void importLatestCalibration() {
210
211         String meanPath   = StorageMedia.findRecentCalibration("mean",   GlobalSettings.
                ↪ MEAN_FILE);
212         String stddevPath = StorageMedia.findRecentCalibration("stddev", GlobalSettings.
                ↪ STDDEV_FILE);
213         String stderrPath = StorageMedia.findRecentCalibration("stderr", GlobalSettings.
                ↪ STDERR_FILE);
214         String maskPath   = StorageMedia.findRecentCalibration("mask",   GlobalSettings.
                ↪ MASK_FILE);
215
216         Allocation mean   = newFloatAllocation();
217         Allocation stddev = newFloatAllocation();
218         Allocation stderr = newFloatAllocation();
219         Allocation mask   = newUCharAllocation();
220
221         boolean hasMean = false;
222         if (meanPath != null) {
223             mean.copyFrom( new InputWrapper(meanPath).getStatisticsData() );
224             hasMean = true;
225         }
226         else {
227             mLiveProcessing.forEach_zeroFloatAllocation(mean);
228         }
229
230         boolean hasStdDev = false;
231         if (stddevPath != null) {
232             stddev.copyFrom( new InputWrapper(stddevPath).getStatisticsData() );
233             hasStdDev = true;
```

```
234         }
235         else {
236             mLiveProcessing.forEach_oneFloatAllocation(stddev);
237         }
238
239         boolean hasStdErr = false;
240         if (stderrPath != null) {
241             stderr.copyFrom( new InputWrapper(stderrPath).getStatisticsData() );
242             hasStdErr = true;
243         }
244         else {
245             mLiveProcessing.forEach_zeroFloatAllocation(stderr);
246         }
247
248         boolean hasMask = false;
249         if (maskPath != null) {
250             mask.copyFrom( new InputWrapper(maskPath).getMaskData() );
251             hasMask = true;
252         }
253         else {
254             mLiveProcessing.forEach_oneCharAllocation(mask);
255         }
256
257         // Doesn't formally need stderr
258         mNeedsCalibration = !(hasMean && hasStdDev && hasMask);
259         ImageProcessor.setStatistics(mean, stddev, stderr, mask);
260         ImageProcessor.resetTotals();
261     }
262
263     // makePixelMask...............
264     /**
265      * Loads most recent calibration files from ShRAMP/Calibrations, and generates/saves a
            ↪ pixel mask
266      * of what pixels should be used in significance computation.
267      * Also computes/saves an estimate for the mean, stddev and stderr at 10 fps and 35
            ↪ Celsius.
268      * Note: assumes "hot" is hotter than "cold" and "fast" is faster than "slow"
269      * TODO: return true if successful, false if not
270      */
271     public static void makePixelMask() {
272         ApplyCuts.makePixelMask();
```

```
273         }
274
275         // needsCalibration ...............
276         /**
277          * @return True if calibration run is needed, false if calibrations were successfully
                 ↪ loaded
278          */
279         @Contract(pure = true)
280         public static boolean needsCalibration() {
281             return mNeedsCalibration;
282         }
283
284         // enableSignificance ...............
285         /**
286          * Enable live significance measurement: (pixel value - mean) / stddev
287          */
288         public static void enableSignificance() {
289             ImageProcessor.enableSignificance();
290         }
291
292         // disableSignificance ...............
293         /**
294          * Disable live significance measurement
295          */
296         public static void disableSignificance() {
297             ImageProcessor.disableSignificance();
298         }
299
300         // isSignificanceEnabled ...............
301         /**
302          * @return True if significance is being computed, false if not
303          */
304         @Contract(pure = true)
305         public static boolean isSignificanceEnabled() {
306             return ImageProcessor.isSignificanceEnabled();
307         }
308
309         // setSignificanceThreshold ...............
310         /**
311          * Figure out what the threshold should be for declaring a recorded pixel value
                 ↪ significant
```

```
312         * @param n_frames The number of frames that will be processed in this run
313         */
314        public static void setSignificanceThreshold(int n_frames) {
315            double n_samples = (double) mNpixels * n_frames;
316            double n_chanceAboveThreshold = 1.;
317
318            double probabilityThreshold = n_chanceAboveThreshold / n_samples;
319
320            // TODO: threshold still a work in progress
321            //double threshold = Math.sqrt(2.) * Erf.erfInv(1. - 2. * probabilityThreshold);
322            double threshold = Math.sqrt(2.) * Erf.erfInv(1. - probabilityThreshold) + 1.;
323
324            // TODO: remove in the future
325            //threshold += mThresholdOffset;
326
327            ImageProcessor.setSignificanceThreshold((float) threshold);
328            Log.e(Thread.currentThread().getName(), "Significance threshold level: "
329                    + NumToString.decimal(threshold));
330        }
331
332        // isBusy...............
333        /**
334         * @return True if image processor is working, false if in idle
335         */
336        public static boolean isBusy() {
337            return ImageProcessor.isBusy();
338        }
339
340        // resetRunningTotals...............
341        /**
342         * Reset running totals in ImageProcessor
343         */
344        public static void resetRunningTotals() {
345            ImageProcessor.resetTotals();
346        }
347
348        // runStatistics...............
349        /**
350         * Post process a run and compute run statistics
351         */
352        public static void runStatistics(String filename) {
```

```
353         synchronized (WAIT) {
354
355             DataQueue.purge();
356             while (!DataQueue.isEmpty() || ImageProcessor.isBusy()) {
357                 try {
358                     Log.e(Thread.currentThread().getName(), "Waiting for queue to empty/
                        ↪ processor to finish before running statistics");
359                     DataQueue.purge();
360                     WAIT.wait(GlobalSettings.DEFAULT_WAIT_MS);
361                 }
362                 catch (InterruptedException e) {
363                     // TODO: error
364                 }
365             }
366
367             ImageProcessor.runStatistics(filename);
368
369             while (ImageProcessor.isBusy()) {
370                 try {
371                     Log.e(Thread.currentThread().getName(), "Waiting for processor to finish
                        ↪  with statistics");
372                     WAIT.wait(GlobalSettings.DEFAULT_WAIT_MS);
373                 }
374                 catch (InterruptedException e) {
375                     // TODO: error
376                 }
377             }
378         }
379     }
380
381     // Package-private Class Methods
382     //::::::::::::::::::::::
383
384     // newUCharAllocation..............
385     /**
386      * @return Empty unsigned char Allocation [width x height pixels]
387      */
388     @NonNull
389     static Allocation newUCharAllocation() {
390         return Allocation.createTyped(mRS, mUCharType, Allocation.USAGE_SCRIPT);
391     }
```

```
392
393     // newUShortAllocation...............
394     /**
395      * @return Empty unsigned short Allocation [width x height pixels]
396      */
397     @NonNull
398     static Allocation newUShortAllocation() {
399         return Allocation.createTyped(mRS, mUShortType, Allocation.USAGE_SCRIPT);
400     }
401
402     // newUIntAllocation...............
403     /**
404      * @return Empty unsigned integer Allocation [width x height pixels]
405      */
406     static Allocation newUIntAllocation() {
407         return Allocation.createTyped(mRS, mUIntType, Allocation.USAGE_SCRIPT);
408     }
409
410     // newFloatAllocation...............
411     /**
412      * @return Empty float Allocation [width x height pixels]
413      */
414     @NonNull
415     static Allocation newFloatAllocation() {
416         return Allocation.createTyped(mRS, mFloatType, Allocation.USAGE_SCRIPT);
417     }
418
419     // newDoubleAllocation...............
420     /**
421      * @return Empty double Allocation [width x height pixels]
422      */
423     @NonNull
424     static Allocation newDoubleAllocation() {
425         return Allocation.createTyped(mRS, mDoubleType, Allocation.USAGE_SCRIPT);
426     }
427
428     // newSimpleLongAllocation
429     /**
430      * @return Empty signed long Allocation [1 x 1]
431      */
432     static Allocation newSimpleLongAllocation() {
```

```
433             return Allocation.createTyped(mRS, mSimpleLongType, Allocation.USAGE_SCRIPT);
434         }
435
436         // destroyAllocation...............
437         /**
438          * TODO: might not be needed, still not completely sure about freeing Allocations
439          * @param allocation Allocation to be destroyed
440          */
441         static void destroyAllocation(@Nullable Allocation allocation) {
442             if (allocation == null) {
443                 return;
444             }
445             allocation.destroy();
446             allocation = null;
447         }
448
449         /**
450          * TODO: remove in the future, fudge-factor for controlling significance rate
451          */
452         //static void increaseSignificanceThreshold() {
453             //mThresholdOffset += GlobalSettings.THRESHOLD_STEP;
454             //CaptureController.resetSession();
455         //}
456
457     }
```

Listing E.6: Calibration Cuts (`analysis/ApplyCuts.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.renderscript.Allocation;
import android.util.Log;
import android.util.Range;

import sci.crayfis.shramp.GlobalSettings;

import sci.crayfis.shramp.camera2.capture.CaptureConfiguration;
import sci.crayfis.shramp.util.Datestamp;
import sci.crayfis.shramp.util.HeapMemory;
import sci.crayfis.shramp.util.NumToString;
import sci.crayfis.shramp.util.StorageMedia;

/**
 * Given calibration files, applies cuts to determine trustworthy pixels.
 * This could be performed in RenderScript for a substantial performance boost, but as doing so would
 * be quite cumbersome and the app can afford to take a little time on this calculation without
 * sacrificing data capture abilities, it's done in Java for simplicity / ease in changing.
 * TODO: fine tune cuts
 * TODO: make cut return successful or fail
```

```
39  * TODO: (PRIORITY) update InputWrapper/this code to process bytes from files instead of
        ↪ whole file
40  */
41 @TargetApi(21)
42 abstract class ApplyCuts {
43
44     // Private Class Constants
45     //::::::::::::::::::::::
46
47     // FPS..............
48     // When generating estimated values for statistics, use this frames-per-second
49     // TODO: consider making the estimates based on 10 fps (raw) and 15-20 fps (yuv)?
50     private static final float FPS = 10.f;
51
52     // TEMPERATURE..............
53     // When generating estimates values for statistics, use this temperature [Celsius]
54     private static final float TEMPERATURE = 35.f;
55
56     // HISTOGRAM_BOUNDS
57     // Low and high bound for histograms (pixel value)
58     private static final Range<Integer> HISTOGRAM_BOUNDS = new Range<Integer>(-100, 100);
59
60     // Private Class Fields
61     //::::::::::::::::::::::
62
63     // Allocations..............
64     // For transferring the findings of this class over to ImageProcessor
65     private static Allocation mMeanAlloc;
66     private static Allocation mStdDevAlloc;
67     private static Allocation mStdErrAlloc;
68     private static Allocation mMaskAlloc;
69
70     // mMask..............
71     // Array to hold the masking bits (1 or 0) while cuts are being made
72     private static byte[] mMask;
73
74     // mCutStatistic..............
75     // A general slush array for pixel-wise statistics used for making cuts
76     private static float[] mCutStatistic;
77
78     // mTotalMeanFrames..............
```

```
    // The total number of frames used across all "mean" files
    private static Long mTotalMeanFrames;

    // mTotalStdDevFrames...............
    // The total number of frames used across all "stddev" files
    private static Long mTotalStdDevFrames;

    // mMaxPixelValue...............
    // The maximum value a pixel can have (255 for 8-bit YUV, 1023 for 16-bit RAW)
    private static int mMaxPixelValue;

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Package-private Class Methods
    //:::::::::::::::::::::::

    // makePixelMask...............
    /**
     * Loads most recent calibration files from ShRAMP/Calibrations, and generates/saves a pixel mask
     * of what pixels should be used in significance computation.
     * Also computes/saves an estimate for the mean, stddev and stderr at FPS fps and TEMPERATURE Celsius
     * Note: assumes "hot" is hotter than "cold" and "fast" is faster than "slow"
     */
    static void makePixelMask() {

        // TODO: possibly a bug if settings change between writes / runs
        if (OutputWrapper.mBitsPerPixel == 8) {
            mMaxPixelValue = 255;
        } else { // OutputWrapper.mBitsPerPixel == 16
            mMaxPixelValue = 1023;
        }

        // Apply cuts
        if (!applyMeanCuts()) {
            return;
        }
        System.gc();
```

```
118
119         if (!applyStdDevCuts()) {
120             return;
121         }
122         System.gc();
123
124         HeapMemory.logAvailableMiB();
125
126         // Update statistics in ImageProcessor
127         ImageProcessor.setStatistics(mMeanAlloc, mStdDevAlloc, mStdErrAlloc, mMaskAlloc);
128
129         // Save statistics to disk
130         String date = Datestamp.getDate();
131         StorageMedia.writeCalibration(new OutputWrapper("mean_"   + date + GlobalSettings.
                ↪ MEAN_FILE,   mMeanAlloc,   mTotalMeanFrames,  35.f));
132         StorageMedia.writeCalibration(new OutputWrapper("stddev_" + date + GlobalSettings.
                ↪ STDDEV_FILE, mStdDevAlloc, mTotalStdDevFrames,35.f));
133         StorageMedia.writeCalibration(new OutputWrapper("stderr_" + date + GlobalSettings.
                ↪ STDERR_FILE, mStdErrAlloc, mTotalStdDevFrames,35.f));
134         StorageMedia.writeCalibration(new OutputWrapper("mask_"   + date + GlobalSettings.
                ↪ MASK_FILE,   mMask));
135     }
136
137     // Private Class Methods
138     //::::::::::::::::::::::
139
140     /**
141      * Apply cuts based on "mean" files, e.g. Temperature and Exposure-based cuts
142      * @return True if cuts were applied, false if cuts could not be made
143      */
144     private static boolean applyMeanCuts() {
145
146         HeapMemory.logAvailableMiB();
147
148         String coldFastMeanPath = StorageMedia.findRecentCalibration("cold_fast",
                ↪ GlobalSettings.MEAN_FILE);
149         String coldSlowMeanPath = StorageMedia.findRecentCalibration("cold_slow",
                ↪ GlobalSettings.MEAN_FILE);
150         String hotFastMeanPath  = StorageMedia.findRecentCalibration("hot_fast",
                ↪ GlobalSettings.MEAN_FILE);
```

```
151         String hotSlowMeanPath  = StorageMedia.findRecentCalibration("hot_slow",
                ↪ GlobalSettings.MEAN_FILE);
152
153         boolean allFilesPresent = true;
154
155         if (coldFastMeanPath == null) {
156             Log.e(Thread.currentThread().getName(), "Missing cold-fast-mean calibration file
                    ↪ , cannot continue");
157             allFilesPresent = false;
158         }
159         if (coldSlowMeanPath == null) {
160             Log.e(Thread.currentThread().getName(), "Missing cold-slow-mean calibration file
                    ↪ , cannot continue");
161             allFilesPresent = false;
162         }
163         if (hotFastMeanPath == null) {
164             Log.e(Thread.currentThread().getName(), "Missing hot-fast-mean calibration file,
                    ↪  cannot continue");
165             allFilesPresent = false;
166         }
167         if (hotSlowMeanPath == null) {
168             Log.e(Thread.currentThread().getName(), "Missing hot-slow-mean calibration file,
                    ↪  cannot continue");
169             allFilesPresent = false;
170         }
171
172         if (!allFilesPresent) {
173             return false;
174         }
175
176         // Initialize mMask
177         //==================
178         int npixels = ImageWrapper.getNpixels();
179         mMask = new byte[npixels];
180         for (int i = 0; i < npixels; i++) {
181             mMask[i] = 1;
182         }
183
184         // Reading in 4 calibration files is going to take ~200 MB of heap memory
185         if (!HeapMemory.isMemoryAmple()) {
186             // TODO: error
```

```
187                 Log.e(Thread.currentThread().getName(), "Not enough memory to apply cuts");
188                 HeapMemory.logAvailableMiB();
189                 return false;
190             }
191 
192             // Please don't run out of memory, please don't run out of memory, please don't run
                    ↪ out of..
193             HeapMemory.logAvailableMiB();
194             InputWrapper coldFast = new InputWrapper(coldFastMeanPath);
195             HeapMemory.logAvailableMiB();
196             InputWrapper coldSlow = new InputWrapper(coldSlowMeanPath);
197             HeapMemory.logAvailableMiB();
198             InputWrapper hotFast = new InputWrapper(hotFastMeanPath);
199             HeapMemory.logAvailableMiB();
200             InputWrapper hotSlow = new InputWrapper(hotSlowMeanPath);
201             HeapMemory.logAvailableMiB();
202 
203             if (HeapMemory.isMemoryLow()) {
204                 // TODO: error
205                 Log.e(Thread.currentThread().getName(), "Not enough memory to apply cuts");
206                 HeapMemory.logAvailableMiB();
207                 coldFast = null;
208                 coldSlow = null;
209                 hotFast = null;
210                 hotSlow = null;
211                 System.gc();
212                 return false;
213             }
214 
215             // Checks
216             //=======
217 
218             float[] cf = coldFast.getStatisticsData();
219             float[] cs = coldSlow.getStatisticsData();
220             float[] hf = hotFast.getStatisticsData();
221             float[] hs = hotSlow.getStatisticsData();
222 
223             if (cf == null || cs == null || hf == null || hs == null) {
224                 // TODO: error
225                 Log.e(Thread.currentThread().getName(), "Missing statistical data, cannot
                        ↪ continue");
```

```
226                 coldFast = null;
227                 coldSlow = null;
228                 hotFast = null;
229                 hotSlow = null;
230                 System.gc();
231                 return false;
232             }
233 
234             Long coldFastFrames = coldFast.getNframes();
235             Long coldSlowFrames = coldSlow.getNframes();
236             Long hotFastFrames  = hotFast.getNframes();
237             Long hotSlowFrames  = hotSlow.getNframes();
238 
239             if (coldFastFrames == null || coldSlowFrames == null || hotFastFrames == null ||
                    ↪ hotSlowFrames == null) {
240                 // TODO: error
241                 Log.e(Thread.currentThread().getName(), "Missing number of frames, cannot
                        ↪ continue");
242                 return false;
243             }
244 
245             mTotalMeanFrames = coldFastFrames + coldSlowFrames + hotFastFrames + hotSlowFrames;
246 
247             mCutStatistic = new float[npixels];
248             Histogram histogram = new Histogram(HISTOGRAM_BOUNDS);
249             HeapMemory.logAvailableMiB();
250 
251             // Temperature-based cut
252             ////////////////////////////
253             Log.e(Thread.currentThread().getName(), "Applying temperature-based cut..");
254 
255             for (int i = 0; i < npixels; i++) {
256                 mCutStatistic[i] = mMaxPixelValue * ((hf[i] + hs[i]) - (cf[i] + cs[i])) / 2.f;
257                 histogram.add(mCutStatistic[i]);
258             }
259 
260             double maxValue = histogram.getBinCenter(histogram.getMaxBin());
261             double stddev = histogram.getMaxStdDev();
262             double upperLimit = maxValue + Math.max(1., 3. * stddev);
263             double lowerLimit = maxValue - Math.max(1., 3. * stddev);
264 
```

```
265         String status = "Max value: " + NumToString.decimal(maxValue)
266                 + ", Max std dev: " + NumToString.decimal(stddev)
267                 + ", upper/lower limit: " + NumToString.decimal(upperLimit)
268                 + "/" + NumToString.decimal(lowerLimit);
269         Log.e(Thread.currentThread().getName(), status);
270
271         String filename = "hot-cold_" + Datestamp.getDate() + GlobalSettings.HISTOGRAM_FILE;
272         StorageMedia.writeCalibration(new OutputWrapper(filename, histogram,
273                                 new Range<Float>((float) lowerLimit, (float)
                                        ↪ upperLimit)));
274
275         int kept = 0;
276         for (int i = 0; i < npixels; i++) {
277             float val = mCutStatistic[i];
278             if (val < lowerLimit || val > upperLimit) {
279                 mMask[i] = 0;
280             } else {
281                 kept++;
282             }
283         }
284
285         String efficiency = NumToString.number(100. * kept / (float) npixels);
286         String cut = "cut " + NumToString.number(npixels - kept) + " out of " + NumToString.
                ↪ number(npixels);
287         Log.e(Thread.currentThread().getName(), " \n\n\t\t\tTemperature cut efficiency: " +
                ↪ cut + " = " + efficiency + "%\n ");
288
289         // Exposure-based cut
290         ////////////////////////////
291         Log.e(Thread.currentThread().getName(), "Applying exposure-based cut..");
292
293         histogram.reset();
294         for (int i = 0; i < npixels; i++) {
295             mCutStatistic[i] = mMaxPixelValue * ((hs[i] + cs[i]) - (hf[i] + cf[i])) / 2.f;
296             histogram.add(mCutStatistic[i]);
297         }
298
299         maxValue = histogram.getBinCenter(histogram.getMaxBin());
300         stddev = histogram.getMaxStdDev();
301         upperLimit = maxValue + Math.max(1., 3. * stddev);
302         lowerLimit = maxValue - Math.max(1., 3. * stddev);
```

```
303
304         status = "Max value: " + NumToString.decimal(maxValue)
305                 + ", Max std dev: " + NumToString.decimal(stddev)
306                 + ", upper/lower limit: " + NumToString.decimal(upperLimit)
307                 + "/" + NumToString.decimal(lowerLimit);
308         Log.e(Thread.currentThread().getName(), status);
309
310         filename = "slow-fast_" + Datestamp.getDate() + GlobalSettings.HISTOGRAM_FILE;
311         StorageMedia.writeCalibration(new OutputWrapper(filename, histogram,
312                                         new Range<Float>((float) lowerLimit, (float)
                                                ↪ upperLimit)));
313
314         kept = 0;
315         for (int i = 0; i < npixels; i++) {
316             float val = mCutStatistic[i];
317             if (val < lowerLimit || val > upperLimit) {
318                 mMask[i] = 0;
319             } else {
320                 kept++;
321             }
322         }
323
324         HeapMemory.logAvailableMiB();
325         efficiency = NumToString.number(100. * kept / (float) npixels);
326         cut = "cut " + NumToString.number(npixels - kept) + " out of " + NumToString.number(
                ↪ npixels);
327         Log.e(Thread.currentThread().getName(), " \n\n\t\t\tExposure cut efficiency: " + cut
                ↪  + " = " + efficiency + "%\n ");
328
329         // Estimate the mean for FPS fps at TEMPERATURE deg Celsius
330         // coordinate system:
331         //      x-axis:  temperature (cold to hot)
332         //      y-axis:  exposure (short to long)
333         ////////////////////////////
334
335         Log.e(Thread.currentThread().getName(), "Estimating mean value for " + NumToString.
                ↪ number(FPS)
336                 + " fps at " + NumToString.number(TEMPERATURE) + " Celsius ..");
337
338         Float coldFastTemp = coldFast.getTemperature();
339         Float coldSlowTemp = coldSlow.getTemperature();
```

```
340         Float hotFastTemp = hotFast.getTemperature();
341         Float hotSlowTemp = hotSlow.getTemperature();
342
343         if (coldFastTemp == null || coldSlowTemp == null || hotFastTemp == null ||
                ↪ hotSlowTemp == null) {
344             // TODO: error
345             Log.e(Thread.currentThread().getName(), "At least one temperature is null,
                    ↪ cannot continue");
346             coldFast = null;
347             coldSlow = null;
348             hotFast = null;
349             hotSlow = null;
350             System.gc();
351             return false;
352         }
353
354         float coldTemp = (coldFastTemp + coldSlowTemp) / 2.f;
355         float hotTemp = (hotFastTemp + hotSlowTemp) / 2.f;
356         float tempRange = hotTemp - coldTemp;
357         float temp = TEMPERATURE;
358         float x = (temp - coldTemp) / tempRange;
359
360         Long coldFastExp = CaptureConfiguration.EXPOSURE_BOUNDS.getLower();
361         Long coldSlowExp = CaptureConfiguration.EXPOSURE_BOUNDS.getUpper();
362         Long hotFastExp  = CaptureConfiguration.EXPOSURE_BOUNDS.getLower();
363         Long hotSlowExp  = CaptureConfiguration.EXPOSURE_BOUNDS.getUpper();
364
365         float shortExp = (coldFastExp + hotFastExp) / 2.f;
366         float longExp = (coldSlowExp + hotSlowExp) / 2.f;
367         float expRange = longExp - shortExp;
368         float exp = (float) 1e9 / FPS;
369         float y = (exp - shortExp) / expRange;
370
371         for (int i = 0; i < npixels; i++) {
372             float f00 = cf[i];
373             float f10 = hf[i];
374             float f01 = cs[i];
375             float f11 = hs[i];
376
377             mCutStatistic[i] = f00 * (1.f - x) * (1.f - y) + f10 * x * (1.f - y) + f01 * (1.
                    ↪ f - x) * y + f11 * x * y;
```

```
378         }
379
380         // Store in allocation
381         mMeanAlloc = AnalysisController.newFloatAllocation();
382         mMeanAlloc.copyFrom(mCutStatistic);
383
384         return true;
385     }
386
387     /**
388      * Apply cuts based on "stddev" files, e.g. Standard Deviation-based cuts
389      * @return True if cuts were applied, false if cuts could not be made
390      */
391     private static boolean applyStdDevCuts() {
392
393         HeapMemory.logAvailableMiB();
394
395         String coldFastStdDevPath = StorageMedia.findRecentCalibration("cold_fast",
                ↪ GlobalSettings.STDDEV_FILE);
396         String coldSlowStdDevPath = StorageMedia.findRecentCalibration("cold_slow",
                ↪ GlobalSettings.STDDEV_FILE);
397         String hotFastStdDevPath  = StorageMedia.findRecentCalibration("hot_fast",
                ↪ GlobalSettings.STDDEV_FILE);
398         String hotSlowStdDevPath  = StorageMedia.findRecentCalibration("hot_slow",
                ↪ GlobalSettings.STDDEV_FILE);
399
400         boolean allFilesPresent = true;
401
402         if (coldFastStdDevPath== null) {
403             Log.e(Thread.currentThread().getName(), "Missing cold-fast-stddev calibration
                    ↪ file, cannot continue");
404             allFilesPresent = false;
405         }
406         if (coldSlowStdDevPath == null) {
407             Log.e(Thread.currentThread().getName(), "Missing cold-slow-stddev calibration
                    ↪ file, cannot continue");
408             allFilesPresent = false;
409         }
410         if (hotFastStdDevPath == null) {
411             Log.e(Thread.currentThread().getName(), "Missing hot-fast-stddev calibration
                    ↪ file, cannot continue");
```

```
412                 allFilesPresent = false;
413             }
414             if (hotSlowStdDevPath == null) {
415                 Log.e(Thread.currentThread().getName(), "Missing hot-slow-stddev calibration
                        ↪ file, cannot continue");
416                 allFilesPresent = false;
417             }
418
419             if (!allFilesPresent) {
420                 return false;
421             }
422
423             // Please don't run out of memory, please don't run out of memory, please don't run
                    ↪ out of..
424             InputWrapper coldFast = new InputWrapper(coldFastStdDevPath);
425             HeapMemory.logAvailableMiB();
426             InputWrapper coldSlow = new InputWrapper(coldSlowStdDevPath);
427             HeapMemory.logAvailableMiB();
428             InputWrapper hotFast  = new InputWrapper(hotFastStdDevPath);
429             HeapMemory.logAvailableMiB();
430             InputWrapper hotSlow  = new InputWrapper(hotSlowStdDevPath);
431             HeapMemory.logAvailableMiB();
432
433             float[] cf = coldFast.getStatisticsData();
434             float[] cs = coldSlow.getStatisticsData();
435             float[] hf = hotFast.getStatisticsData();
436             float[] hs = hotSlow.getStatisticsData();
437
438             HeapMemory.logAvailableMiB();
439
440             if (cf == null || cs == null || hf == null || hs == null) {
441                 // TODO: error
442                 Log.e(Thread.currentThread().getName(), "Missing statistical data, cannot
                        ↪ continue");
443                 coldFast = null;
444                 coldSlow = null;
445                 hotFast  = null;
446                 hotSlow  = null;
447                 System.gc();
448                 return false;
449             }
```

```
450
451         int npixels = ImageWrapper.getNpixels();
452
453         // Standard Deviation-based cut
454         ///////////////////////////
455
456         Log.e(Thread.currentThread().getName(), "Applying standard deviation-based cut..");
457         Histogram histogram = new Histogram(HISTOGRAM_BOUNDS);
458
459         int kept = 0;
460         for (int i = 0; i < npixels; i++) {
461             float val = (float) Math.sqrt(hs[i]*hs[i]+ hf[i]*hf[i] + cs[i]*cs[i] + cf[i]*cf[
                    ↪ i]) / 4.f;
462             histogram.add(mMaxPixelValue * val);
463             if (val > 0.03f) {
464                 mMask[i] = 0;
465             }
466             else {
467                 kept++;
468             }
469         }
470
471         String filename = "stddev_" + Datestamp.getDate() + GlobalSettings.HISTOGRAM_FILE;
472         StorageMedia.writeCalibration(new OutputWrapper(filename, histogram,
473                                       new Range<Float>(0.f, 0.03f * mMaxPixelValue)));
474
475         HeapMemory.logAvailableMiB();
476         String efficiency = NumToString.number(100. * kept / (float) npixels);
477         String cut = "cut " + NumToString.number(npixels - kept) + " out of " + NumToString.
                ↪ number(npixels);
478         Log.e(Thread.currentThread().getName(), " \n\n\t\t\tStandard deviation cut
                ↪ efficiency: " + cut + " = " + efficiency + "%\n ");
479
480         // Summary
481         ///////////////////////////
482
483         kept = 0;
484         for (int i = 0; i < npixels; i++) {
485             if (mMask[i] == 1) {
486                 kept++;
487             }
```

```
488         }
489
490         // Store in allocation
491         mMaskAlloc = AnalysisController.newUCharAllocation();
492         mMaskAlloc.copyFrom(mMask);
493
494         efficiency = NumToString.number(100. * kept / (float) npixels);
495         cut = "cut " + NumToString.number(npixels - kept) + " out of " + NumToString.number(
            ↪ npixels);
496         Log.e(Thread.currentThread().getName(), " \n\n\t\t\tCombined cut efficiency: " + cut
            ↪  + " = " + efficiency + "%\n ");
497
498         // Estimate the standard deviation for FPS fps at TEMPERATURE deg Celsius
499         // coordinate system:
500         //      x-axis:  temperature (cold to hot)
501         //      y-axis:  exposure (short to long)
502         ////////////////////////////
503
504         Log.e(Thread.currentThread().getName(), "Estimating mean value for " + NumToString.
            ↪ number(FPS)
505             + " fps at " + NumToString.number(TEMPERATURE) + " Celsius ..");
506
507         Float coldFastTemp = coldFast.getTemperature();
508         Float coldSlowTemp = coldSlow.getTemperature();
509         Float hotFastTemp  = hotFast.getTemperature();
510         Float hotSlowTemp  = hotSlow.getTemperature();
511
512         if (coldFastTemp == null || coldSlowTemp == null || hotFastTemp == null ||
            ↪ hotSlowTemp == null) {
513             // TODO: error
514             Log.e(Thread.currentThread().getName(), "At least one temperature is null,
                ↪ cannot continue");
515             coldFast = null;
516             coldSlow = null;
517             hotFast  = null;
518             hotSlow  = null;
519             System.gc();
520             return false;
521         }
522
523         float coldTemp  = (coldFastTemp + coldSlowTemp) / 2.f;
```

```
524         float hotTemp   = (hotFastTemp  + hotSlowTemp ) / 2.f;
525         float tempRange = hotTemp - coldTemp;
526         float temp      = TEMPERATURE;
527         float x         = (temp - coldTemp) / tempRange;
528
529         Long coldFastExp = CaptureConfiguration.EXPOSURE_BOUNDS.getLower();
530         Long coldSlowExp = CaptureConfiguration.EXPOSURE_BOUNDS.getUpper();
531         Long hotFastExp  = CaptureConfiguration.EXPOSURE_BOUNDS.getLower();
532         Long hotSlowExp  = CaptureConfiguration.EXPOSURE_BOUNDS.getUpper();
533
534         float shortExp = (coldFastExp + hotFastExp) / 2.f;
535         float longExp  = (coldSlowExp + hotSlowExp) / 2.f;
536         float expRange = longExp - shortExp;
537         float exp      = (float) 1e9 / FPS;
538         float y        = (exp - shortExp) / expRange;
539
540         for (int i = 0; i < npixels; i++) {
541             float f00 = cf[i];
542             float f10 = hf[i];
543             float f01 = cs[i];
544             float f11 = hs[i];
545
546             mCutStatistic[i] = f00*(1.f - x)*(1.f - y) + f10*x*(1.f - y) + f01*(1.f - x)*y +
                    ↪  f11*x*y;
547         }
548
549         HeapMemory.logAvailableMiB();
550
551         // Store in allocation
552         mStdDevAlloc = AnalysisController.newFloatAllocation();
553         mStdDevAlloc.copyFrom(mCutStatistic);
554
555         // Compute average standard error
556         ///////////////////////////
557
558         Long coldFastFrames = coldFast.getNframes();
559         Long coldSlowFrames = coldSlow.getNframes();
560         Long hotFastFrames  = hotFast.getNframes();
561         Long hotSlowFrames  = hotSlow.getNframes();
562
```

```
563         if (coldFastFrames == null || coldSlowFrames == null || hotFastFrames == null ||
                ↪ hotSlowFrames == null) {
564             // TODO: error
565             Log.e(Thread.currentThread().getName(), "Missing number of frames, cannot
                    ↪ continue");
566             return false;
567         }
568
569         mTotalStdDevFrames = coldFastFrames + coldSlowFrames + hotFastFrames + hotSlowFrames
                ↪ ;
570
571         for (int i = 0; i < npixels; i++) {
572             float cferr = cf[i] / (float) Math.sqrt(coldFastFrames);
573             float cserr = cs[i] / (float) Math.sqrt(coldSlowFrames);
574             float hferr = hf[i] / (float) Math.sqrt(hotFastFrames);
575             float hserr = hs[i] / (float) Math.sqrt(hotSlowFrames);
576
577             mCutStatistic[i] = (float) Math.sqrt(cferr*cferr + cserr*cserr + hferr*hferr +
                    ↪ hserr*hserr);
578         }
579
580         // Store in allocation
581         mStdErrAlloc = AnalysisController.newFloatAllocation();
582         mStdErrAlloc.copyFrom(mCutStatistic);
583
584         return true;
585     }
586
587 }
```

Listing E.7: Data Queue (`analysis/DataQueue.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.hardware.camera2.CaptureResult;
import android.hardware.camera2.TotalCaptureResult;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.ArrayList;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.TimeCode;
import sci.crayfis.shramp.util.HandlerManager;
import sci.crayfis.shramp.util.NumToString;
import sci.crayfis.shramp.util.StopWatch;

/**
 * Intermediate queue between receiving image data and its processing
 */
@TargetApi(21)
abstract public class DataQueue {
```

```
41
42      // Private Class Constants
43      //::::::::::::::::::::::
44
45      // THREAD_NAME..............
46      // The queue acts on itself using its own thread to take the load off data receivers
47      private static final String THREAD_NAME = "QueueThread";
48
49      // mHandler...............
50      // Reference to QueueThread Handler
51      private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
52                                                          GlobalSettings.
                                                              ↪ DATA_QUEUE_THREAD_PRIORITY);
53
54      // ACCESS_LOCK..............
55      // Force actions on the two image queues to happen sequentially.
56      // Needed because isBusy() can be called from any thread.
57      private static final Object ACCESS_LOCK = new Object();
58
59      // mCaptureResultQueue...............
60      // Queue for TotalCaptureResults (metadata about the capture)
61      private static final List<TotalCaptureResult> mCaptureResultQueue = new ArrayList<>();
62
63      // mImageDataQueue...............
64      // Queue for the actual pixel image data
65      private static final List<ImageWrapper> mImageQueue = new ArrayList<>();
66
67      // ProcessNextImage...............
68      // Runnable for queue to process itself on its own thread when called from another
          ↪ thread
69      private static class ProcessNextImage implements Runnable {
70
71          // When true, continue processing image queues until queues are emptied, or clears
              ↪ them
72          // if needed.
73          // When false, processes as many elements of the queue as currently possible without
74          // explicitly clearing the queues.
75          static boolean nPurge = false;
76
77          DataQueue.ProcessNextImage setPurge() {
78              nPurge = true;
```

```
79              return this;
80          }
81
82          DataQueue.ProcessNextImage unsetPurge() {
83              nPurge = false;
84              return this;
85          }
86
87          @Override
88          public void run() {
89              // Runs processImageQueues() until all possible processing has happened (nPurge
                    ↪ = false)
90              // or forces a clear of the queues after that point (nPurge = true) to purge any
91              // unprocessable stragglers.
92              while (processImageQueues(nPurge)) {
93                  synchronized (ACCESS_LOCK) {
94                      Log.e(Thread.currentThread().getName(),
95                              "Metadata Queue Size: " + NumToString.number(mCaptureResultQueue
                                    ↪ .size())
96                              + ", Image Queue Size: "     + NumToString.number(mImageQueue.
                                    ↪ size())
97                              + ", Processor Backlog: "    + NumToString.number(ImageProcessor
                                    ↪ .getBacklog()));
98                  }
99              }
100         }
101     }
102     private static final DataQueue.ProcessNextImage ProcessNextImage = new ProcessNextImage
            ↪ ();
103
104     // For now, monitor performance (TODO: remove in the future)
105     private abstract static class StopWatches {
106         final static StopWatch AddTotalCaptureResult = new StopWatch("DataQueue.
                ↪ addTotalCaptureResult()");
107         final static StopWatch AddImageWrapper       = new StopWatch("DataQueue.
                ↪ addImageWrapper()");
108         final static StopWatch IsEmpty               = new StopWatch("DataQueue.isEmpty()");
109         final static StopWatch ProcessImageQueues    = new StopWatch("DataQueue.
                ↪ processImageQueues() (no problems)");
110         final static StopWatch ProcessImageQueues2   = new StopWatch("DataQueue.
                ↪ processImageQueues() (problems)");
```

```
111     }
112
113     ////////////////////////////
114     //::::::::::::::::::::::::
115     ////////////////////////////
116
117     // Public Class Methods
118     //::::::::::::::::::::::::
119
120     // add...............
121     /**
122      * Add capture metadata to the end of the TotalCaptureResult queue
123      * (Called from a CameraCaptureSession.CaptureCallback->onCaptureCompleted() method)
124      * Doesn't directly add to queue, but rather queues (posts) the add operation itself
         ↪ onto the
125      * QueueThread Handler to return from this method ASAP
126      * @param result TotalCaptureResult generated from an image capture
127      */
128     public static void add(@NonNull TotalCaptureResult result) {
129         StopWatches.AddTotalCaptureResult.start();
130
131         Long time = result.get(CaptureResult.SENSOR_TIMESTAMP);
132         if (time == null) {
133             // TODO: error
134             Log.e(Thread.currentThread().getName(), "Sensor timestamp cannot be null");
135             MasterController.quitSafely();
136             return;
137         }
138
139         if (GlobalSettings.DEBUG_DISABLE_QUEUE) {
140             Log.e(Thread.currentThread().getName(), "[DISABLED] Time code of metadata to
                ↪ queue: " + TimeCode.toString(time));
141             return;
142         }
143         Log.e(Thread.currentThread().getName(), "Time code of metadata to queue: " +
            ↪ TimeCode.toString(time));
144
145         // Runnable action to add metadata to TotalCaptureResult queue using the QueueThread
146         class Add implements Runnable {
147             // Payload
148             private TotalCaptureResult nResult;
```

```
149
150             // Constructor
151             private Add(TotalCaptureResult result) {
152                 nResult = result;
153             }
154
155             // Action
156             @Override
157             public void run() {
158                 synchronized (ACCESS_LOCK) {
159                     mCaptureResultQueue.add(nResult);
160                 }
161             }
162         }
163
164         // Execute Add action on QueueThread when the opportunity arises
165         mHandler.post(new Add(result));
166
167         StopWatches.AddTotalCaptureResult.addTime();
168     }
169
170     // add...............
171     /**
172      * Add captured image data to the end of the ImageWrapper queue
173      * (Called from an ImageReader.OnImageAvailableListener->onImageAvailable() method)
174      * Doesn't directly add to queue, but rather queues (posts) the add operation itself
         ↪ onto the
175      * QueueThread Handler to return from this method ASAP
176      * @param wrapper ImageWrapper created from an image capture
177      */
178     public static void add(@NonNull ImageWrapper wrapper) {
179         StopWatches.AddImageWrapper.start();
180
181         if (GlobalSettings.DEBUG_DISABLE_QUEUE) {
182             Log.e(Thread.currentThread().getName(), "[DISABLED] Time code of image to queue:
                ↪  " + wrapper.getTimeCode());
183             return;
184         }
185         Log.e(Thread.currentThread().getName(), "Time code of image to queue: " + wrapper.
            ↪ getTimeCode());
186
```

```
187         // Runnable action to add image data to ImageWrapper queue using the QueueThread
188         class Add implements Runnable {
189             // Payload
190             private ImageWrapper mWrapper;
191
192             // Constructor
193             private Add(ImageWrapper wrapper) {
194                 mWrapper = wrapper;
195             }
196
197             // Action
198             @Override
199             public void run() {
200                 synchronized (ACCESS_LOCK) {
201                     mImageQueue.add(mWrapper);
202                 }
203             }
204         }
205
206         // Execute Add action on QueueThread when the opportunity arises
207         mHandler.post(new Add(wrapper));
208
209         // 99 times out of 100 the image data comes in after the metadata, therefore the
                ↪ image queues
210         // are only now asked to process itself assuming the metadata is already queued.
211         // A single process request is made; purging the queues is not needed at this time.
212         // Every now and then, a frame of image data can get dropped as the system tries to
                ↪ keep up
213         // with everything, therefore in a typical run often there are more metadatas queued
                ↪  up
214         // than actual image data, so usually processImage() is not over-called this way.
215         mHandler.post(ProcessNextImage.unsetPurge());
216
217         StopWatches.AddImageWrapper.addTime();
218     }
219
220     ////////////////////////////
221
222     // clear...............
223     /**
224      * Wipe/reset all queues clean and start fresh -- use only when all hope is lost.
```

```
225         * Action is performed on data queue thread.
226         */
227        public static void clear() {
228            mHandler.post(new Runnable() {
229                @Override
230                public void run() {
231                    synchronized (ACCESS_LOCK) {
232                        mCaptureResultQueue.clear();
233                        mImageQueue.clear();
234                    }
235                }
236            });
237        }
238
239        // isEmpty...............
240        /**
241         * Note: called on caller's thread, there could be a delay if queue is in use already
242         * @return True if all queues are empty, false if at least one queue is not empty
243         */
244        public static boolean isEmpty() {
245            StopWatches.IsEmpty.start();
246
247            int resultSize;
248            int imageSize;
249            synchronized (ACCESS_LOCK) {
250                resultSize = mCaptureResultQueue.size();
251                imageSize = mImageQueue.size();
252            }
253
254            StopWatches.IsEmpty.addTime();
255            return (resultSize == 0) && (imageSize == 0);
256        }
257
258        // logQueueSizes...............
259        /**
260         * Display number of items in each queue.
261         * Note: called on caller's thread, there could be a delay if queue is in use already
262         */
263        public static void logQueueSizes() {
264            synchronized (ACCESS_LOCK) {
265                int resultSize = mCaptureResultQueue.size();
```

```
266             int imageSize  = mImageQueue.size();
267
268             Log.e(Thread.currentThread().getName(), "Items in queue (metadata, image data) =
                ↪  ("
269             + NumToString.number(resultSize) + ", " + NumToString.number(imageSize) + ")");
270         }
271     }
272
273     // logQueueContents...............
274     /**
275      * Display a listing of queue contents.
276      * Note: called on caller's thread, there could be a delay if queue is in use already
277      */
278     public static void logQueueContents() {
279         synchronized (ACCESS_LOCK) {
280             String metaString   = "";
281             String imageString  = "";
282
283             for (TotalCaptureResult result : mCaptureResultQueue) {
284                 Long timestamp = result.get(CaptureResult.SENSOR_TIMESTAMP);
285                 if (timestamp == null) {
286                     // TODO: error
287                     Log.e(Thread.currentThread().getName(), "Timestamp cannot be null");
288                     MasterController.quitSafely();
289                     return;
290                 }
291                 metaString += " " + TimeCode.toString(timestamp) + " ";
292             }
293
294             for (ImageWrapper wrapper : mImageQueue) {
295                 imageString += " " + wrapper.getTimeCode() + " ";
296             }
297
298             String out = " \n\n";
299             out += "\tMetadata time-codes: " + metaString + "\n";
300             out += "\tImage time-codes:    " + imageString + "\n";
301
302             Log.e(Thread.currentThread().getName(), out);
303         }
304     }
305
```

```
306     // purge...............
307     /**
308      * Purges (processes) all queues for any unfinished jobs until their empty using the
            ↪ queue thread
309      */
310     public static void purge() {
311         if (isEmpty()) {
312             return;
313         }
314         mHandler.post(ProcessNextImage.setPurge());
315     }
316
317     // Private Class Methods
318     //:::::::::::::::::::::::
319
320     // processImageQueues...............
321     /**
322      * Sends the next image (and metadata) staged in the image queues off to ImageProcessor
323      * @param purging True if no new data is expected and clears both queues when at least
            ↪ one queue
324      *                has no more elements
325      * @return True if after running this method, image queues still have more data staged
            ↪ for
326      *         processing, false if queues are now empty
327      */
328     private static boolean processImageQueues(boolean purging) {
329         StopWatches.ProcessImageQueues.start();
330         StopWatches.ProcessImageQueues2.start();
331
332         // All actions occur under ACCESS_LOCK
333         synchronized (ACCESS_LOCK) {
334
335             int resultSize = mCaptureResultQueue.size();
336             int imageSize  = mImageQueue.size();
337
338             // Image queues are not empty
339             if (resultSize > 0 && imageSize > 0) {
340                 TotalCaptureResult result = mCaptureResultQueue.remove(0);
341                 ImageWrapper wrapper      = mImageQueue.remove(0);
342                 resultSize -= 1;
343                 imageSize  -= 1;
```

```
344
345                 Long result_timestamp = result.get(CaptureResult.SENSOR_TIMESTAMP);
346                 if (result_timestamp == null) {
347                     // TODO: error
348                     Log.e(Thread.currentThread().getName(), "Sensor timestamp cannot be null
                        ↪ ");
349                     MasterController.quitSafely();
350                     return false;
351                 }
352                 String result_timecode = TimeCode.toString(result_timestamp);
353
354                 // Everything checks out, process image
355                 if (result_timestamp == wrapper.getTimestamp()) {
356                     Log.e(Thread.currentThread().getName(), "Timestamp match, time-codes: "
357                             + result_timecode + " == " + wrapper.getTimeCode());
358
359                     if (!GlobalSettings.DEBUG_DISABLE_PROCESSING) {
360                         // ImageProcessor returns rapidly as it builds a processing Runnable
                            ↪  that
361                         // runs on the ImageProcessorThread instead of directly processing
                            ↪ now
362                         ImageProcessor.process(result, wrapper);
363                     }
364
365                     StopWatches.ProcessImageQueues.addTime();
366                     return (resultSize != 0 && imageSize != 0);
367                 }
368                 //————————————————————————————————————
                    ↪ ————————————————————————————————————————————
369                 // Head-ache .. figure out what's wrong
370                 else {
371                     Log.e(Thread.currentThread().getName(), "Timestamps do not match, time-
                        ↪ codes: "
372                             + result_timecode + " != " + wrapper.getTimeCode());
373
374                     // Timestamps don't match and at least one queue is now empty
375                     //————————————————————————————————————————————————————————
376                     if (resultSize == 0 || imageSize == 0) {
377
378                         // No new data coming in, go ahead and clear the queues
379                         if (purging) {
```

```
380                         Log.e(Thread.currentThread().getName(), "Purging image queues");
381                         mCaptureResultQueue.clear();
382                         mImageQueue.clear();
383                     }
384                     // New data will be coming in, wait for it
385                     else {
386                         Log.e(Thread.currentThread().getName(), "Requeing both image and
                                ↪  result");
387                         mCaptureResultQueue.add(0, result);
388                         mImageQueue.add(0, wrapper);
389                     }
390
391                     StopWatches.ProcessImageQueues2.addTime();
392                     return false;
393                 }
394                 // Timestamps don't match and neither queue is empty
395                 //-----------------------------------------------------
396                 else {
397                     // Look at what's next in the queues
398                     TotalCaptureResult nextResult = mCaptureResultQueue.get(0);
399                     ImageWrapper nextWrapper      = mImageQueue.get(0);
400
401                     Long nextResult_timestamp = nextResult.get(CaptureResult.
                            ↪ SENSOR_TIMESTAMP);
402                     if (nextResult_timestamp == null) {
403                         // TODO: error
404                         Log.e(Thread.currentThread().getName(), "Sensor timestamp cannot
                                ↪  be null");
405                         MasterController.quitSafely();
406                         return false;
407                     }
408                     String nextResult_timecode  = TimeCode.toString(nextResult_timestamp
                            ↪ );
409
410                     // If current ImageWrapper matches next TotalCaptureResult
411                     // i.e. an image was dropped by the system
412                     // Requeue for next processImageQueues() call
413                     if (wrapper.getTimestamp() == nextResult_timestamp) {
414                         Log.e(Thread.currentThread().getName(), "An image was dropped
                                ↪ that would have had time-code: "
```

```
415                                 + result_timecode + ", dropping that metadata from queue
                                        ↪ ");
416                             mImageQueue.add(0, wrapper);
417                             StopWatches.ProcessImageQueues2.addTime();
418                             return true;
419                         }
420                         // If current TotalCaptureResult matches next ImageWrapper
421                         // i.e. metadata was dropped (extremely rare)
422                         // Requeue for next processImageQueues() call
423                         else if (result_timestamp == nextWrapper.getTimestamp()) {
424                             Log.e(Thread.currentThread().getName(), "A metadata was dropped
                                    ↪ that would have had time-code: "
425                                 + wrapper.getTimeCode() + ", dropping that image from
                                        ↪ queue");
426                             mCaptureResultQueue.add(0, result);
427                             StopWatches.ProcessImageQueues2.addTime();
428                             return true;
429                         }
430                         // ImageWrappers and TotalCaptureResults have fallen out of sync by
                                ↪ more than
431                         // one capture (e.g. the system dropped two or more consecutive
                                ↪ image frames)
432                         else {
433                             Log.e(Thread.currentThread().getName(), "Multiple consecutive
                                    ↪ images were dropped, dropping metadata from queue to
                                    ↪ catch up");
434                             mCaptureResultQueue.remove(0);
435                             while (mCaptureResultQueue.size() > 0) {
436                                 nextResult = mCaptureResultQueue.remove(0);
437
438                                 nextResult_timestamp = nextResult.get(CaptureResult.
                                        ↪ SENSOR_TIMESTAMP);
439                                 if (nextResult_timestamp == null) {
440                                     // TODO: error
441                                     Log.e(Thread.currentThread().getName(), "Sensor
                                            ↪ timestamp cannot be null");
442                                     MasterController.quitSafely();
443                                     return false;
444                                 }
445                                 nextResult_timecode = TimeCode.toString(nextResult_timestamp
                                        ↪ );
```

```
446
447                                 // Everything checks out at last, requeue for next
                                        ↪ processImageQueues() call
448                                 if (wrapper.getTimestamp() == nextResult_timestamp) {
449                                     Log.e(Thread.currentThread().getName(), "Timestamp match
                                            ↪ , time-codes: "
450                                             + nextResult_timecode + " == " + wrapper.
                                                ↪ getTimeCode());
451                                     mImageQueue.add(0, wrapper);
452                                     mCaptureResultQueue.add(0, nextResult);
453                                     StopWatches.ProcessImageQueues2.addTime();
454                                     return true;
455                                 }
456                                 // Still not caught up
457                                 else {
458                                     Log.e(Thread.currentThread().getName(), "Dropping
                                            ↪ metadata with time-code: " + nextResult_timecode)
                                            ↪ ;
459                                 }
460                             }
461
462                             // This is exceptionally rare, could happen if the system
                                    ↪ dropped two
463                             // consecutive TotalCaptureResults, but pretty much unheard of.
464                             // Most likely this is an edge condition, either at the start or
                                    ↪  end of
465                             // a run.
466                             Log.e(Thread.currentThread().getName(), "Ran out of metadata to
                                    ↪ drop, dropping everything from both queues");
467                             mCaptureResultQueue.clear();
468                             mImageQueue.clear();
469                             StopWatches.ProcessImageQueues2.addTime();
470                             return false;
471                         }
472                     }
473                 }
474             }
475             // At least one image queue is empty
476             else {
477                 // No new data coming in, go ahead and clear the queues
478                 if (purging) {
```

```
                    Log.e(Thread.currentThread().getName(), "Purging queues");
                    mCaptureResultQueue.clear();
                    mImageQueue.clear();
                }
                StopWatches.ProcessImageQueues2.addTime();
                return false;
            }

        }
    }

}
```

Listing E.8: Histogram (`analysis/Histogram.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.util.Range;

/**
 * Represents a histogram and related functions
 */
@TargetApi(21)
public class Histogram {

    // Private Instance Fields
    //::::::::::::::::::::::

    // mBins..............
    // Histogram bin left edges
    int[] mBins;

    // mNbins..............
    // Number of bins
    int mNbins;

    // mValues..............
```

```
41      // Histogram values for each bin
42      int[] mValues;
43
44      // mUnderflow...............
45      // Histogram value for underflow
46      int mUnderflow;
47
48      // mOverflow...............
49      // Histogram value for overflow
50      int mOverflow;
51
52      ///////////////////////////
53      //:::::::::::::::::::::::
54      ///////////////////////////
55
56      // Constructors
57      //:::::::::::::::::::::::
58
59      // Histogram...............
60      /**
61       * Disabled
62       */
63      private Histogram() {}
64
65      // Histogram...............
66      /**
67       * Creates a new histogram from low to high in integer pixel steps
68       * @param low Low limit in pixel value units
69       * @param high High limit in pixel value units
70       */
71      public Histogram(int low, int high) {
72          mNbins  = high - low;
73          mBins   = new int[mNbins];
74          mValues = new int[mNbins];
75
76          int index = 0;
77          for (int i = low; i < high; i++) {
78              mBins[index]   = i;
79              mValues[index] = 0;
80              index++;
81          }
```

```
        mUnderflow = 0;
        mOverflow  = 0;
    }

    // Histogram...............
    /**
     * Creates a new histogram from low to high in integer pixel steps
     * @param range Low and high limit in pixel value units
     */
    public Histogram(@NonNull Range<Integer> range) {
        this(range.getLower(), range.getUpper());
    }

    // Public Instance Methods
    //:::::::::::::::::::::::

    // add...............
    /**
     * Add the value to the histogram
     * @param value Value to add
     * @return The bin number it was added to, -1 = underflow, Nbins = overflow
     */
    public int add(double value) {
      int bin = getBinNumber(value);
      if (bin == -1) {
          mUnderflow++;
      }
      else if (bin == mNbins) {
          mOverflow++;
      }
      else {
          mValues[bin]++;
      }
      return bin;
    }

    // getBinCenter...............
    /**
     * @param bin Bin number
```

```
122         * @return The value for the center of the bin, Double.NaN if bin number is beyond [0,
                ↪ nBins - 1]
123         */
124        public double getBinCenter(int bin) {
125            if (bin < 0 || bin > mNbins - 1) {
126                return Double.NaN;
127            }
128            return mBins[bin] + 0.5;
129        }
130
131        // getBinNumber...............
132        /**
133         * @param value Value to find the bin number
134         * @return The bin number where value lies, -1 if underflow, Nbins if overflow
135         */
136        public int getBinNumber(double value) {
137            if (value < mBins[0]) {
138                return -1;
139            }
140
141            for (int i = 0; i < mNbins; i++) {
142                if (value >= mBins[i] && value < mBins[i] + 1) {
143                    return i;
144                }
145            }
146
147            return mNbins;
148        }
149
150        // getValue...............
151        /**
152         * @param bin Bin number for the histogram value wanted
153         * @return The value at that bin (bin number = -1 is underflow, = Nbins is overflow)
154         */
155        public int getValue(int bin) {
156            if (bin == -1) {
157                return mUnderflow;
158            }
159            if (bin == mNbins) {
160                return mOverflow;
161            }
```

```
        return mValues[bin];
    }

    // getNbins...............
    /**
     * @return The number of bins
     */
    public int getNbins() { return mNbins; }

    // getUnderflow...............
    /**
     * @return The value of the underflow bin
     */
    public int getUnderflow() { return mUnderflow; }

    // getOverflow...............
    /**
     * @return The value of the overflow bin
     */
    public int getOverflow() { return mOverflow; }

    // getMaxBin...............
    /**
     * @return The bin number where the maximum histogram value is, if there are more than one equal
     *         maximum, returns the first occurrence (does not search underflow/overflow bins)
     */
    public int getMaxBin() {
        int maxIndex = 0;
        int maxValue = mValues[0];
        for (int i = 1; i < mNbins; i++) {
            if (mValues[i] > maxValue) {
                maxIndex = i;
                maxValue = mValues[i];
            }
        }
        return maxIndex;
    }

    // getMaxStdDev...............
```

```java
    /**
     * @return The standard deviation immediately surrounding the max bin (+/- 10 pixel values)
     */
    public double getMaxStdDev() {
        int delta   = 10;
        int maxBin  = getMaxBin();
        int lowBin  = Math.max(0, maxBin - delta);
        int highbin = Math.min(mNbins - 1, maxBin + delta);

        int N = 0;
        double stddev = 0.;
        for (int i = lowBin; i <= highbin; i++) {
            int val = getValue(i);
            stddev += val * (getBinCenter(i) - getBinCenter(maxBin)) * (getBinCenter(i) - getBinCenter(maxBin));
            N += val;
        }
        return Math.sqrt( stddev / ( (double) N) );
    }

    // reset...............
    /**
     * Resets (clears) histogram values including overflow/underflow but keeps the same bins
     */
    public void reset() {
        mUnderflow = 0;
        mOverflow  = 0;
        for (int i = 0; i < mNbins; i++) {
            mValues[i] = 0;
        }
    }

}
```

Listing E.9: Image Processing (`analysis/ImageProcessor.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.hardware.camera2.CaptureResult;
import android.hardware.camera2.TotalCaptureResult;
import android.os.Handler;
import android.renderscript.Allocation;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import org.jetbrains.annotations.Contract;

import java.util.Locale;
import java.util.concurrent.atomic.AtomicBoolean;
import java.util.concurrent.atomic.AtomicInteger;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.ScriptC_PostProcessing;
import sci.crayfis.shramp.ScriptC_LiveProcessing;
import sci.crayfis.shramp.battery.BatteryController;
import sci.crayfis.shramp.util.Datestamp;
import sci.crayfis.shramp.util.HandlerManager;
import sci.crayfis.shramp.util.NumToString;
```

```
41  import sci.crayfis.shramp.util.StopWatch;
42  import sci.crayfis.shramp.util.StorageMedia;
43
44
45  /**
46   * Oversees both live and post image processing with RenderScript
47   */
48  @TargetApi(21)
49  abstract class ImageProcessor {
50
51      // Private Class Constants
52      //::::::::::::::::::::::
53
54      // THREAD_NAME..............
55      // To maximize performance and avoid loading down calling threads, run image processing
            ↪ on its own thread
56      private static final String THREAD_NAME = "ImageProcessorThread";
57
58      // mHandler...............
59      // Reference to this thread's Handler
60      private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
61                                                          GlobalSettings.
                                                                ↪ IMAGE_PROCESSOR_THREAD_PRIORITY);
62
63      // mIsFirstFrame...............
64      // Thread-safe flag denoting the first frame to be processed
65      private static final AtomicBoolean mIsFirstFrame = new AtomicBoolean();
66
67      // mBacklog...............
68      // Thread-safe count of jobs waiting for processing on this thread
69      private static final AtomicInteger mBacklog = new AtomicInteger();
70
71      // mFramesAboveThreshold...............
72      // Thread-safe count of frames with at least one pixel found to be above threshold
73      private static final AtomicInteger mFramesAboveThreshold = new AtomicInteger();
74
75      // mCountAboveThresholdArray...............
76      // Number of pixels in a frame that were found to be above threshold.
77      // Corresponds to mCountAboveThreshold (RenderScript Allocation) below
78      private static final long[] mCountAboveThresholdArray = new long[1];
79
```

```
80      // mAnomalousStdDevArray...............
81      // In the process of determining the mean and standard deviation, an unlikely overflow
            ↪ in
82      // the summing variables might occur under extreme conditions, if this happens the
            ↪ number of
83      // pixels with this problem are recorded in this variable.
84      // Corresponds to mAnomalousStdDev (RenderScript Allocation) below
85      private static final long[] mAnomalousStdDevArray = new long[1];
86
87      // ENABLED / DISABLED...............
88      // Constants denoting whether significance testing is enabled or disabled
89      private static final int ENABLED  = 1;
90      private static final int DISABLED = 0;
91
92      // Private Class Fields
93      //:::::::::::::::::::::::
94
95      // mLiveScript...............
96      // Reference to the LiveProcessing.rs RenderScript
97      private static ScriptC_LiveProcessing mLiveScript;
98
99      // mPostScript...............
100     // Reference to the PostProcessing.rs RenderScript
101     private static ScriptC_PostProcessing mPostScript;
102
103     // mImage...............
104     // Image data (received from an ImageWrapper) converted into a RenderScript Allocation
105     private static Allocation mImage;
106
107     // mEnableSignificance...............
108     // Denotes whether significance testing is enabled or disabled
109     private static int mEnableSignificance = DISABLED;
110
111     // mSignificance...............
112     // Significance of each pixel in an image as a RenderScript Allocation
113     private static Allocation mSignificance;
114
115     // mSignifArray...............
116     // Direct access of significance from allocation, only used/initialized if
117     // GlobalSettings.DEBUG_SAVE_SIGNIF_HIST = true
118     private static float[] mSignifArray;
```

```
119
120     // mSignifPosHist ...............
121     // Significance of each mask=1 pixel in histogram form as a RenderScript Allocation
122     private static Allocation mSignifPosHist;
123
124     // mSignifNegHist ...............
125     // Significance of each mask=0 pixel in histogram form as a RenderScript Allocation
126     private static Allocation mSignifNegHist;
127
128     // mCountAboveThreshold ...............
129     // Number of pixels in a frame that were found to above threshold.
130     // Corresponds to mCountAboveThresholdArray above
131     private static Allocation mCountAboveThreshold;
132
133     // mAnomalousStdDev ...............
134     // In the process of determining the mean and standard deviation, an unlikely overflow
            ↪ in
135     // the summing variables might occur under extreme conditions, if this happens the
            ↪ number of
136     // pixels with this problem are recorded in this variable.
137     // Corresponds to mAnomalousStdDevArray above
138     private static Allocation mAnomalousStdDev;
139
140     // Inner Classes
141     //:::::::::::::::::::::::
142
143     // RunningTotal ...............
144     // Collection of quantities that increase with each image processed
145     private abstract static class RunningTotal {
146         static long       Nframes;
147         static Allocation ValueSum;
148         static Allocation Value2Sum;
149     }
150
151     // PostProcessing ...............
152     // Collection of quantities of a statistical nature
153     private abstract static class Statistics {
154         static Allocation Mean;
155         static Allocation StdDev;
156         static Allocation StdErr;
157         static Allocation Mask;
```

```
158         static float      SignificanceThreshold;
159     }
160
161     // For now, monitor performance (TODO: remove in the future)
162     private abstract static class StopWatches {
163         final static StopWatch LiveProcessing = new StopWatch("ImageProcessor.process()");
164         final static StopWatch PostProcessing = new StopWatch("ImageProcessor.runStatistics
            ↪ ()");
165     }
166
167     ///////////////////////////
168     //:::::::::::::::::::::::
169     ///////////////////////////
170
171     // Package-private Class Methods
172     //:::::::::::::::::::::::
173
174     // isBusy...............
175     /**
176      * @return True if there are image processing jobs still in queue, false if idling
177      */
178     static boolean isBusy() {
179         return mBacklog.get() != 0;
180     }
181
182     // getBacklog...............
183     /**
184      * @return The number of backlogged image processing jobs waiting to run
185      */
186     static int getBacklog() {
187         return mBacklog.get();
188     }
189
190     ///////////////////////////
191
192     // enableSignificance...............
193     /**
194      * Enable live statistical significance testing on each pixel of input images
195      */
196     static void enableSignificance() {
197         mEnableSignificance = ENABLED;
```

```
198             mLiveScript.set_gEnableSignificance(mEnableSignificance);
199         }
200
201         // disableSignificance ...............
202         /**
203          * Disable live statistical significance testing on each pixel of input images
204          */
205         static void disableSignificance() {
206             mEnableSignificance = DISABLED;
207             mLiveScript.set_gEnableSignificance(mEnableSignificance);
208         }
209
210         // isSignificanceEnabled ...............
211         /**
212          * @return True if significance testing is being done, false if it is disabled
213          */
214         @Contract(pure = true)
215         static boolean isSignificanceEnabled() {
216             return mEnableSignificance == ENABLED;
217         }
218
219         // getSignificance ...............
220         /**
221          * @return RenderScript Allocation of pixel statistical significance for last image
                 ↪ processed
222          */
223         @Contract(pure = true)
224         @NonNull
225         static Allocation getSignificance() {
226             return mSignificance;
227         }
228
229         // enableSignificanceHistogram ...............
230         /**
231          * Allocates memory for significance histogram
232          * @param npixels the number of pixels of the sensor
233          */
234         static void enableSignificanceHistogram(int npixels) { mSignifArray = new float[npixels
                ↪ ]; }
235
236         ////////////////////////////
```

```
237
238     // getMean...............
239     /**
240      * @return RenderScript Allocation of pixel mean values currently being used
241      */
242     @Contract(pure = true)
243     @NonNull
244     static Allocation getMean() {
245         return Statistics.Mean;
246     }
247
248     // getStdDev...............
249     /**
250      * @return RenderScript Allocation of pixel standard deviation values currently being
         ↪ used
251      */
252     @Contract(pure = true)
253     @NonNull
254     static Allocation getStdDev() {
255         return Statistics.StdDev;
256     }
257
258     // getStdErr...............
259     /**
260      * @return RenderScript Allocation of pixel standard error values currently being used
261      */
262     @Contract(pure = true)
263     @NonNull
264     static Allocation getStdErr() {
265         return Statistics.StdErr;
266     }
267
268     // getMask...............
269     /**
270      * @return RenderScript Allocation of pixel mask currently being used
271      */
272     @Contract(pure = true)
273     @NonNull
274     static Allocation getMask() { return Statistics.Mask; }
275
276     ////////////////////////////
```

```
277
278     // getValueSum...............
279     /**
280      * @return RenderScript Allocation of the pixel-wise sum of processed pixel values
281      */
282     @Contract(pure = true)
283     @NonNull
284     static Allocation getValueSum() {
285         return RunningTotal.ValueSum;
286     }
287
288     // getValue2Sum...............
289     /**
290      * @return RenderScript Allocation of the pixel-wise sum of processed pixel values**2
291      */
292     @Contract(pure = true)
293     @NonNull
294     static Allocation getValue2Sum() {
295         return RunningTotal.Value2Sum;
296     }
297
298     //////////////////////////
299
300     // setLiveProcessor...............
301     /**
302      * @param script Reference to RenderScript LiveProcessing.rs
303      */
304     static void setLiveProcessor(@NonNull ScriptC_LiveProcessing script) {
305         mLiveScript = script;
306     }
307
308     // setPostProcessor...............
309     /**
310      * @param script Reference to RenderScript PostProcessing.rs
311      */
312     static void setPostProcessor(@NonNull ScriptC_PostProcessing script) { mPostScript =
            ↪ script; }
313
314     // setImageAllocation...............
315     /**
316      * @param image Initialized RenderScript Allocation to contain image data
```

```
317         */
318         static void setImageAllocation(@NonNull Allocation image) {
319             mImage = image;
320         }
321
322         // setSignificanceAllocation ..............
323         /**
324          * @param significance Initialized RenderScript Allocation to contain pixel significance
325          */
326         static void setSignificanceAllocation(@NonNull Allocation significance) { mSignificance
                ↪ = significance; }
327
328         // setCountAboveThresholdAllocation ..............
329         /**
330          * @param countAboveThreshold Initialized RenderScript Allocation to count pixels above
                 ↪ threshold
331          */
332         static void setCountAboveThresholdAllocation(@NonNull Allocation countAboveThreshold) {
333             mCountAboveThreshold = countAboveThreshold;
334         }
335
336         // setAnomalousStdDevAllocation ..............
337         /**
338          * @param anomalousStdDev Initialized RenderScript Allocation to count overflows in
                 ↪ summing
339          */
340         static void setAnomalousStdDevAllocation(@NonNull Allocation anomalousStdDev) {
341             mAnomalousStdDev = anomalousStdDev;
342         }
343
344         // setStatistics ..............
345         /**
346          * @param mean Initialized RenderScript Allocation to contain pixel means
347          * @param stdDev Initialized RenderScript Allocation to contain pixel standard
                 ↪ deviations
348          * @param stdErr Initialized RenderScript Allocation to contain pixel standard errors
349          * @param mask Initialized RenderScript Allocation to contain pixel mask
350          */
351         static void setStatistics(@NonNull Allocation mean,
352                                   @NonNull Allocation stdDev,
353                                   @NonNull Allocation stdErr,
```

```
                                @NonNull Allocation mask) {
        Statistics.Mean   = mean;
        Statistics.StdDev = stdDev;
        Statistics.StdErr = stdErr;
        Statistics.Mask   = mask;
    }

    // setSignificanceThreshold...............
    /**
     * @param threshold Threshold to determine if a pixel's value is statistically
         ↪ significant
     */
    static void setSignificanceThreshold(float threshold) {
        mLiveScript.set_gSignificanceThreshold(threshold);
        Statistics.SignificanceThreshold = threshold;
    }

    ////////////////////////////

    // resetTotals...............
    /**
     * Reset all running / summing variables for a fresh start, reset live-processing
         ↪ RenderScript globals
     */
    static void resetTotals() {
        mBacklog.set(0);
        mFramesAboveThreshold.set(0);
        mIsFirstFrame.set(true);

        RunningTotal.Nframes = 0L;
        if (RunningTotal.ValueSum == null || RunningTotal.Value2Sum == null) {
            RunningTotal.ValueSum  = AnalysisController.newUIntAllocation();
            RunningTotal.Value2Sum = AnalysisController.newUIntAllocation();
        }

        mLiveScript.forEach_zeroUIntAllocation(RunningTotal.ValueSum);
        mLiveScript.forEach_zeroUIntAllocation(RunningTotal.Value2Sum);

        mLiveScript.set_gValueSum(RunningTotal.ValueSum);
        mLiveScript.set_gValue2Sum(RunningTotal.Value2Sum);

```

```
393         mLiveScript.set_gMean(Statistics.Mean);
394         mLiveScript.set_gStdDev(Statistics.StdDev);
395         mLiveScript.set_gMask(Statistics.Mask);
396
397         // Values are set in RenderScript LiveProcessing.rs
398         mLiveScript.set_gSignificance(mSignificance);
399
400         // Zeroed in process()
401         mLiveScript.set_gCountAboveThreshold(mCountAboveThreshold);
402     }
403
404     ////////////////////////////
405     ////////////////////////////
406
407     // process...............
408     /**
409      * This method doesn't directly process an image, rather it builds a Runnable that
            ↪ processes
410      * the image and posts it to the ImageProcessorThread to avoid slowing down the calling
            ↪ thread
411      * @param result Image metadata
412      * @param wrapper Image data
413      */
414     static void process(@NonNull TotalCaptureResult result, @NonNull ImageWrapper wrapper) {
415
416         // skip the first frame, for YUV_420_888 in particular pixel values tend to be
            ↪ anomalously
417         // big, I don't know why exactly, but it seems to be
418         if (mIsFirstFrame.get()) {
419             mIsFirstFrame.set(false);
420             return;
421         }
422
423         // This Runnable is the image processor that runs on the ImageProcessorThread
424         class Processor implements Runnable {
425
426             // Payloads
427             private TotalCaptureResult Result;
428             private ImageWrapper Wrapper;
429
430             // Constructor
```

```
431             private Processor(@NonNull TotalCaptureResult result, @NonNull ImageWrapper
                    ↪ wrapper) {
432                 Result  = result;
433                 Wrapper = wrapper;
434             }
435
436             // Action
437             @Override
438             public void run() {
439                 StopWatches.LiveProcessing.start();
440
441                 RunningTotal.Nframes += 1;
442
443                 // Save every DEBUG_IMAGE_SAVING_INTERVAL image
444                 // WARNING: each image will be ~20-30 MB or so
445                 if (GlobalSettings.DEBUG_ENABLE_IMAGE_SAVING
446                         && RunningTotal.Nframes % GlobalSettings.DEBUG_IMAGE_SAVING_INTERVAL
                            ↪  == 0) {
447                     // filename = [frame number]_[nanoseconds since start].frame
448                     String filename = String.format(Locale.US,"%05d", RunningTotal.Nframes);
449                     filename += "_" + String.format(Locale.US, "%015d", Datestamp.
                            ↪ getElapsedTimestampNanos(Wrapper.getTimestamp()));
450                     filename += GlobalSettings.IMAGE_FILE;
451                     Long exposure = Result.get(CaptureResult.SENSOR_EXPOSURE_TIME);
452                     Double temperature = BatteryController.getCurrentTemperature();
453                     if (temperature == null) {
454                         temperature = Double.NaN;
455                     }
456                     StorageMedia.writeInternalStorage(new OutputWrapper(filename, Wrapper,
                            ↪ exposure, temperature.floatValue()), null);
457                 }
458
459                 // Zero count of number of pixels above threshold
460                 mCountAboveThresholdArray[0] = 0L;
461                 mCountAboveThreshold.copyFrom(mCountAboveThresholdArray);
462                 mLiveScript.set_gCountAboveThreshold(mCountAboveThreshold);
463
464                 // RenderScript image processing
465                 if (ImageWrapper.is8bitData()) {
466                     mImage.copyFrom(Wrapper.get8bitData());
467                     mLiveScript.forEach_process8bitData(mImage);
```

```
468                 }
469                 else { // ImageWrapper.is16bitData()
470                     mImage.copyFrom(Wrapper.get16bitData());
471                     mLiveScript.forEach_process16bitData(mImage);
472                 }
473
474                 if (mEnableSignificance == ENABLED) {
475
476                     mLiveScript.forEach_getCountAboveThreshold(mCountAboveThreshold);
477                     mCountAboveThreshold.copyTo(mCountAboveThresholdArray);
478                     Log.e(Thread.currentThread().getName(), "Pixel count above threshold: "
479                             + NumToString.number(mCountAboveThresholdArray[0]));
480
481                     // TODO: in the future when i'm happy with the rates over threshold,
                            ↪ save it
482                     if (mCountAboveThresholdArray[0] > 0L) {
483                         //mLiveScript.forEach_getSignificance(mSignificance);
484                         // filename = [frame number]_[nanoseconds since start].signif
485                         //String filename = String.format(Locale.US, "%05d", RunningTotal.
                                ↪ Nframes);
486                         //filename += "_" + String.format(Locale.US, "%015d", Datestamp.
                                ↪ getElapsedTimestampNanos(Wrapper.getTimestamp()));
487                         //filename += GlobalSettings.SIGNIF_FILE;
488                         //DataQueue.add(new OutputWrapper(filename, mSignificance, 1));
489                     }
490
491                     // TODO: for now:
492                     // Save every DEBUG_SIGNIFICANCE_SAVING_INTERVAL significance
493                     // WARNING: each image will be ~40-50 MB or so and will slow down
                            ↪ processing
494                     if (GlobalSettings.DEBUG_SAVE_SIGNIFICANCE
495                             && RunningTotal.Nframes % GlobalSettings.
                                    ↪ DEBUG_SIGNIFICANCE_SAVING_INTERVAL == 0) {
496                         mLiveScript.forEach_getSignificance(mSignificance);
497                         // filename = [frame number]_[nanoseconds since start].signif
498                         String filename = String.format(Locale.US, "%05d", RunningTotal.
                                ↪ Nframes);
499                         filename += "_" + String.format(Locale.US, "%015d", Datestamp.
                                ↪ getElapsedTimestampNanos(Wrapper.getTimestamp()));
500                         filename += GlobalSettings.SIGNIF_FILE;
501                         Double temperature = BatteryController.getCurrentTemperature();
```

```
502                         if (temperature == null) {
503                             temperature = Double.NaN;
504                         }
505                         StorageMedia.writeInternalStorage(new OutputWrapper(filename,
                                ↪ mSignificance, 1, temperature.floatValue()), null);
506                     }
507                     if (GlobalSettings.DEBUG_SAVE_SIGNIF_HIST
508                             && RunningTotal.Nframes % GlobalSettings.
                                    ↪ DEBUG_IMAGE_SAVING_INTERVAL == 0) {
509                         mLiveScript.forEach_getSignificance(mSignificance);
510                         Histogram histogram = new Histogram(-1000, 1000);
511                         mSignificance.copyTo(mSignifArray);
512                         for (float val : mSignifArray) {
513                             histogram.add(val);
514                         }
515                         // filename = signif_[frame number]_[nanoseconds since start].hist
516                         String filename = "signif_" + String.format(Locale.US, "%05d",
                                ↪ RunningTotal.Nframes);
517                         filename += "_" + String.format(Locale.US, "%015d", Datestamp.
                                ↪ getElapsedTimestampNanos(Wrapper.getTimestamp()));
518                         filename += GlobalSettings.HISTOGRAM_FILE;
519                         StorageMedia.writeInternalStorage(new OutputWrapper(filename,
                                ↪ histogram, null), null);
520                     }
521
522                     // TODO: remove in the future / figuring out threshold details
523                     //if (GlobalSettings.DEBUG_ENABLE_THRESHOLD_INCREASE &&
                            ↪ mCountAboveThresholdArray[0] > 0L) {
524                         //int nFrames = mFramesAboveThreshold.incrementAndGet();
525                         //if (nFrames >= GlobalSettings.MAX_FRAMES_ABOVE_THRESHOLD) {
526                         //    Log.e(Thread.currentThread().getName(), "::::::: REQUESTING
                                ↪ THRESHOLD INCREASE :::::::");
527                         //    AnalysisController.increaseSignificanceThreshold();
528                         //    mFramesAboveThreshold.set(0);
529                         //}
530                     //}
531                 }
532
533                 Log.e(Thread.currentThread().getName(), "Image processor backlog: " +
                        ↪ NumToString.number(mBacklog.decrementAndGet()));
534                 StopWatches.LiveProcessing.addTime( StopWatches.LiveProcessing.stop() );
```

```
535                 }
536             }
537
538             mBacklog.incrementAndGet();
539             mHandler.post(new Processor(result, wrapper));
540         }
541
542         // runStatistics...............
543         /**
544          * This method doesn't directly process statistics, rather it builds a Runnable that
                 ↪ does
545          * and posts it to the ImageProcessorThread to avoid slowing down the calling thread and
                 ↪  avoid
546          * running statistics in the middle of live image processing
547          * @param filename Optional filename to save statistics (file extension is provided by
                 ↪ this
548          *                 method)
549          */
550         static void runStatistics(@Nullable String filename) {
551
552             class RunStatistics implements Runnable {
553                 // Payload
554                 private String mFilename;
555
556                 // Constructor
557                 private RunStatistics(String filename) {
558                     mFilename = filename;
559                 }
560
561                 // Action
562                 @Override
563                 public void run() {
564                     StopWatches.PostProcessing.start();
565
566                     if (ImageWrapper.is8bitData()) {
567                         mPostScript.set_gIs8bit(1); // true
568                     }
569                     else { // ImageWrapper.is16bitData()
570                         mPostScript.set_gIs8bit(0); // false
571                     }
572
```

```
573                 // Move value sum from LiveProcessing.rs to PostProcessing.rs
574                 mLiveScript.forEach_getValueSum(RunningTotal.ValueSum);
575                 mPostScript.set_gValueSum(RunningTotal.ValueSum);
576
577                 // Move value**2 sum from LiveProcessing.rs to PostProcessing.rs
578                 mLiveScript.forEach_getValue2Sum(RunningTotal.Value2Sum);
579                 mPostScript.set_gValue2Sum(RunningTotal.Value2Sum);
580
581                 // Zero overflow detection
582                 mAnomalousStdDevArray[0] = 0L;
583                 mAnomalousStdDev.copyFrom(mAnomalousStdDevArray);
584                 mPostScript.set_gAnomalousStdDev(mAnomalousStdDev);
585
586                 // Finish setting remaining globals
587                 mPostScript.set_gNframes(RunningTotal.Nframes);
588                 mPostScript.set_gMean(Statistics.Mean);
589                 mPostScript.set_gStdDev(Statistics.StdDev);
590                 mPostScript.set_gStdErr(Statistics.StdErr);
591
592                 // Compute statistics and fetch from RenderScript
593                 mPostScript.forEach_getMean(Statistics.Mean);
594                 mPostScript.forEach_getStdDev(Statistics.StdDev);
595                 mPostScript.forEach_getStdErr(Statistics.StdErr);
596
597                 // Move new statistics over to LiveProcessing.rs
598                 mLiveScript.set_gMean(Statistics.Mean);
599                 mLiveScript.set_gStdDev(Statistics.StdDev);
600
601                 // Check for overflows
602                 mPostScript.forEach_getAnomalousStdDev(mAnomalousStdDev);
603                 mAnomalousStdDev.copyTo(mAnomalousStdDevArray);
604                 // TODO: make more of a big deal about this
605                 Log.e(Thread.currentThread().getName(), "Anomalous Std Dev Count: "
606                                                 + NumToString.number(
                                                     ↪ mAnomalousStdDevArray[0]));
607
608                 Double temperature = BatteryController.getCurrentTemperature();
609                 if (temperature == null) {
610                     temperature = Double.NaN;
611                 }
612
```

```
613                     if (GlobalSettings.DEBUG_SAVE_MEAN) {
614                         StorageMedia.writeCalibration(new OutputWrapper(mFilename +
                                ↪ GlobalSettings.MEAN_FILE, Statistics.Mean, RunningTotal.Nframes,
                                ↪ temperature.floatValue()));
615                     }
616                     if (GlobalSettings.DEBUG_SAVE_STDDEV) {
617                         StorageMedia.writeCalibration(new OutputWrapper(mFilename +
                                ↪ GlobalSettings.STDDEV_FILE, Statistics.StdDev, RunningTotal.
                                ↪ Nframes, temperature.floatValue()));
618                     }
619
620                     mBacklog.decrementAndGet();
621                     StopWatches.PostProcessing.addTime();
622
623                     // TODO: remove in future
624                     PrintAllocations.printMaxMin();
625                 }
626             }
627
628             mBacklog.incrementAndGet();
629             mHandler.post(new RunStatistics(filename));
630         }
631
632     }
```

Listing E.10: Image Wrapper (`analysis/ImageWrapper.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.media.Image;
import android.media.ImageReader;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import org.jetbrains.annotations.Contract;

import java.nio.ByteBuffer;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.TimeCode;
import sci.crayfis.shramp.util.StopWatch;

/**
 * Encapsulate image data received by an ImageReader.onImageAvailable() method,
 * e.g. in ImageReaderListener
 */
@TargetApi(21)
public final class ImageWrapper {

```

```
41      // Private Class Fields
42      //::::::::::::::::::::::
43
44      // ImageMetadata..............
45      // Image format properties common to all images being produced
46      private static abstract class ImageMetadata {
47          static int nPixels = 0;
48          static int nRows   = 0;
49          static int nCols   = 0;
50
51          static boolean is8bitData  = false;
52          static boolean is16bitData = false;
53
54          static void is8bitFormat() {
55              is8bitData  = true;
56              is16bitData = false;
57          }
58
59          static void is16bitFormat() {
60              is8bitData  = false;
61              is16bitData = true;
62          }
63
64          static void setRowsCols(int rows, int cols) {
65              nRows = rows;
66              nCols = cols;
67              nPixels = rows * cols;
68          }
69      }
70
71      // Private Instance Fields
72      //::::::::::::::::::::::
73
74      // ImageData..............
75      // Sensor timestamp of the image and its data
76      private class ImageData {
77          long    Timestamp;
78          byte[]  Data_8bit;
79          short[] Data_16bit;
80
81          // Set the data and timestamp from an Image
```

```
82          void setData(Image image) {
83              Timestamp = image.getTimestamp();
84
85              StopWatches.ByteBuffer.start();
86              ByteBuffer byteBuffer = image.getPlanes()[0].getBuffer();
87              int capacity          = byteBuffer.capacity();
88              StopWatches.ByteBuffer.addTime();
89
90              if (ImageMetadata.is8bitData && ImageMetadata.nPixels == capacity) {
91                  StopWatches.NewArray.start();
92                  Data_8bit = new byte[capacity];
93                  StopWatches.NewArray.addTime();
94                  StopWatches.LoadBuffer.start();
95                  byteBuffer.get(Data_8bit);
96                  StopWatches.LoadBuffer.addTime();
97                  Data_16bit = null;
98              }
99              else if (ImageMetadata.is16bitData && ImageMetadata.nPixels == capacity / 2){
100                 StopWatches.NewArray.start();
101                 Data_16bit = new short[capacity / 2];
102                 StopWatches.NewArray.addTime();
103                 StopWatches.LoadBuffer.start();
104                 byteBuffer.asShortBuffer().get(Data_16bit);
105                 StopWatches.LoadBuffer.addTime();
106                 Data_8bit = null;
107             }
108             else {
109                 // TODO: error
110                 Log.e(Thread.currentThread().getName(), "Image data cannot be unknown format
                        ↪ ");
111                 MasterController.quitSafely();
112             }
113         }
114     }
115     private final ImageData mImageData = new ImageData();
116
117     // For now, monitor performance (TODO: remove in the future)
118     abstract private static class StopWatches {
119         private final static StopWatch NewImageWrapper  = new StopWatch("new ImageWrapper()"
                ↪ );
```

```
120         private final static StopWatch AcquireNextImage = new StopWatch("new ImageWrapper()
                ↪ ->reader.acquireNextImage()");
121         private final static StopWatch SetData          = new StopWatch("new ImageWrapper()
                ↪ ->setData()");
122         private final static StopWatch ByteBuffer       = new StopWatch("ImageWrapper->image
                ↪ .getPlanes()[0].getBuffer()");
123         private final static StopWatch NewArray         = new StopWatch("ImageWrapper->new
                ↪ byte[]");
124         private final static StopWatch LoadBuffer       = new StopWatch("ImageWrapper->
                ↪ byteBuffer.get()");
125     }
126
127     ///////////////////////////
128     //:::::::::::::::::::::::
129     ///////////////////////////
130
131     // Constructors
132     //:::::::::::::::::::::::
133
134     // ImageWrapper...............
135     /**
136      * Disabled
137      */
138     private ImageWrapper() {}
139
140     // ImageWrapper...............
141     /**
142      * Wrap Image data to this object, and purge it from the ImageReader buffer
143      * @param reader ImageReader buffer of images
144      */
145     public ImageWrapper(@NonNull ImageReader reader) {
146         StopWatches.NewImageWrapper.start();
147
148         Image image = null;
149         try {
150             StopWatches.AcquireNextImage.start();
151             image = reader.acquireNextImage();
152             StopWatches.AcquireNextImage.addTime();
153             if (image == null) {
154                 return;
155             }
```

```
156                StopWatches.SetData.start();
157                mImageData.setData(image);
158                StopWatches.SetData.addTime();
159                image.close();
160            }
161            catch (IllegalStateException e) {
162                if (image != null) {
163                    image.close();
164                }
165                // TODO: error
166                Log.e(Thread.currentThread().getName(), "ImageReader Illegal State Exception");
167                MasterController.quitSafely();
168            }
169
170            StopWatches.NewImageWrapper.addTime();
171        }
172
173        // Package-private Class Methods
174        //::::::::::::::::::::::
175
176        // setAs8bitData...............
177        /**
178         * Notify ImageWrapper that the images received will have 8-bit pixel depth (e.g.
             ↪ YUV_420_888)
179         */
180        static void setAs8bitData() { ImageMetadata.is8bitFormat();}
181
182        // setAs16bitData...............
183        /**
184         * Notify ImageWrapper that the images received will have 16-bit pixel depth (
185         */
186        static void setAs16bitData() { ImageMetadata.is16bitFormat(); }
187
188        // setRowsCols...............
189        /**
190         * Notify ImageWrapper that the images received will have "rows", "cols" and n_pixels =
             ↪ rows * cols
191         * @param rows Number of pixel rows in an image
192         * @param cols Number of pixel columns in an image
193         */
194        static void setRowsCols(int rows, int cols) { ImageMetadata.setRowsCols(rows, cols); }
```

```
195
196     // Public Instance Methods
197     //::::::::::::::::::::::
198
199     // get8bitData..............
200     /**
201      * @return 8 bit data (if that's what the image is, null if it's 16 bit)
202      */
203     @Nullable
204     @Contract(pure = true)
205     byte[] get8bitData() { return mImageData.Data_8bit; }
206
207     // get16bitData..............
208     /**
209      * @return 16 bit data (if that's what the image is, null if it's 8 bit)
210      */
211     @Nullable
212     @Contract(pure = true)
213     short[] get16bitData() {return mImageData.Data_16bit;}
214
215     // getTimestamp..............
216     /**
217      * @return Sensor timestamp for the image
218      */
219     @Contract(pure = true)
220     long getTimestamp() { return mImageData.Timestamp; }
221
222     // getTimeCode..............
223     /**
224      * @return A short human-friendly character representation of the timestamp
225      */
226     @Contract(pure = true)
227     @NonNull
228     String getTimeCode() { return TimeCode.toString(mImageData.Timestamp); }
229
230     // getNpixels..............
231     /**
232      * @return The number of pixels in an image
233      */
234     @Contract(pure = true)
235     static int getNpixels() { return ImageMetadata.nPixels; }
```

```
236
237         // getNrows...............
238         /**
239          * @return The number of rows in an image
240          */
241         @Contract(pure = true)
242         static int getNrows() { return ImageMetadata.nRows; }
243
244         // getNcols...............
245         /**
246          * @return The number of columns in an image
247          */
248         @Contract(pure = true)
249         static int getNcols() { return ImageMetadata.nCols; }
250
251         ///////////////////////////
252
253         // is8bitData...............
254         /**
255          * @return True if image data is 8-bit depth, false if not
256          */
257         @Contract(pure = true)
258         static boolean is8bitData() { return ImageMetadata.is8bitData; }
259
260         // is16bitData...............
261         /**
262          * @return True if image data is 16-bit depth, false if not
263          */
264         @Contract(pure = true)
265         static boolean is16bitData() { return ImageMetadata.is16bitData; }
266
267     }
```

Listing E.11: Input Wrapper (`analysis/InputWrapper.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import org.jetbrains.annotations.Contract;

import java.io.File;
import java.io.FileInputStream;
import java.io.FileNotFoundException;
import java.io.IOException;
import java.nio.ByteBuffer;
import java.nio.FloatBuffer;
import java.nio.ShortBuffer;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.util.NumToString;

/**
 * Encapsulates metadata and statistical, image or mask data that is read in from disk.
 * TODO: option for ascii text?  ..or should that just go to logger?
```

```
 * TODO: read in data overwrites OutputWrapper static members, this is possibly a bug if global
 * TODO: settings are changed between runs, but therefore not a problem in the final release ..
 * TODO: (PRIORITY) read in a few bytes as needed instead of the whole file
 */
@TargetApi(21)
public final class InputWrapper extends OutputWrapper {

    // Instance Fields
    //::::::::::::::::::::::

    // mExposure..............
    // Sensor exposure for image data
    private Long mExposure;

    // mNframes..............
    // The number of frames that were involved to produce this statistical data
    private Long mNframes;

    // mTemperature..............
    // The temperature the data (image or statistical) was taken at [Celsius]
    private Float mTemperature;

    // mStatisticsData..............
    // The statistics data (if that's what it is)
    private float[] mStatisticsData;

    // mImage8bit..............
    // The image data (if that's what it is)
    private byte[] mImage8bit;

    // mImage16bit..............
    // The image data (if that's what it is)
    private short[] mImage16bit;

    // mMaskData..............
    // The mask data (if that's what it is)
    private byte[] mMaskData;

    ////////////////////////////
```

```
    //::::::::::::::::::::::
    ////////////////////////

    // Constructors
    //::::::::::::::::::::::

    // InputWrapper..............
    /**
     * Create an input wrapper for image, statistical, or mask data
     * Note: reading is done on the calling thread
     * @param filepath Absolute file path for data, data type is inferred from the extension
     */
    InputWrapper(@NonNull String filepath) {
        Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> Reading " + filepath + " <<\n
            ↪  ");

        File infile = new File(filepath);

        if (!infile.exists() || infile.isDirectory() || !infile.canRead()) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Cannot read file: " + filepath);
            return;
        }

        super.mFilename = infile.getName();
        int length      = (int) infile.length();

        // Check file size is correct
        if (super.mFilename.endsWith(GlobalSettings.IMAGE_FILE)) {
            super.mDatatype = Datatype.IMAGE;
            if (length != OutputWrapper.mSensorBytes) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), "File has wrong size, cannot read");
                return;
            }
        }
        else if (super.mFilename.endsWith(GlobalSettings.MASK_FILE)) {
            super.mDatatype = Datatype.MASK;
            if (length != OutputWrapper.mMaskBytes) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), "File has wrong size, cannot read");
```

```
119                 return;
120             }
121         }
122         else { // .mean, .stddev, .stderr or .signif
123             super.mDatatype = Datatype.STATISTICS;
124             if (length != OutputWrapper.mStatisticsBytes) {
125                 // TODO: error
126                 Log.e(Thread.currentThread().getName(), "File has wrong size, cannot read");
127                 return;
128             }
129         }
130 
131         // Read into ByteBuffer
132         int bytesRead;
133         FileInputStream inputStream = null;
134         try {
135             super.mByteBuffer = ByteBuffer.allocate(length);
136             inputStream = new FileInputStream(filepath);
137             bytesRead = inputStream.getChannel().read(super.mByteBuffer);
138         }
139         catch (FileNotFoundException e) {
140             // TODO: error
141             Log.e(Thread.currentThread().getName(), "Cannot read file: " + filepath);
142             return;
143         }
144         catch (IOException e) {
145             // TODO: error
146             Log.e(Thread.currentThread().getName(), "IO Exception on file: " + filepath);
147             return;
148         }
149         finally {
150             try {
151                 if (inputStream != null) {
152                     inputStream.close();
153                 }
154             }
155             catch (IOException e) {
156                 // TODO: error
157                 Log.e(Thread.currentThread().getName(), "IO Exception on close, read aborted
                    ↪ ");
158                 return;
```

```
159                 }
160             }
161             if (bytesRead != length) {
162                 // TODO: error
163                 Log.e(Thread.currentThread().getName(), "Reading unsuccessful, cannot continue")
                        ↪ ;
164                 return;
165             }
166
167             // Decode binary data
168             //————————————————————————————————————————
                    ↪ ————————————————————————————————————————————————————
169
170             // Reset buffer position to 0 and set limit to length
171             super.mByteBuffer.flip();
172
173             OutputWrapper.mBitsPerPixel = super.mByteBuffer.get();
174
175             OutputWrapper.mRows    = super.mByteBuffer.getInt();
176             OutputWrapper.mColumns = super.mByteBuffer.getInt();
177
178             if (super.mDatatype == Datatype.IMAGE) {
179                 mExposure = super.mByteBuffer.getLong();
180             }
181             else if (super.mDatatype == Datatype.STATISTICS) {
182                 mNframes = super.mByteBuffer.getLong();
183             }
184
185             if (super.mDatatype != Datatype.MASK) {
186                 mTemperature = super.mByteBuffer.getFloat();
187             }
188             else {
189                 mMaskData = new byte[super.mByteBuffer.remaining()];
190                 super.mByteBuffer.get(mMaskData, 0, super.mByteBuffer.remaining());
191             }
192
193             if (super.mDatatype == Datatype.IMAGE) {
194                 if (OutputWrapper.mBitsPerPixel == 8) {
195                     mImage8bit = new byte[super.mByteBuffer.remaining()];
196                     super.mByteBuffer.get(mImage8bit, 0, super.mByteBuffer.remaining());
197                 }
```

```
198             else { // OutputWrapper.mBitsPerPixel == 16
199                 ShortBuffer shortBuffer = super.mByteBuffer.asShortBuffer();
200                 mImage16bit = new short[shortBuffer.remaining()];
201                 shortBuffer.get(mImage16bit, 0, shortBuffer.remaining());
202             }
203         }
204         else if (super.mDatatype == Datatype.STATISTICS) {
205             FloatBuffer floatBuffer = super.mByteBuffer.asFloatBuffer();
206             mStatisticsData = new float[floatBuffer.remaining()];
207             floatBuffer.get(mStatisticsData, 0, floatBuffer.remaining());
208         }
209
210         // Free memory
211         super.mByteBuffer = null;
212     }
213
214     // Public Instance Methods
215     //::::::::::::::::::::::
216
217     // isStatisticsData...............
218     /**
219      * @return True if this is statistical data, false if it isn't
220      */
221     @Contract(pure = true)
222     public boolean isStatisticsData() { return mStatisticsData != null; }
223
224     // is8bitData...............
225     /**
226      * @return True if this is 8-bit image data, false if it isn't
227      */
228     @Contract(pure = true)
229     public boolean is8bitData() { return mImage8bit != null; }
230
231     // is16bitData...............
232     /**
233      * @return True if this is 16-bit image data, false if it isn't
234      */
235     @Contract(pure = true)
236     public boolean is16bitData() { return mImage16bit != null; }
237
238     // isMaskData...............
```

```
239     /**
240      * @return True if this is mask data, false if it isn't
241      */
242     @Contract(pure = true)
243     public boolean isMaskData() { return mMaskData != null; }
244
245     // getStatisticsData...............
246     /**
247      * @return Statistics data (null if this wasn't statistical data)
248      */
249     @Nullable
250     @Contract(pure = true)
251     public float[] getStatisticsData() { return mStatisticsData; }
252
253     // get8bitData...............
254     /**
255      * @return 8-bit image data (null if this wasn't that)
256      */
257     @Nullable
258     @Contract(pure = true)
259     public byte[] get8bitData() { return mImage8bit; }
260
261     // get16bitData...............
262     /**
263      * @return 16-bit image data (null if this wasn't that)
264      */
265     @Nullable
266     @Contract(pure = true)
267     public short[] get16bitData() { return mImage16bit; }
268
269     // getMaskData...............
270     /**
271      * @return Mask data (null if this wasn't that)
272      */
273     @Nullable
274     @Contract(pure = true)
275     public byte[] getMaskData() { return mMaskData; }
276
277     // getTemperature...............
278     /**
279      * @return Temperature in Celsius (null if not available)
```

```
280         */
281        @Nullable
282        @Contract(pure = true)
283        public Float getTemperature() { return mTemperature; }
284
285        // getExposure...............
286        /**
287         * @return Exposure in nanoseconds (null if not available)
288         */
289        @Nullable
290        @Contract(pure = true)
291        public Long getExposure() { return mExposure; }
292
293        // getNframes...............
294        /**
295         * @return The number of frames used to make this data (null if not available)
296         */
297        @Nullable
298        @Contract(pure = true)
299        public Long getNframes() { return mNframes; }
300
301    }
```

Listing E.12: Output Wrapper (`analysis/OutputWrapper.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.analysis;

import android.annotation.TargetApi;
import android.renderscript.Allocation;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Range;

import org.jetbrains.annotations.Contract;

import java.nio.ByteBuffer;

import sci.crayfis.shramp.MasterController;

/**
 * Encapsulates statistical, image data, mask data or histograms and packages it, along with
 * metadata, into a ByteBuffer ready to write to disk.
 * TODO: option for ascii text?  ..or should that just go to logger?
 */
@TargetApi(21)
public class OutputWrapper {

    // Class Constants
```

```
41      //::::::::::::::::::::::
42
43      // What this OutputWrapper can contain
44      public enum Datatype { IMAGE, STATISTICS, MASK, HISTOGRAM }
45
46      // String shortcuts
47      private static final String ByteSize   = Integer.toString(Byte.SIZE    / 8);
48      private static final String ShortSize  = Integer.toString(Short.SIZE   / 8);
49      private static final String IntSize    = Integer.toString(Integer.SIZE / 8);
50      private static final String LongSize   = Integer.toString(Integer.SIZE / 8);
51      private static final String FloatSize  = Integer.toString(Float.SIZE   / 8);
52      private static final String DoubleSize = Integer.toString(Double.SIZE  / 8);
53
54      // CACHE_LOCK..............
55      // Prevent two OutputWrappers from simultaneously using the cache (float[] array)
56      private static final Object CACHE_LOCK = new Object();
57
58      // Class Fields
59      //::::::::::::::::::::::
60
61      // mBitsPerPixel..............
62      // Bits per pixel for image data
63      protected static byte mBitsPerPixel;
64
65      // mRows..............
66      // Number of rows of pixel sensor
67      protected static int mRows;
68
69      // mColumns..............
70      // Number of columns of pixel sensor
71      protected static int mColumns;
72
73      // mSensorBytes..............
74      // Total number of bytes for image data
75      protected static int mSensorBytes;
76
77      // mStatisticsBytes..............
78      // Total number of bytes for statistical data
79      protected static int mStatisticsBytes;
80
81      // mMaskBytes..............
```

```
82      // Total number of bytes for mask data
83      protected static int mMaskBytes;
84
85      // mSensorHeader...............
86      // Description of byte-ordering for image data
87      private static String mSensorHeader;
88
89      // mStatisticsHeader...............
90      // Description of byte-ordering for statistical data
91      private static String mStatisticsHeader;
92
93      // mMaskHeader...............
94      // Description of byte-ordering for mask data
95      private static String mMaskHeader;
96
97      // mHistogramHeader...............
98      // Description of byte-ordering for histogram data
99      private static String mHistogramHeader;
100
101     // mFloatCache...............
102     // Used in an intermediate step in converting a statistical RenderScript Allocation into
            ↪ bytes,
103     // rather than create/destroy a new array every time since it's around 30-50 MB
104     private static float[] mFloatCache;
105
106     // Instance Fields
107     //:::::::::::::::::::::::
108
109     // mFilename...............
110     // Intended filename for writing data
111     protected String mFilename;
112
113     // mDatatype...............
114     // Denotes if this OutputWrapper is for image data or statistics
115     protected Datatype mDatatype;
116
117     // mByteBuffer...............
118     // Packaged bytes ready to write
119     protected ByteBuffer mByteBuffer;
120
121     ///////////////////////////
```

```
    //::::::::::::::::::::::
    ////////////////////////

    // Constructors
    //::::::::::::::::::::::

    // OutputWrapper..............
    /**
     * Default constructor for object inheritance, does nothing
     */
    protected OutputWrapper() {}

    // OutputWrapper..............
    /**
     * Create an output wrapper for float-type RenderScript Allocation data, e.g. statistics
     * @param filename Filename for data (no path, just filename)
     * @param statistics Float-type RenderScript Allocation data, e.g. mean, stddev, significance, etc
     * @param Nframes The number of frames that went into making this data,
     *                e.g. significance would be 1, mean and stddev would be 1000 for example
     * @param temperature The approximate temperature when the data was taken in Celsius
     */
    OutputWrapper(@NonNull String filename, @NonNull Allocation statistics, long Nframes, float temperature) {
        mFilename = filename;
        mByteBuffer = ByteBuffer.allocate(mStatisticsBytes);
        mByteBuffer.put(mBitsPerPixel);
        mByteBuffer.putInt(mRows);
        mByteBuffer.putInt(mColumns);
        mByteBuffer.putLong(Nframes);
        mByteBuffer.putFloat(temperature);
        synchronized (CACHE_LOCK) {
            statistics.copyTo(mFloatCache);
            mByteBuffer.asFloatBuffer().put(mFloatCache);
        }
        mByteBuffer.position(0);
        mByteBuffer.limit(mByteBuffer.capacity());
        mDatatype = Datatype.STATISTICS;
    }

```

```
    // OutputWrapper...............
    /**
     * Create an output wrapper for 8 or 16-bit image data
     * @param filename Filename for data (no path, just filename)
     * @param wrapper ImageWrapper containing image data
     * @param exposure (Optional) Sensor exposure in nanoseconds if available, if null
        ↪ defaults to 0
     * @param temperature Temperature data was taken at in Celsius
     */
    OutputWrapper(@NonNull String filename, @NonNull ImageWrapper wrapper, @Nullable Long
        ↪ exposure, float temperature) {
        mFilename = filename;
        mByteBuffer = ByteBuffer.allocate(mSensorBytes);
        mByteBuffer.put(mBitsPerPixel);
        mByteBuffer.putInt(mRows);
        mByteBuffer.putInt(mColumns);
        if (exposure == null) {
            exposure = 0L;
        }
        mByteBuffer.putLong(exposure);
        mByteBuffer.putFloat(temperature);
        if (ImageWrapper.is8bitData()) {
            mByteBuffer.put(wrapper.get8bitData());
        }
        else {
            mByteBuffer.asShortBuffer().put(wrapper.get16bitData());
        }
        mByteBuffer.position(0);
        mByteBuffer.limit(mByteBuffer.capacity());
        mDatatype = Datatype.IMAGE;
    }

    // OutputWrapper...............
    /**
     * Create an output wrapper for cut mask data
     * @param filename Filename for data (no path, just filename)
     * @param mask Pixel mask data
     */
    OutputWrapper(@NonNull String filename, @NonNull byte[] mask) {
        mFilename = filename;
        mByteBuffer = ByteBuffer.allocate(mMaskBytes);
```

```
        mByteBuffer.put(mBitsPerPixel);
        mByteBuffer.putInt(mRows);
        mByteBuffer.putInt(mColumns);
        mByteBuffer.put(mask);
        mByteBuffer.position(0);
        mByteBuffer.limit(mByteBuffer.capacity());
        mDatatype = Datatype.MASK;
    }

    // OutputWrapper...............
    /**
     * Create an output wrapper for histogram data
     * @param filename Filename for data (no path, just filename)
     * @param histogram Histogram object
     * @param cutBounds (Optional) Pixel value used for cuts (low and high)
     */
    OutputWrapper(@NonNull String filename, @NonNull Histogram histogram, @Nullable Range<
        ↪ Float> cutBounds) {
        mFilename = filename;

        int histogramBytes = 0;
        histogramBytes += Integer.SIZE / 8; // N bins
        histogramBytes += Integer.SIZE / 8; // underflow
        histogramBytes += Integer.SIZE / 8; // overflow
        histogramBytes += Float.SIZE   / 8; // optional cut low bound
        histogramBytes += Float.SIZE   / 8; // optional cut high bound
        histogramBytes += histogram.mNbins * Float.SIZE / 8;   // bin centers
        histogramBytes += histogram.mNbins * Integer.SIZE / 8; // bin values

        mByteBuffer = ByteBuffer.allocate(histogramBytes);
        mByteBuffer.putInt(histogram.getNbins());
        mByteBuffer.putInt(histogram.getUnderflow());
        mByteBuffer.putInt(histogram.getOverflow());
        if (cutBounds == null) {
            mByteBuffer.putFloat(Float.NaN);
            mByteBuffer.putFloat(Float.NaN);
        }
        else {
            mByteBuffer.putFloat(cutBounds.getLower());
            mByteBuffer.putFloat(cutBounds.getUpper());
        }
```

```
239         int length = histogram.getNbins();
240         for (int i = 0; i < length; i++) {
241             mByteBuffer.putFloat( (float) histogram.getBinCenter(i) );
242         }
243         for (int i = 0; i < length; i++) {
244             mByteBuffer.putInt(histogram.getValue(i));
245         }
246         mByteBuffer.position(0);
247         mByteBuffer.limit(mByteBuffer.capacity());
248         mDatatype = Datatype.HISTOGRAM;
249     }
250 
251     // Package-private Class Methods
252     //::::::::::::::::::::::
253 
254     // configure..............
255     /**
256      * Sets up cache and initializes all important fields
257      * TODO: gets information from ImageWrapper, consider subclassing this? .. or making it
         ↪ its own?
258      */
259     static void configure() {
260         mSensorBytes     = 0;
261         mStatisticsBytes = 0;
262         mMaskBytes       = 0;
263 
264         int Npixels = ImageWrapper.getNpixels();
265         mFloatCache = new float[Npixels];
266 
267         // Image data bytes
268         if (ImageWrapper.is8bitData()) {
269             mBitsPerPixel = 8;
270             mSensorBytes += Npixels * Byte.SIZE / 8;
271         }
272         else if (ImageWrapper.is16bitData()) {
273             mBitsPerPixel = 16;
274             mSensorBytes += Npixels * Short.SIZE / 8;
275         }
276         else {
277             // TODO: error
278             Log.e(Thread.currentThread().getName(), "Unknown image format");
```

```
            MasterController.quitSafely();
            return;
        }
        mStatisticsBytes += Npixels * Float.SIZE / 8;
        mMaskBytes       += Npixels * Byte.SIZE / 8;

        // Bits per pixel
        mSensorBytes     += 1;
        mStatisticsBytes += 1;
        mMaskBytes       += 1;

        mRows = ImageWrapper.getNrows();
        mSensorBytes     += Integer.SIZE / 8;
        mStatisticsBytes += Integer.SIZE / 8;
        mMaskBytes       += Integer.SIZE / 8;

        mColumns = ImageWrapper.getNcols();
        mSensorBytes     += Integer.SIZE / 8;
        mStatisticsBytes += Integer.SIZE / 8;
        mMaskBytes       += Integer.SIZE / 8;

        // Sensor exposure
        mSensorBytes += Long.SIZE / 8;

        // Frames count
        mStatisticsBytes += Long.SIZE / 8;

        // Temperature
        mSensorBytes     += Float.SIZE / 8;
        mStatisticsBytes += Float.SIZE / 8;

        mSensorHeader  = "Byte order (big endian): \t Bits-per-pixel \t Number of Rows \t Number of Columns \t Sensor Exposure [ns] \t Temperature [C] \t Pixel data\n";
        mSensorHeader += "Number of bytes: \t " + ByteSize + " \t " + IntSize + " \t " + IntSize + " \t " + LongSize + " \t " + FloatSize + "\t"
            + Byte.toString(mBitsPerPixel) + "x" + Integer.toString(Npixels) + "\n";

        mStatisticsHeader  = "Byte order (big endian): \t Bits-per-pixel \t Number of Rows \t Number of Columns \t Number of Stacked Images \t Temperature [C] \t PostProcessing\n";
```

```
        mStatisticsHeader += "Number of bytes: \t " + ByteSize + "\t" + IntSize + " \t " + IntSize + " \t " + LongSize + " \t " + FloatSize + "\t" + FloatSize + "x" + Integer.toString(Npixels) + "\n";

        mMaskHeader  = "Byte order (big endian): \t Bits-per-pixel \t Number of Rows \t Number of Columns \t Mask data\n";
        mMaskHeader += "Number of bytes: \t " + ByteSize + "\t" + IntSize + " \t " + IntSize + " \t " + ByteSize + "x" + Integer.toString(Npixels) + "\n";

        mHistogramHeader  = "Byte order (big endian): \t Number of Bins \t Underflow Bin Value \t Overflow Bin Value \t Cut low bound (NaN if no cuts) \t Cut high bound (NaN if no cuts) \t Bin Centers \t Bin Values\n";
        mHistogramHeader += "Number of bytes: \t" + IntSize + "\t" + IntSize + "\t" + IntSize + "\t" + FloatSize + "\t" + FloatSize + "\t" + FloatSize + "x{N bins} " + "\t" + IntSize + "x {N bins}\n";
    }

    // Public Instance Methods
    //:::::::::::::::::::::::

    /**
     * @return Get what kind of data is being held, image data or statistical
     */
    @NonNull
    @Contract(pure = true)
    public Datatype getType() { return mDatatype; }

    /**
     * @return A String describing the byte-order of image data
     */
    @NonNull
    @Contract(pure = true)
    public String getSensorHeader() { return mSensorHeader; }

    /**
     * @return A String describing the byte-order of statistical data
     */
    @NonNull
    @Contract(pure = true)
    public String getStatisticsHeader() { return mStatisticsHeader; }

```

```
349         /**
350          * @return The filename for writing this data
351          */
352         @NonNull
353         @Contract(pure = true)
354         public String getFilename() { return mFilename; }
355
356         /**
357          * @return The ByteBuffer containing this data and metadata as described in the header
358          */
359         @Nullable
360         @Contract(pure = true)
361         public ByteBuffer getByteBuffer() { return mByteBuffer; }
362
363     }
```

Listing E.13: Battery Controller (`battery/BatteryController.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.battery;

import android.annotation.TargetApi;
import android.app.Activity;
import android.content.Context;
import android.os.BatteryManager;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;

import org.jetbrains.annotations.Contract;

import sci.crayfis.shramp.util.NumToString;
import sci.crayfis.shramp.util.StopWatch;

///////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
///////////////////////////
// This class is basically fine, the to-do is adding additional broadcast listeners (low-
    ↪ priority)

/**
 * Public interface to battery functions
 */
@TargetApi(21)
```

```
40  public class BatteryController {
41
42      // Private Class Constants
43      //:::::::::::::::::::::::
44
45      // mInstance..............
46      // Reference to single instance of BatteryController
47      private static final BatteryController mInstance = new BatteryController();
48
49      // Private Instance Fields
50      //:::::::::::::::::::::::
51
52      // mBatteryManager...............
53      // Reference to system battery manager
54      private BatteryManager mBatteryManager;
55
56      // mBatteryChanged...............
57      // Reference to battery broadcast listener
58      private BatteryChanged mBatteryChanged;
59
60      /*
61      // TODO: other broadcast listeners that may or may not be added soon
62      private static Intent mBatteryOkay;
63      private static Intent mBatteryLow;
64      private static Intent mPowerConnected;
65      private static Intent mPowerDisconnected;
66      private static Intent mPowerSummary;
67      */
68
69      // mStopWatch1...............
70      // For now, monitoring performance for getting temperature -- (TODO) to be removed later
71      private static final StopWatch mStopWatch = new StopWatch("BatteryController.
            ↪ getCurrentTemperature()");
72
73      ///////////////////////////
74      //:::::::::::::::::::::::
75      ///////////////////////////
76
77      // Constructors
78      //:::::::::::::::::::::::
79
```

```
80      /**
81       * Disable ability to create multiple instances
82       */
83      private BatteryController() {}
84
85      // Public Class Methods
86      //:::::::::::::::::::::::
87
88      // initialize..............
89      /**
90       * Start up battery monitoring
91       * @param activity Main activity that is controlling the app
92       */
93      public static void initialize(@NonNull Activity activity) {
94          mInstance.mBatteryManager = (BatteryManager) activity.getSystemService(Context.
                ↪ BATTERY_SERVICE);
95
96          mInstance.mBatteryChanged = new BatteryChanged(activity);
97
98          /*
99          // TODO: other broadcast listeners that may or may not be added soon
100         mBatteryOkay       = activity.registerReceiver(this, new IntentFilter(Intent.
                ↪ ACTION_BATTERY_OKAY));
101         mBatteryLow        = activity.registerReceiver(this, new IntentFilter(Intent.
                ↪ ACTION_BATTERY_LOW));
102         mPowerConnected    = activity.registerReceiver(this, new IntentFilter(Intent.
                ↪ ACTION_POWER_CONNECTED));
103         mPowerDisconnected = activity.registerReceiver(this, new IntentFilter(Intent.
                ↪ ACTION_POWER_DISCONNECTED));
104         //mPowerSummary      = activity.registerReceiver(this, new IntentFilter(Intent.
                ↪ ACTION_POWER_USAGE_SUMMARY));
105         */
106     }
107
108     // refresh..............
109     /**
110      * Refresh battery information to latest values
111      */
112     public static void refresh() {
113         if (mInstance.mBatteryChanged == null) {
114             return;
```

```
115         }
116         mInstance.mBatteryChanged.refresh();
117     }
118
119     // getRemainingCapacity...............
120     /**
121      * @return remaining battery level as a percent with no decimal part
122      */
123     public static int getRemainingCapacity() {
124         if (mInstance.mBatteryManager == null) {
125             return -1;
126         }
127         return mInstance.mBatteryManager.getIntProperty(BatteryManager.
                ↪ BATTERY_PROPERTY_CAPACITY);
128     }
129
130     // getBatteryCapacity...............
131     /**
132      * Warning: could be garbage
133      * @return capacity in milli-amp-hours
134      */
135     public static double getBatteryCapacity() {
136         if (mInstance.mBatteryManager == null) {
137             return Double.NaN;
138         }
139         return mInstance.mBatteryManager.getIntProperty(BatteryManager.
                ↪ BATTERY_PROPERTY_CHARGE_COUNTER) / 1e3;
140     }
141
142     // getInstantaneousCurrent...............
143     /**
144      * Warning: could be net current (out - in) or out only
145      * @return current current in milli-amps
146      */
147     public static double getInstantaneousCurrent() {
148         if (mInstance.mBatteryManager == null) {
149             return Double.NaN;
150         }
151         return mInstance.mBatteryManager.getIntProperty(BatteryManager.
                ↪ BATTERY_PROPERTY_CURRENT_NOW) / 1e3;
152     }
```

```
153
154     // getAverageCurrent...............
155     /**
156      * Warning: could be garbage
157      * @return average current in milli-amps
158      */
159     public static double getAverageCurrent() {
160         if (mInstance.mBatteryManager == null) {
161             return Double.NaN;
162         }
163         return mInstance.mBatteryManager.getIntProperty(BatteryManager.
            ↪ BATTERY_PROPERTY_CURRENT_AVERAGE) / 1e3;
164     }
165
166     // getRemainingTime...............
167     /**
168      * Warning: garbage if getAverageCurrent() is garbage
169      * @return hours remaining
170      */
171     public static double getRemainingTime() {
172         return getBatteryCapacity() / getAverageCurrent();
173     }
174
175     // getRemainingEnergy...............
176     /**
177      * Warning: usually garbage
178      * @return remaining power in milli-watt-hours
179      */
180     public static double getRemainingEnergy() {
181         if (mInstance.mBatteryManager == null) {
182             return Double.NaN;
183         }
184         return mInstance.mBatteryManager.getLongProperty(BatteryManager.
            ↪ BATTERY_PROPERTY_ENERGY_COUNTER) / 1e6;
185     }
186
187     // getRemainingPower...............
188     /**
189      * Warning: garbage if either getRemainingEnergy() or getRemainingTime() is garbage,
190      * i.e. most likely garbage
191      * @return average continuous milli-watts of power remaining
```

```
192         */
193     public static double getRemainingPower() {
194         return getRemainingEnergy() / getRemainingTime();
195     }
196 
197     // getInstantaneousPower ..............
198     /**
199      * Warning: either net power (out - in) or out power
200      * @return instantaneous power in milli-watts
201      */
202     @Nullable
203     public static Double getInstantaneousPower() {
204         Double voltage = BatteryChanged.getCurrentVoltage();
205         if (voltage == null) {
206             return null;
207         }
208         double current = getInstantaneousCurrent();
209         return voltage * current;
210     }
211 
212     // getAveragePower ..............
213     /**
214      * Warning: garbage if getAverageCurrent() is garbage
215      * @return average power in milli-watts
216      */
217     @Nullable
218     public static Double getAveragePower() {
219         Double voltage = BatteryChanged.getCurrentVoltage();
220         if (voltage == null) {
221             return null;
222         }
223         double current = getAverageCurrent();
224         return voltage * current;
225     }
226 
227     ///////////////////////////
228 
229     // getCurrentIcon ..............
230     /**
231      * TODO: No idea what the hell this is
232      * @return it's an integer, that's all I know
```

```
233         */
234        @Contract(pure = true)
235        @Nullable
236        public static Integer getCurrentIcon() {
237            return BatteryChanged.getCurrentIcon();
238        }
239
240        // getTechnology ...............
241        /**
242         * Warning: most devices don't have this
243         * @return Likely a null string, otherwise it's text describing the technology (e.g. Li-
             ↪ ion)
244         */
245        @Contract(pure = true)
246        @Nullable
247        public static String getTechnology() {
248            return BatteryChanged.getTechnology();
249        }
250
251        // isBatteryPresent ...............
252        /**
253         * @return True if battery is identified by the system, false if not
254         */
255        @Contract(pure = true)
256        @NonNull
257        public static Boolean isBatteryPresent() {
258            return BatteryChanged.isBatteryPresent();
259        }
260
261        // getCurrentHealth ...............
262        /**
263         * @return "GOOD", "COLD", "DEAD", "OVERHEAT", "OVER VOLTAGE", "UNKNOWN", "UNSPECIFIED
             ↪ FAILURE",
264         *          "UNKNOWN CONDITION OR NOT AVAILABLE"
265         */
266        @Contract(pure = true)
267        @Nullable
268        public static String getCurrentHealth() {
269            return BatteryChanged.getCurrentHealth();
270        }
271
```

```
272     // getCurrentStatus...............
273     /**
274      * @return "CHARGING", "DISCHARGING", "FULLY CHARGED", "NOT CHARGING", "CHARGING STATUS
         ↪ UNKNOWN",
275      *         "UNKNOWN STATUS"
276      */
277     @Contract(pure = true)
278     @Nullable
279     public static String getCurrentStatus() {
280         return BatteryChanged.getCurrentStatus();
281     }
282
283     // getCurrentPowerSource...............
284     /**
285      * @return "USING BATTERY POWER ONLY", "USING AC ADAPTER POWER", "USING USB POWER",
286      *         "USING WIRELESS POWER", "UNKNOWN POWER SOURCE"
287      */
288     @Contract(pure = true)
289     @Nullable
290     public static String getCurrentPowerSource() {
291         return BatteryChanged.getCurrentPowerSource();
292     }
293
294     // getCurrentVoltage...............
295     /**
296      * @return Battery voltage in volts
297      */
298     @Contract(pure = true)
299     @Nullable
300     public static Double getCurrentVoltage() {
301         return BatteryChanged.getCurrentVoltage();
302     }
303
304     // mBatteryTemperature...............
305     /**
306      * @return Battery temperature in degrees Celsius
307      */
308     @Contract(pure = true)
309     @Nullable
310     public static Double getCurrentTemperature() {
311         mStopWatch.start();
```

```
312         Double temperature = BatteryChanged.getCurrentTemperature();
313         mStopWatch.addTime();
314         return temperature;
315     }
316 
317     // getCurrentLevel...............
318     /**
319      * @return Usually the same as getRemainingCapacity(), but could be energy or charge
            ↪ units
320      */
321     @Contract(pure = true)
322     @Nullable
323     public static Integer getCurrentLevel() {
324         return BatteryChanged.getCurrentLevel();
325     }
326 
327     // getScale...............
328     /**
329      * @return Maximal value of getCurrentLevel(), usually 100 as in percent, but could be
330      *         energy or charge or something..
331      */
332     @Contract(pure = true)
333     @Nullable
334     public static Integer getScale() {
335         return BatteryChanged.getScale();
336     }
337 
338     // getCurrentPercent...............
339     /**
340      * @return Same as getRemainingCapacity(), but possibly (not often) higher precision
341      */
342     @Contract(pure = true)
343     @Nullable
344     public static Double getCurrentPercent() { return BatteryChanged.getCurrentPercent(); }
345 
346     ////////////////////////////
347 
348     // getString...............
349     /**
350      * @return Status string of current battery conditions
351      */
```

```
352     @NonNull
353     public static String getString() {
354         refresh();
355 
356         String out = " \n";
357         out += "\t" + "Battery charge level:       " + NumToString.number(
            ↪ getRemainingCapacity())     + "%\n";
358         out += "\t" + "Battery capacity:           " + NumToString.number(getBatteryCapacity
            ↪ ())       + " [mA hr]\n";
359         out += "\t" + "Instantaneous current:      " + NumToString.number(
            ↪ getInstantaneousCurrent()) + " [mA]\n";
360         out += "\t" + "Average current:            " + NumToString.number(getAverageCurrent
            ↪ ())       + " [mA]\n";
361         out += "\t" + "Time until drained:         " + NumToString.number(getRemainingTime()
            ↪ )        + " [hr]\n";
362         out += "\t" + "Remaining energy:           " + NumToString.number(getRemainingEnergy
            ↪ ())      + " [mW hr]\n";
363         out += "\t" + "Remaining continuous power: " + NumToString.number(getRemainingPower
            ↪ ())       + " [mW]\n";
364 
365         Double power = getInstantaneousPower();
366         String powerString;
367         if (power == null) {
368             powerString = "UNKNOWN\n";
369         }
370         else {
371             powerString = NumToString.number(power) + " [mW]\n";
372         }
373         out += "\t" + "Instantaneous power:        " + powerString;
374 
375         power = getAveragePower();
376         if (power == null) {
377             powerString = "UNKNOWN\n";
378         }
379         else {
380             powerString = NumToString.number(power) + " [mW]\n";
381         }
382         out += "\t" + "Average power:              " + powerString;
383 
384         out += "\n";
385 
```

```
386             out += mInstance.mBatteryChanged.getString();
387
388             return out;
389         }
390
391         // shutdown..............
392         /**
393          * Disable battery broadcast listening
394          */
395         public static void shutdown() {
396             mInstance.mBatteryChanged.shutdown();
397         }
398
399     }
```

Listing E.14: Battery Broadcast Listener (`battery/BatteryReceiver.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.battery;

import android.annotation.TargetApi;
import android.app.Activity;
import android.content.BroadcastReceiver;
import android.content.Context;
import android.content.Intent;
import android.content.IntentFilter;
import android.support.annotation.NonNull;
import android.util.Log;

import sci.crayfis.shramp.MasterController;

/**
 * Base class for all battery status receivers
 */
@TargetApi(21)
abstract public class BatteryReceiver extends BroadcastReceiver {

    // Protected Instance Fields
    //::::::::::::::::::::::

    // mActivity..............
    // A reference to the main activity running the app
```

```
41      protected Activity mActivity;
42
43      // mIntent...............
44      // A reference to the last broadcasted battery data intent
45      protected Intent mIntent;
46
47      // mIntentString...............
48      // Needed to tell the system what kind of broadcast listener this is, e.g. Intent.
            ↪ ACTION_BATTERY_CHANGED
49      protected String mIntentString;;
50
51      ///////////////////////////
52      //:::::::::::::::::::::::
53      ///////////////////////////
54
55      // Constructors
56      //:::::::::::::::::::::::
57
58      // BatteryReceiver...............
59      /**
60       * !! DO NOT CALL THIS !!
61       * The default constructor has to be here to satisfy Android manifest requirements to
            ↪ receive
62       * battery broadcast.
63       */
64      public BatteryReceiver() {}
65
66      // BatteryReceiver...............
67      /**
68       * Register this broadcast listener with the system
69       * @param activity Reference to the main activity running the app
70       * @param intentString What kind of listener, e.g. Intent.ACTION_BATTERY_CHANGED
71       */
72      BatteryReceiver(@NonNull Activity activity, @NonNull String intentString) {
73          mActivity       = activity;
74          mIntentString   = intentString;
75          mIntent         = activity.registerReceiver(this, new IntentFilter(mIntentString));
76          if (mIntent == null) {
77              // TODO: error
78              Log.e(Thread.currentThread().getName(), "Activity failed to register battery
                    ↪ receiver");
```

```
            MasterController.quitSafely();
            return;
        }
        refresh();
    }

    // Package-private Instance Methods
    //::::::::::::::::::::::

    // refresh..............
    /**
     * Process last broadcasted battery information Intent
     */
    void refresh() {
        onReceive(mActivity, mIntent);
    }

    // getString..............
    /**
     * @return A string describing what is known by this object
     */
    @NonNull
    abstract String getString();

    // shutdown..............
    /**
     * Unregister this listener from the system
     */
    void shutdown() {
        mActivity.unregisterReceiver(this);
    }

    // Public Overriding Instance Methods
    //::::::::::::::::::::::

    // isOkToProceed..............
    /**
     * Android recommended practice is to double-check the broadcasted Intent matches the
       ↪ Intent
     * that was intended to be received
     * @param context The context this receiver is running in
```

```
119         * @param intent The intent received containing the broadcast data
120         * @return True if this was the correct Intent, false if not
121         */
122        protected boolean isOkToProceed(@NonNull Context context, @NonNull Intent intent) {
123            return intent.getAction().equals(mIntentString);
124        }
125
126        // onReceive...............
127        /**
128         * Called by the system every time the battery broadcasts
129         * @param context The context this receiver is running in
130         * @param intent The intent received containing the broadcast data
131         */
132        @Override
133        abstract public void onReceive(@NonNull Context context, @NonNull Intent intent);
134
135    }
```

Listing E.15: Battery Change Actions (`battery/BatteryChanged.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.battery;

import android.annotation.TargetApi;
import android.app.Activity;
import android.content.Context;
import android.content.Intent;
import android.os.BatteryManager;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;

import org.jetbrains.annotations.Contract;

import sci.crayfis.shramp.util.NumToString;

/**
 * TODO: description, comments and logging
 */
@TargetApi(21)
final public class BatteryChanged extends BatteryReceiver {

    // Private Class Fields
    //:::::::::::::::::::::::

    // mBatteryIcon..............
```

```
41      // TODO: No idea what the hell this is
42      private static Integer mBatteryIcon;
43
44      // mBatteryTechnology ...............
45      // Simple description string of battery technology, e.g. Li-ion
46      private static String mBatteryTechnology;
47
48      // mBatteryPresent ...............
49      // Battery is present, yes or no
50      private static Boolean mBatteryPresent;
51
52      // mBatteryHealth ...............
53      // Simple string describing battery condition, e.g. "GOOD" or "DEAD"
54      private static String mBatteryHealth;
55
56      // mBatteryStatus ...............
57      // Simple string describing what the battery is doing right now, e.g. "CHARGING"
58      private static String mBatteryStatus;
59
60      // mBatteryPlugged ...............
61      // Simple string describing power source, e.g. "USING USB POWER", "USING BATTERY POWER
        ↪ ONLY"
62      private static String mBatteryPlugged;
63
64      // mBatteryVoltage ...............
65      // Battery voltage in volts
66      private static Double mBatteryVoltage;
67
68      // mBatteryTemperature ...............
69      // Battery temperature in degrees Celsius
70      private static Double mBatteryTemperature;
71
72      // mBatteryLevel ...............
73      // Battery level, usually integer percent, but could be energy/charge/etc
74      private static Integer mBatteryLevel;
75
76      // mBatteryScale ...............
77      // Maximum value of mBatteryLevel, usually 100 percent, but could be energy/charge/etc
78      private static Integer mBatteryScale;
79
80      ////////////////////////////
```

```
    //::::::::::::::::::::::
    //////////////////////////

    // Constructors
    //::::::::::::::::::::::

    // BatteryChanged..............
    /**
     * !! DO NOT CALL THIS !!
     * The default constructor has to be here to satisfy Android manifest requirements to
       ↪ receive
     * battery broadcast.
     */
    public BatteryChanged() {
        super();
    }

    // BatteryChanged..............
    /**
     * Call this to initialize
     * @param activity Main activity controlling the app
     */
    BatteryChanged(@NonNull Activity activity) {
        super(activity, Intent.ACTION_BATTERY_CHANGED);
    }

    // Package-private Class Methods
    //::::::::::::::::::::::

    // getCurrentIcon..............
    /**
     * TODO: No idea what the hell this is
     * @return An integer
     */
    @Contract(pure = true)
    @Nullable
    static Integer getCurrentIcon() {
        return mBatteryIcon;
    }

    // getTechnology..............
```

```
121         /**
122          * @return A simple string describing the technology, e.g. "Li-ion"
123          */
124         @Contract(pure = true)
125         @Nullable
126         static String getTechnology() {
127             return mBatteryTechnology;
128         }
129 
130         // isBatteryPresent...............
131         /**
132          * @return Is the battery present?  yes/no
133          */
134         @Contract(pure = true)
135         @NonNull
136         static Boolean isBatteryPresent() {
137             return mBatteryPresent;
138         }
139 
140         // getCurrentHealth...............
141         /**
142          * @return A simple string describing the health of the battery, e.g. "GOOD", "DEAD"
143          */
144         @Contract(pure = true)
145         @Nullable
146         static String getCurrentHealth() {
147             return mBatteryHealth;
148         }
149 
150         // getCurrentStatus...............
151         /**
152          * @return A simple string describing what the battery is doing, e.g. "CHARGING"
153          */
154         @Contract(pure = true)
155         @Nullable
156         static String getCurrentStatus() {
157             return mBatteryStatus;
158         }
159 
160         // getCurrentPowerSource..............
161         /**
```

```
     * @return A simple string describing where the power is coming from, e.g. "USING USB
       ↪ POWER"
     */
    @Contract(pure = true)
    @Nullable
    static String getCurrentPowerSource() {
        return mBatteryPlugged;
    }

    // getCurrentVoltage...............
    /**
     * @return Battery voltage in volts
     */
    @Contract(pure = true)
    @Nullable
    static Double getCurrentVoltage() {
        return mBatteryVoltage;
    }

    // mBatteryTemperature...............
    /**
     * @return Battery temperature in degrees Celsius
     */
    @Contract(pure = true)
    @Nullable
    static Double getCurrentTemperature() {
        return mBatteryTemperature;
    }

    // getCurrentLevel...............
    /**
     * @return Battery level, usually as integer percent, but could be energy/charge/etc
     */
    @Contract(pure = true)
    @Nullable
    static Integer getCurrentLevel() {
        return mBatteryLevel;
    }

    // getScale...............
    /**
```

```
202         * @return Maximal value of getCurrentLevel, usually 100%, but could be energy/charge/
                ↪ etc
203         */
204        @Contract(pure = true)
205        @Nullable
206        static Integer getScale() {
207            return mBatteryScale;
208        }
209
210        // getCurrentPercent...............
211        /**
212         * @return getCurrentLevel() / getScale() as a percent
213         */
214        @Contract(pure = true)
215        @Nullable
216        static Double getCurrentPercent() {
217            if (mBatteryLevel == null || mBatteryScale == null) {
218                return null;
219            }
220            return 100. * mBatteryLevel / (double) mBatteryScale;
221        }
222
223        ///////////////////////////
224
225        // getString...............
226        /**
227         * @return A string representation of the battery's current condition
228         */
229        @Override
230        @NonNull
231        String getString() {
232            final String nullString = "NOT AVAILABLE";
233
234            String batteryIcon;
235            if (mBatteryIcon == null) {
236                batteryIcon = nullString;
237            }
238            else {
239                batteryIcon = NumToString.number(mBatteryIcon) + " [TODO: what the hell is this
                    ↪ ..]";
240            }
```

```
241
242         String batteryTechnology;
243         if (mBatteryTechnology == null) {
244             batteryTechnology = nullString;
245         }
246         else {
247             batteryTechnology = mBatteryTechnology;
248         }
249
250         String batteryPresent;
251         if (mBatteryPresent == null) {
252             batteryPresent = nullString;
253         }
254         else {
255             if (mBatteryPresent) {
256                 batteryPresent = "YES";
257             }
258             else {
259                 batteryPresent = "NO";
260             }
261         }
262
263         String batteryHealth;
264         if (mBatteryHealth == null) {
265             batteryHealth = nullString;
266         }
267         else {
268             batteryHealth = mBatteryHealth;
269         }
270
271         String batteryStatus;
272         if (mBatteryStatus == null) {
273             batteryStatus = nullString;
274         }
275         else {
276             batteryStatus = mBatteryStatus;
277         }
278
279         String batteryPlugged;
280         if (mBatteryPlugged == null) {
281             batteryPlugged = nullString;
```

```
282         }
283         else {
284             batteryPlugged = mBatteryPlugged;
285         }
286
287         String batteryVoltage;
288         if (mBatteryVoltage == null) {
289             batteryVoltage = nullString;
290         }
291         else {
292             batteryVoltage = NumToString.number(mBatteryVoltage) + " [Volts]";
293         }
294
295         String batteryTemperature;
296         if (mBatteryTemperature == null) {
297             batteryTemperature = nullString;
298         }
299         else {
300             batteryTemperature = NumToString.number(mBatteryTemperature) + " [Celsius]";
301         }
302
303         String batteryLevel;
304         if (mBatteryLevel == null) {
305             batteryLevel = nullString;
306         }
307         else {
308             batteryLevel = NumToString.number(mBatteryLevel) + " [level units]";
309         }
310
311         String batteryScale;
312         if (mBatteryScale == null) {
313             batteryScale = nullString;
314         }
315         else {
316             batteryScale = NumToString.number(mBatteryScale) + " [level units]";
317         }
318
319         String batteryPercent;
320         Double percent = getCurrentPercent();
321         if (percent == null) {
322             batteryPercent = nullString;
```

```
323         }
324         else {
325             batteryPercent = NumToString.number(percent) + "%";
326         }
327
328         String out = "";
329         out += "\t" + "Battery icon:         " + batteryIcon        + "\n";
330         out += "\t" + "Battery technology:   " + batteryTechnology  + "\n";
331         out += "\t" + "Is battery present:   " + batteryPresent     + "\n";
332         out += "\t" + "Battery health:       " + batteryHealth      + "\n";
333         out += "\t" + "Battery status:       " + batteryStatus      + "\n";
334         out += "\t" + "Battery power source: " + batteryPlugged     + "\n";
335         out += "\t" + "Battery voltage:      " + batteryVoltage     + "\n";
336         out += "\t" + "Battery temperature:  " + batteryTemperature + "\n";
337         out += "\t" + "Battery level:        " + batteryLevel       + "\n";
338         out += "\t" + "Battery scale:        " + batteryScale       + "\n";
339         out += "\t" + "Battery percent:      " + batteryPercent     + "\n";
340         return out;
341     }
342
343     // Public Overriding Instance Methods
344     //::::::::::::::::::::::
345
346     // onReceive..............
347     /**
348      * Called by the system every time the battery broadcasts a change
349      * @param context The context this receiver is running in
350      * @param intent The intent received containing the broadcast data
351      */
352     @Override
353     public void onReceive(@NonNull Context context, @NonNull Intent intent) {
354         if (!super.isOkToProceed(context, intent)) {
355             return;
356         }
357
358         // Icon
359         //————————————————————————————————————————
            ↪ ————————————————————————————————————————
360
361         int icon = intent.getIntExtra(BatteryManager.EXTRA_ICON_SMALL, -1);
362         if (icon == -1) {
```

```
363                 mBatteryIcon = null;
364             }
365             else {
366                 mBatteryIcon = icon;
367             }
368 
369             // Technology
370             //————————————
```

```
                mBatteryHealth = "OVERHEAT";
                break;
            }
            case (BatteryManager.BATTERY_HEALTH_UNKNOWN): {
                mBatteryHealth = "UNKNOWN";
                break;
            }
            case (BatteryManager.BATTERY_HEALTH_UNSPECIFIED_FAILURE): {
                mBatteryHealth = "UNSPECIFIED FAILURE";
                break;
            }
            default:
                mBatteryHealth = "UNKNOWN CONDITION OR NOT AVAILABLE";
        }

        // Status
        //————————————————————————————————————————————————————————————————————————————————————————

        int status = intent.getIntExtra(BatteryManager.EXTRA_STATUS, -1);
        switch (status) {
            case (-1): {
                mBatteryStatus = null;
                break;
            }
            case (BatteryManager.BATTERY_STATUS_CHARGING): {
                mBatteryStatus = "CHARGING";
                break;
            }
            case (BatteryManager.BATTERY_STATUS_DISCHARGING): {
                mBatteryStatus = "DISCHARGING";
                break;
            }
            case (BatteryManager.BATTERY_STATUS_FULL): {
                mBatteryStatus = "FULLY CHARGED";
                break;
            }
            case (BatteryManager.BATTERY_STATUS_NOT_CHARGING): {
                mBatteryStatus = "NOT CHARGING";
                break;
            }
```

```
441                 case (BatteryManager.BATTERY_STATUS_UNKNOWN): {
442                     mBatteryStatus = "CHARGING STATUS UNKNOWN";
443                     break;
444                 }
445                 default: {
446                     mBatteryStatus = "UNKNOWN STATUS";
447                 }
448             }
449 
450             // Plugged
451             //————————————————————————————————————————
                ↪ ————————————————————————————————————————
452 
453             int plugged = intent.getIntExtra(BatteryManager.EXTRA_PLUGGED, -1);
454             switch (plugged) {
455                 case (-1): {
456                     mBatteryPlugged = null;
457                     break;
458                 }
459                 case (0): {
460                     mBatteryPlugged = "USING BATTERY POWER ONLY";
461                     break;
462                 }
463                 case (BatteryManager.BATTERY_PLUGGED_AC): {
464                     mBatteryPlugged = "USING AC ADAPTER POWER";
465                     break;
466                 }
467                 case (BatteryManager.BATTERY_PLUGGED_USB): {
468                     mBatteryPlugged = "USING USB POWER";
469                     break;
470                 }
471                 case (BatteryManager.BATTERY_PLUGGED_WIRELESS): {
472                     mBatteryPlugged = "USING WIRELESS POWER";
473                     break;
474                 }
475                 default: {
476                     mBatteryPlugged = "UNKNOWN POWER SOURCE";
477                 }
478             }
479 
480             // Voltage
```

```
481         //-------------------------------------------
            ↪ ---------------------------------------------------
482
483         int voltage = intent.getIntExtra(BatteryManager.EXTRA_VOLTAGE, -1);
484         if (voltage == -1) {
485             mBatteryVoltage = null;
486         }
487         else {
488             mBatteryVoltage = voltage / 1e3;
489         }
490
491         // Temperature
492         //-------------------------------------------
            ↪ ---------------------------------------------------
493
494         int temperature = intent.getIntExtra(BatteryManager.EXTRA_TEMPERATURE, -1);
495         if (temperature == -1) {
496             mBatteryTemperature = null;
497         }
498         else {
499             mBatteryTemperature = temperature / 10.;
500         }
501
502         // Level
503         //-------------------------------------------
            ↪ ---------------------------------------------------
504
505         int level = intent.getIntExtra(BatteryManager.EXTRA_LEVEL, -1);
506         if (level == -1) {
507             mBatteryLevel = null;
508         }
509         else {
510             mBatteryLevel = level;
511         }
512
513         // Scale
514         //-------------------------------------------
            ↪ ---------------------------------------------------
515
516         int scale = intent.getIntExtra(BatteryManager.EXTRA_SCALE, -1);
517         if (scale == -1) {
```

```
518                 mBatteryScale = null;
519             }
520             else {
521                 mBatteryScale = scale;
522             }
523         }
524
525     }
```

Listing E.16: Camera Controller (`camera2/CameraController.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraAccessException;
import android.hardware.camera2.CameraCaptureSession;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraDevice;
import android.hardware.camera2.CameraManager;
import android.hardware.camera2.CaptureRequest;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Size;
import android.view.Surface;

import org.jetbrains.annotations.Contract;

import java.util.HashMap;
import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
```

```
41  import sci.crayfis.shramp.camera2.requests.RequestMaker;
42  import sci.crayfis.shramp.camera2.util.Parameter;
43  import sci.crayfis.shramp.util.HandlerManager;
44
45  /**
46   * Public access to cameras and camera actions
47   */
48  @TargetApi(21)
49  abstract public class CameraController {
50
51      // Public Class Constants
52      //::::::::::::::::::::::::
53
54      // Select...............
55      // Camera selection, FRONT is the same side as the screen
56      public enum Select {FRONT, BACK, EXTERNAL}
57
58      // Private Constants
59      //::::::::::::::::::::::::
60
61      // THREAD_NAME..............
62      // TODO: the camera controller probably does not need its own thread -- remove in the
            ↪ future
63      private static final String THREAD_NAME = "CameraControllerThread";
64
65      // mHandler...............
66      // Reference to the Handler for the camera controller thread
67      private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
68                                                  GlobalSettings.
                                                        ↪ CAMERA_CONTROLLER_THREAD_PRIORITY);
69
70      // mCameras...............
71      // Collection of cameras on this device
72      private static final HashMap<Select, Camera> mCameras = new HashMap<>();
73
74      // Private Class Fields
75      //::::::::::::::::::::::::
76
77      // mCameraManager...............
78      // Reference to system camera manager
79      private static CameraManager mCameraManager;
```

```
80
81      // mOpenCamera...............
82      // Reference to the currently opened camera
83      private static Camera mOpenCamera;
84
85      // mNextRunnable...............
86      // Action to perform following the camera's asynchronous opening
87      private static Runnable mNextRunnable;
88
89      // mNextHandler...............
90      // Thread to continue execution on via mNextRunnable
91      private static Handler mNextHandler;
92
93      //////////////////////////
94      //:::::::::::::::::::::::
95      //////////////////////////
96
97      // Constructors
98      //:::::::::::::::::::::::
99
100     // CameraController...............
101     private CameraController() {
102         mOpenCamera = null;
103     }
104
105     // Public Class Methods
106     //:::::::::::::::::::::::
107
108     // discoverCameras...............
109     /**
110      * Discover all cameras on this device
111      * @param cameraManager Reference to the system camera manager
112      */
113     public static void discoverCameras(@NonNull CameraManager cameraManager) {
114         mCameraManager = cameraManager;
115
116         String[] cameraIds;
117         try {
118             cameraIds = mCameraManager.getCameraIdList();
119             for (String id : cameraIds) {
120                 CameraCharacteristics cameraCharacteristics
```

```
                        = mCameraManager.getCameraCharacteristics(id);
                Integer lens_facing  = cameraCharacteristics.get(CameraCharacteristics.LENS_FACING);
                if (lens_facing == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens facing cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                switch (lens_facing) {
                    case (CameraCharacteristics.LENS_FACING_FRONT): {
                        Camera camera = new Camera("FrontCamera", id, cameraCharacteristics);
                        mCameras.put(Select.FRONT, camera);
                        break;
                    }

                    case (CameraCharacteristics.LENS_FACING_BACK): {
                        Camera camera = new Camera("BackCamera", id, cameraCharacteristics);
                        mCameras.put(Select.BACK, camera);
                        break;
                    }

                    case (CameraCharacteristics.LENS_FACING_EXTERNAL): {
                        Camera camera = new Camera("ExternalCamera", id, cameraCharacteristics);
                        mCameras.put(Select.EXTERNAL, camera);
                        break;
                    }

                    default: {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Unknown camera lens facing");
                        MasterController.quitSafely();
                        return;
                    }
                }
            }
        }
```

```
158         catch (CameraAccessException e) {
159             // TODO: error
160             Log.e(Thread.currentThread().getName(), "Camera is not accessible");
161             MasterController.quitSafely();
162         }
163     }
164
165     // openCamera...............
166     /**
167      * Open camera for capture.  Camera opens asynchronously, therefore to wait for the
            ↪ camera to
168      * open before continuing execution, pass in a runnable and its thread to run on.
169      * @param select Which camera (FRONT, BACK, or EXTERNAL)
170      * @param runnable (Optional) Execution continues with this Runnable
171      * @param handler (Optional) Runnable is executed on this thread (camera controller
            ↪ thread default)
172      * @return True if camera is opening, false if request is unsuccessful
173      */
174     public static boolean openCamera(@NonNull Select select,
175                                      @Nullable Runnable runnable, @Nullable Handler handler)
                                             ↪  {
176
177         Camera camera = mCameras.get(select);
178         if (camera == null) {
179             return false;
180         }
181
182         mNextRunnable = runnable;
183         mNextHandler  = handler;
184
185         try {
186             mCameraManager.openCamera(camera.getCameraId(), camera, mHandler);
187             return true;
188         }
189         catch (SecurityException e) {
190             // TODO: error
191             Log.e(Thread.currentThread().getName(), "Camera permissions have not been
                    ↪ granted");
192             MasterController.quitSafely();
193             return false;
194         }
```

```
195         catch (CameraAccessException e) {
196             // TODO: error
197             Log.e(Thread.currentThread().getName(), "Camera cannot be accessed");
198             MasterController.quitSafely();
199             return false;
200         }
201     }
202 
203     // createCaptureSession...............
204     /**
205      * Initialize capture session on currently opened camera, no action if no camera is open
            ↪ .
206      * Upon successful setup, stateCallback.on(TODO: I forgot) is called
207      * TODO: return boolean for success/fail, maybe default configuration if parameters are
            ↪ null..
208      * @param surfaceList Output surface list
209      * @param stateCallback Callback for capture session state
210      * @param handler Capture session state callback thread
211      */
212     public static void createCaptureSession(@NonNull List<Surface> surfaceList,
213                                             @NonNull CameraCaptureSession.StateCallback
                                                ↪ stateCallback,
214                                             @NonNull Handler handler) {
215         if (mOpenCamera != null) {
216             CameraDevice cameraDevice = mOpenCamera.getCameraDevice();
217             if (cameraDevice == null) {
218                 // TODO: error
219                 Log.e(Thread.currentThread().getName(), "Camera in unknown state");
220                 MasterController.quitSafely();
221                 return;
222             }
223             try {
224                 // TODO: execution continues asynchronously in (forgot what)
225                 cameraDevice.createCaptureSession(surfaceList, stateCallback, handler);
226             }
227             catch (CameraAccessException e) {
228                 // TODO: error
229                 Log.e(Thread.currentThread().getName(), "Camera cannot be accessed");
230                 MasterController.quitSafely();
231             }
232         }
```

```
    }

    // closeCamera...............
    /**
     * Close any opened cameras, execution continues asynchronously in cameraHasClosed()
     */
    public static void closeCamera() {
        if (mOpenCamera == null) {
            return;
        }
        mOpenCamera.close();
    }

    //////////////////////////

    // getAvailableCaptureRequestKeys...............
    /**
     * @return Open camera's available capture request keys, or null if no camera is open
     */
    @Nullable
    public static List<CaptureRequest.Key<?>> getAvailableCaptureRequestKeys() {
        if (mOpenCamera == null) {
            return null;
        }
        return mOpenCamera.getAvailableCaptureRequestKeys();
    }

    // getBitsPerPixel...............
    /**
     * @return Open camera's output format bits per pixel, or null if no camera is open
     */
    @Nullable
    @Contract(pure = true)
    public static Integer getBitsPerPixel() {
        if (mOpenCamera == null) {
            return null;
        }
        return mOpenCamera.getBitsPerPixel();
    }

    // getCaptureRequestBuilder...............
```

```
    /**
     * @return Open camera's current CaptureRequest.Builder, or null if no camera is open
     */
    @Nullable
    @Contract(pure = true)
    public static CaptureRequest.Builder getCaptureRequestBuilder() {
        if (mOpenCamera == null) {
            return null;
        }
        return mOpenCamera.getCaptureRequestBuilder();
    }

    // getOpenedCharacteristicsMap ...............
    /**
     * @return Open camera's characteristics map, or null if no camera is open
     */
    @Nullable
    @Contract(pure = true)
    public static LinkedHashMap<CameraCharacteristics.Key, Parameter>
        ↪ getOpenedCharacteristicsMap() {
        if (mOpenCamera == null) {
            return null;
        }
        return mOpenCamera.getCharacteristicsMap();
    }

    // getOpenedCamera ...............
    /**
     * @return Reference to camera device if open, null if not open
     */
    @Nullable
    @Contract(pure = true)
    public static CameraDevice getOpenedCameraDevice() {
        if (mOpenCamera == null) {
            return null;
        }
        return mOpenCamera.getCameraDevice();
    }

    // getOutputFormat ...............
    /**
```

```
314         * @return Open camera's output format (ImageFormat.YUV_420_888 or RAW_SENSOR), or null
                ↪ if not open
315         */
316        @Nullable
317        @Contract(pure = true)
318        public static Integer getOutputFormat() {
319            if (mOpenCamera == null) {
320                return null;
321            }
322            return mOpenCamera.getOutputFormat();
323        }
324
325        // getOutputSize...............
326        /**
327         * @return Open camera's output size (width, height), or null if no camera open
328         */
329        @Nullable
330        @Contract(pure = true)
331        public static Size getOutputSize() {
332            if (mOpenCamera == null) {
333                return null;
334            }
335            return mOpenCamera.getOutputSize();
336        }
337
338        ////////////////////////////
339
340        // setCaptureRequestBuilder...............
341        /**
342         * @param builder Set open camera CaptureRequest.Builder, no action if no camera open
343         */
344        public static void setCaptureRequestBuilder(@NonNull CaptureRequest.Builder builder) {
345            if (mOpenCamera == null) {
346                return;
347            }
348            mOpenCamera.setCaptureRequestBuilder(builder);
349        }
350
351        // setCaptureRequestMap...............
352        /**
353         * @param map Set open camera capture request parameter map, no action if no camera open
```

```
354         */
355     public static void setCaptureRequestMap(@NonNull LinkedHashMap<CaptureRequest.Key,
            ↪ Parameter>  map) {
356         if (mOpenCamera == null) {
357             return;
358         }
359         mOpenCamera.setCaptureRequestMap(map);
360     }
361
362     // setCaptureRequestTemplate...............
363     /**
364      * @param template Set open camera capture request template, no action if no camera open
365      */
366     public static void setCaptureRequestTemplate(@NonNull Integer template) {
367         if (mOpenCamera == null) {
368             return;
369         }
370         mOpenCamera.setCaptureRequestTemplate(template);
371     }
372
373     ///////////////////////////
374
375     // writeFPS...............
376     /**
377      * Display open camera's configured FPS, no action if no camera open
378      */
379     public static void writeFPS() {
380         if (mOpenCamera != null) {
381             mOpenCamera.writeFPS();
382         }
383     }
384
385     // writeCaptureRequest...............
386     /**
387      * Display open camera's full capture request, no action if no camera open
388      */
389     public static void writeCaptureRequest() {
390         if (mOpenCamera != null) {
391             mOpenCamera.writeRequest();
392         }
393     }
```

```
394
395     // writeCameraCharacteristics..............
396     /**
397      * Display all camera's full characteristics and abilities, camera does not need to be
            ↪ open
398      */
399     public static void writeCameraCharacteristics() {
400         for (Camera camera : mCameras.values()) {
401             camera.writeCharacteristics();
402             Log.e(Thread.currentThread().getName(), "::::::::::::::::::::::::::::::::::::::::
                ↪ ::::::::::::::::::::::::::::::::::::::");
403         }
404     }
405
406     // Package-private Instance Methods
407     //::::::::::::::::::::::
408
409     // cameraHasOpened...............
410     /**
411      * Called by Camera asynchronously once it has opened, execution continues with
            ↪ mNextRunnable
412      * if supplied
413      * @param camera Reference to opened Camera object
414      */
415     static void cameraHasOpened(@NonNull Camera camera) {
416
417         mOpenCamera = camera;
418         RequestMaker.makeDefault();
419         camera.writeRequest();
420
421         if (mNextRunnable != null) {
422             if (mNextHandler != null) {
423                 mNextHandler.post(mNextRunnable);
424                 mNextHandler = null;
425             }
426             else {
427                 mHandler.post(mNextRunnable);
428             }
429             mNextRunnable = null;
430         }
431     }
```

```
432
433         // cameraHasClosed...............
434         /**
435          * Called asynchronously by previously open camera upon closing
436          */
437         static void cameraHasClosed() {
438             Log.e(Thread.currentThread().getName(), "Camera has closed");
439             mOpenCamera = null;
440         }
441
442     }
```

Listing E.17: Camera (`camera2/Camera.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2;

import android.annotation.TargetApi;
import android.graphics.ImageFormat;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraDevice;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;

import android.hardware.camera2.params.StreamConfigurationMap;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Range;
import android.util.Size;

import org.jetbrains.annotations.Contract;

import java.util.Collections;
import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
```

```
41 import sci.crayfis.shramp.camera2.characteristics.CharacteristicsReader;
42 import sci.crayfis.shramp.camera2.requests.RequestMaker;
43 import sci.crayfis.shramp.camera2.util.Parameter;
44 import sci.crayfis.shramp.surfaces.SurfaceController;
45 import sci.crayfis.shramp.util.ArrayToList;
46 import sci.crayfis.shramp.util.NumToString;
47 import sci.crayfis.shramp.util.SizeSortedSet;
48
49 /**
50  * Encapsulation of CameraDevice, its characteristics, abilities and configuration for
       ↪ capture
51  */
52 // TODO: figure out who is giving the unchecked warning
53 @SuppressWarnings("unchecked")
54 @TargetApi(21)
55 final class Camera extends CameraDevice.StateCallback{
56
57     // Private Instance Fields
58     //:::::::::::::::::::::::
59
60     // mBitsPerPixel...............
61     // Output format bits per pixel
62     private Integer mBitsPerPixel;
63
64     // mCameraCharacteristics...............
65     // Encapsulation of camera's features
66     private CameraCharacteristics mCameraCharacteristics;
67
68     // mCameraDevice...............
69     // Reference to the camera device hardware
70     private CameraDevice mCameraDevice;
71
72     // mCameraId...............
73     // System-assigned camera ID
74     private String mCameraId;
75
76     // mCaptureRequestBuilder...............
77     // Current capture request builder
78     private CaptureRequest.Builder mCaptureRequestBuilder;
79
80     // mCaptureRequestMap...............
```

```
81      // Current full configuration of camera for capture
82      private LinkedHashMap<CaptureRequest.Key, Parameter> mCaptureRequestMap;
83
84      // mCaptureRequestTemplate...............
85      // Camera capture template
86      private Integer mCaptureRequestTemplate;
87
88      // mCharacteristicsMap...............
89      // Encapsulation of all camera abilities and features
90      private LinkedHashMap<CameraCharacteristics.Key, Parameter> mCharacteristicsMap;
91
92      // mName...............
93      // Human-friendly camera name
94      private String mName;
95
96      // mOutputFormat...............
97      // Output format (ImageFormat.YUV_420_888 or RAW_SENSOR)
98      private Integer mOutputFormat;
99
100     // mOutputSize...............
101     // Output size (width and height in pixels)
102     private Size mOutputSize;
103
104     ///////////////////////////
105     //:::::::::::::::::::::::
106     ///////////////////////////
107
108     // Constructors
109     //:::::::::::::::::::::::
110
111     // Camera...............
112     /**
113      * Public access disabled
114      */
115     private Camera() { super(); }
116
117     // Camera...............
118     /**
119      * Create a new Camera
120      * @param name Human-friendly name for camera
121      * @param cameraId System-assigned camera ID
```

```
122         * @param cameraCharacteristics Encapsulation of camera features
123         */
124        Camera(@NonNull String name, @NonNull String cameraId,
125                @NonNull CameraCharacteristics cameraCharacteristics) {
126            this();
127
128            Log.e(Thread.currentThread().getName(), " \n\n\t\t\tNew camera created: " + name + "
                ↪  with ID: " + cameraId + "\n ");
129
130            mName                  = name;
131            mCameraId              = cameraId;
132            mCameraCharacteristics = cameraCharacteristics;
133            mCharacteristicsMap    = CharacteristicsReader.read(mCameraCharacteristics);
134
135            establishOutputFormatting();
136        }
137
138        // Private Instance Methods
139        //::::::::::::::::::::::
140
141        // establishOutputFormatting..............
142        /**
143         * Figure out optimal output format for capture
144         */
145        private void establishOutputFormatting() {
146            Parameter parameter;
147
148            parameter = mCharacteristicsMap.get(CameraCharacteristics.
                ↪ SCALER_STREAM_CONFIGURATION_MAP);
149            if (parameter == null) {
150                // TODO: error
151                Log.e(Thread.currentThread().getName(), "Stream configuration map cannot be null
                    ↪ ");
152                MasterController.quitSafely();
153                return;
154            }
155
156            StreamConfigurationMap streamConfigurationMap = (StreamConfigurationMap) parameter.
                ↪ getValue();
157            if (streamConfigurationMap == null) {
158                // TODO: error
```

```
159             Log.e(Thread.currentThread().getName(), "Stream configuration map cannot be null
                    ↪ ");
160             MasterController.quitSafely();
161             return;
162         }
163
164         parameter = mCharacteristicsMap.get(CameraCharacteristics.
                ↪ REQUEST_AVAILABLE_CAPABILITIES);
165         if (parameter == null) {
166             // TODO: error
167             Log.e(Thread.currentThread().getName(), "Available capabilities cannot be null")
                    ↪ ;
168             MasterController.quitSafely();
169             return;
170         }
171
172         Integer[] capabilities = (Integer[]) parameter.getValue();
173         if (capabilities == null) {
174             // TODO: error
175             Log.e(Thread.currentThread().getName(), "Capabilities cannot be null");
176         }
177         List<Integer> abilities = ArrayToList.convert(capabilities);
178
179         if (!GlobalSettings.DISABLE_RAW_OUTPUT && abilities.contains(CameraMetadata.
                ↪ REQUEST_AVAILABLE_CAPABILITIES_RAW)) {
180             mOutputFormat = ImageFormat.RAW_SENSOR;
181         }
182         else {
183             mOutputFormat = ImageFormat.YUV_420_888;
184         }
185
186         mBitsPerPixel = ImageFormat.getBitsPerPixel(mOutputFormat);
187
188         // Find the largest output size supported by all output surfaces
189         SizeSortedSet outputSizes = new SizeSortedSet();
190
191         Size[] streamOutputSizes = streamConfigurationMap.getOutputSizes(mOutputFormat);
192         Collections.addAll(outputSizes, streamOutputSizes);
193
194         List<Class> outputClasses = SurfaceController.getOutputSurfaceClasses();
195         for (Class klass : outputClasses) {
```

```
            Size[] classOutputSizes = streamConfigurationMap.getOutputSizes(klass);
            if (classOutputSizes == null) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), "Class output size cannot be null");
                MasterController.quitSafely();
                return;
            }
            for (Size s : classOutputSizes) {
                if (!outputSizes.contains(s)) {
                    outputSizes.remove(s);
                }
            }
        }

        mOutputSize = outputSizes.last();
    }

    // Package-private Instance Methods
    //::::::::::::::::::::::

    // close...............
    /**
     * Close this camera
     */
    void close() {
        Log.e(Thread.currentThread().getName(), "Closing camera: " + mName + " with ID: " +
            ↪ mCameraId);
        if (mCameraDevice != null) {
            mCameraDevice.close();
        }
    }

    //////////////////////////

    // getAvailableCaptureRequestKeys...............
    /**
     * @return Current capture request keys
     */
    @NonNull
    List<CaptureRequest.Key<?>> getAvailableCaptureRequestKeys() {
        return mCameraCharacteristics.getAvailableCaptureRequestKeys();
```

```
236         }
237
238         // getAvailableCharacteristicsKeys...............
239         /**
240          * @return All camera characteristics and abilities
241          */
242         @NonNull
243         List<CameraCharacteristics.Key<?>> getAvailableCharacteristicsKeys() {
244             return mCameraCharacteristics.getKeys();
245         }
246
247         // getBitsPerPixel...............
248         /**
249          * @return Output format bits per pixel
250          */
251         @Contract(pure = true)
252         @Nullable
253         Integer getBitsPerPixel() {
254             return mBitsPerPixel;
255         }
256
257         // getCameraDevice...............
258         /**
259          * @return Reference to CameraDevice contained by this object
260          */
261         @Contract(pure = true)
262         @Nullable
263         CameraDevice getCameraDevice() {
264             return mCameraDevice;
265         }
266
267         // getCameraId...............
268         /**
269          * @return Get system-assigned camera ID
270          */
271         @Contract(pure = true)
272         @NonNull
273         String getCameraId() {
274             return mCameraId;
275         }
276
```

```
    // getCaptureRequestBuilder ...............
    /**
     * @return Current capture request builder
     */
    @Contract(pure = true)
    @Nullable
    CaptureRequest.Builder getCaptureRequestBuilder() {
        return mCaptureRequestBuilder;
    }

    // getCharacteristicsMap ...............
    /**
     * @return Encapsulation of camera features
     */
    @Contract(pure = true)
    @NonNull
    LinkedHashMap<CameraCharacteristics.Key, Parameter> getCharacteristicsMap() {
        return mCharacteristicsMap;
    }

    // getOutputFormat ...............
    /**
     * @return Camera output format (ImageFormat.YUV_420_888 or RAW_SENSOR)
     */
    @Contract(pure = true)
    @Nullable
    Integer getOutputFormat() {
        return mOutputFormat;
    }

    // getOutputSize ...............
    /**
     * @return Output size (width and height in pixels)
     */
    @Contract(pure = true)
    @NonNull
    Size getOutputSize() {
        return mOutputSize;
    }

    ////////////////////////////
```

```
    // setCaptureRequestBuilder...............
    /**
     * @param builder Set camera to use CaptureRequest.Builder for capture
     */
    void setCaptureRequestBuilder(@NonNull CaptureRequest.Builder builder) {
        mCaptureRequestBuilder = builder;
    }

    // setCaptureRequestMap...............
    /**
     * @param map Set full camera request mapping
     */
    void setCaptureRequestMap(@NonNull LinkedHashMap<CaptureRequest.Key, Parameter>  map) {
        mCaptureRequestMap = map;
    }

    // setCaptureRequestTemplate...............
    /**
     * @param template Set camera request template for capture
     */
    void setCaptureRequestTemplate(@NonNull Integer template) {
        mCaptureRequestTemplate = template;
    }

    ///////////////////////////

    // writeFPS...............
    /**
     * Display current Camera FPS settings
     */
    void writeFPS() {

        Log.e(Thread.currentThread().getName(), " \n\n" + mName + ", ID: " + mCameraId);

        Integer mode = mCaptureRequestBuilder.get(CaptureRequest.CONTROL_AE_MODE);
        if (mode == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
            MasterController.quitSafely();
            return;
```

```
359         }
360
361         if (mOutputFormat == ImageFormat.YUV_420_888) {
362             Log.e(Thread.currentThread().getName(), ">>>>>>>>  Output format is YUV_420_888"
                ↪ );
363         }
364         else { // mOutputFormat == ImageFormat.RAW_SENSOR
365             Log.e(Thread.currentThread().getName(), ">>>>>>>>  Output format is RAW_SENSOR")
                ↪ ;
366         }
367
368         if (mode == CameraMetadata.CONTROL_AE_MODE_ON) {
369             Range<Integer> fpsRange = mCaptureRequestBuilder.get(CaptureRequest.
                ↪ CONTROL_AE_TARGET_FPS_RANGE);
370
371             if (fpsRange == null) {
372                 // TODO: error
373                 Log.e(Thread.currentThread().getName(), "FPS range cannot be null");
374                 MasterController.quitSafely();
375                 return;
376             }
377
378             Log.e(Thread.currentThread().getName(), ">>>>>>>>  FPS Range: " + fpsRange.
                ↪ toString() + " [frames per second]");
379         }
380         else {
381             Long frameDuration = mCaptureRequestBuilder.get(CaptureRequest.
                ↪ SENSOR_FRAME_DURATION);
382             Long exposureTime  = mCaptureRequestBuilder.get(CaptureRequest.
                ↪ SENSOR_EXPOSURE_TIME);
383
384             if (frameDuration == null || exposureTime == null) {
385                 // TODO: error
386                 Log.e(Thread.currentThread().getName(), "Sensor exposure time and frame
                    ↪ duration cannot be null");
387                 MasterController.quitSafely();
388                 return;
389             }
390
391             double fps = Math.round(1e9 / (double) frameDuration);
```

```
            Log.e(Thread.currentThread().getName(), ">>>>>>>>  Frame Duration: " + NumToString.decimal(fps) + " [frames per second]");

            double duty = Math.round(100. * exposureTime / (double) frameDuration);
            Log.e(Thread.currentThread().getName(), ">>>>>>>>  Exposure Duty: " + NumToString.decimal(duty) + " [%]");
        }
    }

    // writeCharacteristics...............
    /**
     * Display full camera features
     */
    void writeCharacteristics() {
        String label = mName + ", ID: " + mCameraId;
        CharacteristicsReader.write(label, mCharacteristicsMap, getAvailableCharacteristicsKeys());
    }

    // writeRequest...............
    /**
     * Display current capture request
     */
    void writeRequest() {
        String label = mName + ", ID: " + mCameraId;
        RequestMaker.write(label, mCaptureRequestMap, getAvailableCaptureRequestKeys());
    }

    // Public Overriding Instance Methods
    //:::::::::::::::::::::::

    // onOpened...............
    /**
     * Called by the system when camera comes online, execution continues in CameraController.cameraHasOpened()
     * @param camera CameraDevice that has been opened
     */
    @Override
    public void onOpened(@NonNull CameraDevice camera) {
        Log.e(Thread.currentThread().getName(), " \n\n\t\tCamera: " + mName + " has opened\n\n");
```

```java
        mCameraDevice = camera;

        CameraController.cameraHasOpened(this);
    }

    // onClosed...............
    /**
     * Called by the system when the camera is closing.
     * Execution continues in CameraController.cameraHasClosed()
     * @param camera CameraDevice that has been closed
     */
    @Override
    public void onClosed(@NonNull CameraDevice camera) {
        Log.e(Thread.currentThread().getName(), "Camera: " + mName + " has closed");
        CameraController.cameraHasClosed();
    }

    // onDisconnected...............
    /**
     * Called by the system when the camera has been disconnected
     * @param camera CameraDevice that has been disconnected
     */
    @Override
    public void onDisconnected(@NonNull CameraDevice camera) {
        // TODO: error
        Log.e(Thread.currentThread().getName(), "Camera: " + mName + " has been disconnected
            ↪ ");
        MasterController.quitSafely();
    }

    // onError...............
    /**
     * Called by the system when an error occurs with the camera
     * @param camera CameraDevice that has erred
     */
    @Override
    public void onError(@NonNull CameraDevice camera, int error) {
        // TODO: figure out why the compiler says there are missing options for the switch-
            ↪ case
        String err;
        switch (error) {
```

```
467                 case (CameraDevice.StateCallback.ERROR_CAMERA_DEVICE): {
468                     err = "ERROR_CAMERA_DEVICE";
469                     break;
470                 }
471                 case (CameraDevice.StateCallback.ERROR_CAMERA_DISABLED): {
472                     err = "ERROR_CAMERA_DISABLED";
473                     break;
474                 }
475                 case (CameraDevice.StateCallback.ERROR_CAMERA_IN_USE): {
476                     err = "ERROR_CAMERA_IN_USE";
477                     break;
478                 }
479                 case (CameraDevice.StateCallback.ERROR_CAMERA_SERVICE): {
480                     err = "ERROR_CAMERA_SERVICE";
481                     break;
482                 }
483                 case (CameraDevice.StateCallback.ERROR_MAX_CAMERAS_IN_USE): {
484                     err = "ERROR_MAX_CAMERAS_IN_USE";
485                     break;
486                 }
487                 default: {
488                     err = "UNKNOWN_ERROR";
489                 }
490             }
491 
492             // TODO: error
493             Log.e(Thread.currentThread().getName(), "Camera error: " + mName + " err: " + err);
494             MasterController.quitSafely();
495         }
496 
497     }
```

Listing E.18: Capture Controller (`camera2/capture/CaptureController.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.capture;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraAccessException;
import android.hardware.camera2.CameraCaptureSession;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Range;
import android.view.Surface;

import org.jetbrains.annotations.Contract;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.FlightPlan;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.analysis.AnalysisController;
```

```
41  import sci.crayfis.shramp.analysis.DataQueue;
42  import sci.crayfis.shramp.battery.BatteryController;
43  import sci.crayfis.shramp.camera2.CameraController;
44  import sci.crayfis.shramp.camera2.requests.RequestMaker;
45  import sci.crayfis.shramp.camera2.util.Parameter;
46  import sci.crayfis.shramp.surfaces.SurfaceController;
47  import sci.crayfis.shramp.util.Datestamp;
48  import sci.crayfis.shramp.util.HandlerManager;
49  import sci.crayfis.shramp.util.HeapMemory;
50  import sci.crayfis.shramp.util.NumToString;
51  import sci.crayfis.shramp.util.StopWatch;
52  import sci.crayfis.shramp.util.StorageMedia;
53
54  /**
55   * Oversees the set up of captureMonitor sessions and what to do between them
56   */
57  @TargetApi(21)
58  final public class CaptureController extends CameraCaptureSession.StateCallback {
59
60      // Private Class Constants
61      //::::::::::::::::::::::
62
63      // Mode...............
64      // Available captureMonitor session modes
65      public enum Mode {
66          WARMUP,                 // Stress the device to heat it up
67          COOLDOWN,               // Idle the device to cool it down
68          CALIBRATION_COLD_FAST,  // Perform a calibration run
69          CALIBRATION_COLD_SLOW,  // Perform a calibration run
70          CALIBRATION_HOT_FAST,   // Perform a calibration run
71          CALIBRATION_HOT_SLOW,   // Perform a calibration run
72          OPTIMIZE_DUTY_CYCLE,    // Discover fps for optimum duty cycle
73          DATA,                   // Perform a data run
74          TASK                   // For tasks between runs
75      }
76
77      // THREAD_NAME...............
78      // Control over captureMonitor and its internal actions run on this thread
79      private static final String THREAD_NAME = "CaptureThread";
80
81      // mHandler...............
```

```
82      // Reference to the CaptureManagerThread Handler
83      private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
84                                                  GlobalSettings.
                                                      ↪ CAPTURE_MANAGER_THREAD_PRIORITY);
85
86      // mInstance...............
87      // Reference to single instance of CaptureController
88      private static final CaptureController mInstance = new CaptureController();
89
90      // mFlightPlan...............
91      // Capture sequence to execute
92      private static final FlightPlan mFlightPlan = new FlightPlan();
93
94      // Private Class Fields
95      //:::::::::::::::::::::::
96
97      // mOptimalExposure...............
98      // Exposure time for minimal dead time in capture
99      private static Long mOptimalExposure;
100
101     // mSession...............
102     // Encapsulation of captureMonitor session objects and group actions on them
103     abstract private static class mSession {
104
105         // Current state of the captureMonitor session
106         enum State {OPEN, RUNNING, PAUSED, CLOSED};
107
108         // captureMonitor session objects
109         static CaptureConfiguration configuration;  // conditions to end captureMonitor
110         static CameraCaptureSession captureSession; // the actual session
111         static CaptureRequest       captureRequest; // the session request parameters
112         static List<Surface>        surfaceList;    // output surfaces
113         static CaptureMonitor       captureMonitor; // frame-wise capture callback
114         static State                state;          // current state of captureMonitor
                ↪ session
115         static int                  attemptCount;   // attempts so far for the same
                ↪ configuration
116
117         // reset...............
118         /**
119          * Clear all fields, close any open session and reload output surface list
```

```
120          */
121         static void reset() {
122             configuration = null;
123
124             if (captureSession != null) {
125                 captureSession.close();
126             }
127             captureSession = null;
128             state = State.CLOSED;
129
130             captureRequest = null;
131             surfaceList = SurfaceController.getOpenSurfaces();
132
133             captureMonitor = null;
134         }
135
136         // newSession ...............
137         /**
138          * Opens a new session (builds capture request, etc), but does not begin it
139          * @param session bla
140          */
141         static void newSession(@NonNull CameraCaptureSession session) {
142             captureSession = session;
143             renewSession();
144         }
145
146         // renewSession ...............
147         /**
148          * Reset capture request and configure a new capture monitor for the next capture
                 ↪ session
149          */
150         static void renewSession() {
151
152             // Get next programmed capture session
153             configuration = mFlightPlan.getNext();
154             attemptCount  = 0;
155
156             // Quit the app successfully condition
157             if (configuration == null) {
158                 Log.e(Thread.currentThread().getName(), " \n\n\t\t\tMission Accomplished.
                     ↪ Shutting down..\n ");
```

```
159                 reset();
160                 MasterController.quitSafely();
161                 return;
162             }
163
164             switch (configuration.Mode) {
165                 case COOLDOWN: {
166                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING COOL-
                        ↪ DOWN SESSION <<\n ");
167                     break;
168                 }
169                 case WARMUP: {
170                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING WARM-UP
                        ↪  SESSION <<\n ");
171                     break;
172                 }
173                 case CALIBRATION_COLD_FAST: {
174                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING COLD-
                        ↪ FAST CALIBRATION SESSION <<\n ");
175                     break;
176                 }
177                 case CALIBRATION_COLD_SLOW: {
178                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING COLD-
                        ↪ SLOW CALIBRATION SESSION <<\n ");
179                     break;
180                 }
181                 case CALIBRATION_HOT_FAST: {
182                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING HOT-
                        ↪ FAST CALIBRATION SESSION <<\n ");
183                     break;
184                 }
185                 case CALIBRATION_HOT_SLOW: {
186                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING HOT-
                        ↪ SLOW CALIBRATION SESSION <<\n ");
187                     break;
188                 }
189                 case OPTIMIZE_DUTY_CYCLE: {
190                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING
                        ↪ EXPOSURE OPTIMIZATION SESSION <<\n ");
191                     break;
192                 }
```

```
193                 case DATA: {
194                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING DATA
                        ↪ SESSION <<\n ");
195                     break;
196                 }
197                 case TASK: {
198                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t >> STARTING TASK
                        ↪ SESSION <<\n ");
199                     break;
200                 }
201             }
202 
203             if (configuration.Mode == Mode.COOLDOWN) {
204                 coolDown(configuration.TemperatureLimit, configuration.AttemptLimit);
205                 mHandler.post(new Runnable() {
206                     @Override
207                     public void run() {
208                         renewSession();
209                     }
210                 });
211             }
212             else if (configuration.Mode == Mode.TASK) {
213                 mHandler.post(configuration.Task);
214                 mHandler.post(new Runnable() {
215                     @Override
216                     public void run() {
217                         renewSession();
218                     }
219                 });
220             }
221             else {
222                 AnalysisController.resetRunningTotals();
223                 if (configuration.EnableSignificance) {
224                     AnalysisController.enableSignificance();
225                     AnalysisController.setSignificanceThreshold(configuration.FrameLimit);
226                 }
227                 else {
228                     AnalysisController.disableSignificance();
229                 }
230                 if (configuration.Mode == Mode.DATA && configuration.TargetExposure == null)
                    ↪ {
```

```
                    if (mOptimalExposure == null) {
                        configuration.TargetExposure = CaptureConfiguration.EXPOSURE_BOUNDS.
                            ↪ getLower() * 2;
                    }
                    else {
                        configuration.TargetExposure = mOptimalExposure;
                    }
                }
                captureRequest = buildCaptureRequest();
                captureMonitor = new CaptureMonitor(configuration.FrameLimit, configuration.
                    ↪ TemperatureLimit);
                state = State.OPEN;
                mHandler.post(new Runnable() {
                    @Override
                    public void run() {
                        startCapture();
                    }
                });
            }
        }

        // repeatSession...............
        /**
         * Repeat last capture session
         */
        static void repeatSession() {
            AnalysisController.resetRunningTotals();
            if (configuration.EnableSignificance) {
                AnalysisController.enableSignificance();
                AnalysisController.setSignificanceThreshold(configuration.FrameLimit);
            }
            else {
                AnalysisController.disableSignificance();
            }
            captureMonitor = new CaptureMonitor(configuration.FrameLimit, configuration.
                ↪ TemperatureLimit);
            state = State.OPEN;
            mHandler.post(new Runnable() {
                @Override
                public void run() {
                    startCapture();
```

```
269                 }
270             });
271         }
272 
273         // startCapture...............
274         /**
275          * Repeatedly tries to kick-off a capture session until it finally goes through
276          */
277         static void startCapture() {
278             synchronized (mInstance) {
279                 while (!hasStarted()) {
280                     try {
281                         Log.e(Thread.currentThread().getName(), "Waiting to start capture
                                ↪ session");
282                         mInstance.wait(GlobalSettings.DEFAULT_WAIT_MS);
283                     }
284                     catch (InterruptedException e) {
285                         // TODO: error
286                     }
287                 }
288             }
289             Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> STARTING CAPTURE <<\n ");
290         }
291 
292         // hasStarted...............
293         /**
294          * Attempts to send a repeating capture request if there is sufficient memory and
                ↪ all
295          * other app jobs are idling
296          * @return True if capture has started, false if conditions were not right to start
                ↪ yet
297          */
298         static boolean hasStarted() {
299 
300             if (state == State.RUNNING) {
301                 return true;
302             }
303 
304             if (state == State.CLOSED) {
305                 // TODO: error
306                 Log.e(Thread.currentThread().getName(), "Session cannot be closed");
```

```
307                 MasterController.quitSafely();
308                 return true;
309             }
310
311             if (state == State.OPEN || state == State.PAUSED) {
312                 HeapMemory.logAvailableMiB();
313                 if (!HeapMemory.isMemoryAmple()) {
314                     System.gc();
315                     if (AnalysisController.isBusy() || StorageMedia.isBusy()) {
316                         return false;
317                     }
318
319                     // Sometimes the garbage collector just needs a kick
320                     Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> Forcing Restart
                        ↪ <<\n ");
321                 }
322
323                 try {
324                     captureSession.setRepeatingRequest(captureRequest, captureMonitor,
                        ↪ mHandler);
325                     state = State.RUNNING;
326                     return true;
327                 }
328                 catch (CameraAccessException e) {
329                     // TODO: handle this
330                     Log.e(Thread.currentThread().getName(), "Cannot access camera");
331                     MasterController.quitSafely();
332                     return true;
333                 }
334             }
335
336             // Should never get to this point, silence compiler error for lack of return
337             Log.e(Thread.currentThread().getName(), "Something is really wrong, unknown
                ↪ capture state?");
338             MasterController.quitSafely();
339             return true;
340         }
341
342         // pause...............
343         /**
344          * Pause the capture session
```

```
345          */
346         static void pause() {
347             if (state == State.RUNNING) {
348                 try {
349                     captureSession.stopRepeating();
350                     state = State.PAUSED;
351                 }
352                 catch (CameraAccessException e) {
353                     // TODO:  error
354                     Log.e(Thread.currentThread().getName(), "Cannot access camera");
355                     MasterController.quitSafely();
356                 }
357             }
358         }
359
360     }
361
362     ///////////////////////////
363     //:::::::::::::::::::::::
364     ///////////////////////////
365
366     // Constructors
367     //:::::::::::::::::::::::
368
369     // CaptureController...............
370     /**
371      * Disabled
372      */
373     private CaptureController() { super(); }
374
375     // Public Class Methods
376     //:::::::::::::::::::::::
377
378     // startCaptureSequence...............
379     /**
380      * Opens a new capture session with the opened camera.  This happens asynchronously, but
         ↪ when
381      * opened, execution continues in onConfigured()
382      */
383     public static void startCaptureSequence() {
384         mSession.reset();
```

```
385
386             // execution continues in onConfigured
387             CameraController.createCaptureSession(mSession.surfaceList, mInstance, mHandler);
388         }
389
390         // isOptimalExposureSet...............
391         /**
392          * @return True if optimal exposure is known, false if not
393          */
394         @Contract(pure = true)
395         public static boolean isOptimalExposureSet() { return mOptimalExposure != null; }
396
397         // Public Overriding Instance Methods
398         //:::::::::::::::::::::::
399
400         // onConfigured...............
401         /**
402          * This method is called when the camera device has finished configuring itself,
403          * and the session can start processing capture requests.
404          * @param session Reference to the now opened capture session
405          */
406         @Override
407         public void onConfigured(@NonNull CameraCaptureSession session) {
408             //super.onConfigured(session); is abstract, nothing to call
409             Log.e(Thread.currentThread().getName(), "Capture session is now open for business");
410             mSession.newSession(session);
411         }
412
413         // onClosed...............
414         /**
415          * This method is called when the session is closed.
416          * @param session Reference to capture session
417          */
418         @Override
419         public void onClosed(@NonNull CameraCaptureSession session) {
420             super.onClosed(session);
421             Log.e(Thread.currentThread().getName(), "Capture session has been closed");
422         }
423
424         // Package-private Class Methods
425         //:::::::::::::::::::::::
```

```java

    // coolDown...............
    /**
     * Idle the smartphone with minimal activity to decrease device temperature
     * @param coolTemperature Temperature to cool to [Celsius]
     * @param attemptLimit Maximum idle attempts (minutes) to cool
     */
    static void coolDown(double coolTemperature, int attemptLimit) {
        synchronized (mInstance) {
            Double temperature = BatteryController.getCurrentTemperature();
            if (temperature == null) {
                Log.e(Thread.currentThread().getName(), "Temperature is unknown, shutting down for safety");
                MasterController.quitSafely();
                return;
            }

            int attemptCount = 0;
            while (temperature > coolTemperature) {
                try {
                    Log.e(Thread.currentThread().getName(), "Cooling down: " + NumToString.number(temperature)
                            + " > " + NumToString.number(coolTemperature) + " [Celsius], update in 1 minute..");
                    mInstance.wait(GlobalSettings.DEFAULT_LONG_WAIT);

                    temperature = BatteryController.getCurrentTemperature();
                    if (temperature == null) {
                        Log.e(Thread.currentThread().getName(), "Temperature is unknown, shutting down for safety");
                        MasterController.quitSafely();
                        return;
                    }

                    attemptCount += 1;
                    if (attemptCount >= mSession.configuration.AttemptLimit) {
                        Log.e(Thread.currentThread().getName(), "Cool down cycle exceeding attempt limit: "
                                + NumToString.number(attemptCount) + ", breaking from cool down");
```

```
                        Log.e(Thread.currentThread().getName(), "Ending temperature: " +
                            ↪ NumToString.number(temperature)
                                + " [Celsius]");
                        break;
                    }
                }
                catch (InterruptedException e) {
                    // TODO: error
                }
            }
        }
    }

    // pauseSession ...............
    /**
     * Pause the current capture session
     */
    static void pauseSession() {
        mSession.pause();
    }

    // restartSession ...............
    /**
     * Restart a paused capture session
     */
    static void restartSession() {
        mSession.startCapture();
    }

    // getOptimalExposure ...............
    /**
     * @return Optimal exposure for minimal dead time, null if optimize duty cycle session
         ↪ has not been run
     */
    @Nullable
    @Contract(pure = true)
    static Long getOptimalExposure() {
        return mOptimalExposure;
    }

    // sessionFinished ...............
```

```java
499     /**
500      * Called by CaptureMonitor when the session has finished.
501      * @param averageFps Overall average frames-per-second (i.e. total frames / total
         ↪ session time)
502      * @param averageDuty Overall average duty (i.e. total exposure / total frame duration)
503      */
504     static void sessionFinished(double averageFps, double averageDuty) {
505
506         mSession.attemptCount += 1;
507
508         String string = " \n\nCapture session has finished\n\n";
509         string += "Session effective performance: \n";
510         string += "\t Overall Average FPS:  " + NumToString.decimal(averageFps) + " [frames
            ↪ / sec] \n";
511         string += "\t Overall Average Duty: " + NumToString.decimal(averageDuty * 100.) + "
            ↪ % \n";
512         string += "\t Attempt count:        " + NumToString.number(mSession.attemptCount)
513                 + " out of " + NumToString.number(mSession.configuration.AttemptLimit) + "\n
                    ↪ ";
514         Log.e(Thread.currentThread().getName(), string);
515
516         StorageMedia.removeEmptyDirs(StorageMedia.workInProgressPath());
517
518         if (mSession.configuration.Mode == Mode.OPTIMIZE_DUTY_CYCLE) {
519             mOptimalExposure = (long) (Math.floor(1e9 / averageFps));
520             Log.e(Thread.currentThread().getName(), "New optimal fps: "
521                     + NumToString.decimal(1. / ( mOptimalExposure * 1e-9) )
522                     + " [frames / sec]");
523             mSession.configuration.TargetExposure = mOptimalExposure;
524             mSession.captureRequest = buildCaptureRequest();
525
526             Integer mode = mSession.captureRequest.get(CaptureRequest.CONTROL_AE_MODE);
527             if (mode == null) {
528                 // TODO: error
529                 Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
530                 MasterController.quitSafely();
531                 return;
532             }
533
534             if ( (averageDuty >= GlobalSettings.OPTIMAL_DUTY_THRESHOLD)
```

```
535                     || (mode == CameraMetadata.CONTROL_AE_MODE_ON && mSession.attemptCount >
                            ↪  3)) {
536                 Log.e(Thread.currentThread().getName(), " \n\n\t\t>> Ending Attempts Early,
                        ↪ Goals Met <<\n ");
537                 Log.e(Thread.currentThread().getName(), " \n" + StopWatch.
                        ↪ getLabeledPerformances());
538                 StopWatch.resetLabeled();
539                 mSession.renewSession();
540                 return;
541             }
542         }
543
544         if (mSession.configuration.Mode == Mode.WARMUP) {
545             Double currentTemperature = BatteryController.getCurrentTemperature();
546             if (currentTemperature == null) {
547                 // TODO: error
548                 Log.e(Thread.currentThread().getName(), "Cannot get temperature, shutting
                        ↪ down for safety");
549                 MasterController.quitSafely();
550                 return;
551             }
552
553             if (currentTemperature >= mSession.configuration.TemperatureLimit) {
554                 Log.e(Thread.currentThread().getName(), " \n\n\t\t>> Ending Attempts Early,
                        ↪ Goals Met <<\n ");
555                 Log.e(Thread.currentThread().getName(), " \n" + StopWatch.
                        ↪ getLabeledPerformances());
556                 StopWatch.resetLabeled();
557                 mSession.renewSession();
558                 return;
559             }
560         }
561
562         if (mSession.configuration.Mode == Mode.DATA
563                 && mSession.attemptCount < mSession.configuration.AttemptLimit) {
564             Double currentTemperature = BatteryController.getCurrentTemperature();
565             if (currentTemperature == null) {
566                 // TODO: error
567                 Log.e(Thread.currentThread().getName(), "Cannot get temperature, shutting
                        ↪ down for safety");
568                 MasterController.quitSafely();
```

```
569                 return;
570             }
571
572             if (currentTemperature >= mSession.configuration.TemperatureLimit) {
573                 Log.e(Thread.currentThread().getName(), " \n\n\t\t>> Over Temperature,
                    ↪ Cooling Down <<\n ");
574                 Log.e(Thread.currentThread().getName(), " \n" + StopWatch.
                    ↪ getLabeledPerformances());
575                 StopWatch.resetLabeled();
576                 coolDown(GlobalSettings.TEMPERATURE_GOAL, 10);
577                 Log.e(Thread.currentThread().getName(), " \n\n\t\t>> Reducing FPS by 80% To
                    ↪ Avoid Over Temperature <<\n ");
578                 mSession.configuration.TargetExposure = (long) Math.round(mSession.
                    ↪ configuration.TargetExposure / 0.8);
579                 mSession.captureRequest = buildCaptureRequest();
580                 mSession.repeatSession();
581                 return;
582             }
583         }
584
585         if (mSession.attemptCount < mSession.configuration.AttemptLimit) {
586             Log.e(Thread.currentThread().getName(), " \n" + StopWatch.getLabeledPerformances
                    ↪ ());
587             StopWatch.resetLabeled();
588             mSession.repeatSession();
589             return;
590         }
591
592         if (mSession.configuration.Mode == Mode.CALIBRATION_HOT_SLOW) {
593             AnalysisController.runStatistics("hot_slow_" + Datestamp.getDate());
594             // PrintAllocations.printMeanAndErr();
595         }
596         if (mSession.configuration.Mode == Mode.CALIBRATION_HOT_FAST) {
597             AnalysisController.runStatistics("hot_fast_" + Datestamp.getDate());
598             // PrintAllocations.printMeanAndErr();
599         }
600         if (mSession.configuration.Mode == Mode.CALIBRATION_COLD_SLOW) {
601             AnalysisController.runStatistics("cold_slow_" + Datestamp.getDate());
602             // PrintAllocations.printMeanAndErr();
603         }
604         if (mSession.configuration.Mode == Mode.CALIBRATION_COLD_FAST) {
```

```
605                 AnalysisController.runStatistics("cold_fast_" + Datestamp.getDate());
606                 // PrintAllocations.printMeanAndErr();
607             }
608 
609             Log.e(Thread.currentThread().getName(), " \n" + StopWatch.getLabeledPerformances());
610             StopWatch.resetLabeled();
611             mSession.renewSession();
612 
613         }
614 
615         // Private Class Methods
616         //::::::::::::::::::::::
617 
618         // buildCaptureRequest..............
619         /**
620          * @return A new capture request for the session (the only time it will be null is a
                 ↪ critical failure)
621          */
622         @Nullable
623         private static CaptureRequest buildCaptureRequest() {
624 
625             RequestMaker.makeDefault();
626             CaptureRequest.Builder builder = CameraController.getCaptureRequestBuilder();
627             if (builder == null) {
628                 // TODO: error
629                 Log.e(Thread.currentThread().getName(), "Request builder cannot be null");
630                 MasterController.quitSafely();
631                 return null;
632             }
633 
634             for (Surface surface : mSession.surfaceList) {
635                 builder.addTarget(surface);
636             }
637 
638             Integer mode = builder.get(CaptureRequest.CONTROL_AE_MODE);
639             if (mode == null) {
640                 // TODO: error
641                 Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
642                 MasterController.quitSafely();
643                 return null;
644             }
```

```
645
646         if (mode == CameraMetadata.CONTROL_AE_MODE_ON) {
647             Log.e(Thread.currentThread().getName(), "Cannot set exact exposure, finding
                ↪ closest option");
648             builder.set(CaptureRequest.CONTROL_AE_TARGET_FPS_RANGE, getAeTargetFpsRange());
649         }
650         else {
651             builder.set(CaptureRequest.SENSOR_FRAME_DURATION, mSession.configuration.
                ↪ TargetExposure);
652             builder.set(CaptureRequest.SENSOR_EXPOSURE_TIME,  mSession.configuration.
                ↪ TargetExposure);
653         }
654         CameraController.setCaptureRequestBuilder(builder);
655         CameraController.writeFPS();
656
657         return builder.build();
658     }
659
660     // getAeTargetFpsRange...............
661     /**
662      * When sensor cannot be manually controlled, find an fps-range closest to that desired
663      */
664     @SuppressWarnings("unchecked")
665     @NonNull
666     private static Range<Integer> getAeTargetFpsRange() {
667
668         // Set FPS range closest to target FPS
669         LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap;
670         characteristicsMap = CameraController.getOpenedCharacteristicsMap();
671         if (characteristicsMap == null) {
672             // TODO: error
673             Log.e(Thread.currentThread().getName(), "Characteristics map cannot be null");
674             MasterController.quitSafely();
675             return new Range<Integer>(0, 0);  // garbage
676         }
677
678         CameraCharacteristics.Key<Range<Integer>[]> cKey;
679         Parameter<Range<Integer>[]> property;
680
681         cKey = CameraCharacteristics.CONTROL_AE_AVAILABLE_TARGET_FPS_RANGES;
682         property = characteristicsMap.get(cKey);
```

```
683         if (property == null) {
684             // TODO: error
685             Log.e(Thread.currentThread().getName(), "Available target FPS ranges cannot be
                ↪ null");
686             MasterController.quitSafely();
687             return new Range<Integer>(0,0);  // garbage
688         }
689
690         Range<Integer>[] ranges = property.getValue();
691         if (ranges == null) {
692             // TODO: error
693             Log.e(Thread.currentThread().getName(), "FPS ranges cannot be null");
694             MasterController.quitSafely();
695             return new Range<Integer>(0,0);  // garbage
696         }
697
698         int target = (int) Math.round(1e9 / mSession.configuration.TargetExposure);
699         Range<Integer> closest = null;
700         for (Range<Integer> range : ranges) {
701             if (closest == null) {
702                 closest = range;
703                 continue;
704             }
705
706             int diff = Math.min(Math.abs(range.getUpper() - target),
707                                 Math.abs(range.getLower() - target));
708
709             int closestDiff = Math.min(Math.abs(closest.getUpper() - target),
710                                        Math.abs(closest.getLower() - target));
711
712             if (diff < closestDiff) {
713                 closest = range;
714             }
715         }
716         if (closest == null) {
717             // TODO: error
718             Log.e(Thread.currentThread().getName(), "Closest FPS range cannot be null");
719             MasterController.quitSafely();
720             return new Range<Integer>(0,0);  // garbage
721         }
722         return closest;
```

```
723         }
724
725         ////////////////////////////
726         // IGNORE ////////////////////////////
727         ////////////////////////////
728
729         // onReady...............
730         /**
731          * This method is called every time the session has no more capture requests to process.
732          * @param session Reference to capture session
733          */
734         @Override
735         public void onReady(@NonNull CameraCaptureSession session) {
736             super.onReady(session);
737             Log.e(Thread.currentThread().getName(), "Capture session ready");
738         }
739
740         // onActive...............
741         /**
742          * This method is called when the session starts actively processing captureMonitor
             ↪ requests.
743          * @param session Reference to capture session
744          */
745         @Override
746         public void onActive(@NonNull CameraCaptureSession session) {
747             super.onActive(session);
748             Log.e(Thread.currentThread().getName(), "Capture session active");
749         }
750
751         // onCaptureQueueEmpty...............
752         /**
753          * This method is called when camera device's input captureMonitor queue becomes empty,
754          * and is ready to accept the next request.
755          * @param session Reference to capture session
756          */
757         @Override
758         public void onCaptureQueueEmpty(@NonNull CameraCaptureSession session) {
759             super.onCaptureQueueEmpty(session);
760             Log.e(Thread.currentThread().getName(), "Capture queue is empty");
761         }
762
```

```
    // onSurfacePrepared...............
    /**
     * This method is called when the buffer pre-allocation for an output Surface is complete.
     * @param session Reference to capture session
     * @param surface Reference to output surface
     */
    @Override
    public void onSurfacePrepared(@NonNull CameraCaptureSession session, @NonNull Surface surface) {
        super.onSurfacePrepared(session, surface);
        Log.e(Thread.currentThread().getName(), "Output surface: " + surface.toString() + " is ready");
    }

    ///////////////////////////
    // SHUTDOWN ///////////////////////////
    ///////////////////////////

    // onConfiguredFailed...............
    /**
     * This method is called if the session cannot be configured as requested.
     * @param session Reference to capture session
     */
    @Override
    public void onConfigureFailed(@NonNull CameraCaptureSession session) {
        //super.onConfigureFailed(session); is abstract
        // TODO: error
        Log.e(Thread.currentThread().getName(), "Capture configuration failed");
        MasterController.quitSafely();
    }

}
```

Listing E.19: Capture Monitor (camera2/capture/CaptureMonitor.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.capture;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCaptureSession;
import android.hardware.camera2.CaptureFailure;
import android.hardware.camera2.CaptureRequest;
import android.hardware.camera2.CaptureResult;
import android.hardware.camera2.TotalCaptureResult;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.view.Surface;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.analysis.AnalysisController;
import sci.crayfis.shramp.analysis.DataQueue;
import sci.crayfis.shramp.battery.BatteryController;
import sci.crayfis.shramp.camera2.util.TimeCode;
import sci.crayfis.shramp.util.HeapMemory;
import sci.crayfis.shramp.util.NumToString;
import sci.crayfis.shramp.util.StopWatch;
import sci.crayfis.shramp.util.StorageMedia;
import sci.crayfis.shramp.util.Datestamp;
```

```

/**
 * Monitors capture stream on a frame by frame basis, receiving capture metadata
 */
@TargetApi(21)
final class CaptureMonitor extends CameraCaptureSession.CaptureCallback {

    // Private Class Constants
    //:::::::::::::::::::::::

    // state...............
    // state of the capture session
    private enum State {ACTIVE, PAUSED, FINISHED}

    // Private Instance Fields
    //:::::::::::::::::::::::

    // mState...............
    // Current state
    private State mState;

    // mFrame...............
    // Encapsulation of frame count and limit, responsible for determining when to stop capture
    private class Frame {

        int FrameLimit;
        int FrameCount;

        // setLimit...............
        /**
         * Set condition to end capture
         * @param limit Maximum number of frames to capture before stopping
         */
        void setLimit(int limit) {
            FrameLimit = limit;
            FrameCount = 0;
        }

        // raiseFrameCount...............
        /**
```

```
81          * Increase frame capture count, and stop capture if frame count has exceeded the
                ↪ limit
82          */
83         void raiseFrameCount() {
84             FrameCount += 1;
85
86             String dots = ".............";
87             Log.e(Thread.currentThread().getName(), " \n" + dots + "\n"
88                     + "Captured " + Integer.toString(FrameCount) + " of "
89                     + Integer.toString(FrameLimit) + " frames" + "\n" + dots);
90
91             if (FrameCount >= FrameLimit) {
92                 Log.e(Thread.currentThread().getName(), "Frame count met, ending capture");
93                 mState = State.FINISHED;
94                 CaptureController.pauseSession();
95             }
96         }
97     }
98     private final Frame mFrame = new Frame();
99
100    // mTemperature.............
101    // Encapsulation of battery temperature statistics, stop capture if temperature exceeds
           ↪ limit
102    class Temperature {
103        Double First;
104        Double Last;
105        Double Max;
106        Double Min;
107        Double Sum;
108        Long   Count;
109        Double Limit;
110
111        // setLimit.............
112        /**
113         * Set temperature limit to end capture
114         * @param temperatureLimit maximum temperature for capture
115         */
116        void setLimit(double temperatureLimit) {
117            Limit = temperatureLimit;
118        }
119
```

```
120         // logTemperature...............
121         /**
122          * Log current battery temperature
123          */
124         void logTemperature() {
125             Last = BatteryController.getCurrentTemperature();
126             if (Last == null) {
127                 return;
128             }
129
130             if (First == null) {
131                 First = Last;
132                 Max   = Last;
133                 Min   = Last;
134                 Sum   = 0.;
135                 Count = 0L;
136             }
137
138             if (Max < Last) {
139                 Max = Last;
140             }
141             if (Min > Last) {
142                 Min = Last;
143             }
144
145             Sum   += Last;
146             Count += 1;
147
148             if (Last >= Limit) {
149                 Log.e(Thread.currentThread().getName(), "Temperature limit met, ending
                        ↪ capture");
150                 mState = State.FINISHED;
151                 CaptureController.pauseSession();
152             }
153         }
154
155         // getMean...............
156         /**
157          * @return mean temperature recorded
158          */
159         @Nullable
```

```
        Double getMean() {
            if (Sum == null) {
                return null;
            }
            return Sum / (double) Count;
        }

        // getLastString...............
        /**
         * @return a string representation of the last temperature recorded
         */
        @NonNull
        String getLastString() {
            if (Last == null) {
                return "UNKNOWN";
            }
            return NumToString.number(Last) + " [Celsius]";
        }

        // getString...............
        /**
         * @return a string of temperature statistics
         */
        @Nullable
        String getString() {
            if (Count == null) {
                return null;
            }
            String out = " \n";
            out += "Temperature [Celsius] \n";
            out += "\t" + "Start: " + NumToString.number(First) + "\n";
            out += "\t" + "Last:  " + NumToString.number(Last) + "\n";
            out += "\t" + "Low:   " + NumToString.number(Min) + "\n";
            out += "\t" + "High:  " + NumToString.number(Max) + "\n";
            out += "\t" + "Mean:  " + NumToString.number(getMean()) + "\n";
            return out;
        }
    }
    private final Temperature mTemperature = new Temperature();

    // mTimestamp...............
```

```
201     // Encapsulation of timestamp information
202     class Timestamp {
203
204         long First   = 0L;
205         long Last    = 0L;
206         long Elapsed = 0L;
207
208         // add...............
209         /**
210          * Add current sensor timestamp to the record
211          * @param result latest capture result
212          */
213         void add(TotalCaptureResult result) {
214             Long timestamp = result.get(CaptureResult.SENSOR_TIMESTAMP);
215             if (timestamp == null) {
216                 // TODO: error
217                 Log.e(Thread.currentThread().getName(), "Sensor timestamp cannot be null");
218                 MasterController.quitSafely();
219                 return;
220             }
221
222             if (First == 0L) {
223                 First = timestamp;
224                 StorageMedia.newInProgress(Datestamp.getDate());
225                 Datestamp.resetElapsedNanos(timestamp);
226             }
227             else {
228                 Elapsed = timestamp - Last;
229             }
230             Last = timestamp;
231         }
232     }
233     private final Timestamp mTimestamp = new Timestamp();
234
235     // mDeadtime...............
236     // Encapsulation of dead time statistics
237     class Deadtime {
238         long Sum = 0L;
239         long Min = -1L;
240         long Max = -1L;
241         long Count = 0;
```

```
242
243         // add...............
244         /**
245          * Add dead time to record
246          * @param deadtime time between frames in nanoseconds
247          */
248         void add(long deadtime) {
249             if (Min == -1L) {
250                 Min = deadtime;
251             }
252             if (Max == -1L) {
253                 Max = deadtime;
254             }
255             if (Min > deadtime) {
256                 Min = deadtime;
257             }
258             if (Max < deadtime) {
259                 Max = deadtime;
260             }
261             Sum   += deadtime;
262             Count += 1;
263         }
264
265         // getMean...............
266         /**
267          * @return mean dead time
268          */
269         double getMean() {
270             return Sum / (double) Count;
271         }
272
273         // getString...............
274         /**
275          * @return a string of dead time statistics
276          */
277         @NonNull
278         String getString() {
279             String out = " \n";
280             out += "Deadtime [ns] \n";
281             out += "\t" + "Min:   " + NumToString.number(Min) + "\n";
282             out += "\t" + "Max:   " + NumToString.number(Max) + "\n";
```

```
            out += "\t" + "Total: " + NumToString.number(Sum) + "\n";
            out += "\t" + "Mean:  " + NumToString.number(getMean()) + "\n";
            return out;
        }
    }
    private final Deadtime mDeadtime = new Deadtime();

    // mExposure...............
    // Encapsulation of sensor exposure statistics
    class Exposure {

        long Total = 0L;
        long Last  = 0L;
        long Min   = -1L;
        long Max   = -1L;
        long Count = 0;

        // add...............
        /**
         * Add frame exposure to the record
         * @param result capture result to add
         */
        void add(TotalCaptureResult result) {
            Long exposure = result.get(CaptureResult.SENSOR_EXPOSURE_TIME);
            if (exposure == null) {
                Log.e(Thread.currentThread().getName(), "Sensor exposure time is not
                    ↪ available");
                Last = 0L;
            }
            else {
                Last = exposure;
            }

            Total += Last;
            Count += 1;

            if (Count == 1) {
                Min = Last;
                Max = Last;
            }

```

```
323                 if (Min > Last) {
324                     Min = Last;
325                 }
326                 if (Max < Last) {
327                     Max = Last;
328                 }
329             }
330 
331             // getMean...............
332             /**
333              * @return mean exposure
334              */
335             double getMean() {
336                 return Total / (double) Count;
337             }
338 
339             // getString...............
340             /**
341              * @return a string of exposure statistics
342              */
343             @NonNull
344             String getString() {
345                 String out = " \n";
346                 out += "Exposure [ns] \n";
347                 out += "\t" + "Min:   " + NumToString.number(Min) + "\n";
348                 out += "\t" + "Max:   " + NumToString.number(Max) + "\n";
349                 out += "\t" + "Total: " + NumToString.number(Total) + "\n";
350                 out += "\t" + "Mean:  " + NumToString.number(getMean()) + "\n";
351                 return out;
352             }
353         }
354         private final Exposure mExposure = new Exposure();
355 
356         // For now, monitor performance (TODO: remove in the future)
357         private abstract static class StopWatches {
358             final static StopWatch ProgressedNotification = new StopWatch("captureMonitor.
                    ↪ progressedNotification()");
359             final static StopWatch CompletedNotification  = new StopWatch("captureMonitor.
                    ↪ completedNotification()");
360             final static StopWatch OnCaptureProgressed    = new StopWatch("captureMonitor.
                    ↪ onCaptureProgressed()");
```

```
        final static StopWatch OnCaptureCompleted     = new StopWatch("captureMonitor.onCaptureCompleted()");
    }

    ////////////////////////////
    //:::::::::::::::::::::::
    ////////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // captureMonitor...............
    /**
     * Effectively disabled
     */
    private CaptureMonitor() {
        super();
    }

    // captureMonitor...............
    /**
     * Set parameters for ending capture
     * @param frameLimit Maximum number of frames to capture before stopping
     * @param temperatureLimit Maximum temperature before stopping
     */
    CaptureMonitor(int frameLimit, double temperatureLimit) {
        this();
        mState = State.ACTIVE;
        mFrame.setLimit(frameLimit);
        mTemperature.setLimit(temperatureLimit);
        Log.e(Thread.currentThread().getName(), "Capture Frame Limit: " + NumToString.number(frameLimit)
            + ", Capture Temperature Limit: " + NumToString.number(temperatureLimit) + " [Celsius]");
    }

    // Private Instance Methods
    //:::::::::::::::::::::::

    // completedNotification...............
    /**
```

```
399     * Displays information about a completed capture
400     * @param completedResult Completed capture result
401     */
402    private void completedNotification(@NonNull TotalCaptureResult completedResult) {
403        StopWatches.CompletedNotification.start();
404
405        Log.e(Thread.currentThread().getName(), "Capture completed with time-code: " +
               ↪ TimeCode.toString(mTimestamp.Last));
406
407        Long duration = completedResult.get(CaptureResult.SENSOR_FRAME_DURATION);
408        if (duration == null) {
409            Log.e(Thread.currentThread().getName(), "Frame duration time is not available,
                   ↪ cannot compute FPS/Duty/Dead time");
410        }
411        else {
412            double duty     = 100. * mExposure.Last / (double) duration;
413            long   deadTime = mTimestamp.Elapsed - duration;
414            mDeadtime.add(deadTime);
415            Log.e(Thread.currentThread().getName(), "Frame FPS: " + NumToString.decimal(1. /
                   ↪  (duration * 1e-9))
416                    + ", Frame Exposure: " + Long.toString(mExposure.Last) + " [ns]"
417                    + ", Frame Duty: " + NumToString.decimal(duty) + "%"
418                    + ", Frame Dead time: " + NumToString.number(deadTime) + " [ns]");
419        }
420
421        String tempString = mTemperature.getLastString();
422        if (tempString == null) {
423            tempString = "UNAVAILABLE";
424        }
425
426        Double power = BatteryController.getInstantaneousPower();
427        String powerString;
428        if (power == null) {
429            powerString = "UNAVAILABLE";
430        }
431        else {
432            powerString = NumToString.number(power) + " [mW]";
433        }
434
435        double fps = 1. / (mTimestamp.Elapsed * 1e-9);
```

```
436         Log.e(Thread.currentThread().getName(), "Consecutive-frame effective FPS: " +
                ↪ NumToString.decimal(fps)
437                 + ", Temperature: " + tempString + ", Power: " + powerString);
438
439         StopWatches.CompletedNotification.addTime();
440     }
441
442     // Public Overriding Methods
443     //::::::::::::::::::::::
444
445     // onCaptureProgressed..............
446     /**
447      * This method is called when an image capture makes partial forward progress;
448      * some (but not all) results from an image capture are available.
449      * @param session Reference to camera capture session
450      * @param request Reference to capture request
451      * @param partialResult Reference to the partial capture result
452      */
453     @Override
454     public void onCaptureProgressed(@NonNull CameraCaptureSession session,
455                                     @NonNull CaptureRequest request,
456                                     @NonNull CaptureResult partialResult) {
457         StopWatches.OnCaptureProgressed.start();
458
459         super.onCaptureProgressed(session, request, partialResult);
460
461         HeapMemory.logAvailableMiB();
462         Log.e(Thread.currentThread().getName(), "Capture in progress..");
463
464         if (HeapMemory.isMemoryLow()) {
465             Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>>DANGER LOW MEMORY<<\t\t>>
                    ↪ REQUESTING PAUSE<<\n ");
466             mState = State.PAUSED;
467             CaptureController.pauseSession();
468         }
469
470         StopWatches.OnCaptureProgressed.addTime();
471     }
472
473     // onCaptureCompleted..............
474     /**
```

```
475         * This method is called when an image capture has fully completed and all the result
476         * metadata is available.
477         * @param session Reference to camera capture session
478         * @param request Reference to capture request
479         * @param result Reference to completed capture result (capture metadata)
480         */
481        @Override
482        public void onCaptureCompleted(@NonNull CameraCaptureSession session,
483                                       @NonNull CaptureRequest request,
484                                       @NonNull TotalCaptureResult result) {
485            StopWatches.OnCaptureCompleted.start();
486
487            super.onCaptureCompleted(session, request, result);
488
489            DataQueue.add(result);
490            mTimestamp.add(result);
491            mExposure.add(result);
492            mTemperature.logTemperature();
493            mFrame.raiseFrameCount();
494
495            completedNotification(result);
496
497            StopWatches.OnCaptureCompleted.addTime();
498        }
499
500        // onCaptureSequenceCompleted..............
501        /**
502         * This method is called independently of the others in CaptureCallback, when a capture
503         * sequence finishes and all CaptureResult or CaptureFailure for it have been
504         * returned via this listener.
505         * @param session Reference to camera capture session
506         * @param sequenceId Capture sequence ID
507         * @param frameNumber Ending frame number
508         */
509        @Override
510        public void onCaptureSequenceCompleted(@NonNull CameraCaptureSession session,
511                                               int sequenceId,
512                                               long frameNumber) {
513            super.onCaptureSequenceCompleted(session, sequenceId, frameNumber);
514
515            if (mState == State.PAUSED) {
```

```
516                 Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> Capture Stream has Paused
                    ↪  <<\n ");
517                 CaptureController.restartSession();
518             }
519             else {
520                 Log.e(Thread.currentThread().getName(), "Capture sequence has completed a total
                    ↪ of "
521                                                 + NumToString.number(mFrame.FrameCount) + "
                                                        ↪ frames");
522
523                 // Wait briefly for stragglers to come in
524                 synchronized (this) {
525                     try {
526                         this.wait(5 * GlobalSettings.DEFAULT_WAIT_MS);
527                     }
528                     catch (InterruptedException e) {
529                         // TODO: error
530                     }
531                 }
532
533                 DataQueue.purge();
534                 synchronized (this) {
535                     while (!DataQueue.isEmpty() || AnalysisController.isBusy() || StorageMedia.
                        ↪ isBusy()) {
536                         try {
537                             String waitingOn = "";
538                             if (!DataQueue.isEmpty()) {
539                                 waitingOn += " Data Queue is not empty";
540                             }
541                             if (AnalysisController.isBusy()) {
542                                 waitingOn += " Analysis Controller is busy";
543                             }
544                             if (StorageMedia.isBusy()) {
545                                 waitingOn += " Storage Media is busy";
546                             }
547                             if (!waitingOn.equals("")) {
548                                 Log.e(Thread.currentThread().getName(), "Waiting on: " +
                                        ↪ waitingOn);
549                             }
550
```

```
551                         if (!DataQueue.isEmpty() && !AnalysisController.isBusy() && !
                                ↪ StorageMedia.isBusy()) {
552                             Log.e(Thread.currentThread().getName(), ">> Anomalous Situation!
                                    ↪  Clearing Queues! <<");
553                             Log.e(Thread.currentThread().getName(), "
                                    ↪ ******************************************");
554                             DataQueue.logQueueSizes();
555                             DataQueue.logQueueContents();
556                             DataQueue.clear();
557                         }
558
559                         this.wait(GlobalSettings.DEFAULT_WAIT_MS);
560                     }
561                     catch (InterruptedException e) {
562                         // TODO: error
563                     }
564                 }
565             }
566
567             if (mState == State.FINISHED) {
568                 long totalElapsed  = mTimestamp.Last - mTimestamp.First;
569                 double averageFps  = mFrame.FrameCount / (totalElapsed * 1e-9);
570                 double averageDuty = mExposure.Total/ (double) totalElapsed;
571
572                 Log.e(Thread.currentThread().getName(), mExposure.getString());
573                 Log.e(Thread.currentThread().getName(), mDeadtime.getString());
574                 Log.e(Thread.currentThread().getName(), mTemperature.getString());
575                 CaptureController.sessionFinished(averageFps, averageDuty);
576             }
577             else { // mState == state.ACTIVE
578                 // TODO: error
579                 Log.e(Thread.currentThread().getName(), "Something caused this session to
                        ↪ end prematurely");
580                 MasterController.quitSafely();
581             }
582             // TODO: dump mTotalCaptureResult info
583         }
584     }
585
586     ///////////////////////////
587     // Not Needed ///////////////////////////
```

```
588     ////////////////////////////
589
590     // onCaptureStarted...............
591     /**
592      * This method is called when the camera device has started capturing the output image
593      * for the request, at the beginning of image exposure, or when the camera device has
594      * started processing an input image for a reprocess request.
595      * @param session Reference to capture session
596      * @param request Reference to capture request
597      * @param timestamp Sensor timestamp of capture in progress
598      * @param frameNumber Frame number of capture in progress
599      */
600     @Override
601     public void onCaptureStarted(@NonNull CameraCaptureSession session,
602                                  @NonNull CaptureRequest request,
603                                  long timestamp, long frameNumber) {
604         super.onCaptureStarted(session, request, timestamp, frameNumber);
605     }
606
607     // onCaptureBufferLost...............
608     /**
609      * This method is called if a single buffer for a capture could not be sent to its
610      * destination surfaces.
611      * @param session Reference to capture session
612      * @param request Reference to capture request
613      * @param target Reference to intended output surface
614      * @param frameNumber Frame number of capture in progress
615      */
616     @Override
617     public void onCaptureBufferLost(@NonNull CameraCaptureSession session,
618                                     @NonNull CaptureRequest request,
619                                     @NonNull Surface target, long frameNumber) {
620         super.onCaptureBufferLost(session, request, target, frameNumber);
621         Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> CAPTURE BUFFER LOST <<"
622                 + " >> Frame Number: " + NumToString.number(frameNumber) + " <<\n ");
623     }
624
625     // onCaptureFailed...............
626     /**
627      * This method is called instead of onCaptureCompleted(CameraCaptureSession,
         ↪ captureRequest,
```

```
628         * TotalCaptureResult) when the camera device failed to produce a CaptureResult for the
                ↪ request.
629         * @param session Reference to capture session
630         * @param request Reference to capture request
631         * @param failure Reference to failure mode
632         */
633        @Override
634        public void onCaptureFailed(@NonNull CameraCaptureSession session,
635                                    @NonNull CaptureRequest request,
636                                    @NonNull CaptureFailure failure) {
637            super.onCaptureFailed(session, request, failure);
638            Log.e(Thread.currentThread().getName(), ">> Capture Failed <<");
639
640            String reason = null;
641            if (failure.getReason() == CaptureFailure.REASON_ERROR) {
642                reason = "Dropped frame due to error in framework";
643            } else {
644                reason = "Failure due to CameraCaptureSession.abortCaptures()";
645            }
646            String errInfo = "Camera device failed to produce a CaptureResult\n"
647                    + "\t Reason:         " + reason + "\n"
648                    + "\t Frame number:   " + Long.toString(failure.getFrameNumber()) + "\n"
649                    + "\t Sequence ID:    " + Integer.toString(failure.getSequenceId()) + "\n"
650                    + "\t Image captured: " + Boolean.toString(failure.wasImageCaptured()) + "\n
                        ↪ ";
651            Log.e(Thread.currentThread().getName(), errInfo);
652
653            // TODO: failure isn't always terminal..
654            //MasterController.quitSafely();
655        }
656
657        ////////////////////////////
658        // Shutdown Conditions ////////////////////////////
659        ////////////////////////////
660
661        // onCaptureSequenceAborted...............
662        /**
663         * This method is called independently of the others in CaptureCallback, when a capture
664         * sequence aborts before any CaptureResult or CaptureFailure before it has been
                ↪ returned
665         * via this listener.
```

```
666         * @param session Reference to capture session
667         * @param sequenceId capture sequence ID
668         */
669        @Override
670        public void onCaptureSequenceAborted(@NonNull CameraCaptureSession session, int
               ↪ sequenceId) {
671            super.onCaptureSequenceAborted(session, sequenceId);
672            Log.e(Thread.currentThread().getName(), ">> Capture Sequence Aborted <<");
673            MasterController.quitSafely();
674        }
675
676    }
```

Listing E.20: Capture Configuration (`camera2/capture/CaptureConfiguration.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.capture;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Range;


/**
 * Object representing a capture sequence to perform
 */
@TargetApi(21)
public class CaptureConfiguration {

    // Private Class Constants
    //::::::::::::::::::::::

    private static final Integer DEFAULT_FRAME_LIMIT       = 1000;
    private static final Double  DEFAULT_TEMPERATURE_LIMIT = 40.;
    private static final Integer DEFAULT_ATTEMPT_LIMIT     = 1;

    private static final Long FPS_30 =  33333333L;
    private static final Long FPS_05 = 200000000L;

```

```
41      private static final Range<Double>  TEMPERATURE_BOUNDS = new Range<>(0., 60.);
42      private static final Range<Integer> FRAME_BOUNDS       = new Range<>(0, 2000);
43      private static final Range<Integer> ATTEMPT_BOUNDS     = new Range<>(1, 1000);
44
45      // Public Class Constant
46      //::::::::::::::::::::::
47
48      // TODO: consider adding fps to the OutputWrapper file header
49      public static final Range<Long> EXPOSURE_BOUNDS = new Range<>(FPS_30, FPS_05);
50
51      // Package-Private Instance Fields
52      //::::::::::::::::::::::
53
54      // Mode..............
55      // capture mode category for this capture sequence
56      CaptureController.Mode Mode;
57
58      // TargetExposure...............
59      // Requested sensor exposure (in nanoseconds), depending on the ability of the device
            ↪ the
60      // actual exposure used may differ from that requested, if null, CaptureController will
            ↪ attempt
61      // to set it to the optimal exposure that minimizes dead time if possible, otherwise it
            ↪ will
62      // be set at EXPOSURE_BOUNDS.getLower() * 2, i.e. half the fps of maxium (usually 15 fps
            ↪ )
63      Long TargetExposure;
64
65      // FrameLimit...............
66      // Request this number of captured frames before ending the session
67      int FrameLimit;
68
69      // TemperatureLimit...............
70      // If this temperature (in Celsius) is exceeded, capture will end
71      double TemperatureLimit;
72
73      // AttemptLimit...............
74      // Be it attempts at matching the duty cycle, or just repeating the capture sequence,
75      // terminate this sequence once attempt limit is met
76      int AttemptLimit;
77
```

```
    // EnableSignificance ..............
    // Only applicable for data sessions, enables computation of pixel value significance
    boolean EnableSignificance;

    // Task ..............
    // For any odd-ball tasks to be done between capture sessions
    Runnable Task;

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // CaptureConfiguration ..............
    /**
     * Disabled
     */
    private CaptureConfiguration() {}

    // Public Class Methods
    //:::::::::::::::::::::::

    // newWarmUpSession ..............
    /**
     * Create a new WARMUP session.
     * @param temperatureLimit Maximum temperature to end the session
     * @param attemptLimit (Optional) Attempts to heat up (default is 1)
     * @param frameLimit (Optional) End capture after this many frames (default is 1000)
     * @return A capture configuration object ready for use
     */
    @NonNull
    public static CaptureConfiguration newWarmUpSession(double temperatureLimit,
                                                        @Nullable Integer attemptLimit,
                                                        @Nullable Integer frameLimit) {
        CaptureConfiguration instance = new CaptureConfiguration();
        instance.Mode = CaptureController.Mode.WARMUP;

        instance.TargetExposure     = EXPOSURE_BOUNDS.getLower();
        instance.FrameLimit         = setFrameLimit(frameLimit);
        instance.TemperatureLimit   = setTemperatureLimit(temperatureLimit);
        instance.AttemptLimit       = setAttemptLimit(attemptLimit);
        instance.EnableSignificance = false;
```

```
119         instance.Task               = null;
120
121         return instance;
122     }
123
124     // newCoolDownSession...............
125     /**
126      * Create a new COOLDOWN session
127      * @param temperatureLimit Minimum temperature to end the session
128      * @param attemptLimit (Optional) Attempts to cool down (default is 1) [minutes]
129      * @return A capture configuration object ready for use
130      */
131     @NonNull
132     public static CaptureConfiguration newCoolDownSession(double temperatureLimit,
133                                                           @Nullable Integer attemptLimit) {
134         CaptureConfiguration instance = new CaptureConfiguration();
135         instance.Mode = CaptureController.Mode.COOLDOWN;
136
137         instance.TargetExposure     = 0L;
138         instance.FrameLimit         = 0;
139         instance.TemperatureLimit   = setTemperatureLimit(temperatureLimit);
140         instance.AttemptLimit       = setAttemptLimit(attemptLimit);
141         instance.EnableSignificance = false;
142         instance.Task               = null;
143
144         return instance;
145     }
146
147     // newColdFastCalibration...............
148     /**
149      * Create a new CALIBRATION_COLD_FAST session.
150      * Exposure is automatically set to fastest fps, frame limit is the default (1000),
151      * temperature limit is 30 Celsius and it is a single attempt.
152      * @return A capture configuration object ready for use
153      */
154     @NonNull
155     public static CaptureConfiguration newColdFastCalibration() {
156         CaptureConfiguration instance = new CaptureConfiguration();
157         instance.Mode = CaptureController.Mode.CALIBRATION_COLD_FAST;
158
159         instance.TargetExposure     = EXPOSURE_BOUNDS.getLower();
```

```
        instance.FrameLimit         = DEFAULT_FRAME_LIMIT;
        instance.TemperatureLimit   = DEFAULT_TEMPERATURE_LIMIT;
        instance.AttemptLimit       = 1;
        instance.EnableSignificance = false;
        instance.Task               = null;

        return instance;
    }

    // newColdSlowCalibration...............
    /**
     * Create a new CALIBRATION_COLD_SLOW session.
     * Exposure is automatically set to slowest fps, frame limit is the default (1000),
     * temperature limit is 30 Celsius and it is a single attempt.
     * @return A capture configuration object ready for use
     */
    @NonNull
    public static CaptureConfiguration newColdSlowCalibration() {
        CaptureConfiguration instance = new CaptureConfiguration();
        instance.Mode = CaptureController.Mode.CALIBRATION_COLD_SLOW;

        instance.TargetExposure     = EXPOSURE_BOUNDS.getUpper();
        instance.FrameLimit         = DEFAULT_FRAME_LIMIT;
        instance.TemperatureLimit   = DEFAULT_TEMPERATURE_LIMIT;
        instance.AttemptLimit       = 1;
        instance.EnableSignificance = false;
        instance.Task               = null;

        return instance;
    }

    // newHotFastCalibration...............
    /**
     * Create a new CALIBRATION_HOT_FAST session.
     * Exposure is automatically set to fastest fps, frame limit is the default (1000),
     * temperature limit is 50 Celsius and it is a single attempt.
     * @return A capture configuration object ready for use
     */
    @NonNull
    public static CaptureConfiguration newHotFastCalibration() {
        CaptureConfiguration instance = new CaptureConfiguration();
```

```
        instance.Mode = CaptureController.Mode.CALIBRATION_HOT_FAST;

        instance.TargetExposure     = EXPOSURE_BOUNDS.getLower();
        instance.FrameLimit         = DEFAULT_FRAME_LIMIT;
        instance.TemperatureLimit   = TEMPERATURE_BOUNDS.getUpper();
        instance.AttemptLimit       = 1;
        instance.EnableSignificance = false;
        instance.Task               = null;

        return instance;
    }

    // newHotSlowCalibration...............
    /**
     * Create a new CALIBRATION_HOT_SLOW session.
     * Exposure is automatically set to slowest fps, frame limit is the default (1000),
     * temperature limit is 50 Celsius and it is a single attempt.
     * @return A capture configuration object ready for use
     */
    @NonNull
    public static CaptureConfiguration newHotSlowCalibration() {
        CaptureConfiguration instance = new CaptureConfiguration();
        instance.Mode = CaptureController.Mode.CALIBRATION_HOT_SLOW;

        instance.TargetExposure     = EXPOSURE_BOUNDS.getUpper();
        instance.FrameLimit         = DEFAULT_FRAME_LIMIT;
        instance.TemperatureLimit   = TEMPERATURE_BOUNDS.getUpper();
        instance.AttemptLimit       = 1;
        instance.EnableSignificance = false;
        instance.Task               = null;

        return instance;
    }

    // newOptimizationSession...............
    /**
     * Create a new OPTIMIZE_DUTY_CYCLE session.
     * Discovers sensor exposure / frame rate that maximizes the duty cycle between
     * exposure time and dead time (not possible for devices that do not support manual
       ↪ control)
```

```
240      * @param temperatureLimit (Optional) Maximum temperature to end the session (default is
             ↪  40 C)
241      * @return A capture configuration object ready for use
242      */
243     @NonNull
244     public static CaptureConfiguration newOptimizationSession(@Nullable Double
            ↪ temperatureLimit) {
245         CaptureConfiguration instance = new CaptureConfiguration();
246         instance.Mode = CaptureController.Mode.OPTIMIZE_DUTY_CYCLE;
247
248         instance.TargetExposure     = EXPOSURE_BOUNDS.getLower();
249         instance.FrameLimit         = 100;
250         instance.TemperatureLimit   = setTemperatureLimit(temperatureLimit);
251         instance.AttemptLimit       = 10;
252         instance.EnableSignificance = false;
253         instance.Task               = null;
254
255         return instance;
256     }
257
258     // newDataSession ...............
259     /**
260      * Create a new DATA session
261      * @param frameLimit End capture after this many frames
262      * @param targetExposure (Optional) Desired sensor exposure in nanoseconds (default is
             ↪ optimum fps)
263      * @param temperatureLimit (Optional) Maximum temperature to end the session (default is
             ↪  40 C)
264      * @param attemptLimit (Optional) Repeat this many times (default is 1)
265      * @param enableSignificance (Optional) Enables statistical significance (default is
             ↪ true)
266      * @return A capture configuration object ready for use
267      */
268     @NonNull
269     public static CaptureConfiguration newDataSession(int frameLimit,
270                                                       @Nullable Long targetExposure,
271                                                       @Nullable Double temperatureLimit,
272                                                       @Nullable Integer attemptLimit,
273                                                       @Nullable Boolean enableSignificance)
                                                              ↪ {
274         CaptureConfiguration instance = new CaptureConfiguration();
```

```
275         instance.Mode = CaptureController.Mode.DATA;
276
277         instance.TargetExposure   = setTargetExposure(targetExposure);
278         instance.FrameLimit       = setFrameLimit(frameLimit);
279         instance.TemperatureLimit = setTemperatureLimit(temperatureLimit);
280         instance.AttemptLimit     = setAttemptLimit(attemptLimit);
281         instance.Task             = null;
282
283         if (enableSignificance == null) {
284             instance.EnableSignificance = true;
285         }
286         else {
287             instance.EnableSignificance = enableSignificance;
288         }
289
290         return instance;
291     }
292
293     // newTaskSession ...............
294     /**
295      * Create a new TASK session
296      * @param task A Runnable to perform a task between sessions
297      * @return A capture configuration object ready for use
298      */
299     public static CaptureConfiguration newTaskSession(Runnable task) {
300         CaptureConfiguration instance = new CaptureConfiguration();
301         instance.Mode = CaptureController.Mode.TASK;
302
303         instance.FrameLimit         = 0;
304         instance.TargetExposure     = setTargetExposure(null);
305         instance.TemperatureLimit   = setTemperatureLimit(null);
306         instance.AttemptLimit       = 0;
307         instance.EnableSignificance = false;
308         instance.Task               = task;
309
310         return instance;
311     }
312
313     // Private Class Methods
314     //:::::::::::::::::::::::
315
```

```
    // setTargetExposure...............
    /**
     * Make sure requested targetExposure is within bounds
     * @param targetExposure Optionally null for default setting
     * @return Default is optimized duty fps if available, longest exposure (5 FPS) if not,
     *         otherwise clipped between EXPOSURE_BOUNDS low and high
     */
    @Nullable
    private static Long setTargetExposure(@Nullable Long targetExposure) {
        if (targetExposure == null) {
            return null;
        }

        if (targetExposure > EXPOSURE_BOUNDS.getUpper()) {
            return EXPOSURE_BOUNDS.getUpper();
        }

        if (targetExposure < EXPOSURE_BOUNDS.getLower()) {
            return EXPOSURE_BOUNDS.getLower();
        }

        return targetExposure;
    }

    // setFrameLimit...............
    /**
     * Make sure requested frameLimit is within bounds
     * @param frameLimit Optionally null for default setting
     * @return Default is 1000 frames, otherwise clipped between FRAME_BOUNDS low and high
     */
    private static int setFrameLimit(@Nullable Integer frameLimit) {
        if (frameLimit == null) {
            return DEFAULT_FRAME_LIMIT;
        }

        if (frameLimit > FRAME_BOUNDS.getUpper()) {
            return FRAME_BOUNDS.getUpper();
        }

        if (frameLimit < FRAME_BOUNDS.getLower()) {
            return FRAME_BOUNDS.getLower();
```

```
        }

        return frameLimit;
    }

    // setTemperatureLimit...............
    /**
     * Make sure requested temperatureLimit is within bounds
     * @param temperatureLimit Optionally null for default setting
     * @return Default is 40 Celsius, otherwise clipped between TEMPERATURE_BOUNDS low and
       ↪ high
     */
    private static double setTemperatureLimit(@Nullable Double temperatureLimit) {
        if (temperatureLimit == null) {
            return DEFAULT_TEMPERATURE_LIMIT;
        }

        if (temperatureLimit > TEMPERATURE_BOUNDS.getUpper()) {
            return TEMPERATURE_BOUNDS.getUpper();
        }

        if (temperatureLimit < TEMPERATURE_BOUNDS.getLower()) {
            return TEMPERATURE_BOUNDS.getLower();
        }

        return temperatureLimit;
    }

    // setAttemptLimit...............
    /**
     * Make sure requested attemptLimit is within bounds
     * @param attemptLimit Optionally null for default setting
     * @return Default is 1 attempt, otherwise clipped between ATTEMPT_BOUNDS low and high
     */
    private static int setAttemptLimit(@Nullable Integer attemptLimit) {
        if (attemptLimit == null) {
            return DEFAULT_ATTEMPT_LIMIT;
        }

        if (attemptLimit > ATTEMPT_BOUNDS.getUpper()) {
            return ATTEMPT_BOUNDS.getUpper();
```

```
        }

        if (attemptLimit < ATTEMPT_BOUNDS.getLower()) {
            return ATTEMPT_BOUNDS.getLower();
        }

        return attemptLimit;
    }

}
```

Listing E.21: Characteristics Reader

(camera2/characteristics/CharacteristicsReader.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.camera2.util.Parameter;

/**
 * Public access to discovering all abilities of a camera
 */
@TargetApi(21)
public final class CharacteristicsReader extends Tonemap_ {

    // Private Class Constants
    //:::::::::::::::::::::::

```

```
    // mInstance...............
    // Reference to single instance of this class
    private static final CharacteristicsReader mInstance = new CharacteristicsReader();

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // CharacteristicsReader...............
    /**
     * Disabled
     */
    private CharacteristicsReader() {}

    // Public Class Methods
    //:::::::::::::::::::::::

    // read...............
    /**
     * Discovers the abilities of the active camera.  In some cases, filters or optimizes
     * parameter options.
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @return A mapping of characteristics names to their respective parameter options
     */
    @NonNull
    public static LinkedHashMap<CameraCharacteristics.Key, Parameter> read(
                                        @NonNull CameraCharacteristics
                                            ↪ cameraCharacteristics) {

        LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap
                                        = new LinkedHashMap<>();
        Log.e(Thread.currentThread().getName(), "CharacteristicsReader read");
        mInstance.read(cameraCharacteristics, characteristicsMap);
        return characteristicsMap;
    }

    // write...............
    /**
```

```
79      * Display all of the abilities of the camera
80      * @param label (Optional) Custom title
81      * @param map Details of camera abilities in terms of Parameters<T>
82      * @param keychain (Optional) All keys that can be potentially set
83      */
84     public static void write(@Nullable String label,
85                              @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                     ↪ map,
86                              @Nullable List<CameraCharacteristics.Key<?>> keychain) {
87
88         if (label == null) {
89             label = "CharacteristicsReader";
90         }
91
92         Log.e(Thread.currentThread().getName(), " \n\n\t\t" + label + " Camera
               ↪ Characteristics Summary:\n\n");
93         for (Parameter parameter : map.values()) {
94             Log.e(Thread.currentThread().getName(), parameter.toString());
95         }
96
97         if (keychain != null) {
98             Log.e(Thread.currentThread().getName(), "Keys unset:\n");
99             for (CameraCharacteristics.Key<?> key : keychain) {
100                if (!map.containsKey(key)) {
101                    Log.e(Thread.currentThread().getName(), key.getName());
102                }
103            }
104        }
105    }
106
107    // Protected Overriding Instance Methods
108    //::::::::::::::::::::::
109
110    // read..............
111    /**
112     * Continue discovering abilities with specialized super classes
113     * @param cameraCharacteristics Encapsulation of camera abilities
114     * @param characteristicsMap A mapping of characteristics names to their respective
            ↪ parameter options
115     */
116    @Override
```

```
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                            ↪ characteristicsMap) {
        Log.e("CharacteristicsReader", "reading characteristics");
        super.read(cameraCharacteristics, characteristicsMap);
    }

}
```

Listing E.22: Color Characteristics (`camera2/characteristics/Color_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * Super-most class for discovering camera abilities, the parameters searched for include:
 *    COLOR_CORRECTION_AVAILABLE_ABERRATION_MODES
 */
@TargetApi(21)
abstract class Color_ {

```

```
    // Protected Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {

        Log.e("               Color_", "reading Color_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=========================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.COLOR_CORRECTION_AVAILABLE_ABERRATION_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Aberration modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }
```

```
77                  List<Integer> options = ArrayToList.convert(modes);
78
79                  Integer OFF          = CameraMetadata.COLOR_CORRECTION_ABERRATION_MODE_OFF;
80                  Integer FAST         = CameraMetadata.COLOR_CORRECTION_ABERRATION_MODE_FAST;
81                  //Integer HIGH_QUALITY = CameraMetadata.
                        ↪ COLOR_CORRECTION_ABERRATION_MODE_HIGH_QUALITY;
82
83                  if (options.contains(OFF)) {
84                      value       =  OFF;
85                      valueString = "OFF (PREFERRED)";
86                  }
87                  else {
88                      value       =  FAST;
89                      valueString = "FAST (FALLBACK)";
90                  }
91
92                  if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
93                      value       = FAST;
94                      valueString = "FAST (WORST CONFIGURATION)";
95                  }
96
97                  formatter = new ParameterFormatter<Integer>(valueString) {
98                      @NonNull
99                      @Override
100                     public String formatValue(@NonNull Integer value) {
101                         return getValueString();
102                     }
103                 };
104                 property = new Parameter<>(name, value, null, formatter);
105             }
106             else {
107                 property = new Parameter<>(name);
108                 property.setValueString("NOT SUPPORTED");
109             }
110             characteristicsMap.put(key, property);
111         }
112         //=========================================
                ↪ ==================================================
113     }
114
115 }
```

Listing E.23: Control Characteristics (`camera2/characteristics/Control_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Range;
import android.util.Rational;

import java.util.ArrayList;
import java.util.Collections;
import java.util.Comparator;
import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
```

```
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    CONTROL_AE_AVAILABLE_ANTIBANDING_MODES
 *    CONTROL_AE_AVAILABLE_MODES
 *    CONTROL_AE_AVAILABLE_TARGET_FPS_RANGES
 *    CONTROL_AE_COMPENSATION_RANGE
 *    CONTROL_AE_COMPENSATION_STEP
 *    CONTROL_AE_LOCK_AVAILABLE
 *    CONTROL_AF_AVAILABLE_MODES
 *    CONTROL_AVAILABLE_EFFECTS
 *    CONTROL_AVAILABLE_MODES
 *    CONTROL_AVAILABLE_SCENE_MODES
 *    CONTROL_AVAILABLE_VIDEO_STABILIZATION_MODES
 *    CONTROL_AWB_AVAILABLE_MODES
 *    CONTROL_AWB_LOCK_AVAILABLE
 *    CONTROL_MAX_REGIONS_AE
 *    CONTROL_MAX_REGIONS_AF
 *    CONTROL_MAX_REGIONS_AWB
 */
@TargetApi(21)
@SuppressWarnings("unchecked")
abstract class Control_ extends Color_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read...............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("             Control_", "reading Control_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();
```

```

        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AE_AVAILABLE_ANTIBANDING_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AE antibanding modes cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

                Integer OFF   = CameraMetadata.CONTROL_AE_ANTIBANDING_MODE_OFF;
                //Integer _50HZ = CameraMetadata.CONTROL_AE_ANTIBANDING_MODE_50HZ;
                Integer _60HZ = CameraMetadata.CONTROL_AE_ANTIBANDING_MODE_60HZ;
                Integer AUTO  = CameraMetadata.CONTROL_AE_ANTIBANDING_MODE_AUTO;

                if (options.contains(OFF)) {
                    value       =  OFF;
                    valueString = "OFF (PREFERRED)";
                }
                else if (options.contains(AUTO)) {
                    value       =  AUTO;
                    valueString = "AUTO (FALLBACK)";
                }
                else {
```

```
                    value       = _60HZ;
                    valueString = "60HZ (LAST CHOICE)";
                }

                if (options.contains(AUTO) && GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value       = AUTO;
                    valueString = "AUTO (WORST CONFIGURATINO)";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==============================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AE_AVAILABLE_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
```

```
156                 if (modes == null) {
157                     // TODO: error
158                     Log.e(Thread.currentThread().getName(), "AE modes cannot be null");
159                     MasterController.quitSafely();
160                     return;
161                 }
162                 List<Integer> options = ArrayToList.convert(modes);
163
164                 Integer OFF                  = CameraMetadata.CONTROL_AE_MODE_OFF;
165                 Integer ON                   = CameraMetadata.CONTROL_AE_MODE_ON;
166                 //Integer ON_AUTO_FLASH        = CameraMetadata.
                        ↪ CONTROL_AE_MODE_ON_AUTO_FLASH;
167                 //Integer ON_ALWAYS_FLASH      = CameraMetadata.
                        ↪ CONTROL_AE_MODE_ON_ALWAYS_FLASH;
168                 //Integer ON_AUTO_FLASH_REDEYE = CameraMetadata.
                        ↪ CONTROL_AE_MODE_ON_AUTO_FLASH_REDEYE;
169                 //Integer ON_EXTERNAL_FLASH    = CameraMetadata.
                        ↪ CONTROL_AE_MODE_ON_EXTERNAL_FLASH;
170
171                 if (options.contains(OFF)) {
172                     value       =  OFF;
173                     valueString = "OFF (PREFERRED)";
174                 }
175                 else {
176                     value       =  ON;
177                     valueString = "ON (FALLBACK)";
178                 }
179
180                 formatter = new ParameterFormatter<Integer>(valueString) {
181                     @NonNull
182                     @Override
183                     public String formatValue(@NonNull Integer value) {
184                         return getValueString();
185                     }
186                 };
187                 property = new Parameter<>(name, value, null, formatter);
188             }
189             else {
190                 property = new Parameter<>(name);
191                 property.setValueString("NOT SUPPORTED");
192             }
```

```
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Range<Integer>[]> key;
            ParameterFormatter<Range<Integer>[]> formatter;
            Parameter<Range<Integer>[]> property;

            String name;
            Range<Integer>[] value;
            String units;

            key   = CameraCharacteristics.CONTROL_AE_AVAILABLE_TARGET_FPS_RANGES;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "frames per second";

            if (keychain.contains(key)) {

                // Sort by upper FPS limit
                class SortByUpper implements Comparator<Range<Integer>> {
                    public int compare( Range<Integer> a, Range<Integer> b) {
                        return a.getUpper() - b.getUpper();
                    }
                }

                Range<Integer>[] options = cameraCharacteristics.get(key);
                if (options == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "FPS range cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                List<Range<Integer>> fpsRanges = ArrayToList.convert(options);
                Collections.sort(fpsRanges, new SortByUpper());

                List<Range<Integer>> keep = new ArrayList<>();
                for (Range<Integer> range : fpsRanges) {
                    if (range.getUpper() - range.getLower() <= GlobalSettings.MAX_FPS_DIFF
```

```
232                         && range.getUpper() <= GlobalSettings.MAX_FPS) {
233                         keep.add(range);
234                     }
235                 }
236
237                 if (keep.size() == 0) {
238                     keep = fpsRanges;
239                 }
240
241                 // TODO: figure out how to do toArray(new Range<Integer>[])
242                 value = (Range<Integer>[]) keep.toArray(new Range[0]);
243                 if (value == null) {
244                     // TODO: error
245                     Log.e(Thread.currentThread().getName(), "FPS range cannot be null");
246                     MasterController.quitSafely();
247                     return;
248                 }
249
250                 formatter = new ParameterFormatter<Range<Integer>[]>() {
251                     @NonNull
252                     @Override
253                     public String formatValue(@NonNull Range<Integer>[] value) {
254                         String out = "{ ";
255                         for (Range<Integer> val : value) {
256                             out += val.toString() + " ";
257                         }
258                         return out + "}";
259                     }
260                 };
261                 property = new Parameter<>(name, value, units, formatter);
262             }
263             else {
264                 property = new Parameter<>(name);
265                 property.setValueString("NOT SUPPORTED");
266             }
267             characteristicsMap.put(key, property);
268         }
269         //==========================================
            ↪ ==================================================
270         {
271             CameraCharacteristics.Key<Range<Integer>> key;
```

```
272                 ParameterFormatter<Integer> formatter;
273                 Parameter<Integer> property;
274
275                 String  name;
276                 Integer value;
277                 String  units;
278
279                 key   = CameraCharacteristics.CONTROL_AE_COMPENSATION_RANGE;//
                        ↪ ////////////////////////
280                 name  = key.getName();
281                 units = "compensation steps";
282
283                 if (keychain.contains(key)) {
284                     Range<Integer> range = cameraCharacteristics.get(key);
285                     if (range == null) {
286                         // TODO: error
287                         Log.e(Thread.currentThread().getName(), "AE compensation range cannot be
                            ↪  null");
288                         MasterController.quitSafely();
289                         return;
290                     }
291                     value = range.getUpper();
292
293                     if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
294                         value = range.getLower();
295                     }
296
297                     formatter = new ParameterFormatter<Integer>() {
298                         @NonNull
299                         @Override
300                         public String formatValue(@NonNull Integer value) {
301                             String out = value.toString();
302                             if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
303                                 out += " (WORST CONFIGURATION)";
304                             }
305                             return out;
306                         }
307                     };
308                     property = new Parameter<>(name, value, units, formatter);
309                 }
310                 else {
```

```
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Rational> key;
            ParameterFormatter<Rational> formatter;
            Parameter<Rational> property;

            String   name;
            Rational value;
            String   units;

            key   = CameraCharacteristics.CONTROL_AE_COMPENSATION_STEP;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "exposure value";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AE compensation step cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Rational>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Rational value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
```

```
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Boolean> key;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> property;

            String  name;
            Boolean value;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.CONTROL_AE_LOCK_AVAILABLE;//
                    ↪ ////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "AE lock cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    if (value && GlobalSettings.FORCE_WORST_CONFIGURATION) {
                        value = false;
                    }

                    formatter = new ParameterFormatter<Boolean>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Boolean value) {
                            if (value) {
                                return "YES (PREFERRED)";
                            }
                            if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
```

```
                                return "NO (WORST CONFIGURATION)";
                            }
                            return "NO (FALLBACK)";
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AF_AVAILABLE_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AF modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

                Integer OFF                = CameraMetadata.CONTROL_AF_MODE_OFF;
                Integer AUTO               = CameraMetadata.CONTROL_AF_MODE_AUTO;
```

```
427                 //Integer MACRO              = CameraMetadata.CONTROL_AF_MODE_MACRO;
428                 //Integer CONTINUOUS_VIDEO   = CameraMetadata.
                        ↪ CONTROL_AF_MODE_CONTINUOUS_VIDEO;
429                 //Integer CONTINUOUS_PICTURE = CameraMetadata.
                        ↪ CONTROL_AF_MODE_CONTINUOUS_PICTURE;
430                 //Integer EDOF               = CameraMetadata.CONTROL_AF_MODE_EDOF;
431
432                 if (options.contains(OFF)) {
433                     value       =  OFF;
434                     valueString = "OFF (PREFERRED)";
435                 }
436                 else {
437                     value       =  AUTO;
438                     valueString = "AUTO (FALLBACK)";
439                 }
440
441                 formatter = new ParameterFormatter<Integer>(valueString) {
442                     @NonNull
443                     @Override
444                     public String formatValue(@NonNull Integer value) {
445                         return getValueString();
446                     }
447                 };
448                 property = new Parameter<>(name, value, null, formatter);
449             }
450             else {
451                 property = new Parameter<>(name);
452                 property.setValueString("NOT SUPPORTED");
453             }
454             characteristicsMap.put(key, property);
455         }
456         //==========================================
                ↪ ==================================================
457         {
458             CameraCharacteristics.Key<int[]> key;
459             ParameterFormatter<Integer> formatter;
460             Parameter<Integer> property;
461
462             String  name;
463             Integer value;
464             String  valueString;
```

```
465
466             key  = CameraCharacteristics.CONTROL_AVAILABLE_EFFECTS;//
                ↪ ////////////////////////
467             name = key.getName();
468
469             if (keychain.contains(key)) {
470                 int[]  modes  = cameraCharacteristics.get(key);
471                 if (modes == null) {
472                     // TODO: error
473                     Log.e(Thread.currentThread().getName(), "Effects cannot be null");
474                     MasterController.quitSafely();
475                     return;
476                 }
477                 List<Integer> options = ArrayToList.convert(modes);
478
479                 Integer OFF        = CameraMetadata.CONTROL_EFFECT_MODE_OFF;
480                 //Integer MONO       = CameraMetadata.CONTROL_EFFECT_MODE_MONO;
481                 //Integer NEGATIVE   = CameraMetadata.CONTROL_EFFECT_MODE_NEGATIVE;
482                 //Integer SOLARIZE   = CameraMetadata.CONTROL_EFFECT_MODE_SOLARIZE;
483                 //Integer SEPIA      = CameraMetadata.CONTROL_EFFECT_MODE_SEPIA;
484                 //Integer POSTERIZE  = CameraMetadata.CONTROL_EFFECT_MODE_POSTERIZE;
485                 //Integer WHITEBOARD = CameraMetadata.CONTROL_EFFECT_MODE_WHITEBOARD;
486                 //Integer BLACKBOARD = CameraMetadata.CONTROL_EFFECT_MODE_BLACKBOARD;
487                 //Integer AQUA       = CameraMetadata.CONTROL_EFFECT_MODE_AQUA;
488
489                 value       =  OFF;
490                 valueString = "OFF (PREFERRED)";
491
492                 formatter = new ParameterFormatter<Integer>(valueString) {
493                     @NonNull
494                     @Override
495                     public String formatValue(@NonNull Integer value) {
496                         return getValueString();
497                     }
498                 };
499                 property = new Parameter<>(name, value, null, formatter);
500             }
501             else {
502                 property = new Parameter<>(name);
503                 property.setValueString("NOT SUPPORTED");
504             }
```

```
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.CONTROL_AVAILABLE_MODES;//
                    ↪ ////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    int[] modes = cameraCharacteristics.get(key);
                    if (modes == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Available modes cannot be
                            ↪ null");
                        MasterController.quitSafely();
                        return;
                    }
                    List<Integer> options = ArrayToList.convert(modes);

                    Integer OFF            = CameraMetadata.CONTROL_MODE_OFF;
                    Integer AUTO           = CameraMetadata.CONTROL_MODE_AUTO;
                    //Integer USE_SCENE_MODE = CameraMetadata.CONTROL_MODE_USE_SCENE_MODE;
                    //Integer OFF_KEEP_STATE = CameraMetadata.CONTROL_MODE_OFF_KEEP_STATE;

                    if (options.contains(OFF)) {
                        value = OFF;
                        valueString = "OFF (PREFERRED)";
                    }
                    else {
                        value = AUTO;
                        valueString = "AUTO (FALLBACK)";
```

```
                    }

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AVAILABLE_SCENE_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Scene modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }
```

```
582                 List<Integer> options = ArrayToList.convert(modes);
583
584                 Integer DISABLED         = CameraMetadata.CONTROL_SCENE_MODE_DISABLED;
585                 //Integer FACE_PRIORITY    = CameraMetadata.CONTROL_SCENE_MODE_FACE_PRIORITY
                        ↪ ;
586                 //Integer ACTION           = CameraMetadata.CONTROL_SCENE_MODE_ACTION;
587                 //Integer PORTRAIT         = CameraMetadata.CONTROL_SCENE_MODE_PORTRAIT;
588                 //Integer LANDSCAPE        = CameraMetadata.CONTROL_SCENE_MODE_LANDSCAPE;
589                 //Integer NIGHT            = CameraMetadata.CONTROL_SCENE_MODE_NIGHT;
590                 //Integer NIGHT_PORTRAIT   = CameraMetadata.
                        ↪ CONTROL_SCENE_MODE_NIGHT_PORTRAIT;
591                 //Integer THEATRE          = CameraMetadata.CONTROL_SCENE_MODE_THEATRE;
592                 //Integer BEACH            = CameraMetadata.CONTROL_SCENE_MODE_BEACH;
593                 //Integer SNOW             = CameraMetadata.CONTROL_SCENE_MODE_SNOW;
594                 //Integer SUNSET           = CameraMetadata.CONTROL_SCENE_MODE_SUNSET;
595                 //Integer STEADYPHOTO      = CameraMetadata.CONTROL_SCENE_MODE_STEADYPHOTO;
596                 //Integer FIREWORKS        = CameraMetadata.CONTROL_SCENE_MODE_FIREWORKS;
597                 //Integer SPORTS           = CameraMetadata.CONTROL_SCENE_MODE_SPORTS;
598                 //Integer PARTY            = CameraMetadata.CONTROL_SCENE_MODE_PARTY;
599                 //Integer CANDLELIGHT      = CameraMetadata.CONTROL_SCENE_MODE_CANDLELIGHT;
600                 //Integer BARCODE          = CameraMetadata.CONTROL_SCENE_MODE_BARCODE;
601                 //Integer HIGH_SPEED_VIDEO = CameraMetadata.CONTROL_AF_MODE_CONTINUOUS_VIDEO
                        ↪ ;
602                 //Integer HDR              = null;
603                 //if (Build.VERSION.SDK_INT >= 22) {
604                 //    HDR = CameraMetadata.CONTROL_SCENE_MODE_HDR;
605                 //}
606
607                 value       =  DISABLED;
608                 valueString = "DISABLED (PREFERRED)";
609
610                 formatter = new ParameterFormatter<Integer>(valueString) {
611                     @NonNull
612                     @Override
613                     public String formatValue(@NonNull Integer value) {
614                         return getValueString();
615                     }
616                 };
617                 property = new Parameter<>(name, value, null, formatter);
618             }
619             else {
```

```
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AVAILABLE_VIDEO_STABILIZATION_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Video stabilization modes
                        ↪ cannot be null");
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

                Integer OFF = CameraMetadata.CONTROL_VIDEO_STABILIZATION_MODE_OFF;
                Integer ON  = CameraMetadata.CONTROL_VIDEO_STABILIZATION_MODE_ON;

                value       =  OFF;
                valueString = "OFF (PREFERRED)";

                if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value       = ON;
                    valueString = "ON (WORST CONFIGURATION)";
                }
```

```
                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //==========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.CONTROL_AWB_AVAILABLE_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AWB modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

```

```
697                 Integer OFF              = CameraMetadata.CONTROL_AWB_MODE_OFF;
698                 Integer AUTO             = CameraMetadata.CONTROL_AWB_MODE_AUTO;
699                 //Integer INCANDESCENT     = CameraMetadata.CONTROL_AWB_MODE_INCANDESCENT;
700                 //Integer FLUORESCENT      = CameraMetadata.CONTROL_AWB_MODE_FLUORESCENT;
701                 //Integer WARM_FLUORESCENT = CameraMetadata.
                        ↪ CONTROL_AWB_MODE_WARM_FLUORESCENT;
702                 //Integer DAYLIGHT         = CameraMetadata.CONTROL_AWB_MODE_DAYLIGHT;
703                 //Integer CLOUDY_DAYLIGHT  = CameraMetadata.CONTROL_AWB_MODE_CLOUDY_DAYLIGHT
                        ↪ ;
704                 //Integer TWILIGHT         = CameraMetadata.CONTROL_AWB_MODE_TWILIGHT;
705                 //Integer SHADE            = CameraMetadata.CONTROL_AWB_MODE_SHADE;
706
707                 if (options.contains(OFF)) {
708                     value       =  OFF;
709                     valueString = "OFF (PREFERRED)";
710                 }
711                 else {
712                     value       =  AUTO;
713                     valueString = "AUTO (FALLBACK)";
714                 }
715
716                 formatter = new ParameterFormatter<Integer>(valueString) {
717                     @NonNull
718                     @Override
719                     public String formatValue(@NonNull Integer value) {
720                         return getValueString();
721                     }
722                 };
723                 property = new Parameter<>(name, value, null, formatter);
724             }
725             else {
726                 property = new Parameter<>(name);
727                 property.setValueString("NOT SUPPORTED");
728             }
729             characteristicsMap.put(key, property);
730         }
731         //=========================================
                ↪ ==================================================
732         {
733             CameraCharacteristics.Key<Boolean> key;
734             ParameterFormatter<Boolean> formatter;
```

```
735                 Parameter<Boolean> property;
736
737                 String  name;
738                 Boolean value;
739
740                 if (Build.VERSION.SDK_INT >= 23) {
741                     key  = CameraCharacteristics.CONTROL_AWB_LOCK_AVAILABLE;//
                        ↪ ////////////////////////
742                     name = key.getName();
743
744                     if (keychain.contains(key)) {
745                         value = cameraCharacteristics.get(key);
746                         if (value == null) {
747                             // TODO: error
748                             Log.e(Thread.currentThread().getName(), "AWB lock cannot be null");
749                             MasterController.quitSafely();
750                             return;
751                         }
752
753                         if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
754                             value = false;
755                         }
756
757                         formatter = new ParameterFormatter<Boolean>() {
758                             @NonNull
759                             @Override
760                             public String formatValue(@NonNull Boolean value) {
761                                 if (value) {
762                                     return "YES (PREFERRED)";
763                                 }
764                                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
765                                     return "NO (WORST CONFIGURATION)";
766                                 }
767                                 return "NO (FALLBACK)";
768                             }
769                         };
770                         property = new Parameter<>(name, value, null, formatter);
771                     }
772                     else {
773                         property = new Parameter<>(name);
774                         property.setValueString("NOT SUPPORTED");
```

```
775                 }
776                 characteristicsMap.put(key, property);
777             }
778         }
779         //==========================================
            ↪ ==================================================
780         {
781             CameraCharacteristics.Key<Integer> key;
782             ParameterFormatter<Integer> formatter;
783             Parameter<Integer> property;
784
785             String  name;
786             Integer value;
787
788             key  = CameraCharacteristics.CONTROL_MAX_REGIONS_AE;//////////////////////////
789             name = key.getName();
790
791             if (keychain.contains(key)) {
792                 value = cameraCharacteristics.get(key);
793                 if (value == null) {
794                     // TODO: error
795                     Log.e(Thread.currentThread().getName(), "AE regions cannot be null");
796                     MasterController.quitSafely();
797                     return;
798                 }
799
800                 formatter = new ParameterFormatter<Integer>() {
801                     @NonNull
802                     @Override
803                     public String formatValue(@NonNull Integer value) {
804                         return value.toString();
805                     }
806                 };
807                 property = new Parameter<>(name, value, null, formatter);
808             }
809             else {
810                 property = new Parameter<>(name);
811                 property.setValueString("NOT SUPPORTED");
812             }
813             characteristicsMap.put(key, property);
814         }
```

```
815         //==========================================
            ↪ ==================================================
816         {
817             CameraCharacteristics.Key<Integer> key;
818             ParameterFormatter<Integer> formatter;
819             Parameter<Integer> property;
820
821             String  name;
822             Integer value;
823
824             key  = CameraCharacteristics.CONTROL_MAX_REGIONS_AF;//////////////////////////
825             name = key.getName();
826
827             if (keychain.contains(key)) {
828                 value = cameraCharacteristics.get(key);
829                 if (value == null) {
830                     // TODO: error
831                     Log.e(Thread.currentThread().getName(), "AF regions cannot be null");
832                     MasterController.quitSafely();
833                     return;
834                 }
835
836                 formatter = new ParameterFormatter<Integer>() {
837                     @NonNull
838                     @Override
839                     public String formatValue(@NonNull Integer value) {
840                         return value.toString();
841                     }
842                 };
843                 property = new Parameter<>(name, value, null, formatter);
844             }
845             else {
846                 property = new Parameter<>(name);
847                 property.setValueString("NOT SUPPORTED");
848             }
849             characteristicsMap.put(key, property);
850         }
851         //==========================================
            ↪ ==================================================
852         {
853             CameraCharacteristics.Key<Integer> key;
```

```
854                 ParameterFormatter<Integer> formatter;
855                 Parameter<Integer> property;
856
857                 String  name;
858                 Integer value;
859
860                 key  = CameraCharacteristics.CONTROL_MAX_REGIONS_AWB;//////////////////////////
861                 name = key.getName();
862
863                 if (keychain.contains(key)) {
864                     value = cameraCharacteristics.get(key);
865                     if (value == null) {
866                         // TODO: error
867                         Log.e(Thread.currentThread().getName(), "AWB regions cannot be null");
868                         MasterController.quitSafely();
869                         return;
870                     }
871
872                     formatter = new ParameterFormatter<Integer>() {
873                         @NonNull
874                         @Override
875                         public String formatValue(@NonNull Integer value) {
876                             return value.toString();
877                         }
878                     };
879                     property = new Parameter<>(name, value, null, formatter);
880                 }
881                 else {
882                     property = new Parameter<>(name);
883                     property.setValueString("NOT SUPPORTED");
884                 }
885                 characteristicsMap.put(key, property);
886             }
887             //=========================================
                ↪ ==================================================
888             {
889                 CameraCharacteristics.Key<Range<Integer>> key;
890                 ParameterFormatter<Integer> formatter;
891                 Parameter<Integer> property;
892
893                 String  name;
```

```
894                 Integer value;
895                 String  units;
896
897                 if (Build.VERSION.SDK_INT >= 24) {
898                     key   = CameraCharacteristics.CONTROL_POST_RAW_SENSITIVITY_BOOST_RANGE;//
                        ↪ ////////////////////////
899                     name  = key.getName();
900                     units = "ISO";
901
902                     if (keychain.contains(key)) {
903                         Range<Integer> range = cameraCharacteristics.get(key);
904                         if (range == null) {
905                             // TODO: error
906                             Log.e(Thread.currentThread().getName(), "Sensitivity boost cannot be
                                ↪  null");
907                             MasterController.quitSafely();
908                             return;
909                         }
910
911                         Integer UNITY = 100;
912
913                         if (range.contains(UNITY)) {
914                             value = UNITY;
915                         }
916                         else {
917                             value = range.getUpper();
918                         }
919
920                         if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
921                             value = range.getLower();
922                         }
923
924                         formatter = new ParameterFormatter<Integer>() {
925                             @NonNull
926                             @Override
927                             public String formatValue(@NonNull Integer value) {
928                                 String out = value.toString() + " / 100";
929                                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
930                                     out += " (WORST CONFIGURATION)";
931                                 }
932                                 return out;
```

```
                            }
                        };
                        property = new Parameter<>(name, value, units, formatter);
                    }
                    else {
                        property = new Parameter<>(name);
                        property.setValueString("NOT SUPPORTED");
                    }
                    characteristicsMap.put(key, property);
                }
            }
            //==========================================
                ↪ ==================================================
        }

    }
```

Listing E.24: Depth Characteristics (`camera2/characteristics/Depth_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    DEPTH_DEPTH_IS_EXCLUSIVE
 */
@TargetApi(21)
abstract class Depth_ extends Control_ {

    // Protected Overriding Instance Methods
```

```
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("               Depth_", "reading Depth_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=========================================================================
        {
            CameraCharacteristics.Key<Boolean> key;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> property;

            String  name;
            Boolean value;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.DEPTH_DEPTH_IS_EXCLUSIVE;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Depth cannot be null");
                        MasterController.quitSafely();
                        return;
                    }
```

```
                    formatter = new ParameterFormatter<Boolean>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Boolean value) {
                            if (value) {
                                return "YES";
                            }
                            return "NO";
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.25: Distortion Characteristics

(camera2/characteristics/Distortion_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include
    ↪ :
 *    DISTORTION_CORRECTION_AVAILABLE_MODES
```

```
 */
@TargetApi(21)
abstract class Distortion_ extends Depth_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("          Distortion_", "reading Distortion_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 28) {
                key  = CameraCharacteristics.DISTORTION_CORRECTION_AVAILABLE_MODES;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    int[]  modes  = cameraCharacteristics.get(key);
```

```
75                      if (modes == null) {
76                          // TODO: error
77                          Log.e(Thread.currentThread().getName(), "Distortion modes cannot be
                                ↪ null");
78                          MasterController.quitSafely();
79                          return;
80                      }
81                      List<Integer> options = ArrayToList.convert(modes);
82
83                      Integer OFF          = CameraMetadata.DISTORTION_CORRECTION_MODE_OFF;
84                      Integer FAST         = CameraMetadata.DISTORTION_CORRECTION_MODE_FAST;
85                      //Integer HIGH_QUALITY = CameraMetadata.
                            ↪ DISTORTION_CORRECTION_MODE_HIGH_QUALITY;
86
87                      if (options.contains(OFF)) {
88                          value       =  OFF;
89                          valueString = "OFF (PREFERRED)";
90                      }
91                      else {
92                          value       =  FAST;
93                          valueString = "FAST (FALLBACK)";
94                      }
95
96                      if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
97                          value       =  FAST;
98                          valueString = "FAST (WORST CONFIGURATION)";
99                      }
100
101                     formatter = new ParameterFormatter<Integer>(valueString) {
102                         @NonNull
103                         @Override
104                         public String formatValue(@NonNull Integer value) {
105                             return getValueString();
106                         }
107                     };
108                     property = new Parameter<>(name, value, null, formatter);
109                 }
110                 else {
111                     property = new Parameter<>(name);
112                     property.setValueString("NOT SUPPORTED");
113                 }
```

```
                    characteristicsMap.put(key, property);
                }
            }
            //==========================================
                ↪ ==================================================
        }

}
```

Listing E.26: Edge Characteristics (`camera2/characteristics/Edge_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    EDGE_AVAILABLE_EDGE_MODES
 */
@TargetApi(21)
```

```
abstract class Edge_ extends Distortion_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("                Edge_", "reading Edge_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.EDGE_AVAILABLE_EDGE_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Edge modes cannot be null");
```

```
                MasterController.quitSafely();
                return;
            }
            List<Integer> options = ArrayToList.convert(modes);

            Integer OFF              = CameraMetadata.EDGE_MODE_OFF;
            Integer FAST             = CameraMetadata.EDGE_MODE_FAST;
            //Integer HIGH_QUALITY     = CameraMetadata.EDGE_MODE_HIGH_QUALITY;
            //Integer ZERO_SHUTTER_LAG = null;
            //if ( Build.VERSION.SDK_INT >= 23) {
            //    ZERO_SHUTTER_LAG = CameraMetadata.EDGE_MODE_ZERO_SHUTTER_LAG;
            //}

            if (options.contains(OFF)) {
                value       =  OFF;
                valueString = "OFF (PREFERRED)";
            }
            else {
                value       =  FAST;
                valueString = "FAST (FALLBACK)";
            }

            if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                value       =  FAST;
                valueString = "FAST (WORST CONFIGURATION)";
            }

            formatter = new ParameterFormatter<Integer>(valueString) {
                @NonNull
                @Override
                public String formatValue(@NonNull Integer value) {
                    return getValueString();
                }
            };
            property = new Parameter<>(name, value, null, formatter);
        }
        else {
            property = new Parameter<>(name);
            property.setValueString("NOT SUPPORTED");
        }
        characteristicsMap.put(key, property);
```

```
            }
            //==========================================
                ↪ ==========================================================
        }

}
```

Listing E.27: Flash Characteristics (`camera2/characteristics/Flash_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    FLASH_INFO_AVAILABLE
 */
@TargetApi(21)
abstract class Flash_ extends Edge_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::
```

```
40
41      // read...............
42      /**
43       * Continue discovering abilities with specialized classes
44       * @param cameraCharacteristics Encapsulation of camera abilities
45       * @param characteristicsMap A mapping of characteristics names to their respective
             ↪ parameter options
46       */
47      @Override
48      protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
49                          @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                ↪ characteristicsMap) {
50          super.read(cameraCharacteristics, characteristicsMap);
51
52          Log.e("               Flash_", "reading Flash_ characteristics");
53          List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();
54
55          //=====================================
                ↪ ====================================================
56          {
57              CameraCharacteristics.Key<Boolean> key;
58              ParameterFormatter<Boolean> formatter;
59              Parameter<Boolean> property;
60
61              String  name;
62              Boolean value;
63              key  = CameraCharacteristics.FLASH_INFO_AVAILABLE;//////////////////////////
64              name = key.getName();
65
66              if (keychain.contains(key)) {
67                  value = cameraCharacteristics.get(key);
68                  if (value == null) {
69                      // TODO: error
70                      Log.e(Thread.currentThread().getName(), "Flash info cannot be null");
71                      MasterController.quitSafely();
72                      return;
73                  }
74
75                  formatter = new ParameterFormatter<Boolean>() {
76                      @NonNull
77                      @Override
```

```
                    public String formatValue(@NonNull Boolean value) {
                        if (value) {
                            return "YES";
                        }
                        return "NO";
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.28: Hot Characteristics (`camera2/characteristics/Hot_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    HOT_PIXEL_AVAILABLE_HOT_PIXEL_MODES
 */
@TargetApi(21)
abstract class Hot_ extends Flash_ {
```

```java

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("                 Hot_", "reading Hot_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.HOT_PIXEL_AVAILABLE_HOT_PIXEL_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Hot pixel modes cannot be null");
```

```
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

                Integer OFF              = CameraMetadata.HOT_PIXEL_MODE_OFF;
                Integer FAST             = CameraMetadata.HOT_PIXEL_MODE_FAST;
                //Integer HIGH_QUALITY     = CameraMetadata.HOT_PIXEL_MODE_HIGH_QUALITY;

                if (options.contains(OFF)) {
                    value       =  OFF;
                    valueString = "OFF (PREFERRED)";
                }
                else {
                    value       =  FAST;
                    valueString = "FAST (FALLBACK)";
                }

                if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value       =  FAST;
                    valueString = "FAST (WORST CONFIGURATION)";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
    }
```

```

}
```

Listing E.29: Info Characteristics (`camera2/characteristics/Info_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    INFO_SUPPORTED_HARDWARE_LEVEL
 *    INFO_VERSION
 */
@TargetApi(21)
abstract class Info_ extends Hot_ {
```

```java

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("                Info_", "reading Info_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.INFO_SUPPORTED_HARDWARE_LEVEL;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                Integer level  = cameraCharacteristics.get(key);
                if ( level == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Hardware level cannot be null");
```

```
76                      MasterController.quitSafely();
77                      return;
78                  }
79
80                  value = null;
81                  valueString = null;
82                  switch (level) {
83                      case (CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_LEGACY): {
84                          value = CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_LEGACY;
85                          valueString = "LEGACY";
86                          break;
87                      }
88
89                      case (CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_LIMITED): {
90                          value = CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_LIMITED;
91                          valueString = "LIMITED";
92                          break;
93                      }
94
95                      case (CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_FULL): {
96                          value = CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_FULL;
97                          valueString = "FULL";
98                          break;
99                      }
100
101                     case (CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_3): {
102                         if (Build.VERSION.SDK_INT >= 24) {
103                             value = CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_3;
104                             valueString = "LEVEL_3";
105                         }
106                         break;
107                     }
108
109                     case (CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_EXTERNAL): {
110                         if (Build.VERSION.SDK_INT >= 28) {
111                             value = CameraMetadata.INFO_SUPPORTED_HARDWARE_LEVEL_EXTERNAL;
112                             valueString = "EXTERNAL";
113                         }
114                         break;
115                     }
116                 }
```

```
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Unknown hardware level");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<String> key;
            ParameterFormatter<String> formatter;
            Parameter<String> property;

            String name;
            String value;

            if (Build.VERSION.SDK_INT >= 28) {
                key  = CameraCharacteristics.INFO_VERSION;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
```

```
                        Log.e(Thread.currentThread().getName(), "Version info cannot be null
                            ↪ ");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<String>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull String value) {
                            return value;
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                } else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.30: Jpeg Characteristics (`camera2/characteristics/Jpeg_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Size;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    JEPG_AVAILABLE_THUMBNAIL_SIZES
 */
@TargetApi(21)
abstract class Jpeg_ extends Info_ {

    // Protected Overriding Instance Methods
```

```
40      //::::::::::::::::::::::
41
42      // read..............
43      /**
44       * Continue discovering abilities with specialized classes
45       * @param cameraCharacteristics Encapsulation of camera abilities
46       * @param characteristicsMap A mapping of characteristics names to their respective
             ↪ parameter options
47       */
48      @Override
49      protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
50                          @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                ↪ characteristicsMap) {
51          super.read(cameraCharacteristics, characteristicsMap);
52
53          Log.e("                Jpeg_", "reading Jpeg_ characteristics");
54          List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();
55
56          //=====================================
                ↪ ====================================================
57          {
58              CameraCharacteristics.Key<Size[]> key;
59              ParameterFormatter<Size> formatter;
60              Parameter<Size> property;
61
62              String  name;
63              Size    value;
64              String  units;
65
66              key   = CameraCharacteristics.JPEG_AVAILABLE_THUMBNAIL_SIZES;//
                    ↪ ////////////////////////
67              name  = key.getName();
68              units = "pixels";
69
70              if (keychain.contains(key)) {
71                  Size[] sizes  = cameraCharacteristics.get(key);
72                  if (sizes == null) {
73                      // TODO: error
74                      Log.e(Thread.currentThread().getName(), "Thumbnail sizes cannot be null"
                            ↪ );
75                      MasterController.quitSafely();
```

```
                    return;
                }

                Size smallest = null;
                for (Size size : sizes) {
                    if (smallest == null) {
                        smallest = size;
                        continue;
                    }
                    long thisArea     =     size.getWidth() *     size.getHeight();
                    long smallestArea = smallest.getWidth() * smallest.getHeight();
                    if (thisArea < smallestArea) {
                        smallest = size;
                    }
                }
                if (smallest == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "There must be a smallest
                        ↪ thumbnail size");
                    MasterController.quitSafely();
                    return;
                }
                value = smallest;

                formatter = new ParameterFormatter<Size>("smallest: ") {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Size value) {
                        return getValueString() + value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
```

```
        }

}
```

Listing E.31: Lens Characteristics (`camera2/characteristics/Lens_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    LENS_DISTORTION
 *    LENS_FACING
 *    LENS_INFO_AVAILABLE_APERTURES
```

```
 *     LENS_INFO_AVAILABLE_FILTER_DENSITIES
 *     LENS_INFO_AVAILABLE_FOCAL_LENGTHS
 *     LENS_INFO_AVAILABLE_OPTICAL_STABILIZATION
 *     LENS_INFO_FOCUS_DISTANCE_CALIBRATION
 *     LENS_INFO_HYPERFOCAL_DISTANCE
 *     LENS_INFO_MINIMUM_FOCUS_DISTANCE
 *     LENS_INTRINSIC_CALIBRATION
 *     LENS_POSE_REFERENCE
 *     LENS_POSE_ROTATION
 *     LENS_POSE_TRANSLATION
 */
@SuppressWarnings("unchecked")
@TargetApi(21)
abstract class Lens_ extends Jpeg_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::::

    // read...............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("                Lens_", "reading Lens_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<float[]> key;
            ParameterFormatter<Float[]> formatter;
            Parameter<Float[]> property;

```

```
            String  name;
            Float[] value;
            String  units;

            if (Build.VERSION.SDK_INT >= 28) {
                key   = CameraCharacteristics.LENS_DISTORTION;//////////////////////////
                name  = key.getName();
                units = "unitless correction coefficients";

                if (keychain.contains(key)) {
                    float[] coefficients  = cameraCharacteristics.get(key);
                    if ( coefficients == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Lens distortion cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    value = (Float[]) ArrayToList.convert(coefficients).toArray(new Float[0]);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Lens distortion coefficients cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Float[]>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Float[] value) {
                            String out = "( ";
                            int length = value.length;
                            for (int i = 0; i < length; i++) {
                                out += value[i];
                                if (i < length - 1) {
                                    out += ", ";
                                }
                            }
```

```
                            return out + " )";
                        }
                    };
                    property = new Parameter<>(name, value, units, formatter);
                    }
                    else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.LENS_FACING;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens facing cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                Integer FRONT    = CameraMetadata.LENS_FACING_FRONT;
                Integer BACK     = CameraMetadata.LENS_FACING_BACK;
                Integer EXTERNAL = null;
                if (Build.VERSION.SDK_INT >= 23 ) {
                    EXTERNAL = CameraMetadata.LENS_FACING_EXTERNAL;
                }
```

```

                if (value.equals(FRONT)) {
                    valueString = "FRONT";
                }
                else if (value.equals(BACK)) {
                    valueString = "BACK";
                }
                else {
                    valueString = "EXTERNAL";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<float[]> key;
            ParameterFormatter<Float> formatter;
            Parameter<Float> property;

            String name;
            Float  value;
            String valueString;
            String units;

            key   = CameraCharacteristics.LENS_INFO_AVAILABLE_APERTURES;//
                ↪ ////////////////////////
            name  = key.getName();
```

```
            units = "aperture f-number";

            if (keychain.contains(key)) {
                float[] apertures = cameraCharacteristics.get(key);
                if (apertures == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens apertures cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                Float smallest = null;
                Float largest  = null;
                for (Float val : apertures) {
                    if (smallest == null) {
                        smallest = val;
                        largest  = val;
                        continue;
                    }
                    if (val < smallest) {
                        smallest = val;
                    }
                    if (val > largest) {
                        largest = val;
                    }
                }
                if (smallest == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "There must be a smallest aperture");
                    MasterController.quitSafely();
                    return;
                }
                value = smallest;
                valueString = "smallest: ";

                if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value = largest;
                    valueString = "largest (WORST CONFIGURATION): ";
                }
```

```
234
235                 formatter = new ParameterFormatter<Float>(valueString) {
236                     @NonNull
237                     @Override
238                     public String formatValue(@NonNull Float value) {
239                         return getValueString() + value.toString();
240                     }
241                 };
242                 property = new Parameter<>(name, value, units, formatter);
243             }
244             else {
245                 property = new Parameter<>(name);
246                 property.setValueString("NOT SUPPORTED");
247             }
248             characteristicsMap.put(key, property);
249         }
250         //=========================================
            ↪ ==================================================
251         {
252             CameraCharacteristics.Key<float[]> key;
253             ParameterFormatter<Float> formatter;
254             Parameter<Float> property;
255
256             String name;
257             Float  value;
258             String valueString;
259             String units;
260
261             key   = CameraCharacteristics.LENS_INFO_AVAILABLE_FILTER_DENSITIES;//
                ↪ ////////////////////////
262             name  = key.getName();
263             units = "exposure value";
264
265             if (keychain.contains(key)) {
266                 float[] densities = cameraCharacteristics.get(key);
267                 if (densities == null) {
268                     // TODO: error
269                     Log.e(Thread.currentThread().getName(), "Filter densities cannot be null
                        ↪ ");
270                     MasterController.quitSafely();
271                     return;
```

```
272                 }
273
274                 Float biggest  = null;
275                 Float smallest = null;
276                 for (Float val : densities) {
277                     if (biggest == null) {
278                         biggest  = val;
279                         smallest = val;
280                         continue;
281                     }
282                     if (val > biggest) {
283                         biggest = val;
284                     }
285                     if (val < smallest) {
286                         smallest = val;
287                     }
288                 }
289                 if (biggest == null) {
290                     // TODO: error
291                     Log.e(Thread.currentThread().getName(), "There must be a biggest density
                        ↪ ");
292                     MasterController.quitSafely();
293                     return;
294                 }
295                 value = biggest;
296                 valueString = "biggest: ";
297
298                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
299                     value = smallest;
300                     valueString = "smallest (WORST CONFIGURATION): ";
301                 }
302
303                 formatter = new ParameterFormatter<Float>(valueString) {
304                     @NonNull
305                     @Override
306                     public String formatValue(@NonNull Float value) {
307                         return getValueString() + value.toString();
308                     }
309                 };
310                 property = new Parameter<>(name, value, units, formatter);
311             }
```

```
312                 else {
313                     property = new Parameter<>(name);
314                     property.setValueString("NOT SUPPORTED");
315                 }
316                 characteristicsMap.put(key, property);
317             }
318             //=====================================
                ↪ ==================================================
319             {
320                 CameraCharacteristics.Key<float[]> key;
321                 ParameterFormatter<Float> formatter;
322                 Parameter<Float> property;
323
324                 String name;
325                 Float  value;
326                 String valueString;
327                 String units;
328
329                 key   = CameraCharacteristics.LENS_INFO_AVAILABLE_FOCAL_LENGTHS;//
                    ↪ ////////////////////////
330                 name  = key.getName();
331                 units = "millimeters";
332
333                 if (keychain.contains(key)) {
334                     float[] lengths = cameraCharacteristics.get(key);
335                     if (lengths == null) {
336                         // TODO: error
337                         Log.e(Thread.currentThread().getName(), "Lens focal lengths cannot be
                            ↪ null");
338                         MasterController.quitSafely();
339                         return;
340                     }
341
342                     Float longest  = null;
343                     Float shortest = null;
344                     for (Float val : lengths) {
345                         if (longest == null) {
346                             longest  = val;
347                             shortest = val;
348                             continue;
349                         }
```

```
                    if (val > longest) {
                        longest = val;
                    }
                    if (val < shortest) {
                        shortest = val;
                    }
                }
                if (longest == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Longest focal length must exist
                        ↪ ");
                    MasterController.quitSafely();
                    return;
                }
                value = longest;
                valueString = "longest: ";

                if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value = shortest;
                    valueString = "shortest (WORST CONFIGURATION): ";
                }

                formatter = new ParameterFormatter<Float>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Float value) {
                        return getValueString() + value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==========================================================
        {
            CameraCharacteristics.Key<int[]> key;
```

```
389                 ParameterFormatter<Integer> formatter;
390                 Parameter<Integer> property;
391
392                 String  name;
393                 Integer value;
394                 String  valueString;
395
396                 key  = CameraCharacteristics.LENS_INFO_AVAILABLE_OPTICAL_STABILIZATION;//
                        ↪ ////////////////////////
397                 name = key.getName();
398
399                 if (keychain.contains(key)) {
400                     int[]  modes  = cameraCharacteristics.get(key);
401                     if (modes == null) {
402                         // TODO: error
403                         Log.e(Thread.currentThread().getName(), "Optical stabilization cannot be
                                ↪  null");
404                         MasterController.quitSafely();
405                         return;
406                     }
407                     List<Integer> options = ArrayToList.convert(modes);
408
409                     Integer OFF = CameraMetadata.LENS_OPTICAL_STABILIZATION_MODE_OFF;
410                     Integer ON  = CameraMetadata.LENS_OPTICAL_STABILIZATION_MODE_ON;
411
412                     if (options.contains(OFF)) {
413                         value       =  OFF;
414                         valueString = "OFF (PREFERRED)";
415                     }
416                     else {
417                         value       =  ON;
418                         valueString = "ON (FALLBACK)";
419                     }
420
421                     if (options.contains(ON) && GlobalSettings.FORCE_WORST_CONFIGURATION) {
422                         value       =  ON;
423                         valueString = "ON (WORST CONFIGURATION)";
424                     }
425
426                     formatter = new ParameterFormatter<Integer>(valueString) {
427                         @NonNull
```

```
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.LENS_INFO_FOCUS_DISTANCE_CALIBRATION;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens calibration cannot be null
                        ↪ ");
                    MasterController.quitSafely();
                    return;
                }

                Integer UNCALIBRATED = CameraMetadata.
                    ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION_UNCALIBRATED;
```

```
                Integer APPROXIMATE  = CameraMetadata.
                    ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION_APPROXIMATE;
                Integer CALIBRATED   = CameraMetadata.
                    ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION_CALIBRATED;

                if (value.equals(UNCALIBRATED)) {
                    valueString = "UNCALIBRATED";
                }
                else if (value.equals(APPROXIMATE)) {
                    valueString = "APPROXIMATE";
                }
                else {
                    valueString = "CALIBRATED";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Float> key;
            ParameterFormatter<Float> formatter;
            Parameter<Float> property;

            String name;
            Float  value;
            String units;

```

```
502                 key   = CameraCharacteristics.LENS_INFO_HYPERFOCAL_DISTANCE;//
                        ↪ ////////////////////////
503                 name  = key.getName();
504                 units = null;
505
506                 if (keychain.contains(key)) {
507
508                     if (characteristicsMap.containsKey(CameraCharacteristics.
                            ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION)) {
509                         Parameter<Integer> calibration;
510                         calibration = characteristicsMap.get(CameraCharacteristics.
                                ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION);
511                         if (calibration == null) {
512                             // TODO: error
513                             Log.e(Thread.currentThread().getName(), "Lens hyperfocal distances
                                    ↪ cannot be null");
514                             MasterController.quitSafely();
515                             return;
516                         }
517
518                         Integer calValue = calibration.getValue();
519                         if (calValue == null) {
520                             // TODO: error
521                             Log.e(Thread.currentThread().getName(), "Lens calibration cannot be
                                    ↪ null");
522                             MasterController.quitSafely();
523                             return;
524                         }
525
526                         if (!calValue.equals(CameraMetadata.
                                ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION_UNCALIBRATED)){
527                             units = "diopters";
528                         }
529                         else {
530                             units = "uncalibrated diopters";
531                         }
532                     }
533
534                     value = cameraCharacteristics.get(key);
535                     if (value == null) {
536                         // TODO: error
```

```
                    Log.e(Thread.currentThread().getName(), "Lens hyperfocal distances cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Float>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Float value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================================================================
        {
            CameraCharacteristics.Key<Float> key;
            ParameterFormatter<Float> formatter;
            Parameter<Float> property;

            String name;
            Float  value;
            String units;

            key   = CameraCharacteristics.LENS_INFO_MINIMUM_FOCUS_DISTANCE;////////////////////////
            name  = key.getName();
            units = null;

            if (keychain.contains(key)) {

                if (characteristicsMap.containsKey(CameraCharacteristics.LENS_INFO_FOCUS_DISTANCE_CALIBRATION)) {
```

```
574                     Parameter<Integer> calibration;
575                     calibration = characteristicsMap.get(CameraCharacteristics.
                            ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION);
576                     if (calibration == null) {
577                         // TODO: error
578                         Log.e(Thread.currentThread().getName(), "Lens calibration cannot be
                                ↪ null");
579                         MasterController.quitSafely();
580                         return;
581                     }
582
583                     Integer calValue = calibration.getValue();
584                     if (calValue == null) {
585                         units = "uncalibrated diopters";
586                     }
587                     else if (!calValue.equals(CameraMetadata.
                            ↪ LENS_INFO_FOCUS_DISTANCE_CALIBRATION_UNCALIBRATED)){
588                         units = "diopters";
589                     }
590                     else {
591                         units = "uncalibrated diopters";
592                     }
593                 }
594
595                 value = cameraCharacteristics.get(key);
596                 if (value == null) {
597                     // TODO: error
598                     Log.e(Thread.currentThread().getName(), "Lens minimum focus cannot be
                            ↪ null");
599                     MasterController.quitSafely();
600                     return;
601                 }
602
603                 formatter = new ParameterFormatter<Float>() {
604                     @NonNull
605                     @Override
606                     public String formatValue(@NonNull Float value) {
607                         return value.toString();
608                     }
609                 };
610                 property = new Parameter<>(name, value, units, formatter);
```

```
611                 }
612                 else {
613                     property = new Parameter<>(name);
614                     property.setValueString("NOT SUPPORTED");
615                 }
616                 characteristicsMap.put(key, property);
617             }
618             //=========================================
                ↪ ==================================================
619             {
620                 CameraCharacteristics.Key<float[]> key;
621                 ParameterFormatter<Float[]> formatter;
622                 Parameter<Float[]> property;
623
624                 String  name;
625                 Float[] value;
626                 String  units;
627
628                 if (Build.VERSION.SDK_INT >= 23) {
629                     key   = CameraCharacteristics.LENS_INTRINSIC_CALIBRATION;//
                        ↪ ////////////////////////
630                     name  = key.getName();
631                     units = "pixels";
632
633                     if (keychain.contains(key)) {
634                         float[] coefficients  = cameraCharacteristics.get(key);
635                         if ( coefficients == null) {
636                             // TODO: error
637                             Log.e(Thread.currentThread().getName(), "Lens calibration cannot be
                                ↪ null");
638                             MasterController.quitSafely();
639                             return;
640                         }
641
642                         value = ArrayToList.convert(coefficients).toArray(new Float[0]);
643                         if (value == null) {
644                             // TODO: error
645                             Log.e(Thread.currentThread().getName(), "Lens coefficients cannot be
                                ↪  null");
646                             MasterController.quitSafely();
647                             return;
```

```
                    }

                    formatter = new ParameterFormatter<Float[]>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Float[] value) {
                            String out = "( ";
                            int length = value.length;
                            for (int i = 0; i < length; i++ ) {
                                out += value[i];
                                if (i < length - 1) {
                                    out += ", ";
                                }
                            }
                            return out + " )";
                        }
                    };
                    property = new Parameter<>(name, value, units, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 28) {
                key  = CameraCharacteristics.LENS_POSE_REFERENCE;//////////////////////////
                name = key.getName();

```

```
688                 if (keychain.contains(key)) {
689                     value = cameraCharacteristics.get(key);
690                     if (value == null) {
691                         // TODO: error
692                         Log.e(Thread.currentThread().getName(), "Lens reference cannot be
                                ↪ null");
693                         MasterController.quitSafely();
694                         return;
695                     }
696
697                     Integer PRIMARY_CAMERA = CameraMetadata.
                            ↪ LENS_POSE_REFERENCE_PRIMARY_CAMERA;
698                     Integer GYROSCOPE      = CameraMetadata.LENS_POSE_REFERENCE_GYROSCOPE;
699
700                     if (value.equals(PRIMARY_CAMERA)) {
701                         valueString = "PRIMARY_CAMERA";
702                     } else {
703                         valueString = "GYROSCOPE";
704                     }
705
706                     formatter = new ParameterFormatter<Integer>(valueString) {
707                         @NonNull
708                         @Override
709                         public String formatValue(@NonNull Integer value) {
710                             return getValueString();
711                         }
712                     };
713                     property = new Parameter<>(name, value, null, formatter);
714                 }
715                 else {
716                     property = new Parameter<>(name);
717                     property.setValueString("NOT SUPPORTED");
718                 }
719                 characteristicsMap.put(key, property);
720             }
721         }
722         //=========================================
            ↪ ==================================================
723         {
724             CameraCharacteristics.Key<float[]> key;
725             ParameterFormatter<Float[]> formatter;
```

```
726                 Parameter<Float[]> property;
727
728                 String  name;
729                 Float[] value;
730                 String  units;
731
732                 if (Build.VERSION.SDK_INT >= 23) {
733                     key   = CameraCharacteristics.LENS_POSE_ROTATION;//////////////////////////
734                     name  = key.getName();
735                     units = "quaternion coefficients";
736
737                     if (keychain.contains(key)) {
738                         float[] coefficients  = cameraCharacteristics.get(key);
739                         if ( coefficients == null) {
740                             // TODO: error
741                             Log.e(Thread.currentThread().getName(), "Lens rotation cannot be
                                ↪ null");
742                             MasterController.quitSafely();
743                             return;
744                         }
745
746                         value = ArrayToList.convert(coefficients).toArray(new Float[0]);
747                         if (value == null) {
748                             // TODO: error
749                             Log.e(Thread.currentThread().getName(), "Lens coefficients cannot be
                                ↪  null");
750                             MasterController.quitSafely();
751                             return;
752                         }
753
754                         formatter = new ParameterFormatter<Float[]>() {
755                             @NonNull
756                             @Override
757                             public String formatValue(@NonNull Float[] value) {
758                                 String out = "( ";
759                                 int length = value.length;
760                                 for (int i = 0; i < length; i++ ) {
761                                     out += value[i];
762                                     if (i < length - 1) {
763                                         out += ", ";
764                                     }
```

```
                        }
                        return out + " )";
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
    }
    //=====================================
        ↪ ==================================================
    {
        CameraCharacteristics.Key<float[]> key;
        ParameterFormatter<Float[]> formatter;
        Parameter<Float[]> property;

        String  name;
        Float[] value;
        String  units;

        if (Build.VERSION.SDK_INT >= 23) {
            key   = CameraCharacteristics.LENS_POSE_TRANSLATION;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "meters";

            if (keychain.contains(key)) {
                float[] coefficients  = cameraCharacteristics.get(key);
                if ( coefficients == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens translation cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                value = ArrayToList.convert(coefficients).toArray(new Float[0]);
```

```
                        if (value == null) {
                            // TODO: error
                            Log.e(Thread.currentThread().getName(), "Lens coefficients cannot be null");
                            MasterController.quitSafely();
                            return;
                        }

                        formatter = new ParameterFormatter<Float[]>() {
                            @NonNull
                            @Override
                            public String formatValue(@NonNull Float[] value) {
                                String out = "( ";
                                int length = value.length;
                                for (int i = 0; i < length; i++ ) {
                                    out += value[i];
                                    if (i < length - 1) {
                                        out += ", ";
                                    }
                                }
                                return out + " )";
                            }
                        };
                        property = new Parameter<>(name, value, units, formatter);
                    }
                    else {
                        property = new Parameter<>(name);
                        property.setValueString("NOT SUPPORTED");
                    }
                    characteristicsMap.put(key, property);
                }
            }
            //=========================================================================
        }

}
```

Listing E.32: Logical Characteristics (`camera2/characteristics/Logical_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    LOGICAL_MULTI_CAMERA_SENSOR_SYNC_TYPE
 */
@TargetApi(21)
abstract class Logical_ extends Lens_ {

```

```
    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("             Logical_", "reading Logical_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 28) {
                key  = CameraCharacteristics.LOGICAL_MULTI_CAMERA_SENSOR_SYNC_TYPE;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Logical multi-camera sensor cannot be null");
```

```
                        MasterController.quitSafely();
                        return;
                    }

                    Integer APPROXIMATE = CameraMetadata.
                        ↪ LOGICAL_MULTI_CAMERA_SENSOR_SYNC_TYPE_APPROXIMATE;
                    Integer CALIBRATED  = CameraMetadata.
                        ↪ LOGICAL_MULTI_CAMERA_SENSOR_SYNC_TYPE_CALIBRATED;

                    if (value.equals(APPROXIMATE)) {
                        valueString = "APPROXIMATE";
                    }
                    else {
                        valueString = "CALIBRATED";
                    }

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.33: Noise Characteristics (`camera2/characteristics/Noise_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    NOISE_REDUCTION_AVAILABLE_NOISE_REDUCTION_MODES
 */
@TargetApi(21)
```

```
abstract class Noise_ extends Logical_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("               Noise_", "reading Noise_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.NOISE_REDUCTION_AVAILABLE_NOISE_REDUCTION_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
```

```
76                      Log.e(Thread.currentThread().getName(), "Noise reduction modes cannot be
                            ↪  null");
77                      MasterController.quitSafely();
78                      return;
79                  }
80                  List<Integer> options = ArrayToList.convert(modes);
81
82                  Integer OFF              = CameraMetadata.NOISE_REDUCTION_MODE_OFF;
83                  Integer FAST             = CameraMetadata.NOISE_REDUCTION_MODE_FAST;
84                  //Integer HIGH_QUALITY     = CameraMetadata.
                        ↪ NOISE_REDUCTION_MODE_HIGH_QUALITY;
85                  Integer MINIMAL          = null;
86                  //Integer ZERO_SHUTTER_LAG = null;
87                  if (Build.VERSION.SDK_INT >= 23) {
88                      MINIMAL          = CameraMetadata.NOISE_REDUCTION_MODE_MINIMAL;
89                  //    ZERO_SHUTTER_LAG = CameraMetadata.
                        ↪ NOISE_REDUCTION_MODE_ZERO_SHUTTER_LAG;
90                  }
91
92                  if (options.contains(OFF)) {
93                      value       =  OFF;
94                      valueString = "OFF (PREFERRED)";
95                  }
96                  else if (MINIMAL != null && options.contains(MINIMAL)) {
97                      value       =  MINIMAL;
98                      valueString = "MINIMAL (FALLBACK)";
99                  }
100                 else {
101                     value       =  FAST;
102                     valueString = "FAST (LAST CHOICE)";
103                 }
104
105                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
106                     value       =  FAST;
107                     valueString = "FAST (WORST CONFIGURATION)";
108                 }
109
110                 formatter = new ParameterFormatter<Integer>(valueString) {
111                     @NonNull
112                     @Override
113                     public String formatValue(@NonNull Integer value) {
```

```
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.34: Reprocess Characteristics (`camera2/characteristics/Reprocess_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    REPROCESS_MAX_CAPTURE_STALL
 */
@TargetApi(21)
abstract class Reprocess_ extends Noise_ {

    // Protected Overriding Instance Methods
```

```
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("           Reprocess_", "reading Reprocess_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  units;

            if (Build.VERSION.SDK_INT >= 23) {
                key   = CameraCharacteristics.REPROCESS_MAX_CAPTURE_STALL;//////////////////////////
                name  = key.getName();
                units = "number of frames";

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Max capture stall cannot be null");
```

```
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Integer>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return value.toString();
                        }
                    };
                    property = new Parameter<>(name, value, units, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.35: Request Characteristics (`camera2/characteristics/Request_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *     REQUEST_AVAILABLE_CAPABILITIES
 *     REQUEST_MAX_NUM_INPUT_STREAMS
 *     REQUEST_MAX_NUM_OUTPUT_PROC
 *     REQUEST_MAX_NUM_OUTPUT_PROC_STALLING
```

```
 *     REQUEST_MAX_NUM_OUTPUT_RAW
 *     REQUEST_PARTIAL_RESULT_COUNT
 *     REQUEST_PIPELINE_MAX_DEPTH
 */
@TargetApi(21)
abstract class Request_ extends Reprocess_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("             Request_", "reading Request_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer[]> formatter;
            Parameter<Integer[]> property;

            String    name;
            Integer[] value;
            String    valueString;

            key  = CameraCharacteristics.REQUEST_AVAILABLE_CAPABILITIES;//////////////////////////
            name = key.getName();

```

```
77              if (keychain.contains(key)) {
78                  int[]  capabilities  = cameraCharacteristics.get(key);
79                  if (capabilities == null) {
80                      // TODO: error
81                      Log.e(Thread.currentThread().getName(), "Capabilities cannot be null");
82                      MasterController.quitSafely();
83                      return;
84                  }
85                  List<Integer> available = ArrayToList.convert(capabilities);
86
87                  Integer BACKWARD_COMPATIBLE          = CameraMetadata.
                        ↪ REQUEST_AVAILABLE_CAPABILITIES_BACKWARD_COMPATIBLE;
88                  Integer MANUAL_SENSOR                = CameraMetadata.
                        ↪ REQUEST_AVAILABLE_CAPABILITIES_MANUAL_SENSOR;
89                  Integer MANUAL_POST_PROCESSING       = CameraMetadata.
                        ↪ REQUEST_AVAILABLE_CAPABILITIES_MANUAL_POST_PROCESSING;
90                  Integer RAW                          = CameraMetadata.
                        ↪ REQUEST_AVAILABLE_CAPABILITIES_RAW;
91                  Integer PRIVATE_REPROCESSING         = null;
92                  Integer READ_SENSOR_SETTINGS         = null;
93                  Integer BURST_CAPTURE                = null;
94                  Integer YUV_REPROCESSING             = null;
95                  Integer DEPTH_OUTPUT                 = null;
96                  Integer CONSTRAINED_HIGH_SPEED_VIDEO = null;
97                  Integer MOTION_TRACKING              = null;
98                  Integer LOGICAL_MULTI_CAMERA         = null;
99                  Integer MONOCHROME                   = null;
100
101                 if (Build.VERSION.SDK_INT >= 22) {
102                     READ_SENSOR_SETTINGS         = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_READ_SENSOR_SETTINGS;
103                     BURST_CAPTURE                = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_BURST_CAPTURE;
104                 }
105
106                 if (Build.VERSION.SDK_INT >= 23) {
107                     PRIVATE_REPROCESSING         = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_PRIVATE_REPROCESSING;
108                     YUV_REPROCESSING             = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_YUV_REPROCESSING;
```

```
109                     DEPTH_OUTPUT                 = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_DEPTH_OUTPUT;
110                     CONSTRAINED_HIGH_SPEED_VIDEO = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_CONSTRAINED_HIGH_SPEED_VIDEO;
111                 }
112
113                 if (Build.VERSION.SDK_INT >= 28) {
114                     MOTION_TRACKING              = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_MOTION_TRACKING;
115                     LOGICAL_MULTI_CAMERA         = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_LOGICAL_MULTI_CAMERA;
116                     MONOCHROME                   = CameraMetadata.
                            ↪ REQUEST_AVAILABLE_CAPABILITIES_MONOCHROME;
117                 }
118
119                 valueString = "( ";
120                 if (available.contains(BACKWARD_COMPATIBLE)) {
121                     valueString += "BACKWARD_COMPATIBLE ";
122                 }
123                 if (available.contains(MANUAL_SENSOR)) {
124                     valueString += "MANUAL_SENSOR ";
125                 }
126                 if (available.contains(MANUAL_POST_PROCESSING)) {
127                     valueString += "MANUAL_POST_PROCESSING ";
128                 }
129                 if (available.contains(RAW)) {
130                     valueString += "RAW ";
131                 }
132                 if (PRIVATE_REPROCESSING != null && available.contains(PRIVATE_REPROCESSING)
                        ↪ ) {
133                     valueString += "PRIVATE_REPROCESSING ";
134                 }
135                 if (READ_SENSOR_SETTINGS != null && available.contains(READ_SENSOR_SETTINGS)
                        ↪ ) {
136                     valueString += "READ_SENSOR_SETTINGS ";
137                 }
138                 if (BURST_CAPTURE != null && available.contains(BURST_CAPTURE)) {
139                     valueString += "BURST_CAPTURE ";
140                 }
141                 if (YUV_REPROCESSING != null && available.contains(YUV_REPROCESSING)) {
142                     valueString += "YUV_REPROCESSING ";
```

```
143                 }
144                 if (DEPTH_OUTPUT != null && available.contains(DEPTH_OUTPUT)) {
145                     valueString += "DEPTH_OUTPUT ";
146                 }
147                 if (CONSTRAINED_HIGH_SPEED_VIDEO != null && available.contains(
                    ↪ CONSTRAINED_HIGH_SPEED_VIDEO)) {
148                     valueString += "CONSTRAINED_HIGH_SPEED_VIDEO ";
149                 }
150                 if (available.contains(MOTION_TRACKING)) {
151                     valueString += "MOTION_TRACKING ";
152                 }
153                 if (available.contains(LOGICAL_MULTI_CAMERA)) {
154                     valueString += "LOGICAL_MUTLI_CAMERA ";
155                 }
156                 if (available.contains(MONOCHROME)) {
157                     valueString += "MONOCHROME ";
158                 }
159                 valueString += ")";
160
161                 value = available.toArray(new Integer[0]);
162                 if (value == null) {
163                     // TODO: error
164                     Log.e(Thread.currentThread().getName(), "Abilities cannot be null");
165                     MasterController.quitSafely();
166                     return;
167                 }
168
169                 formatter = new ParameterFormatter<Integer[]>(valueString) {
170                     @NonNull
171                     @Override
172                     public String formatValue(@NonNull Integer[] value) {
173                         return getValueString();
174                     }
175                 };
176                 property = new Parameter<>(name, value, null, formatter);
177             }
178             else {
179                 property = new Parameter<>(name);
180                 property.setValueString("NOT SUPPORTED");
181             }
182             characteristicsMap.put(key, property);
```

```
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.REQUEST_MAX_NUM_INPUT_STREAMS;//
                    ↪ ////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Max number of input streams
                            ↪  cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Integer>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return value.toString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
```

```
221         }
222         //=========================================
            ↪ ====================================================
223         {
224             CameraCharacteristics.Key<Integer> key;
225             ParameterFormatter<Integer> formatter;
226             Parameter<Integer> property;
227
228             String  name;
229             Integer value;
230
231             key  = CameraCharacteristics.REQUEST_MAX_NUM_OUTPUT_PROC;//
                ↪ ////////////////////////
232             name = key.getName();
233
234             if (keychain.contains(key)) {
235                 value = cameraCharacteristics.get(key);
236                 if (value == null) {
237                     // TODO: error
238                     Log.e(Thread.currentThread().getName(), "Max number of output proc
                        ↪ cannot be null");
239                     MasterController.quitSafely();
240                     return;
241                 }
242
243                 formatter = new ParameterFormatter<Integer>() {
244                     @NonNull
245                     @Override
246                     public String formatValue(@NonNull Integer value) {
247                         return value.toString();
248                     }
249                 };
250                 property = new Parameter<>(name, value, null, formatter);
251             }
252             else {
253                 property = new Parameter<>(name);
254                 property.setValueString("NOT SUPPORTED");
255             }
256             characteristicsMap.put(key, property);
257         }
```

```
258         //=========================================
            ↪ ==================================================
259         {
260             CameraCharacteristics.Key<Integer> key;
261             ParameterFormatter<Integer> formatter;
262             Parameter<Integer> property;
263
264             String  name;
265             Integer value;
266
267             key  = CameraCharacteristics.REQUEST_MAX_NUM_OUTPUT_PROC_STALLING;//
                ↪ ////////////////////////
268             name = key.getName();
269
270             if (keychain.contains(key)) {
271                 value = cameraCharacteristics.get(key);
272                 if (value == null) {
273                     // TODO: error
274                     Log.e(Thread.currentThread().getName(), "Max number of output proc
                        ↪ stalling cannot be null");
275                     MasterController.quitSafely();
276                     return;
277                 }
278
279                 formatter = new ParameterFormatter<Integer>() {
280                     @NonNull
281                     @Override
282                     public String formatValue(@NonNull Integer value) {
283                         return value.toString();
284                     }
285                 };
286                 property = new Parameter<>(name, value, null, formatter);
287             }
288             else {
289                 property = new Parameter<>(name);
290                 property.setValueString("NOT SUPPORTED");
291             }
292             characteristicsMap.put(key, property);
293         }
294         //=========================================
            ↪ ==================================================
```

```
295         {
296             CameraCharacteristics.Key<Integer> key;
297             ParameterFormatter<Integer> formatter;
298             Parameter<Integer> property;
299
300             String  name;
301             Integer value;
302
303             key  = CameraCharacteristics.REQUEST_MAX_NUM_OUTPUT_RAW;//
                ↪ ////////////////////////
304             name = key.getName();
305
306             if (keychain.contains(key)) {
307                 value = cameraCharacteristics.get(key);
308                 if (value == null) {
309                     // TODO: error
310                     Log.e(Thread.currentThread().getName(), "Max number of output raw cannot
                        ↪  be null");
311                     MasterController.quitSafely();
312                     return;
313                 }
314
315                 formatter = new ParameterFormatter<Integer>() {
316                     @NonNull
317                     @Override
318                     public String formatValue(@NonNull Integer value) {
319                         return value.toString();
320                     }
321                 };
322                 property = new Parameter<>(name, value, null, formatter);
323             }
324             else {
325                 property = new Parameter<>(name);
326                 property.setValueString("NOT SUPPORTED");
327             }
328             characteristicsMap.put(key, property);
329         }
330         //=====================================
            ↪ ==================================================
331         {
332             CameraCharacteristics.Key<Integer> key;
```

```
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;

            key  = CameraCharacteristics.REQUEST_PARTIAL_RESULT_COUNT;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Partial result count cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Byte> key;
            ParameterFormatter<Byte> formatter;
            Parameter<Byte> property;
```

```
371
372             String name;
373             Byte   value;
374
375             key  = CameraCharacteristics.REQUEST_PIPELINE_MAX_DEPTH;//
                ↪ ////////////////////////
376             name = key.getName();
377
378             if (keychain.contains(key)) {
379                 value = cameraCharacteristics.get(key);
380                 if (value == null) {
381                     // TODO: error
382                     Log.e(Thread.currentThread().getName(), "Pipeline depth cannot be null")
                        ↪ ;
383                     MasterController.quitSafely();
384                     return;
385                 }
386
387                 formatter = new ParameterFormatter<Byte>() {
388                     @NonNull
389                     @Override
390                     public String formatValue(@NonNull Byte value) {
391                         return value.toString();
392                     }
393                 };
394                 property = new Parameter<>(name, value, null, formatter);
395             }
396             else {
397                 property = new Parameter<>(name);
398                 property.setValueString("NOT SUPPORTED");
399             }
400             characteristicsMap.put(key, property);
401         }
402         //=====================================
            ↪ ==================================================
403     }
404
405 }
```

Listing E.36: Scaler Characteristics (`camera2/characteristics/Scaler_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.params.StreamConfigurationMap;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    SCALER_AVAILABLE_MAX_DIGITAL_ZOOM
 *    SCALER_CROPPING_TYPE
 *    SCALER_STREAM_CONFIGURATION_MAP
 */
@TargetApi(21)
```

```
abstract class Scaler_ extends Request_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("              Scaler_","reading Scaler_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================
        {
            CameraCharacteristics.Key<Float> key;
            ParameterFormatter<Float> formatter;
            Parameter<Float> property;

            String name;
            Float  value;
            String units;

            key   = CameraCharacteristics.SCALER_AVAILABLE_MAX_DIGITAL_ZOOM;//////////////////////////
            name  = key.getName();
            units = "zoom scale factor";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
```

```
                    Log.e(Thread.currentThread().getName(), "Max digital zoom cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Float>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Float value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.SCALER_CROPPING_TYPE;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Cropping type cannot be null");
                    MasterController.quitSafely();
```

```
                    return;
                }

                Integer CENTER_ONLY = CameraMetadata.SCALER_CROPPING_TYPE_CENTER_ONLY;
                Integer FREEFORM    = CameraMetadata.SCALER_CROPPING_TYPE_FREEFORM;

                if (value.equals(CENTER_ONLY)) {
                    valueString = "CENTER_ONLY";
                }
                else {
                    valueString = "FREEFORM";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<StreamConfigurationMap> key;
            ParameterFormatter<StreamConfigurationMap> formatter;
            Parameter<StreamConfigurationMap> property;

            String                 name;
            StreamConfigurationMap value;

            key  = CameraCharacteristics.SCALER_STREAM_CONFIGURATION_MAP;//
                ↪ ////////////////////////
            name = key.getName();
```

```
155
156                 if (keychain.contains(key)) {
157                     value = cameraCharacteristics.get(key);
158                     if (value == null) {
159                         // TODO: error
160                         Log.e(Thread.currentThread().getName(), "Stream configuration map cannot
                                ↪  be null");
161                         MasterController.quitSafely();
162                         return;
163                     }
164
165                     formatter = new ParameterFormatter<StreamConfigurationMap>() {
166                         @NonNull
167                         @Override
168                         public String formatValue(@NonNull StreamConfigurationMap value) {
169                             return value.toString();
170                         }
171                     };
172                     property = new Parameter<>(name, value, null, formatter);
173                 }
174                 else {
175                     property = new Parameter<>(name);
176                     property.setValueString("NOT SUPPORTED");
177                 }
178                 characteristicsMap.put(key, property);
179             }
180             //=========================================
                ↪ ==================================================
181         }
182
183     }
```

Listing E.37: Sensor Characteristics (`camera2/characteristics/Sensor_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.graphics.Rect;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.params.BlackLevelPattern;
import android.hardware.camera2.params.ColorSpaceTransform;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Range;
import android.util.Size;
import android.util.SizeF;

import java.text.DecimalFormat;
import java.text.NumberFormat;
import java.util.LinkedHashMap;
import java.util.List;
import java.util.Locale;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
```

```
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *     SENSOR_AVAILABLE_TEST_PATTERN_MODES
 *     SENSOR_BLACK_LEVEL_PATTERN
 *     SENSOR_CALIBRATION_TRANSFORM1
 *     SENSOR_CALIBRATION_TRANSFORM2
 *     SENSOR_COLOR_TRANSFORM1
 *     SENSOR_COLOR_TRANSFORM2
 *     SENSOR_FORWARD_MATRIX1
 *     SENSOR_FORWARD_MATRIX2
 *     SENSOR_INFO_ACTIVE_ARRAY_SIZE
 *     SENSOR_INFO_COLOR_FILTER_ARRANGEMENT
 *     SENSOR_INFO_EXPOSURE_TIME_RANGE
 *     SENSOR_INFO_LENS_SHADING_APPLIED
 *     SENSOR_INFO_MAX_FRAME_DURATION
 *     SENSOR_INFO_PHYSICAL_SIZE
 *     SENSOR_INFO_PIXEL_ARRAY_SIZE
 *     SENSOR_INFO_SENSITIVITY_RANGE
 *     SENSOR_INFO_TIMESTAMP_SOURCE
 *     SENSOR_INFO_WHITE_LEVEL
 *     SENSOR_MAX_ANALOG_SENSITIVITY
 *     SENSOR_OPTICAL_BLACK_REGIONS
 *     SENSOR_ORIENTATION
 *     SENSOR_REFERENCE_ILLUMINANT1
 *     SENSOR_REFERENCE_ILLUMINANT2
 */
@TargetApi(21)
abstract class Sensor_ extends Scaler_ {

    // Protected Overriding Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
```

```
80          */
81         @Override
82         protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
83                             @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                    ↪ characteristicsMap) {
84             super.read(cameraCharacteristics, characteristicsMap);
85
86             Log.e("              Sensor_", "reading Sensor_ characteristics");
87             List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();
88
89             //=====================================
                    ↪ ==================================================
90             {
91                 CameraCharacteristics.Key<int[]> key;
92                 ParameterFormatter<Integer> formatter;
93                 Parameter<Integer> property;
94
95                 String  name;
96                 Integer value;
97                 String  valueString;
98
99                 key  = CameraCharacteristics.SENSOR_AVAILABLE_TEST_PATTERN_MODES;//
                        ↪ ////////////////////////
100                name = key.getName();
101
102                if (keychain.contains(key)) {
103                    int[]  modes  = cameraCharacteristics.get(key);
104                    if (modes == null) {
105                        // TODO: error
106                        Log.e(Thread.currentThread().getName(), "Test pattern cannot be null");
107                        MasterController.quitSafely();
108                        return;
109                    }
110                    List<Integer> options = ArrayToList.convert(modes);
111
112                    Integer OFF                     = CameraMetadata.
                            ↪ SENSOR_TEST_PATTERN_MODE_OFF;
113                    //Integer SOLID_COLOR             = CameraMetadata.
                            ↪ SENSOR_TEST_PATTERN_MODE_SOLID_COLOR;
114                    //Integer COLOR_BARS              = CameraMetadata.
                            ↪ SENSOR_TEST_PATTERN_MODE_COLOR_BARS;
```

```
                //Integer COLOR_BARS_FADE_TO_GRAY = CameraMetadata.SENSOR_TEST_PATTERN_MODE_COLOR_BARS_FADE_TO_GRAY;
                //Integer PN9                     = CameraMetadata.SENSOR_TEST_PATTERN_MODE_PN9;
                //Integer CUSTOM1                 = CameraMetadata.SENSOR_TEST_PATTERN_MODE_CUSTOM1;

                value       =  OFF;
                valueString = "OFF (PREFERRED)";

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================================================================
        {
            CameraCharacteristics.Key<BlackLevelPattern> key;
            ParameterFormatter<BlackLevelPattern> formatter;
            Parameter<BlackLevelPattern> property;

            String            name;
            BlackLevelPattern value;

            key  = CameraCharacteristics.SENSOR_BLACK_LEVEL_PATTERN;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
```

```
151                 if (value == null) {
152                     // TODO: error
153                     Log.e(Thread.currentThread().getName(), "Black level pattern cannot be
                        ↪ null");
154                     MasterController.quitSafely();
155                     return;
156                 }
157
158                 formatter = new ParameterFormatter<BlackLevelPattern>() {
159                     @NonNull
160                     @Override
161                     public String formatValue(@NonNull BlackLevelPattern value) {
162                         return value.toString();
163                     }
164                 };
165                 property = new Parameter<>(name, value, null, formatter);
166             }
167             else {
168                 property = new Parameter<>(name);
169                 property.setValueString("NOT SUPPORTED");
170             }
171             characteristicsMap.put(key, property);
172         }
173         //=====================================
            ↪ ==================================================
174         {
175             CameraCharacteristics.Key<ColorSpaceTransform> key;
176             ParameterFormatter<ColorSpaceTransform> formatter;
177             Parameter<ColorSpaceTransform> property;
178
179             String              name;
180             ColorSpaceTransform value;
181
182             key  = CameraCharacteristics.SENSOR_CALIBRATION_TRANSFORM1;//
                ↪ ////////////////////////
183             name = key.getName();
184
185             if (keychain.contains(key)) {
186                 value = cameraCharacteristics.get(key);
187                 if (value == null) {
188                     // TODO: error
```

```
                    Log.e(Thread.currentThread().getName(), "Calibration transform 1 cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================================================================
        {
            CameraCharacteristics.Key<ColorSpaceTransform> key;
            ParameterFormatter<ColorSpaceTransform> formatter;
            Parameter<ColorSpaceTransform> property;

            String              name;
            ColorSpaceTransform value;

            key  = CameraCharacteristics.SENSOR_CALIBRATION_TRANSFORM2;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Calibration transform 2 cannot be null");
```

```
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<ColorSpaceTransform> key;
            ParameterFormatter<ColorSpaceTransform> formatter;
            Parameter<ColorSpaceTransform> property;

            String              name;
            ColorSpaceTransform value;

            key  = CameraCharacteristics.SENSOR_COLOR_TRANSFORM1;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Color transform 1 cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }
```

```

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==========================================================
        {
            CameraCharacteristics.Key<ColorSpaceTransform> key;
            ParameterFormatter<ColorSpaceTransform> formatter;
            Parameter<ColorSpaceTransform> property;

            String              name;
            ColorSpaceTransform value;

            key  = CameraCharacteristics.SENSOR_COLOR_TRANSFORM2;///////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Color transform 2 cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
```

```
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<ColorSpaceTransform> key;
            ParameterFormatter<ColorSpaceTransform> formatter;
            Parameter<ColorSpaceTransform> property;

            String              name;
            ColorSpaceTransform value;

            key  = CameraCharacteristics.SENSOR_FORWARD_MATRIX1;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Sensor matrix 1 cannot be null"
                        ↪ );
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
```

```
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<ColorSpaceTransform> key;
            ParameterFormatter<ColorSpaceTransform> formatter;
            Parameter<ColorSpaceTransform> property;

            String              name;
            ColorSpaceTransform value;

            key  = CameraCharacteristics.SENSOR_FORWARD_MATRIX2;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Sensor matrix 2 cannot be null"
                        ↪ );
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<ColorSpaceTransform>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull ColorSpaceTransform value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
```

```
382                 }
383                 else {
384                     property = new Parameter<>(name);
385                     property.setValueString("NOT SUPPORTED");
386                 }
387                 characteristicsMap.put(key, property);
388             }
389             //=========================================
                ↪ ==================================================
390             {
391                 CameraCharacteristics.Key<Rect> key;
392                 ParameterFormatter<Rect> formatter;
393                 Parameter<Rect> property;
394
395                 String name;
396                 Rect   value;
397                 String units;
398
399                 key   = CameraCharacteristics.SENSOR_INFO_ACTIVE_ARRAY_SIZE;//
                    ↪ ////////////////////////
400                 name  = key.getName();
401                 units = "pixel coordinates";
402
403                 if (keychain.contains(key)) {
404                     value = cameraCharacteristics.get(key);
405                     if (value == null) {
406                         // TODO: error
407                         Log.e(Thread.currentThread().getName(), "Active array size cannot be
                            ↪ null");
408                         MasterController.quitSafely();
409                         return;
410                     }
411
412                     formatter = new ParameterFormatter<Rect>() {
413                         @NonNull
414                         @Override
415                         public String formatValue(@NonNull Rect value) {
416                             return value.flattenToString();
417                         }
418                     };
419                     property = new Parameter<>(name, value, units, formatter);
```

```
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Color filter arrangement cannot
                        ↪  be null");
                    MasterController.quitSafely();
                    return;
                }

                Integer RGGB = CameraMetadata.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT_RGGB;
                Integer GRBG = CameraMetadata.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT_GRBG;
                Integer GBRG = CameraMetadata.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT_GBRG;
                Integer BGGR = CameraMetadata.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT_BGGR;
                Integer RGB  = CameraMetadata.SENSOR_INFO_COLOR_FILTER_ARRANGEMENT_RGB;

                valueString = null;
                if (value.equals(RGGB)) {
                    valueString = "RGGB";
```

```
458                 }
459                 if (value.equals(GRBG)) {
460                     valueString = "GRBG";
461                 }
462                 if (value.equals(GBRG)) {
463                     valueString = "GBRG";
464                 }
465                 if (value.equals(BGGR)) {
466                     valueString = "BGGR";
467                 }
468                 if (value.equals(RGB)) {
469                     valueString = "RGB";
470                 }
471                 if (valueString == null) {
472                     // TODO: error
473                     Log.e(Thread.currentThread().getName(), "Unknown color arrangement");
474                     MasterController.quitSafely();
475                     return;
476                 }
477
478                 formatter = new ParameterFormatter<Integer>(valueString) {
479                     @NonNull
480                     @Override
481                     public String formatValue(@NonNull Integer value) {
482                         return getValueString();
483                     }
484                 };
485                 property = new Parameter<>(name, value, null, formatter);
486             }
487             else {
488                 property = new Parameter<>(name);
489                 property.setValueString("NOT SUPPORTED");
490             }
491             characteristicsMap.put(key, property);
492         }
493         //=========================================
            ↪ ==========================================================
494         {
495             CameraCharacteristics.Key<Range<Long>> key;
496             ParameterFormatter<Range<Long>> formatter;
497             Parameter<Range<Long>> property;
```

```
            String      name;
            Range<Long> value;
            String      units;

            key   = CameraCharacteristics.SENSOR_INFO_EXPOSURE_TIME_RANGE;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "nanoseconds";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Exposure time range cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Range<Long>>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Range<Long> value) {
                        DecimalFormat nanosFormatter;
                        nanosFormatter = (DecimalFormat) NumberFormat.getInstance(Locale.US)
                            ↪ ;
                        return "( " + nanosFormatter.format(value.getLower()) + " to "
                                    + nanosFormatter.format(value.getUpper()) + " )";
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
```

```
535         {
536             CameraCharacteristics.Key<Boolean> key;
537             ParameterFormatter<Boolean> formatter;
538             Parameter<Boolean> property;
539
540             String name;
541             Boolean value;
542
543             if (Build.VERSION.SDK_INT >= 23) {
544                 key  = CameraCharacteristics.SENSOR_INFO_LENS_SHADING_APPLIED;//
                    ↪ ////////////////////////
545                 name = key.getName();
546
547                 if (keychain.contains(key)) {
548                     value = cameraCharacteristics.get(key);
549                     if (value == null) {
550                         // TODO: error
551                         Log.e(Thread.currentThread().getName(), "Lens shading cannot be null
                            ↪ ");
552                         MasterController.quitSafely();
553                         return;
554                     }
555
556                     formatter = new ParameterFormatter<Boolean>() {
557                         @NonNull
558                         @Override
559                         public String formatValue(@NonNull Boolean value) {
560                             if (value) {
561                                 return "YES";
562                             }
563                             return "NO";
564                         }
565                     };
566                     property = new Parameter<>(name, value, null, formatter);
567                 }
568                 else {
569                     property = new Parameter<>(name);
570                     property.setValueString("NOT SUPPORTED");
571                 }
572                 characteristicsMap.put(key, property);
573             }
```

```
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Long> key;
            ParameterFormatter<Long> formatter;
            Parameter<Long> property;

            String name;
            Long   value;
            String units;

            key   = CameraCharacteristics.SENSOR_INFO_MAX_FRAME_DURATION;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "nanoseconds";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Max frame duration cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Long>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Long value) {
                        DecimalFormat nanosFormatter;
                        nanosFormatter = (DecimalFormat) NumberFormat.getInstance(Locale.US)
                            ↪ ;
                        return nanosFormatter.format(value);
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
```

```
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<SizeF> key;
            ParameterFormatter<SizeF> formatter;
            Parameter<SizeF> property;

            String name;
            SizeF  value;
            String units;

            key   = CameraCharacteristics.SENSOR_INFO_PHYSICAL_SIZE;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "millimeters";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Physical size cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<SizeF>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull SizeF value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
```

```
650                 }
651                 characteristicsMap.put(key, property);
652             }
653             //=========================================
                ↪ ==================================================
654             {
655                 CameraCharacteristics.Key<Size> key;
656                 ParameterFormatter<Size> formatter;
657                 Parameter<Size> property;
658
659                 String name;
660                 Size   value;
661                 String units;
662
663                 key   = CameraCharacteristics.SENSOR_INFO_PIXEL_ARRAY_SIZE;//
                    ↪ ////////////////////////
664                 name  = key.getName();
665                 units = "pixels";
666
667                 if (keychain.contains(key)) {
668                     value = cameraCharacteristics.get(key);
669                     if (value == null) {
670                         // TODO: error
671                         Log.e(Thread.currentThread().getName(), "Array size cannot be null");
672                         MasterController.quitSafely();
673                         return;
674                     }
675
676                     formatter = new ParameterFormatter<Size>() {
677                         @NonNull
678                         @Override
679                         public String formatValue(@NonNull Size value) {
680                             return value.toString();
681                         }
682                     };
683                     property = new Parameter<>(name, value, units, formatter);
684                 }
685                 else {
686                     property = new Parameter<>(name);
687                     property.setValueString("NOT SUPPORTED");
688                 }
```

```
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Rect> key;
            ParameterFormatter<Rect> formatter;
            Parameter<Rect> property;

            String name;
            Rect value;
            String units;

            if (Build.VERSION.SDK_INT >= 23) {
                key   = CameraCharacteristics.SENSOR_INFO_PRE_CORRECTION_ACTIVE_ARRAY_SIZE;
                    ↪ /////////
                name  = key.getName();
                units = "pixel coordinates";

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Pre-correction array size
                            ↪ cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Rect>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Rect value) {
                            return value.flattenToString();
                        }
                    };
                    property = new Parameter<>(name, value, units, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
```

```
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Range<Integer>> key;
            ParameterFormatter<Range<Integer>> formatter;
            Parameter<Range<Integer>> property;

            String         name;
            Range<Integer> value;
            String         units;

            key   = CameraCharacteristics.SENSOR_INFO_SENSITIVITY_RANGE;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "ISO";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Sensitivity range cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Range<Integer>>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Range<Integer> value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
```

```
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
            //=========================================
                ↪ ==================================================
            {
                CameraCharacteristics.Key<Integer> key;
                ParameterFormatter<Integer> formatter;
                Parameter<Integer> property;

                String  name;
                Integer value;
                String  valueString;

                key  = CameraCharacteristics.SENSOR_INFO_TIMESTAMP_SOURCE;//
                    ↪ ////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Timestamp source cannot be null
                            ↪ ");
                        MasterController.quitSafely();
                        return;
                    }

                    Integer UNKNOWN  = CameraMetadata.SENSOR_INFO_TIMESTAMP_SOURCE_UNKNOWN;
                    Integer REALTIME = CameraMetadata.SENSOR_INFO_TIMESTAMP_SOURCE_REALTIME;

                    if (value.equals(UNKNOWN)) {
                        valueString = "UNKNOWN";
                    }
                    else {
                        valueString = "REALTIME";
                    }

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
```

```
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;

            key  = CameraCharacteristics.SENSOR_INFO_WHITE_LEVEL;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "White level cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return value.toString();
                    }
```

```
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
            //=========================================
                ↪ ==================================================
            {
                CameraCharacteristics.Key<Integer> key;
                ParameterFormatter<Integer> formatter;
                Parameter<Integer> property;

                String  name;
                Integer value;
                String  units;

                key   = CameraCharacteristics.SENSOR_MAX_ANALOG_SENSITIVITY;//
                    ↪ ////////////////////////
                name  = key.getName();
                units = "ISO";

                if (keychain.contains(key)) {
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Analog sensitivity cannot be
                            ↪ null");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Integer>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return value.toString();
                        }
```

```
                    };
                    property = new Parameter<>(name, value, units, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
            //=========================================
                ↪ ======================================================
            {
                CameraCharacteristics.Key<Rect[]> key;
                ParameterFormatter<Rect[]> formatter;
                Parameter<Rect[]> property;

                String name;
                Rect[] value;
                String units;

                if (Build.VERSION.SDK_INT >= 24) {
                    key   = CameraCharacteristics.SENSOR_OPTICAL_BLACK_REGIONS;//
                        ↪ ////////////////////////
                    name  = key.getName();
                    units = "pixel coordinates";

                    if (keychain.contains(key)) {
                        value = cameraCharacteristics.get(key);
                        if (value == null) {
                            // TODO: error
                            Log.e(Thread.currentThread().getName(), "Black regions cannot be
                                ↪ null");
                            MasterController.quitSafely();
                            return;
                        }

                        formatter = new ParameterFormatter<Rect[]>() {
                            @NonNull
                            @Override
                            public String formatValue(@NonNull Rect[] value) {
                                String out = "( ";
```

```
                            for (Rect rect : value) {
                                out += rect.flattenToString() + " ";
                            }
                            return out + ")";
                        }
                    };
                    property = new Parameter<>(name, value, units, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  units;

            key   = CameraCharacteristics.SENSOR_ORIENTATION;//////////////////////////
            name  = key.getName();
            units = "degrees clockwise";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Orientation cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>() {
                    @NonNull
```

```
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.SENSOR_REFERENCE_ILLUMINANT1;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {

                Integer DAYLIGHT               = CameraMetadata.
                    ↪ SENSOR_REFERENCE_ILLUMINANT1_DAYLIGHT;
                Integer FLUORESCENT            = CameraMetadata.
                    ↪ SENSOR_REFERENCE_ILLUMINANT1_FLUORESCENT;
                Integer TUNGSTEN               = CameraMetadata.
                    ↪ SENSOR_REFERENCE_ILLUMINANT1_TUNGSTEN;
                Integer FLASH                  = CameraMetadata.
                    ↪ SENSOR_REFERENCE_ILLUMINANT1_FLASH;
                Integer FINE_WEATHER           = CameraMetadata.
                    ↪ SENSOR_REFERENCE_ILLUMINANT1_FINE_WEATHER;
```

```
992                 Integer CLOUDY_WEATHER         = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_CLOUDY_WEATHER;
993                 Integer SHADE                  = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_SHADE;
994                 Integer DAYLIGHT_FLUORESCENT   = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_DAYLIGHT_FLUORESCENT;
995                 Integer DAY_WHITE_FLUORESCENT  = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_DAY_WHITE_FLUORESCENT;
996                 Integer COOL_WHITE_FLUORESCENT = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_COOL_WHITE_FLUORESCENT;
997                 Integer WHITE_FLUORESCENT      = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_WHITE_FLUORESCENT;
998                 Integer STANDARD_A             = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_A;
999                 Integer STANDARD_B             = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_B;
1000                Integer STANDARD_C             = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_C;
1001                Integer D55                    = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_D55;
1002                Integer D65                    = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_D65;
1003                Integer D75                    = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_D75;
1004                Integer D50                    = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_D50;
1005                Integer ISO_STUDIO_TUNGSTEN    = CameraMetadata.
                        ↪ SENSOR_REFERENCE_ILLUMINANT1_ISO_STUDIO_TUNGSTEN;
1006
1007                value = cameraCharacteristics.get(key);
1008                if (value == null) {
1009                    // TODO: error
1010                    Log.e(Thread.currentThread().getName(), "Illumination reference cannot
                            ↪ be null");
1011                    MasterController.quitSafely();
1012                    return;
1013                }
1014
1015                valueString = null;
1016                if (value.equals(DAYLIGHT)) {
1017                    valueString = "DAYLIGHT";
```

```
                }
                if (value.equals(FLUORESCENT)) {
                    valueString = "FLUORESCENT";
                }
                if (value.equals(TUNGSTEN)) {
                    valueString = "TUNGSTEN";
                }
                if (value.equals(FLASH)) {
                    valueString = "FLASH";
                }
                if (value.equals(FINE_WEATHER)) {
                    valueString = "FINE_WEATHER";
                }
                if (value.equals(CLOUDY_WEATHER)) {
                    valueString = "CLOUDY_WEATHER";
                }
                if (value.equals(SHADE)) {
                    valueString = "SHADE";
                }
                if (value.equals(DAYLIGHT_FLUORESCENT)) {
                    valueString = "DAYLIGHT_FLUORESCENT";
                }
                if (value.equals(DAY_WHITE_FLUORESCENT)) {
                    valueString = "DAY_WHITE_FLUORESCENT";
                }
                if (value.equals(COOL_WHITE_FLUORESCENT)) {
                    valueString = "COOL_WHITE_FLUORESCENT";
                }
                if (value.equals(WHITE_FLUORESCENT)) {
                    valueString = "WHITE_FLUORESCENT";
                }
                if (value.equals(STANDARD_A)) {
                    valueString = "STANDARD_A";
                }
                if (value.equals(STANDARD_B)) {
                    valueString = "STANDARD_B";
                }
                if (value.equals(STANDARD_C)) {
                    valueString = "STANDARD_C";
                }
                if (value.equals(D55)) {
```

```
                    valueString = "D55";
                }
                if (value.equals(D65)) {
                    valueString = "D65";
                }
                if (value.equals(D75)) {
                    valueString = "D75";
                }
                if (value.equals(D50)) {
                    valueString = "D50";
                }
                if (value.equals(ISO_STUDIO_TUNGSTEN)) {
                    valueString = "ISO_STUDIO_TUNGSTEN";
                }
                if (valueString == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Unknown illumination reference" );
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================================================================
        {
            CameraCharacteristics.Key<Byte> key;
```

```
1098                ParameterFormatter<Byte> formatter;
1099                Parameter<Byte> property;
1100
1101                String name;
1102                Byte   value;
1103                String valueString;
1104
1105                key  = CameraCharacteristics.SENSOR_REFERENCE_ILLUMINANT2;//
                        ↪ ////////////////////////
1106                name = key.getName();
1107
1108                if (keychain.contains(key)) {
1109                    value = cameraCharacteristics.get(key);
1110                    if (value == null) {
1111                        // TODO: error
1112                        Log.e(Thread.currentThread().getName(), "Illumination reference 2 cannot
                            ↪  be null");
1113                        MasterController.quitSafely();
1114                        return;
1115                    }
1116
1117                    Integer DAYLIGHT               = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_DAYLIGHT;
1118                    Integer FLUORESCENT            = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_FLUORESCENT;
1119                    Integer TUNGSTEN               = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_TUNGSTEN;
1120                    Integer FLASH                  = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_FLASH;
1121                    Integer FINE_WEATHER           = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_FINE_WEATHER;
1122                    Integer CLOUDY_WEATHER         = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_CLOUDY_WEATHER;
1123                    Integer SHADE                  = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_SHADE;
1124                    Integer DAYLIGHT_FLUORESCENT   = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_DAYLIGHT_FLUORESCENT;
1125                    Integer DAY_WHITE_FLUORESCENT  = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_DAY_WHITE_FLUORESCENT;
1126                    Integer COOL_WHITE_FLUORESCENT = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_COOL_WHITE_FLUORESCENT;
```

```
1127                    Integer WHITE_FLUORESCENT      = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_WHITE_FLUORESCENT;
1128                    Integer STANDARD_A             = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_A;
1129                    Integer STANDARD_B             = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_B;
1130                    Integer STANDARD_C             = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_STANDARD_C;
1131                    Integer D55                    = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_D55;
1132                    Integer D65                    = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_D65;
1133                    Integer D75                    = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_D75;
1134                    Integer D50                    = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_D50;
1135                    Integer ISO_STUDIO_TUNGSTEN    = CameraMetadata.
                            ↪ SENSOR_REFERENCE_ILLUMINANT1_ISO_STUDIO_TUNGSTEN;
1136
1137                    valueString = null;
1138                    Integer valueInteger = value.intValue();
1139                    if (valueInteger.equals(DAYLIGHT)) {
1140                        valueString = "DAYLIGHT";
1141                    }
1142                    if (valueInteger.equals(FLUORESCENT)) {
1143                        valueString = "FLUORESCENT";
1144                    }
1145                    if (valueInteger.equals(TUNGSTEN)) {
1146                        valueString = "TUNGSTEN";
1147                    }
1148                    if (valueInteger.equals(FLASH)) {
1149                        valueString = "FLASH";
1150                    }
1151                    if (valueInteger.equals(FINE_WEATHER)) {
1152                        valueString = "FINE_WEATHER";
1153                    }
1154                    if (valueInteger.equals(CLOUDY_WEATHER)) {
1155                        valueString = "CLOUDY_WEATHER";
1156                    }
1157                    if (valueInteger.equals(SHADE)) {
1158                        valueString = "SHADE";
```

```
1159                    }
1160                    if (valueInteger.equals(DAYLIGHT_FLUORESCENT)) {
1161                        valueString = "DAYLIGHT_FLUORESCENT";
1162                    }
1163                    if (valueInteger.equals(DAY_WHITE_FLUORESCENT)) {
1164                        valueString = "DAY_WHITE_FLUORESCENT";
1165                    }
1166                    if (valueInteger.equals(COOL_WHITE_FLUORESCENT)) {
1167                        valueString = "COOL_WHITE_FLUORESCENT";
1168                    }
1169                    if (valueInteger.equals(WHITE_FLUORESCENT)) {
1170                        valueString = "WHITE_FLUORESCENT";
1171                    }
1172                    if (valueInteger.equals(STANDARD_A)) {
1173                        valueString = "STANDARD_A";
1174                    }
1175                    if (valueInteger.equals(STANDARD_B)) {
1176                        valueString = "STANDARD_B";
1177                    }
1178                    if (valueInteger.equals(STANDARD_C)) {
1179                        valueString = "STANDARD_C";
1180                    }
1181                    if (valueInteger.equals(D55)) {
1182                        valueString = "D55";
1183                    }
1184                    if (valueInteger.equals(D65)) {
1185                        valueString = "D65";
1186                    }
1187                    if (valueInteger.equals(D75)) {
1188                        valueString = "D75";
1189                    }
1190                    if (valueInteger.equals(D50)) {
1191                        valueString = "D50";
1192                    }
1193                    if (valueInteger.equals(ISO_STUDIO_TUNGSTEN)) {
1194                        valueString = "ISO_STUDIO_TUNGSTEN";
1195                    }
1196                    if (valueString == null) {
1197                        // TODO: error
1198                        Log.e(Thread.currentThread().getName(), "Unknown illumination reference
                            ↪ 2");
```

```
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Byte>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Byte value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.38: Shading Characteristics (`camera2/characteristics/Shading_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    SHADING_AVAILABLE_MODES
 */
@TargetApi(21)
```

```
abstract class Shading_ extends Sensor_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("             Shading_", "reading Shading_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.SHADING_AVAILABLE_MODES;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    int[]  modes  = cameraCharacteristics.get(key);
                    if (modes == null) {
                        // TODO: error
```

```
                        Log.e(Thread.currentThread().getName(), "Shading modes cannot be null");
                        MasterController.quitSafely();
                        return;
                    }
                    List<Integer> options = ArrayToList.convert(modes);

                    Integer OFF          = CameraMetadata.SHADING_MODE_OFF;
                    Integer FAST         = CameraMetadata.SHADING_MODE_FAST;
                    //Integer HIGH_QUALITY = CameraMetadata.SHADING_MODE_HIGH_QUALITY;

                    if (options.contains(OFF)) {
                        value       =  OFF;
                        valueString = "OFF (PREFERRED)";
                    }
                    else {
                        value       =  FAST;
                        valueString = "FAST (FALLBACK)";
                    }

                    if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                        value       =  FAST;
                        valueString = "FAST (WORST CONFIGURATION)";
                    }

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
```

```
            //==========================================
                ↪ ==========================================================
        }

}
```

Listing E.39: Statistics Characteristics (`camera2/characteristics/Statistics_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *     STATISTICS_INFO_AVAILABLE_FACE_DETECT_MODES
 *     STATISTICS_INFO_AVAILABLE_HOT_PIXEL_MAP_MODES
 *     STATISTICS_INFO_AVAILABLE_OIS_DATA_MODES
 *     STATISTICS_INFO_MAX_FACE_COUNT
```

```
 */
@TargetApi(21)
abstract class Statistics_ extends Shading_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("          Statistics_", "reading Statistics_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.STATISTICS_INFO_AVAILABLE_FACE_DETECT_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
```

```
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Face detect modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }
                List<Integer> options = ArrayToList.convert(modes);

                Integer OFF    = CameraMetadata.STATISTICS_FACE_DETECT_MODE_OFF;
                //Integer SIMPLE = CameraMetadata.STATISTICS_FACE_DETECT_MODE_SIMPLE;
                //Integer FULL   = CameraMetadata.STATISTICS_FACE_DETECT_MODE_FULL;

                value       =  OFF;
                valueString = "OFF (PREFERRED)";

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================================================================
        {
            CameraCharacteristics.Key<boolean[]> key;
            ParameterFormatter<Boolean[]> formatter;
            Parameter<Boolean[]> property;

            String    name;
            Boolean[] value;

```

```
            key  = CameraCharacteristics.STATISTICS_INFO_AVAILABLE_HOT_PIXEL_MAP_MODES;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                boolean[] modes  = cameraCharacteristics.get(key);
                if (   modes == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Hot pixel map modes cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                value = ArrayToList.convert(modes).toArray(new Boolean[0]);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Hot pixel map modes cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Boolean[]>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Boolean[] value) {
                        String out = "( ";
                        int length = value.length;
                        for (int i = 0; i < length; i++) {
                            if (value[i]) {
                                out += "YES";
                            }
                            else {
                                out += "NO";
                            }
                            if (i < length - 1) {
                                out += ", ";
                            }
                        }
                        return out + " )";
```

```
                    }
                };
                property = new Parameter<>(name, value, null, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String name;
            Integer value;
            String valueString;

            if (Build.VERSION.SDK_INT >= 23) {
                key  = CameraCharacteristics.
                    ↪ STATISTICS_INFO_AVAILABLE_LENS_SHADING_MAP_MODES;//////
                name = key.getName();

                if (keychain.contains(key)) {
                    int[] modes = cameraCharacteristics.get(key);
                    if (modes == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Shading map modes cannot be
                            ↪  null");
                        MasterController.quitSafely();
                        return;
                    }
                    //List<Integer> options = ArrayToList.convert(modes);

                    Integer OFF = CameraMetadata.STATISTICS_LENS_SHADING_MAP_MODE_OFF;
                    //Integer ON  = CameraMetadata.STATISTICS_LENS_SHADING_MAP_MODE_ON;

                    value = OFF;
```

```
                    valueString = "OFF (PREFERRED)";

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=========================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 28) {
                key  = CameraCharacteristics.STATISTICS_INFO_AVAILABLE_OIS_DATA_MODES;//////////////////////////
                name = key.getName();

                if (keychain.contains(key)) {
                    int[] modes = cameraCharacteristics.get(key);
                    if (modes == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "OIS data modes cannot be null");
                        MasterController.quitSafely();
```

```
                        return;
                    }
                    //List<Integer> options = ArrayToList.convert(modes);

                    Integer OFF = CameraMetadata.STATISTICS_OIS_DATA_MODE_OFF;
                    //Integer ON  = CameraMetadata.STATISTICS_OIS_DATA_MODE_ON;

                    value = OFF;
                    valueString = "OFF (PREFERRED)";

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
        }
        //=====================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;

            key  = CameraCharacteristics.STATISTICS_INFO_MAX_FACE_COUNT;//
                ↪ ////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
```

```
                    value = cameraCharacteristics.get(key);
                    if (value == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Max face count cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    formatter = new ParameterFormatter<Integer>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return value.toString();
                        }
                    };
                    property = new Parameter<>(name, value, null, formatter);
                }
                else {
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
            //=========================================================================================
        }

    }
```

Listing E.40: Sync Characteristics (`camera2/characteristics/Sync_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    SYNC_MAX_LATENCY
 */
@TargetApi(21)
abstract class Sync_ extends Statistics_ {

    // Protected Overriding Instance Methods
```

```
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("                Sync_", "reading Sync_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;
            String  units;

            key   = CameraCharacteristics.SYNC_MAX_LATENCY;//////////////////////////
            name  = key.getName();
            units = "frame counts";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Max latency cannot be null");
                    MasterController.quitSafely();
                    return;
```

```
                }

                Integer PER_FRAME_CONTROL = CameraMetadata.
                    ↪ SYNC_MAX_LATENCY_PER_FRAME_CONTROL;
                Integer UNKNOWN           = CameraMetadata.SYNC_MAX_LATENCY_UNKNOWN;

                if (value.equals(PER_FRAME_CONTROL)) {
                    valueString = "PER_FRAME_CONTROL";
                }
                else if (value.equals(UNKNOWN)){
                    valueString = "UNKNOWN";
                }
                else {
                    valueString = value.toString();
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
    }

}
```

Listing E.41: Tonemap Characteristics (`camera2/characteristics/Tonemap_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.characteristics;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * A specialized class for discovering camera abilities, the parameters searched for include:
 *    TONEMAP_AVAILABLE_TONE_MAP_MODES
 *    TONEMAP_MAX_CURVE_POINTS
 */
```

```
@TargetApi(21)
abstract class Tonemap_ extends Sync_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // read..............
    /**
     * Continue discovering abilities with specialized classes
     * @param cameraCharacteristics Encapsulation of camera abilities
     * @param characteristicsMap A mapping of characteristics names to their respective parameter options
     */
    @Override
    protected void read(@NonNull CameraCharacteristics cameraCharacteristics,
                        @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap) {
        super.read(cameraCharacteristics, characteristicsMap);

        Log.e("            Tonemap_", "reading Tonemap_ characteristics");
        List<CameraCharacteristics.Key<?>> keychain = cameraCharacteristics.getKeys();

        //=====================================================================================
        {
            CameraCharacteristics.Key<int[]> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  valueString;

            key  = CameraCharacteristics.TONEMAP_AVAILABLE_TONE_MAP_MODES;//////////////////////////
            name = key.getName();

            if (keychain.contains(key)) {
                int[]  modes  = cameraCharacteristics.get(key);
                if (modes == null) {
                    // TODO: error
```

```
77                      Log.e(Thread.currentThread().getName(), "Tone map modes cannot be null")
                            ↪ ;
78                      MasterController.quitSafely();
79                      return;
80                  }
81                  List<Integer> options = ArrayToList.convert(modes);
82
83                  Integer CONTRAST_CURVE = CameraMetadata.TONEMAP_MODE_CONTRAST_CURVE;
84                  Integer FAST           = CameraMetadata.TONEMAP_MODE_FAST;
85                  //Integer HIGH_QUALITY   = CameraMetadata.TONEMAP_MODE_HIGH_QUALITY;
86                  //Integer GAMMA_VALUE    = null;
87                  //Integer PRESET_CURVE   = null;
88                  //if (Build.VERSION.SDK_INT >= 23) {
89                  //    GAMMA_VALUE  = CameraMetadata.TONEMAP_MODE_GAMMA_VALUE;
90                  //    PRESET_CURVE = CameraMetadata.TONEMAP_MODE_PRESET_CURVE;
91                  //}
92
93                  if (options.contains(CONTRAST_CURVE)) {
94                      value = CONTRAST_CURVE;
95                      valueString = "CONTRAST_CURVE (PREFERRED)";
96                  }
97                  else {
98                      value = FAST;
99                      valueString = "FAST (FALLBACK)";
100                 }
101
102                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
103                     value = FAST;
104                     valueString = "FAST (WORST CONFIGURATION)";
105                 }
106
107                 formatter = new ParameterFormatter<Integer>(valueString) {
108                     @NonNull
109                     @Override
110                     public String formatValue(@NonNull Integer value) {
111                         return getValueString();
112                     }
113                 };
114                 property = new Parameter<>(name, value, null, formatter);
115             }
116             else {
```

```
                property = new Parameter<>(name);
                property.setValueString("NOT SUPPORTED");
            }
            characteristicsMap.put(key, property);
        }
        //=========================================
            ↪ ==================================================
        {
            CameraCharacteristics.Key<Integer> key;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> property;

            String  name;
            Integer value;
            String  units;

            key   = CameraCharacteristics.TONEMAP_MAX_CURVE_POINTS;//
                ↪ ////////////////////////
            name  = key.getName();
            units = "curve points";

            if (keychain.contains(key)) {
                value = cameraCharacteristics.get(key);
                if (value == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Max curve points cannot be null
                        ↪ ");
                    MasterController.quitSafely();
                    return;
                }

                formatter = new ParameterFormatter<Integer>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return value.toString();
                    }
                };
                property = new Parameter<>(name, value, units, formatter);
            }
            else {
```

```
                    property = new Parameter<>(name);
                    property.setValueString("NOT SUPPORTED");
                }
                characteristicsMap.put(key, property);
            }
            //=========================================
                ↪ ==================================================
        }

    }
```

Listing E.42: Capture Request Maker (`camera2/requests/RequestMaker.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraAccessException;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraDevice;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * Public access to building a CaptureRequest using optimal settings for the current
     ↪ hardware
 */
```

```
@TargetApi(21)
final public class RequestMaker extends step16_Tonemap_ {

    // Private Class Constants
    //::::::::::::::::::::::

    // mInstance..............
    // Reference to single instance of this class
    private final static RequestMaker mInstance = new RequestMaker();

    ///////////////////////////
    //::::::::::::::::::::::
    ///////////////////////////

    //***********************************************
        ↪ ***********************************************
    // Constructors
    //————————————

    // Private
    //::::::::::::::::::::::

    // RequestMaker..............
    /**
     * Disabled
     */
    private RequestMaker() {}

    // Public Class Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Loads an optimized CaptureRequest into the active Camera
     */
    // Quiet compiler — TODO: not sure what causes this
    @SuppressWarnings("unchecked")
    public static void makeDefault() {

        LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap = new LinkedHashMap
            ↪ <>();
```

```
79
80          CameraDevice cameraDevice = CameraController.getOpenedCameraDevice();
81          if (cameraDevice == null) {
82              // TODO: error
83              Log.e(Thread.currentThread().getName(), "Camera device cannot be null");
84              MasterController.quitSafely();
85              return;
86          }
87
88          LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap;
89          characteristicsMap = CameraController.getOpenedCharacteristicsMap();
90          if (characteristicsMap == null) {
91              // TODO: error
92              Log.e(Thread.currentThread().getName(), "Characteristics map cannot be null");
93              MasterController.quitSafely();
94              return;
95          }
96
97          List<CaptureRequest.Key<?>> supportedKeys;
98          supportedKeys = CameraController.getAvailableCaptureRequestKeys();
99          if (supportedKeys == null) {
100             // TODO: error
101             Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
102             MasterController.quitSafely();
103             return;
104         }
105
106         //=========================================
            ↪ ====================================================
107
108         int template;//////////////////////////
109         {
110             CameraCharacteristics.Key<int[]> key;
111             Parameter<Integer[]> parameter;
112
113             key = CameraCharacteristics.REQUEST_AVAILABLE_CAPABILITIES;
114
115             parameter = characteristicsMap.get(key);
116             if (parameter == null) {
117                 // TODO: error
```

```
                Log.e(Thread.currentThread().getName(), "CameraCharacteristics.
                    ↪ REQUEST_AVAILABLE_CAPABILITIES cannot be null");
                MasterController.quitSafely();
                return;
            }

            Integer[] capabilities = parameter.getValue();
            if (capabilities == null) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), "Capabilities array cannot be null")
                    ↪ ;
                MasterController.quitSafely();
                return;
            }
            List<Integer> abilities = ArrayToList.convert(capabilities);

            if (abilities.contains(CameraMetadata.
                ↪ REQUEST_AVAILABLE_CAPABILITIES_MANUAL_SENSOR)) {
                template = CameraDevice.TEMPLATE_MANUAL;
            } else {
                template = CameraDevice.TEMPLATE_PREVIEW;
            }
        }

        //=========================================
            ↪ ==================================================

        CaptureRequest.Builder builder = null;//////////////////////////
        try {
            builder = cameraDevice.createCaptureRequest(template);
        }
        catch (CameraAccessException e) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Camera cannot be accessed");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================

```

```
154         // Pass to superclasses to complete the build
155         mInstance.makeDefault(builder, characteristicsMap, captureRequestMap);
156 
157         CameraController.setCaptureRequestTemplate(template);
158         CameraController.setCaptureRequestBuilder(builder);
159         CameraController.setCaptureRequestMap(captureRequestMap);
160     }
161 
162     // write...............
163     /**
164      * Display the CaptureRequest details, called from Camera
165      * @param label (Optional) Custom title
166      * @param map Details of CaptureRequest in terms of Parameters<T>
167      * @param keychain (Optional) All keys that potentially can be set
168      */
169     public static void write(@Nullable String label,
170                              @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> map,
171                              @Nullable List<CaptureRequest.Key<?>> keychain) {
172 
173         if (label == null) {
174             label = "RequestMaker";
175         }
176 
177         Log.e(Thread.currentThread().getName(), " \n\n\t\t" + label + " Camera Capture
            ↪ Request Summary:\n\n");
178         for (Parameter parameter : map.values()) {
179             Log.e(Thread.currentThread().getName(), parameter.toString());
180         }
181 
182         if (keychain != null) {
183             Log.e(Thread.currentThread().getName(), "Keys unset:\n");
184             for (CaptureRequest.Key<?> key : keychain) {
185                 if (!map.containsKey(key)) {
186                     Log.e(Thread.currentThread().getName(), key.getName());
187                 }
188             }
189         }
190         Log.e(Thread.currentThread().getName(), " \n\n ");
191     }
192 
193     // Protected Overriding Instance Methods
```

```
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Continue creating a default CaptureRequest with specialized super classes
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);
    }

}
```

Listing E.43: Control Request (`camera2/requests/step01_Control_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.hardware.camera2.params.MeteringRectangle;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Range;

import org.apache.commons.math3.exception.MathInternalError;

import java.util.LinkedHashMap;
import java.util.List;

import javax.microedition.khronos.opengles.GL;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
```

```
import sci.crayfis.shramp.util.ArrayToList;

/**
 * Super-most class for default CaptureRequest creation, these parameters are set first and
     ↪ include:
 *     CONTROL_MODE
 *     CONTROL_CAPTURE_INTENT
 *     CONTROL_AWB_MODE
 *     CONTROL_AWB_LOCK
 *     CONTROL_AWB_REGIONS
 *     CONTROL_AF_MODE
 *     CONTROL_AF_REGIONS
 *     CONTROL_AF_TRIGGER
 *     CONTROL_AE_MODE
 *     CONTROL_AE_LOCK
 *     CONTROL_AE_REGIONS
 *     CONTROL_AE_PRECAPTURE_TRIGGER
 *     CONTROL_AE_ANTIBANDING_MODE
 *     CONTROL_AE_EXPOSURE_COMPENSATION
 *     CONTROL_AE_TARGET_FPS_RANGE
 *     CONTROL_EFFECT_MODE
 *     CONTROL_ENABLE_ZSL
 *     CONTROL_POST_RAW_SENSITIVITY_BOOST
 *     CONTROL_SCENE_MODE
 *     CONTROL_VIDEO_STABILIZATION_MODE
 */
@TargetApi(21)
abstract class step01_Control_ {

    // Protected Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting CONTROL_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
```

```
                                @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap,
                                @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap) {

        Log.e("             Control_", "setting default Control_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.CONTROL_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> property;

                Integer OFF            = CameraMetadata.CONTROL_MODE_OFF;
                Integer AUTO           = CameraMetadata.CONTROL_MODE_AUTO;
                //Integer USE_SCENE_MODE = CameraMetadata.CONTROL_MODE_USE_SCENE_MODE;
                //Integer OFF_KEEP_STATE = CameraMetadata.CONTROL_MODE_OFF_KEEP_STATE;

                if (GlobalSettings.FORCE_CONTROL_MODE_AUTO) {
                    value = AUTO;
                    valueString = "AUTO (FORCED)";
```

```
                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    setting = new Parameter<>(name, value, null, formatter);
                }
                else if (Build.VERSION.SDK_INT >= 23) {
                    CameraCharacteristics.Key<int[]> cKey;
                    cKey = CameraCharacteristics.CONTROL_AVAILABLE_MODES;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Control available modes cannot null");
                        MasterController.quitSafely();
                        return;
                    }

                    setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                                    property.getFormatter());
                }
                else {
                    CameraCharacteristics.Key<Integer> cKey;
                    cKey = CameraCharacteristics.INFO_SUPPORTED_HARDWARE_LEVEL;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Supported hardware level cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    if (property.toString().equals("LEGACY")
                            || property.toString().equals("EXTERNAL")) {
```

```

                        value = AUTO;
                        valueString = "AUTO (FALLBACK)";
                    } else {
                        value = OFF;
                        valueString = "OFF (PREFERRED)";
                    }
                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    setting = new Parameter<>(name, value, null, formatter);
                }
                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.CONTROL_CAPTURE_INTENT;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
```

```
195                 Parameter<Integer[]> properties;
196
197                 cKey = CameraCharacteristics.REQUEST_AVAILABLE_CAPABILITIES;
198                 properties = characteristicsMap.get(cKey);
199                 if (properties == null) {
200                     // TODO: error
201                     Log.e(Thread.currentThread().getName(), "Available capabilities cannot
                        ↪ be null");
202                     MasterController.quitSafely();
203                     return;
204                 }
205
206                 Integer[] capabilities = properties.getValue();
207                 if (capabilities == null) {
208                     // TODO: error
209                     Log.e(Thread.currentThread().getName(), "Capabilities cannot be null");
210                     MasterController.quitSafely();
211                     return;
212                 }
213                 List<Integer> abilities = ArrayToList.convert(capabilities);
214
215                 //Integer CUSTOM           = CameraMetadata.CONTROL_CAPTURE_INTENT_CUSTOM;
216                 Integer PREVIEW          = CameraMetadata.CONTROL_CAPTURE_INTENT_PREVIEW;
217                 //Integer STILL_CAPTURE    = CameraMetadata.
                    ↪ CONTROL_CAPTURE_INTENT_STILL_CAPTURE;
218                 //Integer VIDEO_RECORD     = CameraMetadata.
                    ↪ CONTROL_CAPTURE_INTENT_VIDEO_RECORD;
219                 //Integer VIDEO_SNAPSHOT   = CameraMetadata.
                    ↪ CONTROL_CAPTURE_INTENT_VIDEO_SNAPSHOT;
220                 //Integer ZERO_SHUTTER_LAG = CameraMetadata.
                    ↪ CONTROL_CAPTURE_INTENT_ZERO_SHUTTER_LAG;
221                 Integer MANUAL           = CameraMetadata.CONTROL_CAPTURE_INTENT_MANUAL;
222                 //Integer MOTION_TRACKING  = CameraMetadata.
                    ↪ CONTROL_CAPTURE_INTENT_MOTION_TRACKING;
223
224                 if (abilities.contains(CameraMetadata.
                    ↪ REQUEST_AVAILABLE_CAPABILITIES_MANUAL_SENSOR)) {
225                     value = MANUAL;
226                     valueString = "MANUAL (PREFERRED)";
227                 }
228                 else {
```

```
                    value = PREVIEW;
                    valueString = "PREVIEW (FALLBACK)";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, value, null, formatter);

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================================
        //                                    Auto-white Balance
        //=========================================================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.CONTROL_AWB_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> property;
```

```
268
269                     Parameter<Integer> mode;
270                     mode = captureRequestMap.get(CaptureRequest.CONTROL_MODE);
271                     if (mode == null) {
272                         // TODO: error
273                         Log.e(Thread.currentThread().getName(), "Control mode cannot be null");
274                         MasterController.quitSafely();
275                         return;
276                     }
277
278                     if (GlobalSettings.FORCE_CONTROL_MODE_AUTO) {
279                         value = CameraMetadata.CONTROL_AWB_MODE_AUTO;
280                         valueString = "AUTO (FORCED)";
281                         formatter = new ParameterFormatter<Integer>(valueString) {
282                             @NonNull
283                             @Override
284                             public String formatValue(@NonNull Integer value) {
285                                 return getValueString();
286                             }
287                         };
288                         setting = new Parameter<>(name, value, null, formatter);
289                         builder.set(rKey, setting.getValue());
290                     }
291                     else if (mode.toString().contains("AUTO")) {
292                         CameraCharacteristics.Key<int[]> cKey;
293
294                         cKey = CameraCharacteristics.CONTROL_AWB_AVAILABLE_MODES;
295                         property = characteristicsMap.get(cKey);
296                         if (property == null) {
297                             // TODO: error
298                             Log.e(Thread.currentThread().getName(), "AWB modes cannot be null");
299                             MasterController.quitSafely();
300                             return;
301                         }
302
303                         setting = new Parameter<>(name, property.getValue(), property.getUnits()
                                ↪ ,
304                                                                                 property.
                                                                                    ↪ getFormatter
                                                                                    ↪ ());
305
```

```
                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (PREFERRED)");
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Boolean> rKey;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> setting;

            String name;

            rKey = CaptureRequest.CONTROL_AWB_LOCK;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_AWB_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AWB mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                if (!mode.toString().contains("AUTO")) {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (PREFERRED)");
                }
                else if (Build.VERSION.SDK_INT >= 23) {
```

```
346                     CameraCharacteristics.Key<Boolean> cKey;
347                     Parameter<Boolean> property;
348
349                     cKey     = CameraCharacteristics.CONTROL_AWB_LOCK_AVAILABLE;
350                     property = characteristicsMap.get(cKey);
351                     if (property == null) {
352                         // TODO: error
353                         Log.e(Thread.currentThread().getName(), "AWB lock cannot be null");
354                         MasterController.quitSafely();
355                         return;
356                     }
357
358                     formatter = new ParameterFormatter<Boolean>() {
359                         @NonNull
360                         @Override
361                         public String formatValue(@NonNull Boolean value) {
362                             if (value) {
363                                 return "LOCKED (PREFERRED)";
364                             }
365                             return "NOT LOCKED (FALLBACK)";
366                         }
367                     };
368                     setting = new Parameter<>(name, property.getValue(), null, formatter);
369                 }
370                 else {
371                     formatter = new ParameterFormatter<Boolean>() {
372                         @NonNull
373                         @Override
374                         public String formatValue(@NonNull Boolean value) {
375                             return "LOCK ATTEMPTED BUT UNCONFIRMED";
376                         }
377                     };
378                     setting = new Parameter<>(name, true, null, formatter);
379                 }
380
381                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
382                     formatter = new ParameterFormatter<Boolean>() {
383                         @NonNull
384                         @Override
385                         public String formatValue(@NonNull Boolean value) {
386                             return "NOT LOCKED (WORST CONFIGURATION)";
```

```
                        }
                    };
                    setting = new Parameter<>(name, false, null, formatter);
                }

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<MeteringRectangle[]> rKey;
            ParameterFormatter<MeteringRectangle[]> formatter;
            Parameter<MeteringRectangle[]> setting;

            String name;
            String units;

            rKey  = CaptureRequest.CONTROL_AWB_REGIONS;//////////////////////////
            name  = rKey.getName();
            units = "pixel coordinates";

            if (supportedKeys.contains(rKey)) {

                formatter = new ParameterFormatter<MeteringRectangle[]>("NOT APPLICABLE") {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull MeteringRectangle[] value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
```

```
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        //                                  Auto Focus
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.CONTROL_AF_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> property;

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Control mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                if (GlobalSettings.FORCE_CONTROL_MODE_AUTO) {
                    value = CameraMetadata.CONTROL_AF_MODE_AUTO;
                    valueString = "AUTO (FORCED)";
                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
```

```
                        }
                    };
                    setting = new Parameter<>(name, value, null, formatter);
                    builder.set(rKey, setting.getValue());
                }
                else if (mode.toString().contains("AUTO")) {
                    CameraCharacteristics.Key<int[]> cKey;

                    cKey = CameraCharacteristics.CONTROL_AF_AVAILABLE_MODES;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "AF modes cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    setting = new Parameter<>(name, property.getValue(), property.getUnits()
                        ↪ ,
                            property.getFormatter());

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (PREFERRED)");
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<MeteringRectangle[]> rKey;
            ParameterFormatter<MeteringRectangle[]> formatter;
            Parameter<MeteringRectangle[]> setting;

```

```
            String name;
            String units;

            rKey  = CaptureRequest.CONTROL_AF_REGIONS;//////////////////////////
            name  = rKey.getName();
            units = "pixel coordinates";

            if (supportedKeys.contains(rKey)) {

                formatter = new ParameterFormatter<MeteringRectangle[]>("NOT APPLICABLE") {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull MeteringRectangle[] value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String name;

            rKey = CaptureRequest.CONTROL_AF_TRIGGER;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                formatter = new ParameterFormatter<Integer>("NOT APPLICABLE") {
                    @NonNull
                    @Override
```

```
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, null, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        //                                Auto Exposure
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.CONTROL_AE_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> property;

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Control mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }
```

```
584
585                 if (GlobalSettings.FORCE_CONTROL_MODE_AUTO) {
586                     value = CameraMetadata.CONTROL_AWB_MODE_AUTO;
587                     valueString = "AUTO (FORCED)";
588                     formatter = new ParameterFormatter<Integer>(valueString) {
589                         @NonNull
590                         @Override
591                         public String formatValue(@NonNull Integer value) {
592                             return getValueString();
593                         }
594                     };
595                     setting = new Parameter<>(name, value, null, formatter);
596                     builder.set(rKey, setting.getValue());
597                 }
598                 else if (mode.toString().contains("AUTO")) {
599                     CameraCharacteristics.Key<int[]> cKey;
600
601                     cKey = CameraCharacteristics.CONTROL_AE_AVAILABLE_MODES;
602                     property = characteristicsMap.get(cKey);
603                     if (property == null) {
604                         // TODO: error
605                         Log.e(Thread.currentThread().getName(), "AE modes cannot be null");
606                         MasterController.quitSafely();
607                         return;
608                     }
609
610                     setting = new Parameter<>(name, property.getValue(), property.getUnits()
                            ↪ ,
611                             property.getFormatter());
612
613                     builder.set(rKey, setting.getValue());
614                 }
615                 else {
616                     setting = new Parameter<>(name);
617                     setting.setValueString("DISABLED (PREFERRED)");
618                 }
619             }
620             else {
621                 setting = new Parameter<>(name);
622                 setting.setValueString("NOT SUPPORTED");
623             }
```

```
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Boolean> rKey;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> setting;

            String name;

            rKey = CaptureRequest.CONTROL_AE_LOCK;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                if (!mode.toString().contains("AUTO")) {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (PREFERRED)");
                }
                else if (Build.VERSION.SDK_INT >= 23) {
                    CameraCharacteristics.Key<Boolean> cKey;
                    Parameter<Boolean> property;

                    cKey     = CameraCharacteristics.CONTROL_AE_LOCK_AVAILABLE;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "AE lock cannot be null");
                        MasterController.quitSafely();
                        return;
                    }
```

```
664
665                     formatter = new ParameterFormatter<Boolean>() {
666                         @NonNull
667                         @Override
668                         public String formatValue(@NonNull Boolean value) {
669                             if (value) {
670                                 return "LOCKED (PREFERRED)";
671                             }
672                             return "NOT LOCKED (FALLBACK)";
673                         }
674                     };
675                     setting = new Parameter<>(name, property.getValue(), null, formatter);
676                 }
677                 else {
678                     formatter = new ParameterFormatter<Boolean>() {
679                         @NonNull
680                         @Override
681                         public String formatValue(@NonNull Boolean value) {
682                             return "LOCK ATTEMPTED BUT UNCONFIRMED";
683                         }
684                     };
685                     setting = new Parameter<>(name, true, null, formatter);
686                 }
687
688                 if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
689                     formatter = new ParameterFormatter<Boolean>() {
690                         @NonNull
691                         @Override
692                         public String formatValue(@NonNull Boolean value) {
693                             return "NOT LOCKED (WORST CONFIGURATION)";
694                         }
695                     };
696                     setting = new Parameter<>(name, false, null, formatter);
697                 }
698
699                 builder.set(rKey, setting.getValue());
700             }
701             else {
702                 setting = new Parameter<>(name);
703                 setting.setValueString("NOT SUPPORTED");
704             }
```

```
705                 captureRequestMap.put(rKey, setting);
706             }
707             //=========================================
                ↪ ==========================================================
708             {
709                 CaptureRequest.Key<MeteringRectangle[]> rKey;
710                 ParameterFormatter<MeteringRectangle[]> formatter;
711                 Parameter<MeteringRectangle[]> setting;
712
713                 String name;
714                 String units;
715
716                 rKey  = CaptureRequest.CONTROL_AE_REGIONS;//////////////////////////
717                 name  = rKey.getName();
718                 units = "pixel coordinates";
719
720                 if (supportedKeys.contains(rKey)) {
721
722                     formatter = new ParameterFormatter<MeteringRectangle[]>("NOT APPLICABLE") {
723                         @NonNull
724                         @Override
725                         public String formatValue(@NonNull MeteringRectangle[] value) {
726                             return getValueString();
727                         }
728                     };
729                     setting = new Parameter<>(name, null, units, formatter);
730                 }
731                 else {
732                     setting = new Parameter<>(name);
733                     setting.setValueString("NOT SUPPORTED");
734                 }
735                 captureRequestMap.put(rKey, setting);
736             }
737             //=========================================
                ↪ ==========================================================
738             {
739                 CaptureRequest.Key<Integer> rKey;
740                 ParameterFormatter<Integer> formatter;
741                 Parameter<Integer> setting;
742
743                 String name;
```

```
744
745             rKey = CaptureRequest.CONTROL_AE_PRECAPTURE_TRIGGER;//////////////////////////
746             name = rKey.getName();
747
748             if (supportedKeys.contains(rKey)) {
749
750                 formatter = new ParameterFormatter<Integer>("NOT APPLICABLE") {
751                     @NonNull
752                     @Override
753                     public String formatValue(@NonNull Integer value) {
754                         return getValueString();
755                     }
756                 };
757                 setting = new Parameter<>(name, null, null, formatter);
758             }
759             else {
760                 setting = new Parameter<>(name);
761                 setting.setValueString("NOT SUPPORTED");
762             }
763             captureRequestMap.put(rKey, setting);
764         }
765         //=====================================
            ↪ ==================================================
766         {
767             CaptureRequest.Key<Integer> rKey;
768             Parameter<Integer> setting;
769
770             String name;
771
772             rKey = CaptureRequest.CONTROL_AE_ANTIBANDING_MODE;//////////////////////////
773             name = rKey.getName();
774
775             if (supportedKeys.contains(rKey)) {
776
777                 Parameter<Integer> property;
778
779                 Parameter<Integer> mode;
780                 mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
781                 if (mode == null) {
782                     // TODO: error
783                     Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
```

```
                    MasterController.quitSafely();
                    return;
                }

                if (mode.toString().contains("AUTO") || GlobalSettings.
                    ↪ FORCE_WORST_CONFIGURATION) {
                    CameraCharacteristics.Key<int[]> cKey;

                    cKey = CameraCharacteristics.CONTROL_AE_AVAILABLE_ANTIBANDING_MODES;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "AE antibanding modes cannot
                            ↪  be null");
                        MasterController.quitSafely();
                        return;
                    }

                    setting = new Parameter<>(name, property.getValue(), property.getUnits()
                        ↪ ,
                            property.getFormatter());

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (PREFERRED)");
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

```

```
821                 String name;
822
823                 rKey = CaptureRequest.CONTROL_AE_EXPOSURE_COMPENSATION;//
                        ↪ ////////////////////////
824                 name = rKey.getName();
825
826                 if (supportedKeys.contains(rKey)) {
827
828                     Parameter<Integer> property;
829
830                     Parameter<Integer> mode;
831                     mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
832                     if (mode == null) {
833                         // TODO: error
834                         Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
835                         MasterController.quitSafely();
836                         return;
837                     }
838
839                     if (mode.toString().contains("AUTO") || GlobalSettings.
                            ↪ FORCE_WORST_CONFIGURATION) {
840                         CameraCharacteristics.Key<Range<Integer>> cKey;
841
842                         cKey = CameraCharacteristics.CONTROL_AE_COMPENSATION_RANGE;
843                         property = characteristicsMap.get(cKey);
844                         if (property == null) {
845                             // TODO: error
846                             Log.e(Thread.currentThread().getName(), "AE compensation range
                                    ↪ cannot be null");
847                             MasterController.quitSafely();
848                             return;
849                         }
850
851                         setting = new Parameter<>(name, property.getValue(), property.getUnits()
                                ↪ ,
852                                 property.getFormatter());
853
854                         builder.set(rKey, setting.getValue());
855                     }
856                     else {
857                         setting = new Parameter<>(name);
```

```
                    setting.setValueString("DISABLED (PREFERRED)");
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Range<Integer>> rKey;
            ParameterFormatter<Range<Integer>> formatter;
            Parameter<Range<Integer>> setting;

            String name;
            Range<Integer> value;

            rKey = CaptureRequest.CONTROL_AE_TARGET_FPS_RANGE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Range<Integer>[]> property;

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                if (mode.toString().contains("AUTO")) {
                    CameraCharacteristics.Key<Range<Integer>[]> cKey;

                    cKey = CameraCharacteristics.CONTROL_AE_AVAILABLE_TARGET_FPS_RANGES;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
```

```
898                         // TODO: error
899                         Log.e(Thread.currentThread().getName(), "AE target FPS ranges cannot
                                ↪  be null");
900                         MasterController.quitSafely();
901                         return;
902                     }
903
904                     Range<Integer>[] ranges = property.getValue();
905                     if (ranges == null) {
906                         // TODO: error
907                         Log.e(Thread.currentThread().getName(), "FPS ranges cannot be null")
                                ↪ ;
908                         MasterController.quitSafely();
909                         return;
910                     }
911
912                     // Select fastest range
913                     value = ranges[ranges.length - 1];
914
915                     formatter = new ParameterFormatter<Range<Integer>>() {
916                         @NonNull
917                         @Override
918                         public String formatValue(@NonNull Range<Integer> value) {
919                             return value.toString();
920                         }
921                     };
922                     setting = new Parameter<>(name, value, property.getUnits(), formatter);
923
924                     builder.set(rKey, setting.getValue());
925                 }
926                 else {
927                     setting = new Parameter<>(name);
928                     setting.setValueString("DISABLED (PREFERRED)");
929                 }
930             }
931             else {
932                 setting = new Parameter<>(name);
933                 setting.setValueString("NOT SUPPORTED");
934             }
935             captureRequestMap.put(rKey, setting);
936         }
```

```
937         //=========================================
            ↪ ==========================================================
938         {
939             CaptureRequest.Key<Integer> rKey;
940             Parameter<Integer> setting;
941
942             String  name;
943
944             rKey = CaptureRequest.CONTROL_EFFECT_MODE;//////////////////////////
945             name = rKey.getName();
946
947             if (supportedKeys.contains(rKey)) {
948
949                 CameraCharacteristics.Key<int[]> cKey;
950                 Parameter<Integer> properties;
951
952                 cKey = CameraCharacteristics.CONTROL_AVAILABLE_EFFECTS;
953                 properties = characteristicsMap.get(cKey);
954                 if (properties == null) {
955                     // TODO: error
956                     Log.e(Thread.currentThread().getName(), "Available effects cannot be
                        ↪ null");
957                     MasterController.quitSafely();
958                     return;
959                 }
960
961                 setting = new Parameter<>(name, properties.getValue(), properties.getUnits()
                    ↪ ,
962                                                                 properties.
                                                                    ↪ getFormatter()
                                                                    ↪ );
963
964                 builder.set(rKey, setting.getValue());
965             }
966             else {
967                 setting = new Parameter<>(name);
968                 setting.setValueString("NOT SUPPORTED");
969             }
970             captureRequestMap.put(rKey, setting);
971         }
```

```
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Boolean> rKey;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> setting;

            String name;

            if (Build.VERSION.SDK_INT >= 26) {

                rKey = CaptureRequest.CONTROL_ENABLE_ZSL;//////////////////////////
                name = rKey.getName();

                if (supportedKeys.contains(rKey)) {

                    formatter = new ParameterFormatter<Boolean>("DISABLED (PREFERRED)") {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Boolean value) {
                            return getValueString();
                        }
                    };
                    setting = new Parameter<>(name, false, null, formatter);

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String  name;
```

```
1011
1012            if (Build.VERSION.SDK_INT >= 24) {
1013                rKey = CaptureRequest.CONTROL_POST_RAW_SENSITIVITY_BOOST;//
                    ↪ ////////////////////////
1014                name = rKey.getName();
1015
1016                if (supportedKeys.contains(rKey)) {
1017
1018                    CameraCharacteristics.Key<Range<Integer>> cKey;
1019                    Parameter<Integer> properties;
1020
1021                    cKey = CameraCharacteristics.CONTROL_POST_RAW_SENSITIVITY_BOOST_RANGE;
1022                    properties = characteristicsMap.get(cKey);
1023                    if (properties == null) {
1024                        // TODO: error
1025                        Log.e(Thread.currentThread().getName(), "Sensitivity boost range
                            ↪ cannot be null");
1026                        MasterController.quitSafely();
1027                        return;
1028                    }
1029
1030                    setting = new Parameter<>(name, properties.getValue(), properties.
                            ↪ getUnits(),
1031                                                properties.getFormatter());
1032
1033                    builder.set(rKey, setting.getValue());
1034                }
1035                else {
1036                    setting = new Parameter<>(name);
1037                    setting.setValueString("NOT SUPPORTED");
1038                }
1039                captureRequestMap.put(rKey, setting);
1040            }
1041        }
1042        //=====================================
            ↪ ==================================================
1043        {
1044            CaptureRequest.Key<Integer> rKey;
1045            Parameter<Integer> setting;
1046
1047            String  name;
```

```
1048
1049            rKey = CaptureRequest.CONTROL_SCENE_MODE;//////////////////////////
1050            name = rKey.getName();
1051
1052            if (supportedKeys.contains(rKey)) {
1053
1054                CameraCharacteristics.Key<int[]> cKey;
1055                Parameter<Integer> properties;
1056
1057                cKey = CameraCharacteristics.CONTROL_AVAILABLE_SCENE_MODES;
1058                properties = characteristicsMap.get(cKey);
1059                if (properties == null) {
1060                    // TODO: error
1061                    Log.e(Thread.currentThread().getName(), "Available scene modes cannot be
                        ↪  null");
1062                    MasterController.quitSafely();
1063                    return;
1064                }
1065
1066                setting = new Parameter<>(name, properties.getValue(), properties.getUnits()
                        ↪ ,
1067                                                                    properties.
                                                                            ↪ getFormatter()
                                                                            ↪ );
1068
1069                builder.set(rKey, setting.getValue());
1070            }
1071            else {
1072                setting = new Parameter<>(name);
1073                setting.setValueString("NOT SUPPORTED");
1074            }
1075            captureRequestMap.put(rKey, setting);
1076        }
1077        //=====================================
            ↪ ==================================================
1078        {
1079            CaptureRequest.Key<Integer> rKey;
1080            Parameter<Integer> setting;
1081
1082            String  name;
1083
```

```
1084                rKey = CaptureRequest.CONTROL_VIDEO_STABILIZATION_MODE;//
                    ↪ ////////////////////////
1085                name = rKey.getName();
1086
1087                if (supportedKeys.contains(rKey)) {
1088
1089                    CameraCharacteristics.Key<int[]> cKey;
1090                    Parameter<Integer> properties;
1091
1092                    cKey = CameraCharacteristics.CONTROL_AVAILABLE_VIDEO_STABILIZATION_MODES;
1093                    properties = characteristicsMap.get(cKey);
1094                    if (properties == null) {
1095                        // TODO: error
1096                        Log.e(Thread.currentThread().getName(), "Video stabilization modes
                            ↪ cannot be null");
1097                        MasterController.quitSafely();
1098                        return;
1099                    }
1100
1101                    setting = new Parameter<>(name, properties.getValue(), properties.getUnits()
                            ↪ ,
1102                            properties.getFormatter());
1103
1104                    builder.set(rKey, setting.getValue());
1105                }
1106                else {
1107                    setting = new Parameter<>(name);
1108                    setting.setValueString("NOT SUPPORTED");
1109                }
1110                captureRequestMap.put(rKey, setting);
1111            }
1112            //=========================================
                    ↪ ==========================================================
1113        }
1114
1115    }
```

Listing E.44: Black Level Request (camera2/requests/step2_Black_.java)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    BLACK_LEVEL_LOCK
 */
@TargetApi(21)
abstract class step02_Black_ extends step01_Control_ {

```

```
    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting BLACK_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Black_", "setting default Black_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported key cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Boolean> rKey;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> setting;

            String  name;
            Boolean value;
            String  valueString;

            rKey = CaptureRequest.BLACK_LEVEL_LOCK;//////////////////////////
```

```
79                  name = rKey.getName();
80
81                  if (supportedKeys.contains(rKey)) {
82
83                      Boolean OFF = false;
84                      Boolean ON  = true;
85
86                      value       =  ON;
87                      valueString = "ON BUT UNCONFIRMED";
88
89                      if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
90                          value       =  OFF;
91                          valueString = "OFF BUT UNCONFIRMED (WORST CONFIGURATION)";
92                      }
93
94                      formatter = new ParameterFormatter<Boolean>(valueString) {
95                          @NonNull
96                          @Override
97                          public String formatValue(@NonNull Boolean value) {
98                              return getValueString();
99                          }
100                     };
101                     setting = new Parameter<>(name, value, null, formatter);
102
103                     builder.set(rKey, setting.getValue());
104                 }
105                 else {
106                     setting = new Parameter<>(name);
107                     setting.setValueString("NOT SUPPORTED");
108                 }
109                 captureRequestMap.put(rKey, setting);
110             }
111             //=========================================
                ↪ ==================================================
112         }
113
114     }
```

Listing E.45: Color Request (camera2/requests/step03_Color_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.hardware.camera2.params.ColorSpaceTransform;
import android.hardware.camera2.params.RggbChannelVector;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *     COLOR_CORRECTION_ABERRATION_MODE
 *     COLOR_CORRECTION_GAINS
```

```
 *     COLOR_CORRECTION_MODE
 *     COLOR_CORRECTION_TRANSFORM
 */
@TargetApi(21)
abstract class step03_Color_ extends step02_Black_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting COLOR_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("               Color_", "setting default Color_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

```

```
            String  name;

            rKey = CaptureRequest.COLOR_CORRECTION_ABERRATION_MODE;//
                ↪ ////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
                Parameter<Integer> property;

                cKey = CameraCharacteristics.COLOR_CORRECTION_AVAILABLE_ABERRATION_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Color correction modes cannot
                        ↪ be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter()
                                                                        ↪ );
                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<RggbChannelVector> rKey;
            Parameter<RggbChannelVector> setting;
            ParameterFormatter<RggbChannelVector> formatter;

            String name;
            RggbChannelVector value;
```

```
            String units;

            rKey  = CaptureRequest.COLOR_CORRECTION_GAINS;//////////////////////////
            name  = rKey.getName();
            value = new RggbChannelVector(1, 1, 1, 1);
            units = "unitless gain factor";

            if (supportedKeys.contains(rKey)) {

                formatter = new ParameterFormatter<RggbChannelVector>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull RggbChannelVector value) {
                        return value.toString();
                    }
                };
                setting = new Parameter<>(name, value, units, formatter);

                builder.set(rKey, value);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.COLOR_CORRECTION_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {
```

```
156
157                 Parameter<Integer> mode;
158                 mode = captureRequestMap.get(CaptureRequest.CONTROL_AWB_MODE);
159                 if (mode == null) {
160                     // TODO: error
161                     Log.e(Thread.currentThread().getName(), "AWB mode cannot be null");
162                     MasterController.quitSafely();
163                     return;
164                 }
165
166                 if (mode.toString().contains("DISABLED")) {
167
168                     Integer TRANSFORM_MATRIX = CameraMetadata.
                        ↪ COLOR_CORRECTION_MODE_TRANSFORM_MATRIX;
169                     //Integer FAST             = CameraMetadata.COLOR_CORRECTION_MODE_FAST;
170                     //Integer HIGH_QUALITY     = CameraMetadata.
                        ↪ COLOR_CORRECTION_MODE_HIGH_QUALITY;
171
172                     value = TRANSFORM_MATRIX;
173                     valueString = "TRANSFORM_MATRIX (PREFERRED)";
174
175                     formatter = new ParameterFormatter<Integer>(valueString) {
176                         @NonNull
177                         @Override
178                         public String formatValue(@NonNull Integer value) {
179                             return getValueString();
180                         }
181                     };
182                     setting = new Parameter<>(name, value, null, formatter);
183
184                     builder.set(rKey, setting.getValue());
185                 }
186                 else {
187                     setting = new Parameter<>(name);
188                     setting.setValueString("DISABLED (FALLBACK)");
189                 }
190             }
191             else {
192                 setting = new Parameter<>(name);
193                 setting.setValueString("NOT SUPPORTED");
194             }
```

```
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<ColorSpaceTransform> key;
            Parameter<ColorSpaceTransform> setting;
            ParameterFormatter<ColorSpaceTransform> formatter;

            String name;
            ColorSpaceTransform value;
            String valueString;

            key   = CaptureRequest.COLOR_CORRECTION_TRANSFORM;//////////////////////////
            name  = key.getName();
            value = new ColorSpaceTransform(new int[]{
                                                1, 1, 0, 1, 0, 1,    // 1/1 , 0/1 , 0/1 = 1
                                                    ↪ 0 0
                                                0, 1, 1, 1, 0, 1,    // 0/1 , 1/1 , 0/1 = 0
                                                    ↪ 1 0
                                                0, 1, 0, 1, 1, 1     // 0/1 , 0/1 , 1/1 = 0
                                                    ↪ 0 1
                                            });
            valueString = "(1 0 0),(0 1 0),(0 0 1)";

            if (supportedKeys.contains(key)) {

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.COLOR_CORRECTION_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Color correction mode cannot be
                        ↪  null");
                    MasterController.quitSafely();
                    return;
                }

                if (mode.toString().contains("DISABLED")) {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (FALLBACK)");
                }
```

```
                    else {
                        formatter = new ParameterFormatter<ColorSpaceTransform>(valueString) {
                            @NonNull
                            @Override
                            public String formatValue(@NonNull ColorSpaceTransform value) {
                                return getValueString();
                            }
                        };
                        setting = new Parameter<>(name, value, null, formatter);

                        builder.set(key, value);
                    }
                    captureRequestMap.put(key, setting);
                }
            }
            //=========================================
                ↪ ==================================================
        }

    }
```

Listing E.46: Distortion Request (`camera2/requests/step04_Distortion_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    DISTORTION_CORRECTION_MODE
 */
@TargetApi(21)
abstract class step04_Distortion_ extends step03_Color_ {

    // Protected Overriding Instance Methods
```

```
41      //::::::::::::::::::::::
42
43      // makeDefault..............
44      /**
45       * Creating a default CaptureRequest, setting DISTORTION_.* parameters
46       * @param builder CaptureRequest.Builder in progress
47       * @param characteristicsMap Parameter map of characteristics
48       * @param captureRequestMap Parameter map of capture request settings
49       */
50      @SuppressWarnings("unchecked")
51      @Override
52      protected void makeDefault(@NonNull CaptureRequest.Builder builder,
53                                 @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                       ↪ characteristicsMap,
54                                 @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                       ↪ captureRequestMap) {
55          super.makeDefault(builder, characteristicsMap, captureRequestMap);
56
57          Log.e("          Distortion_", "setting default Distortion_ requests");
58          List<CaptureRequest.Key<?>> supportedKeys;
59          supportedKeys = CameraController.getAvailableCaptureRequestKeys();
60          if (supportedKeys == null) {
61              // TODO: error
62              Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
63              MasterController.quitSafely();
64              return;
65          }
66
67          //=========================================
                ↪ ==================================================
68          {
69              if (Build.VERSION.SDK_INT < 28) {
70                  return;
71              }
72
73              CaptureRequest.Key<Integer> rKey;
74              Parameter<Integer> setting;
75
76              String name;
77
78              rKey = CaptureRequest.DISTORTION_CORRECTION_MODE;///////////////////////////
```

```
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
                Parameter<Integer> property;

                cKey = CameraCharacteristics.DISTORTION_CORRECTION_AVAILABLE_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Distortion correction modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter());
                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================
    }

}
```

Listing E.47: Edge Request (camera2/requests/step05_Edge_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    EDGE_MODE
 */
@TargetApi(21)
abstract class step05_Edge_ extends step04_Distortion_ {

    // Protected Overriding Instance Methods
    //:::::::::::::::::::::::
```

```

    // makeDefault...............
    /**
     * Creating a default CaptureRequest, setting EDGE_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Edge_", "setting default Edge_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String name;

            rKey = CaptureRequest.EDGE_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
```

```
                Parameter<Integer> property;

                cKey = CameraCharacteristics.EDGE_AVAILABLE_EDGE_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Edge modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter() );
                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================
    }

}
```

Listing E.48: Flash Request (camera2/requests/step06_Flash_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    FLASH_MODE
 */
@TargetApi(21)
abstract class step06_Flash_ extends step05_Edge_ {

```

```
    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting FLASH_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Flash_", "setting default Flash_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            rKey = CaptureRequest.FLASH_MODE;//////////////////////////
```

```
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<Boolean> cKey;
                Parameter<Boolean> property;

                cKey = CameraCharacteristics.FLASH_INFO_AVAILABLE;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Flash info cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                Boolean isAvailable = property.getValue();
                if (isAvailable == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Flash availability cannot be
                        ↪ null");
                    MasterController.quitSafely();
                    return;
                }

                if (!isAvailable) {
                    return;
                }

                Integer OFF    = CameraMetadata.FLASH_MODE_OFF;
                //Integer SINGLE = CameraMetadata.FLASH_MODE_SINGLE;
                //Integer TORCH  = CameraMetadata.FLASH_MODE_TORCH;

                value = OFF;
                valueString = "OFF (PREFERRED)";

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
```

```
                        }
                    };
                    setting = new Parameter<>(name, value, null, formatter);

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
            //=========================================
                ↪ ==========================================================
        }

    }
```

Listing E.49: Hot Request (camera2/requests/step07_Hot_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    HOT_PIXEL_MODE
 */
@TargetApi(21)
abstract class step07_Hot_ extends step06_Flash_ {

    // Protected Overriding Instance Methods
    //:::::::::::::::::::::::
```

```
41
42      // makeDefault...............
43      /**
44       * Creating a default CaptureRequest, setting HOT_.* parameters
45       * @param builder CaptureRequest.Builder in progress
46       * @param characteristicsMap Parameter map of characteristics
47       * @param captureRequestMap Parameter map of capture request settings
48       */
49      @SuppressWarnings("unchecked")
50      @Override
51      protected void makeDefault(@NonNull CaptureRequest.Builder builder,
52                                 @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                       ↪ characteristicsMap,
53                                 @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                       ↪ captureRequestMap) {
54          super.makeDefault(builder, characteristicsMap, captureRequestMap);
55
56          Log.e("                 Hot_", "setting default Hot_ requests");
57          List<CaptureRequest.Key<?>> supportedKeys;
58          supportedKeys = CameraController.getAvailableCaptureRequestKeys();
59          if (supportedKeys == null) {
60              // TODO: error
61              Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
62              MasterController.quitSafely();
63              return;
64          }
65
66          //=====================================
                ↪ ==================================================
67          {
68              CaptureRequest.Key<Integer> rKey;
69              Parameter<Integer> setting;
70
71              String name;
72
73              rKey = CaptureRequest.HOT_PIXEL_MODE;///////////////////////////
74              name = rKey.getName();
75
76              if (supportedKeys.contains(rKey)) {
77
78                  CameraCharacteristics.Key<int[]> cKey;
```

```
                Parameter<Integer> property;

                cKey = CameraCharacteristics.HOT_PIXEL_AVAILABLE_HOT_PIXEL_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Hot pixel modes cannot be null" );
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter() );

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================================
    }

}
```

Listing E.50: Jpeg Request (camera2/requests/step08_Jpeg_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.location.Location;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Size;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *     JPEG_GPS_LOCATION
 *     JPEG_ORIENTATION
 *     JPEG_QUALITY
 *     JPEG_THUMBNAIL_QUALITY
```

```
 *    JPEG_THUMBNAIL_SIZE
 */
@TargetApi(21)
abstract class step08_Jpeg_ extends step07_Hot_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::::

    // makeDefault...............
    /**
     * Creating a default CaptureRequest, setting JPEG_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Jpeg_", "setting default Jpeg_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Location> rKey;
            ParameterFormatter<Location> formatter;
            Parameter<Location> setting;

```

```
            String name;
            String valueString;

            rKey = CaptureRequest.JPEG_GPS_LOCATION;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Location>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Location value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, null, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String name;
            String valueString;
            String units;

            rKey  = CaptureRequest.JPEG_ORIENTATION;//////////////////////////
            name  = rKey.getName();
            units = "degrees clockwise";

            if (supportedKeys.contains(rKey)) {
```

```

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Byte> rKey;
            ParameterFormatter<Byte> formatter;
            Parameter<Byte> setting;

            String name;
            String valueString;
            String units;

            rKey  = CaptureRequest.JPEG_QUALITY;//////////////////////////
            name  = rKey.getName();
            units = "%";

            if (supportedKeys.contains(rKey)) {

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Byte>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Byte value) {
```

```
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Byte> rKey;
            ParameterFormatter<Byte> formatter;
            Parameter<Byte> setting;

            String name;
            String valueString;
            String units;

            rKey  = CaptureRequest.JPEG_THUMBNAIL_QUALITY;//////////////////////////
            name  = rKey.getName();
            units = "%";

            if (supportedKeys.contains(rKey)) {

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Byte>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Byte value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
```

```
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //========================================
            ↪ ====================================================
        {
            CaptureRequest.Key<Size> rKey;
            ParameterFormatter<Size> formatter;
            Parameter<Size> setting;

            String name;
            String valueString;
            String units;

            rKey  = CaptureRequest.JPEG_THUMBNAIL_SIZE;//////////////////////////
            name  = rKey.getName();
            units = "pixels";

            if (supportedKeys.contains(rKey)) {

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Size>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Size value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //========================================
            ↪ ====================================================
    }
```

```

}
```

Listing E.51: Lens Request (`camera2/requests/step09_Lens_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    LENS_APERTURE
 *    LENS_FILTER_DENSITY
 *    LENS_FOCAL_LENGTH
 *    LENS_FOCUS_DISTANCE
 *    LENS_OPTICAL_STABILIZATION_MODE
 */
```

```
@TargetApi(21)
abstract class step09_Lens_ extends step08_Jpeg_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting LENS_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Lens_", "setting default Lens_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Float> rKey;
            Parameter<Float> setting;

            String name;

            rKey = CaptureRequest.LENS_APERTURE;//////////////////////////
```

```
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<float[]> cKey;
                Parameter<Float> property;

                cKey = CameraCharacteristics.LENS_INFO_AVAILABLE_APERTURES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens apertures cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter();

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================================
        {
            CaptureRequest.Key<Float> rKey;
            Parameter<Float> setting;

            String name;

            rKey = CaptureRequest.LENS_FILTER_DENSITY;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {
```

```

                CameraCharacteristics.Key<float[]> cKey;
                Parameter<Float> property;

                cKey = CameraCharacteristics.LENS_INFO_AVAILABLE_FILTER_DENSITIES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens filter densities cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter());

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================================================================
        {
            CaptureRequest.Key<Float> rKey;
            Parameter<Float> setting;

            String name;

            rKey = CaptureRequest.LENS_FOCAL_LENGTH;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<float[]> cKey;
                Parameter<Float> property;
```

```

                cKey = CameraCharacteristics.LENS_INFO_AVAILABLE_FOCAL_LENGTHS;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Lens focal lengths cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter());

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================================
        {
            CaptureRequest.Key<Float> rKey;
            ParameterFormatter<Float> formatter;
            Parameter<Float> setting;

            String name;
            Float  value;
            String valueString;
            String units;

            rKey = CaptureRequest.LENS_FOCUS_DISTANCE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                value = 0.f;
```

```
                    valueString = "INFINITY";

                    CameraCharacteristics.Key<Integer> cKey;
                    Parameter<Integer> property;

                    cKey = CameraCharacteristics.LENS_INFO_FOCUS_DISTANCE_CALIBRATION;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Lens calibration cannot be null
                            ↪ ");
                        MasterController.quitSafely();
                        return;
                    }

                    units = property.getUnits();

                    formatter = new ParameterFormatter<Float>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Float value) {
                            return getValueString();
                        }
                    };
                    setting = new Parameter<>(name, value, units, formatter);

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
            //=========================================
                ↪ ==================================================
            {
                CaptureRequest.Key<Integer> rKey;
                Parameter<Integer> setting;

                String name;
```

```
232
233             rKey = CaptureRequest.LENS_OPTICAL_STABILIZATION_MODE;//
                    ↪ ////////////////////////
234             name = rKey.getName();
235
236             if (supportedKeys.contains(rKey)) {
237
238                 CameraCharacteristics.Key<int[]> cKey;
239                 Parameter<Integer> property;
240
241                 cKey = CameraCharacteristics.LENS_INFO_AVAILABLE_OPTICAL_STABILIZATION;
242                 property = characteristicsMap.get(cKey);
243                 if (property == null) {
244                     // TODO: error
245                     Log.e(Thread.currentThread().getName(), "Lens stabilization cannot be
                            ↪ null");
246                     MasterController.quitSafely();
247                     return;
248                 }
249
250                 setting = new Parameter<>(name, property.getValue(), property.getUnits(),
251                                                                      property.getFormatter()
                                                                             ↪ );
252
253                 builder.set(rKey, setting.getValue());
254             }
255             else {
256                 setting = new Parameter<>(name);
257                 setting.setValueString("NOT SUPPORTED");
258             }
259             captureRequestMap.put(rKey, setting);
260         }
261         //=========================================
                ↪ ==========================================================
262     }
263
264 }
```

Listing E.52: Noise Request (camera2/requests/step10_Noise_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    NOISE_REDUCTION_MODE
 */
@TargetApi(21)
abstract class step10_Noise_ extends step09_Lens_ {

    // Protected Overriding Instance Methods
    //:::::::::::::::::::::::
```

```java

    // makeDefault...............
    /**
     * Creating a default CaptureRequest, setting NOISE_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("                Noise_", "setting default Noise_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String name;

            rKey = CaptureRequest.NOISE_REDUCTION_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
```

```
                    Parameter<Integer> property;

                    cKey = CameraCharacteristics.NOISE_REDUCTION_AVAILABLE_NOISE_REDUCTION_MODES;
                    property = characteristicsMap.get(cKey);
                    if (property == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Noise reduction modes cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                        property.getFormatter());

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
            //=========================================================================================
        }

}
```

Listing E.53: Reprocess Request (camera2/requests/step11_Reprocess_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;
import sci.crayfis.shramp.util.ArrayToList;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    REPROCESS_EFFECTIVE_EXPOSURE_FACTOR
 */
@TargetApi(21)
```

```
abstract class step11_Reprocess_ extends step10_Noise_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting REPROCESS_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("           Reprocess_", "setting default Reprocess_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================================================
        {
            CaptureRequest.Key<Float> rKey;
            ParameterFormatter<Float> formatter;
            Parameter<Float> setting;

            String name;
            Float  value;
            String units;
```

```
79
80              if (Build.VERSION.SDK_INT < 23) {
81                  return;
82              }
83
84              rKey = CaptureRequest.REPROCESS_EFFECTIVE_EXPOSURE_FACTOR;//
                    ↪ ////////////////////////
85              name = rKey.getName();
86
87              if (supportedKeys.contains(rKey)) {
88
89                  CameraCharacteristics.Key<int[]> cKey;
90                  Parameter<Integer[]> property;
91
92                  cKey = CameraCharacteristics.REQUEST_AVAILABLE_CAPABILITIES;
93                  property = characteristicsMap.get(cKey);
94                  if (property == null) {
95                      // TODO: error
96                      Log.e(Thread.currentThread().getName(), "Available capabilites cannot be
                            ↪  null");
97                      MasterController.quitSafely();
98                      return;
99                  }
100
101                 Integer[] capabilities = property.getValue();
102                 if (capabilities == null) {
103                     // TODO: error
104                     Log.e(Thread.currentThread().getName(), "Capabilities cannot be null");
105                     MasterController.quitSafely();
106                     return;
107                 }
108                 List<Integer> abilities = ArrayToList.convert(capabilities);
109
110                 if (!abilities.contains(CameraMetadata.
                        ↪ REQUEST_AVAILABLE_CAPABILITIES_YUV_REPROCESSING)) {
111                     return;
112                 }
113
114                 value = 1.f;
115                 units = "relative exposure time increase factor";
116
```

```
                    formatter = new ParameterFormatter<Float>() {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Float value) {
                            return value.toString();
                        }
                    };
                    setting = new Parameter<>(name, value, units, formatter);

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
            //=========================================
                ↪ ==================================================
        }

    }
```

Listing E.54: Scaler Request (`camera2/requests/step12_Scaler_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.graphics.Rect;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    SCALAR_CROP_REGION
 */
@TargetApi(21)
abstract class step12_Scaler_ extends step11_Reprocess_ {

```

```
    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting SCALER_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("              Scaler_", "setting default Scaler_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Rect> rKey;
            ParameterFormatter<Rect> formatter;
            Parameter<Rect> setting;

            String name;
            String valueString;
            String units;

            rKey  = CaptureRequest.SCALER_CROP_REGION;//////////////////////////
```

```
            name  = rKey.getName();
            units = "pixel coordinates";

            if (supportedKeys.contains(rKey)) {

                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<Rect>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Rect value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, null, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
    }
}
```

Listing E.55: Sensor Request (camera2/requests/step13_Sensor_.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CaptureRequest;
import android.hardware.camera2.params.StreamConfigurationMap;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Range;
import android.util.Size;

import java.text.DecimalFormat;
import java.text.NumberFormat;
import java.util.LinkedHashMap;
import java.util.List;
import java.util.Locale;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
```

```
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    SENSOR_FRAME_DURATION
 *    SENSOR_EXPOSURE_TIME
 *    SENSOR_SENSITIVITY
 *    SENSOR_TEST_PATTERN_MODE
 *    SENSOR_TEST_PATTERN_DATA
 */
@TargetApi(21)
abstract class step13_Sensor_ extends step12_Scaler_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::::

    // makeDefault...............
    /**
     * Creating a default CaptureRequest, setting SENSOR_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter> characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter> captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("              Sensor_", "setting default Sensor_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================================================
```

```
79          {
80              CaptureRequest.Key<Long> rKey;
81              ParameterFormatter<Long> formatter;
82              Parameter<Long> setting;
83
84              String name;
85              Long   value;
86              String units;
87
88              rKey  = CaptureRequest.SENSOR_FRAME_DURATION;//////////////////////////
89              name  = rKey.getName();
90              units = "nanoseconds";
91
92              if (supportedKeys.contains(rKey)) {
93
94                  Parameter<Integer> mode;
95                  mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
96                  if (mode == null) {
97                      // TODO: error
98                      Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
99                      MasterController.quitSafely();
100                     return;
101                 }
102
103                 if (mode.toString().contains("AUTO")) {
104                     setting = new Parameter<>(name);
105                     setting.setValueString("DISABLED (FALLBACK)");
106                 }
107                 else {
108                     CameraCharacteristics.Key<StreamConfigurationMap> cKey;
109                     Parameter<StreamConfigurationMap> property;
110
111                     cKey = CameraCharacteristics.SCALER_STREAM_CONFIGURATION_MAP;
112                     property = characteristicsMap.get(cKey);
113                     if (property == null) {
114                         // TODO: error
115                         Log.e(Thread.currentThread().getName(), "Stream configuration map
                                ↪ cannot be null");
116                         MasterController.quitSafely();
117                         return;
118                     }
```

```
                        StreamConfigurationMap streamConfigurationMap;
                        streamConfigurationMap = property.getValue();
                        if (streamConfigurationMap == null) {
                            // TODO: error
                            Log.e(Thread.currentThread().getName(), "Configuration map cannot be null");
                            MasterController.quitSafely();
                            return;
                        }

                        Integer imageFormat = CameraController.getOutputFormat();
                        Size    imageSize   = CameraController.getOutputSize();
                        if (imageFormat == null) {
                            // TODO: error
                            Log.e(Thread.currentThread().getName(), "Image format cannot be null");
                            MasterController.quitSafely();
                            return;
                        }
                        if (imageSize == null) {
                            // TODO: error
                            Log.e(Thread.currentThread().getName(), "Image size cannot be null");
                            MasterController.quitSafely();
                            return;
                        }

                        value = streamConfigurationMap.getOutputMinFrameDuration(imageFormat, imageSize);

                        formatter = new ParameterFormatter<Long>("minimum: ") {
                            @NonNull
                            @Override
                            public String formatValue(@NonNull Long value) {
                                DecimalFormat nanosFormatter;
                                nanosFormatter = (DecimalFormat) NumberFormat.getInstance(Locale.US);
                                return getValueString() + nanosFormatter.format(value);
                            }
                        };
```

```
                    setting = new Parameter<>(name, value, units, formatter);

                    builder.set(rKey, setting.getValue());
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Long> rKey;
            Parameter<Long> setting;

            String name;

            rKey = CaptureRequest.SENSOR_EXPOSURE_TIME;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
                if (mode == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                if (mode.toString().contains("AUTO")) {
                    setting = new Parameter<>(name);
                    setting.setValueString("DISABLED (FALLBACK)");
                }
                else {
                    Parameter<Long> frameDuration;
                    frameDuration = captureRequestMap.get(CaptureRequest.
                        ↪ SENSOR_FRAME_DURATION);
```

```
                    if (frameDuration == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Frame duration cannot be null");
                        MasterController.quitSafely();
                        return;
                    }

                    setting = new Parameter<>(name, frameDuration.getValue(), frameDuration.getUnits(),
                                                    frameDuration.getFormatter());

                    builder.set(rKey, setting.getValue());
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;
            String  units;

            rKey  = CaptureRequest.SENSOR_SENSITIVITY;//////////////////////////
            name  = rKey.getName();
            units = "ISO";

            if (supportedKeys.contains(rKey)) {

                Parameter<Integer> mode;
                mode = captureRequestMap.get(CaptureRequest.CONTROL_AE_MODE);
```

```
232                 if (mode == null) {
233                     // TODO: error
234                     Log.e(Thread.currentThread().getName(), "AE mode cannot be null");
235                     MasterController.quitSafely();
236                     return;
237                 }
238
239                 if (mode.toString().contains("AUTO")) {
240                     setting = new Parameter<>(name);
241                     setting.setValueString("DISABLED (FALLBACK)");
242                 }
243                 else {
244                     CameraCharacteristics.Key<Range<Integer>> cKey;
245                     Parameter<Range<Integer>> property;
246
247                     cKey = CameraCharacteristics.SENSOR_INFO_SENSITIVITY_RANGE;
248                     property = characteristicsMap.get(cKey);
249                     if (property == null) {
250                         // TODO: error
251                         Log.e(Thread.currentThread().getName(), "Sensitivity range cannot be
                             ↪  null");
252                         MasterController.quitSafely();
253                         return;
254                     }
255
256                     Range<Integer> range = property.getValue();
257                     if (range == null) {
258                         // TODO: error
259                         Log.e(Thread.currentThread().getName(), "Sensitivity range cannot be
                             ↪  null");
260                         MasterController.quitSafely();
261                         return;
262                     }
263                     value = range.getUpper();
264                     valueString = "maximum: ";
265
266                     if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
267                         value = range.getLower();
268                         valueString = "minimum (WORST CONFIGURATION): ";
269                     }
270
```

```
                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString() + value.toString();
                        }
                    };
                    setting = new Parameter<>(name, value, units, formatter);

                    builder.set(rKey, setting.getValue());
                }
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String name;

            rKey = CaptureRequest.SENSOR_TEST_PATTERN_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
                Parameter<Integer> property;

                cKey = CameraCharacteristics.SENSOR_AVAILABLE_TEST_PATTERN_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Test pattern mode cannot be
                        ↪ null");
                    MasterController.quitSafely();
```

```
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter()
                                                                        ↪ );

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
        {
            CaptureRequest.Key<int[]> rKey;
            ParameterFormatter<int[]> formatter;
            Parameter<int[]> setting;

            String name;
            int[]  value;
            String valueString;
            String units;

            rKey  = CaptureRequest.SENSOR_TEST_PATTERN_DATA;//////////////////////////
            name  = rKey.getName();
            units = null;

            if (supportedKeys.contains(rKey)) {

                value = null;
                valueString = "NOT APPLICABLE";

                formatter = new ParameterFormatter<int[]>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull int[] value) {
                        return getValueString();
```

```
                    }
                };
                setting = new Parameter<>(name, value, units, formatter);
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
    }

}
```

Listing E.56: Shading Request (camera2/requests/step14_Shading_.java)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    SHADING_MODE
 */
@TargetApi(21)
abstract class step14_Shading_ extends step13_Sensor_ {
```

```
    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting SHADING_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("             Shading_", "setting default Shading_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

```

```
            rKey = CaptureRequest.SHADING_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Integer OFF          = CameraMetadata.SHADING_MODE_OFF;
                Integer FAST         = CameraMetadata.SHADING_MODE_FAST;
                //Integer HIGH_QUALITY = CameraMetadata.SHADING_MODE_HIGH_QUALITY;

                value = OFF;
                valueString = "OFF (PREFERRED)";

                if (GlobalSettings.FORCE_WORST_CONFIGURATION) {
                    value = FAST;
                    valueString = "FAST (WORST CONFIGURATION)";
                }

                formatter = new ParameterFormatter<Integer>(valueString) {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Integer value) {
                        return getValueString();
                    }
                };
                setting = new Parameter<>(name, value, null, formatter);

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=====================================
            ↪ ==================================================
    }

}
```

Listing E.57: Statistics Request (`camera2/requests/step15_Statistics_.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *     STATISTICS_FACE_DETECT_MODE
 *     STATISTICS_HOT_PIXEL_MAP_MODE
 *     STATISTICS_LENS_SHADING_MAP_MODE
 *     STATISTICS_OIS_DATA_MODE
```

```
 */
@TargetApi(21)
abstract class step15_Statistics_ extends step14_Shading_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::

    // makeDefault..............
    /**
     * Creating a default CaptureRequest, setting STATISTICS_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("          Statistics_", "setting default Statistics_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String name;

```

```
            rKey = CaptureRequest.STATISTICS_FACE_DETECT_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
                Parameter<Integer> property;

                cKey = CameraCharacteristics.STATISTICS_INFO_AVAILABLE_FACE_DETECT_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Face detect modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter());

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================
        {
            CaptureRequest.Key<Boolean> rKey;
            ParameterFormatter<Boolean> formatter;
            Parameter<Boolean> setting;

            String  name;
            Boolean value;

            rKey = CaptureRequest.STATISTICS_HOT_PIXEL_MAP_MODE;//////////////////////////
```

```
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                Boolean OFF = false;
                //Boolean ON  = true;

                value = OFF;

                formatter = new ParameterFormatter<Boolean>() {
                    @NonNull
                    @Override
                    public String formatValue(@NonNull Boolean value) {
                        if (value) {
                            return "ON (FALLBACK)";
                        }
                        return "OFF (PREFERRED)";
                    }
                };
                setting = new Parameter<>(name, value, null, formatter);

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

```

```
156                 rKey = CaptureRequest.STATISTICS_LENS_SHADING_MAP_MODE;//
                        ↪ ////////////////////////
157                 name = rKey.getName();
158
159                 if (supportedKeys.contains(rKey)) {
160
161                     Integer OFF = CameraMetadata.STATISTICS_LENS_SHADING_MAP_MODE_OFF;
162                     //Integer ON  = CameraMetadata.STATISTICS_LENS_SHADING_MAP_MODE_ON;
163
164                     value = OFF;
165                     valueString = "OFF (PREFERRED)";
166
167                     formatter = new ParameterFormatter<Integer>(valueString) {
168                         @NonNull
169                         @Override
170                         public String formatValue(@NonNull Integer value) {
171                             return getValueString();
172                         }
173                     };
174                     setting = new Parameter<>(name, value, null, formatter);
175
176                     builder.set(rKey, setting.getValue());
177                 }
178                 else {
179                     setting = new Parameter<>(name);
180                     setting.setValueString("NOT SUPPORTED");
181                 }
182                 captureRequestMap.put(rKey, setting);
183             }
184             //=========================================
                    ↪ ==================================================
185             {
186                 CaptureRequest.Key<Integer> rKey;
187                 ParameterFormatter<Integer> formatter;
188                 Parameter<Integer> setting;
189
190                 String  name;
191                 Integer value;
192                 String  valueString;
193
194                 if (Build.VERSION.SDK_INT < 28) {
```

```
                    return;
                }

                rKey = CaptureRequest.STATISTICS_OIS_DATA_MODE;//////////////////////////
                name = rKey.getName();

                if (supportedKeys.contains(rKey)) {

                    Integer OFF = CameraMetadata.STATISTICS_OIS_DATA_MODE_OFF;
                    //Integer ON  = CameraMetadata.STATISTICS_OIS_DATA_MODE_ON;

                    value = OFF;
                    valueString = "OFF (PREFERRED)";

                    formatter = new ParameterFormatter<Integer>(valueString) {
                        @NonNull
                        @Override
                        public String formatValue(@NonNull Integer value) {
                            return getValueString();
                        }
                    };
                    setting = new Parameter<>(name, value, null, formatter);

                    builder.set(rKey, setting.getValue());
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
            //=========================================
                ↪ ==================================================
        }

    }
```

Listing E.58: Tonemap Request (`camera2/requests/step16_Tonemap_.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.requests;

import android.annotation.TargetApi;
import android.hardware.camera2.CameraCharacteristics;
import android.hardware.camera2.CameraMetadata;
import android.hardware.camera2.CaptureRequest;
import android.hardware.camera2.params.TonemapCurve;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

import java.util.LinkedHashMap;
import java.util.List;

import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;
import sci.crayfis.shramp.camera2.util.Parameter;
import sci.crayfis.shramp.camera2.util.ParameterFormatter;

/**
 * Configuration class for default CaptureRequest creation, the parameters set here include:
 *    TONEMAP_MODE
 *    TONEMAP_CURVE
 *    TONEMAP_GAMMA
```

```
 *     TONEMAP_PRESET_CURVE
 */
@TargetApi(21)
abstract class step16_Tonemap_ extends step15_Statistics_ {

    // Protected Overriding Instance Methods
    //::::::::::::::::::::::::

    // makeDefault...............
    /**
     * Creating a default CaptureRequest, setting TONEMAP_.* parameters
     * @param builder CaptureRequest.Builder in progress
     * @param characteristicsMap Parameter map of characteristics
     * @param captureRequestMap Parameter map of capture request settings
     */
    @SuppressWarnings("unchecked")
    @Override
    protected void makeDefault(@NonNull CaptureRequest.Builder builder,
                               @NonNull LinkedHashMap<CameraCharacteristics.Key, Parameter>
                                   ↪ characteristicsMap,
                               @NonNull LinkedHashMap<CaptureRequest.Key, Parameter>
                                   ↪ captureRequestMap) {
        super.makeDefault(builder, characteristicsMap, captureRequestMap);

        Log.e("             Tonemap_", "setting default Tonemap_ requests");
        List<CaptureRequest.Key<?>> supportedKeys;
        supportedKeys = CameraController.getAvailableCaptureRequestKeys();
        if (supportedKeys == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Supported keys cannot be null");
            MasterController.quitSafely();
            return;
        }

        //=========================================
            ↪ ==================================================
        {
            CaptureRequest.Key<Integer> rKey;
            Parameter<Integer> setting;

            String name;
```

```

            rKey = CaptureRequest.TONEMAP_MODE;//////////////////////////
            name = rKey.getName();

            if (supportedKeys.contains(rKey)) {

                CameraCharacteristics.Key<int[]> cKey;
                Parameter<Integer> property;

                cKey = CameraCharacteristics.TONEMAP_AVAILABLE_TONE_MAP_MODES;
                property = characteristicsMap.get(cKey);
                if (property == null) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Tone map modes cannot be null");
                    MasterController.quitSafely();
                    return;
                }

                setting = new Parameter<>(name, property.getValue(), property.getUnits(),
                                                                    property.getFormatter();

                builder.set(rKey, setting.getValue());
            }
            else {
                setting = new Parameter<>(name);
                setting.setValueString("NOT SUPPORTED");
            }
            captureRequestMap.put(rKey, setting);
        }
        //=========================================================================
        {
            CaptureRequest.Key<TonemapCurve> rKey;
            ParameterFormatter<TonemapCurve> formatter;
            Parameter<TonemapCurve> setting;

            String  name;
            TonemapCurve value;
            String  valueString;
```

```
117
118             rKey = CaptureRequest.TONEMAP_CURVE;//////////////////////////
119             name = rKey.getName();
120
121             if (supportedKeys.contains(rKey)) {
122
123                 Parameter<Integer> mode = captureRequestMap.get(CaptureRequest.TONEMAP_MODE)
                        ↪ ;
124                 if (mode == null) {
125                     // TODO: error
126                     Log.e(Thread.currentThread().getName(), "Tone map mode cannot be null");
127                     MasterController.quitSafely();
128                     return;
129                 }
130
131                 if (mode.toString().contains("CONTRAST_CURVE")) {
132                     float[] linear_response = {0, 0, 1, 1};
133                     value = new TonemapCurve(linear_response, linear_response,
                            ↪ linear_response);
134                     valueString = "LINEAR RESPONSE (PREFERRED)";
135
136                     formatter = new ParameterFormatter<TonemapCurve>(valueString) {
137                         @NonNull
138                         @Override
139                         public String formatValue(@NonNull TonemapCurve value) {
140                             return getValueString();
141                         }
142                     };
143                     setting = new Parameter<>(name, value, null, formatter);
144
145                     builder.set(rKey, setting.getValue());
146                 }
147                 else {
148                     setting = new Parameter<>(name);
149                     setting.setValueString("DISABLED");
150                 }
151             }
152             else {
153                 setting = new Parameter<>(name);
154                 setting.setValueString("NOT SUPPORTED");
155             }
```

```
            captureRequestMap.put(rKey, setting);
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Float> rKey;
            ParameterFormatter<Float> formatter;
            Parameter<Float> setting;

            String name;
            Float  value;
            String valueString;

            if (Build.VERSION.SDK_INT >= 23) {
                rKey = CaptureRequest.TONEMAP_GAMMA;//////////////////////////
                name = rKey.getName();

                if (supportedKeys.contains(rKey)) {

                    Parameter<Integer> mode = captureRequestMap.get(CaptureRequest.
                        ↪ TONEMAP_MODE);
                    if (mode == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Tone map mode cannot be
                            ↪ null");
                        MasterController.quitSafely();
                        return;
                    }

                    if (mode.toString().contains("GAMMA_VALUE")) {
                        value = 5.f;
                        valueString = "pow(val, 1./5.) (FALLBACK)";

                        formatter = new ParameterFormatter<Float>(valueString) {
                            @NonNull
                            @Override
                            public String formatValue(@NonNull Float value) {
                                return getValueString();
                            }
                        };
                        setting = new Parameter<>(name, value, null, formatter);
```

```
                        builder.set(rKey, setting.getValue());
                    }
                    else {
                        setting = new Parameter<>(name);
                        setting.setValueString("DISABLED");
                    }
                }
                else {
                    setting = new Parameter<>(name);
                    setting.setValueString("NOT SUPPORTED");
                }
                captureRequestMap.put(rKey, setting);
            }
        }
        //=========================================
            ↪ ==========================================================
        {
            CaptureRequest.Key<Integer> rKey;
            ParameterFormatter<Integer> formatter;
            Parameter<Integer> setting;

            String  name;
            Integer value;
            String  valueString;

            if (Build.VERSION.SDK_INT >= 23) {
                rKey = CaptureRequest.TONEMAP_PRESET_CURVE;///////////////////////////
                name = rKey.getName();

                if (supportedKeys.contains(rKey)) {

                    Parameter<Integer> mode = captureRequestMap.get(CaptureRequest.
                        ↪ TONEMAP_MODE);
                    if (mode == null) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), "Tone map mode cannot be
                            ↪ null");
                        MasterController.quitSafely();
                        return;
                    }
```

```
232
233                     if (mode.toString().contains("FAST") || mode.toString().contains("
                            ↪ HIGH_QUALITY")) {
234
235                         //Integer SRGB   = CameraMetadata.TONEMAP_PRESET_CURVE_SRGB;
236                         Integer REC709 = CameraMetadata.TONEMAP_PRESET_CURVE_REC709;
237
238                         value = REC709;
239                         valueString = "REC709 (LAST CHOICE)";
240
241                         formatter = new ParameterFormatter<Integer>(valueString) {
242                             @NonNull
243                             @Override
244                             public String formatValue(@NonNull Integer value) {
245                                 return getValueString();
246                             }
247                         };
248                         setting = new Parameter<>(name, value, null, formatter);
249
250                         builder.set(rKey, setting.getValue());
251                     }
252                     else {
253                         setting = new Parameter<>(name);
254                         setting.setValueString("DISABLED");
255                     }
256                 }
257                 else {
258                     setting = new Parameter<>(name);
259                     setting.setValueString("NOT SUPPORTED");
260                 }
261                 captureRequestMap.put(rKey, setting);
262             }
263         }
264         //=========================================
                ↪ ==================================================
265     }
266
267 }
```

Listing E.59: Parameter (camera2/util/Parameter.java)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;

/**
 * Encapsulation of a parameter's description, value and units
 * @param <T> Parameter value type
 */
@TargetApi(21)
public class Parameter<T> {

    // Private Instance Constants
    //::::::::::::::::::::::

    // mDefaultFormat..............
    // If a ParameterFormatter<T> is not provided, this is used as default
    private final ParameterFormatter<T> mDefaultFormat = new ParameterFormatter<T>() {
        @NonNull
        @Override
        public String formatValue(@NonNull T value) {
            return value.toString();
        }
```

```
    };

    // Private Instance Fields
    //::::::::::::::::::::::

    // mDescription...............
    // A short description of the Parameter
    private String mDescription;

    // mValue...............
    // The value associated with the Parameter
    private T mValue;

    // mUnits...............
    // The units associated with the parameter
    private String mUnits;

    // mParameterFormatter...............
    // The ParameterFormatter to use when displaying
    private ParameterFormatter<T> mParameterFormatter;

    ///////////////////////////
    //::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //::::::::::::::::::::::

    // Parameter...............
    /**
     * Option 1) create a blank Parameter with a description at minimum
     * @param description A short description of the Parameter
     */
    public Parameter(@NonNull String description) {
        mValue       = null;
        mDescription = description;
        mUnits       = null;
        mParameterFormatter = mDefaultFormat;
    }

    // Parameter...............
```

```
    /**
     * Option 2) create a complete Parameter object
     * @param description A short description of the parameter
     * @param value Of type <T>, the value associated with the Parameter (Optional)
     * @param units The units associated with the value of the Parameter (Optional)
     * @param parameterFormatter The formatter for this Parameter (Optional)
     */
    public Parameter(@NonNull String description, @Nullable T value,
                     @Nullable String units, @Nullable ParameterFormatter<T>
                         ↪ parameterFormatter) {
        mValue       = value;
        mDescription = description;
        mUnits       = units;
        if (parameterFormatter == null) {
            mParameterFormatter = mDefaultFormat;
        }
        else {
            mParameterFormatter = parameterFormatter;
        }
    }

    // Parameter ...............
    /**
     * Disable the default constructor option
     */
    private Parameter() {}

    // Public Instance Methods
    //::::::::::::::::::::::

    // getDescription ...............
    /**
     * @return A short description of the Parameter
     */
    @NonNull
    public String getDescription() { return mDescription; }

    // getFormatter ...............
    /**
     * @return The formatter being used for this Parameter
     */
```

```
    @NonNull
    public ParameterFormatter<T> getFormatter() { return mParameterFormatter; }

    // getUnits...............
    /**
     * @return The units associated with the value of this Parameter
     */
    @Nullable
    public String getUnits() { return  mUnits; }

    // getValue...............
    /**
     * @return The value associated with this Parameter
     */
    @Nullable
    public T getValue() { return  mValue; }

    // setFormatter...............
    /**
     * @param parameterFormatter ParameterFormatter to be used
     */
    public void setFormatter(@Nullable ParameterFormatter<T> parameterFormatter) {
        if (parameterFormatter == null) {
            mParameterFormatter = mDefaultFormat;
        }
        else {
            mParameterFormatter = parameterFormatter;
        }
    }

    // setUnits...............
    /**
     * @param units Units of the value
     */
    public void setUnits(@Nullable String units) { mUnits = units; }

    // setValueString...............
    /**
     * @param valueString A String representation of the value (used if value is null)
     */
```

```
    public void setValueString(@NonNull String valueString) { mParameterFormatter.
        ↪ setValueString(valueString); }

    // Public Overriding Methods
    //:::::::::::::::::::::::

    // toString..............
    /**
     * @return A formatted String representation of this Parameter<T>
     */
    @NonNull
    @Override
    public String toString() {
        return mParameterFormatter.toString(mDescription, mValue, mUnits);
    }

}
```

Listing E.60: Parameter Formatter (`camera2/util/ParameterFormatter.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;

import org.jetbrains.annotations.Contract;

/**
 * The purpose of this class is to format the value of a Parameter<T> for printing as a
    ↪ string
 */
@TargetApi(21)
abstract public class ParameterFormatter<T> {

    // Private Class Constants
    //::::::::::::::::::::::

    // PADDING_SIZE..............
    // Whitespace after Parameter<T>'s name and before the string formatted by this class
    private final static int PADDING_SIZE = 55;

    // Private Class Fields
    //::::::::::::::::::::::
```

```

    // mValueString...............
    // In case the Parameter<T> value is unset
    private String mValueString = "ERROR: VALUE NOT SET";

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // ParameterFormatter...............
    /**
     * Option 1) formatted string can be produced directly from Parameter<T> value
     */
    public ParameterFormatter() {}

    // ParameterFormatter...............
    /**
     * Option 2) formatted string cannot be produced directly, or a custom string is desired
     * Note: Parameter<T> value must be null
     * @param valueString String to display when toString() is called
     */
    public ParameterFormatter(@NonNull String valueString) {
        mValueString = valueString;
    }

    // Package-private Instance Methods
    //:::::::::::::::::::::::

    // toString...............
    /**
     * Make a human-friendly displayable string describing this Parameter<T>
     * @param description Description provided by Parameter<T>
     * @param value Value provided by Parameter<T> (uses value string if null)
     * @param units Units provided by Parameter<T>
     * @return The formatted string
     */
    String toString(@NonNull String description, @Nullable T value,
                                @Nullable String units) {
```

```
        String out = description + ":  ";
        int length = out.length();
        for (int i = length; i <= PADDING_SIZE; i++) {
            out += " ";
        }

        if (value == null) {
            out += mValueString;
        }
        else {
            out += formatValue(value);
        }

        if (units == null) {
            return out;
        }
        return out + "  [" + units + "]";
    }

    // Protected Instance Methods
    //:::::::::::::::::::::::

    // getValueString...............
    /**
     * @return Value string set at construction
     */
    @NonNull
    @Contract(pure = true)
    protected String getValueString() {
        return mValueString;
    }

    // setValueString...............
    /**
     * @param valueString Value string to display if Parameter<T> value is null
     */
    protected void setValueString(@NonNull String valueString) {
        mValueString = valueString;
    }

    // Public Abstract Instance Methods
```

```
    //::::::::::::::::::::::

    // formatValue..............
    /**
     * User must implement a custom formatting routine for each Parameter<T>
     * @param value Value to format
     * @return Formatted value
     */
    @NonNull
    abstract public String formatValue(@NonNull T value);

}
```

Listing E.61: Time Code (`camera2/util/TimeCode.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.camera2.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;

import org.jetbrains.annotations.Contract;

import sci.crayfis.shramp.GlobalSettings;

/**
 * For human readability, convert a timestamp in nanoseconds into a short string of
     ↪ characters
 * e.g. 123,456,789 [ns] -> (1 and 2 are dropped) "D EFG HIJ"
 */
@TargetApi(21)
abstract public class TimeCode {

    /**
     * Convert timestamp in nanoseconds into a 7-character time code
     * @param timestamp timestamp to convert (nanoseconds)
     * @return 7-character time code
     */
    @NonNull
    @Contract(pure = true)
```

```
    public static String toString(@NonNull Long timestamp) {
        double time = (double) timestamp;
        String out = "";

        if (!GlobalSettings.ENABLE_VULGARITY) {
            for (int i = 0; i < 7; i++) {
                time /= 10.;
                long iPart = (long) time;
                char code = 'A';
                code += (char) (10 * (time - iPart));
                time = iPart;
                out += code;
            }
        }
        else {
            char[][] code = { {'K', 'U', 'E', 'S', 'D', 'N', 'S', 'T', 'F', 'S'},
                              {'C', 'O', 'L', 'S', 'R', 'M', 'A', 'S', 'I', 'F'},
                              {'I', 'Y', 'O', 'A', 'U', 'E', 'W', 'H', 'A', 'Y'},
                              {'L', 'K', 'H', 'T', 'F', 'N', 'D', 'H', 'S', 'B'},
                              {'S', 'C', 'I', 'U', 'M', 'D', 'T', 'P', 'R', 'C'},
                              {'S', 'U', 'H', 'O', 'A', 'I', 'E', 'U', 'S', 'O'},
                              {'A', 'F', 'S', 'Y', 'B', 'D', 'G', 'C', 'J', 'D'}
                            };
            for (int i = 0; i < 7; i++) {
                time /= 10.;
                long iPart = (long) time;
                int j = (int) (10 * (time - iPart));
                time = iPart;
                out += code[i][j];
            }
        }

        String temp = out;
        out = "";
        for (int i = 6; i >= 0; i--) {
            out += temp.charAt(i);
            if (i == 3) {
                out += " ";
            }
        }

```

```
            return out;
        }

    }
```

Listing E.62: Sensor Controller (`sensor/SensorController.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.app.Activity;
import android.content.Context;
import android.hardware.Sensor;
import android.hardware.SensorEvent;
import android.hardware.SensorManager;
import android.support.annotation.NonNull;

import java.util.ArrayList;
import java.util.List;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Low priority

/**
 * Public interface to all sensors available
 */
@TargetApi(21)
abstract public class SensorController {

```

```
41      // Private Class Constants
42      //::::::::::::::::::::::
43
44      // Collections of various sensors that might be present (device dependant)
45      private static final List<Temperature> mTemperatureSensors = new ArrayList<>();
46      private static final List<Light>       mLightSensors       = new ArrayList<>();
47      private static final List<Pressure>    mPressureSensors    = new ArrayList<>();
48      private static final List<Humidity>    mHumiditySensors    = new ArrayList<>();
49
50      // Private Class Fields
51      //::::::::::::::::::::::
52
53      // mSensorManager..............
54      // System sensor manager reference
55      private static SensorManager mSensorManager;
56
57      // Public Class Methods
58      //::::::::::::::::::::::
59
60      // initializeAll..............
61      /**
62       * TODO: description, comments and logging
63       * @param activity bla
64       * @param saveAllHistory bla
65       */
66      public static void initializeAll(@NonNull Activity activity, boolean saveAllHistory) {
67          initializeTemperature(activity, saveAllHistory);
68          initializeLight(activity, saveAllHistory);
69          initializePressure(activity, saveAllHistory);
70          initializeHumidity(activity, saveAllHistory);
71
72          // TODO: sensor list
73          /*
74          List<Sensor> accelerometerSensors = mSensorManager.getSensorList(Sensor.
                ↪ TYPE_ACCELEROMETER);
75          List<Sensor> geomagneticRotationSensors = mSensorManager.getSensorList(Sensor.
                ↪ TYPE_GEOMAGNETIC_ROTATION_VECTOR);
76          List<Sensor> gravitySensors = mSensorManager.getSensorList(Sensor.TYPE_GRAVITY);
77          List<Sensor> gyroscopicSensors = mSensorManager.getSensorList(Sensor.TYPE_GYROSCOPE)
                ↪ ;
```

```
        List<Sensor> linearAccelerometerSensors = mSensorManager.getSensorList(Sensor.
            ↪ TYPE_LINEAR_ACCELERATION);
        List<Sensor> magneticFieldSensors = mSensorManager.getSensorList(Sensor.
            ↪ TYPE_MAGNETIC_FIELD);
        //List<Sensor> position6DofSensors = mSensorManager.getSensorList(Sensor.
            ↪ TYPE_POSE_6DOF);

        List<Sensor> rotationSensors = mSensorManager.getSensorList(Sensor.
            ↪ TYPE_ROTATION_VECTOR);
        List<Sensor> significantMotionSensors = mSensorManager.getSensorList(Sensor.
            ↪ TYPE_SIGNIFICANT_MOTION);

        //SensorManager.getAltitude()
        //SensorManager.getInclination()
        //SensorManager.getOrientation()
        */

        onResume();
    }

    // initializeTemperature...............
    /**
     * TODO: description, comments and logging
     * @param activity bla
     * @param saveHistory bla
     */
    public static void initializeTemperature(@NonNull Activity activity, boolean saveHistory
        ↪ ) {
        getSensorManager(activity);
        List<Sensor> sensors = mSensorManager.getSensorList(Sensor.TYPE_AMBIENT_TEMPERATURE)
            ↪ ;
        for (Sensor sensor : sensors ) {
            mTemperatureSensors.add(new Temperature(sensor, saveHistory));
        }

    }

    // initializeLight...............
    /**
     * TODO: description, comments and logging
     * @param activity bla
```

```
112         * @param saveHistory bla
113         */
114        public static void initializeLight(@NonNull Activity activity, boolean saveHistory) {
115            getSensorManager(activity);
116            List<Sensor> sensors = mSensorManager.getSensorList(Sensor.TYPE_LIGHT);
117            for (Sensor sensor : sensors ) {
118                mLightSensors.add(new Light(sensor, saveHistory));
119            }
120        }
121
122        // initializePressure...............
123        /**
124         * TODO: description, comments and logging
125         * @param activity bla
126         * @param saveHistory bla
127         */
128        public static void initializePressure(@NonNull Activity activity, boolean saveHistory) {
129            getSensorManager(activity);
130            List<Sensor> sensors = mSensorManager.getSensorList(Sensor.TYPE_PRESSURE);
131            for (Sensor sensor : sensors ) {
132                mPressureSensors.add(new Pressure(sensor, saveHistory));
133            }
134        }
135
136        // initializeHumidity...............
137        /**
138         * TODO: description, comments and logging
139         * @param activity bla
140         * @param saveHistory bla
141         */
142        public static void initializeHumidity(@NonNull Activity activity, boolean saveHistory) {
143            getSensorManager(activity);
144            List<Sensor> sensors = mSensorManager.getSensorList(Sensor.TYPE_RELATIVE_HUMIDITY);
145            for (Sensor sensor : sensors) {
146                mHumiditySensors.add(new Humidity(sensor, saveHistory));
147            }
148        }
149
150        // onResume...............
151        /**
152         * Register sensor listeners with the system
```

```
153         */
154     public static void onResume() {
155 
156         for (Temperature sensor : mTemperatureSensors) {
157             mSensorManager.registerListener(sensor, sensor.getSensor(), SensorManager.
                    ↪ SENSOR_DELAY_NORMAL);
158         }
159 
160         for (Light sensor : mLightSensors) {
161             mSensorManager.registerListener(sensor, sensor.getSensor(), SensorManager.
                    ↪ SENSOR_DELAY_NORMAL);
162         }
163 
164         for (Pressure sensor : mPressureSensors) {
165             mSensorManager.registerListener(sensor, sensor.getSensor(), SensorManager.
                    ↪ SENSOR_DELAY_NORMAL);
166         }
167 
168         for (Humidity sensor : mHumiditySensors) {
169             mSensorManager.registerListener(sensor, sensor.getSensor(), SensorManager.
                    ↪ SENSOR_DELAY_NORMAL);
170         }
171 
172         // TODO: registerListener()
173     }
174 
175     // onPause...............
176     /**
177      * Release sensor listeners from the system to conserve power and ...
178      */
179     public static void onPause() {
180         for (Temperature sensor : mTemperatureSensors) {
181             mSensorManager.unregisterListener(sensor);
182         }
183 
184         for (Light sensor : mLightSensors) {
185             mSensorManager.unregisterListener(sensor);
186         }
187 
188         for (Pressure sensor : mPressureSensors) {
189             mSensorManager.unregisterListener(sensor);
```

```
        }

        for (Humidity sensor : mHumiditySensors) {
            mSensorManager.unregisterListener(sensor);
        }
        // TODO: unregisterListener()
    }

    // getLatestTemperature...............
    /**
     * TODO: description, comments and logging
     * @return bla
     */
    public static List<SensorEvent> getLatestTemperature() {
        List<SensorEvent> latest = new ArrayList<>();
        for (Temperature sensor : mTemperatureSensors) {
            latest.add(sensor.getLast());
        }
        return latest;
    }

    // Private Class Methods
    //:::::::::::::::::::::::

    // getSensorManager...............
    /**
     * TODO: description, comments and logging
     * @param activity bla
     */
    private static void getSensorManager(@NonNull Activity activity) {
        if (mSensorManager == null) {
            mSensorManager = (SensorManager) activity.getSystemService(Context.
                ↪ SENSOR_SERVICE);
        }
    }

}
```

Listing E.63: Basic Sensor (`sensor/BasicSensor.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.hardware.Sensor;
import android.hardware.SensorEvent;
import android.hardware.SensorEventListener;
import android.hardware.SensorManager;
import android.os.Build;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;

import org.jetbrains.annotations.Contract;

import java.util.ArrayList;
import java.util.List;

import sci.crayfis.shramp.util.NumToString;

//////////////////////////
//                    (TODO)    UNDER CONSTRUCTION    (TODO)
//////////////////////////
// Low priority

/**
```

```
 * Basic functionality common to all sensors (sub-classes)
 */
@TargetApi(21)
abstract class BasicSensor implements SensorEventListener {

    // Protected Class Constants
    //::::::::::::::::::::::::

    // Accuracy...............
    // Sensor accuracy level
    protected enum Accuracy {LOW, MEDIUM, HIGH, UNRELIABLE}

    // ReportingMode...............
    protected enum ReportingMode {CONTINUOUS, ON_CHANGE, ONE_SHOT, SPECIAL_TRIGGER}

    // Protected Instance Fields
    //::::::::::::::::::::::::

    // mMetaData...............
    protected class MetaData {
        Integer id;
        String  name;
        String  type;
        String  vendor;
        Integer version;
        Float   current; // usage in [mA]
        String  description;

        ReportingMode reportingMode;
        String  reportingModeString;
        Integer maxDelay; // microseconds
        Integer minDelay; // microseconds

        Float   maximumRange; // sensor's units
        Float   resolution;   // sensor's units

        Accuracy accuracy;
        String accuracyString;

    }
    protected final MetaData mMetaData = new MetaData();
```

```
82
83      // mSensor...............
84      // Reference to system hardware
85      protected Sensor mSensor;
86
87      // mHistory...............
88      // History of recorded values from sensor (optional)
89      protected final List<SensorEvent> mHistory = new ArrayList<>();
90
91      // mSaveHistory...............
92      // True to record history into mHistory, false to disable
93      protected boolean mSaveHistory;
94
95      // Private Class Fields (TODO: ...I don't remember why I made these private)
96      //::::::::::::::::::::::::
97
98      // mUnits...............
99      private static String mUnits;
100
101     // mDimensions...............
102     private static Integer mDimensions;
103
104     ///////////////////////////
105     //::::::::::::::::::::::::
106     ///////////////////////////
107
108     // Constructors
109     //::::::::::::::::::::::::
110
111     // BasicSensor...............
112     /**
113      * Disable default constructor
114      */
115     private BasicSensor() {}
116
117     // BasicSensor...............
118     /**
119      * Create a new sensor
120      * @param sensor Reference to system hardware
121      * @param description Optional description of sensor
122      * @param units Sensor units
```

```
     * @param dimensions Dimensionality returned by system hardware (e.g. a scalar, a vector
         ↪ , etc)
     * @param saveHistory True to enable saving history, false to disable
     */
    BasicSensor(@NonNull Sensor sensor, @Nullable String description, @NonNull String units,
                int dimensions, boolean saveHistory) {

        mSensor      = sensor;
        mSaveHistory = saveHistory;

        if (Build.VERSION.SDK_INT < Build.VERSION_CODES.N) {
            mMetaData.id = null;
        }
        else {
            mMetaData.id = sensor.getId();
            if (mMetaData.id == 0) {
                mMetaData.id = null;
            }
            // if mId == -1, it means this sensor can be uniquely identified in system by
            // combination of its type and name.
        }

        mMetaData.name    = sensor.getName();
        mMetaData.type    = sensor.getStringType();
        mMetaData.vendor  = sensor.getVendor();
        mMetaData.version = sensor.getVersion();
        mMetaData.current = sensor.getPower();

        if (description == null) {
            mMetaData.description = "N/A";
        }
        else {
            mMetaData.description = description;
        }

        switch (sensor.getReportingMode()) {
            case (Sensor.REPORTING_MODE_CONTINUOUS): {
                mMetaData.reportingMode = ReportingMode.CONTINUOUS;
                mMetaData.reportingModeString = "CONTINUOUS";
                break;
            }
```

```
163                 case (Sensor.REPORTING_MODE_ON_CHANGE): {
164                     mMetaData.reportingMode = ReportingMode.ON_CHANGE;
165                     mMetaData.reportingModeString = "ON_CHANGE";
166                     break;
167                 }
168                 case (Sensor.REPORTING_MODE_ONE_SHOT): {
169                     mMetaData.reportingMode = ReportingMode.ONE_SHOT;
170                     mMetaData.reportingModeString = "ONE_SHOT";
171                     break;
172                 }
173                 case (Sensor.REPORTING_MODE_SPECIAL_TRIGGER): {
174                     mMetaData.reportingMode = ReportingMode.SPECIAL_TRIGGER;
175                     mMetaData.reportingModeString = "SPECIAL_TRIGGER";
176                     break;
177                 }
178                 default: {
179                     // TODO: error
180                 }
181             }
182 
183             // aka lowest frequency of reporting is 1 / mMaxDelay [MHz]
184             mMetaData.maxDelay = sensor.getMaxDelay(); // microseconds
185             if (mMetaData.maxDelay <= 0) {
186                 mMetaData.maxDelay = null;
187             }
188 
189             // aka fastest frequency of reporting is 1 / mMinDelay [MHz]
190             mMetaData.minDelay = sensor.getMinDelay(); // microseconds
191             if (mMetaData.minDelay == 0) {
192                 // this sensor only returns a value when the data it's measuring changes.
193                 mMetaData.minDelay = null;
194             }
195 
196             // In sensor's units, whatever they may be
197             mDimensions   = dimensions;
198             mUnits        = units;
199             mMetaData.maximumRange = sensor.getMaximumRange();
200             mMetaData.resolution   = sensor.getResolution();
201 
202             mMetaData.accuracy = null;
203             mMetaData.accuracyString = "UNKNOWN";
```

```
    }

    // Package-private Instance Methods
    //::::::::::::::::::::::

    // getDimensions..............
    /**
     * @return Dimensionality of sensor (e.g. scalar, vector, etc)
     */
    @Contract(pure = true)
    public static int getDimensions() {
        return mDimensions;
    }

    // getHistory...............
    /**
     * @return History of recorded sensor values
     */
    List<SensorEvent> getHistory() {
        return mHistory;
    }

    // getLast...............
    /**
     * @return Last recorded sensor value
     */
    SensorEvent getLast() {
        if (mHistory.size() == 0) {
            // no values have been reported by the sensor
            return null;
        }
        // if history is disabled, the last value is always stored in element 0
        return mHistory.get( mHistory.size() - 1 );
    }

    // mSensor...............
    /**
     * @return Reference to system hardware
     */
    Sensor getSensor() {
        return mSensor;
```

```
245         }
246
247         // getUnits...............
248         /**
249          * @return The units of the sensor
250          */
251         @Contract(pure = true)
252         public static String getUnits() { return mUnits; }
253
254         // Public Overriding Instance Methods
255         //:::::::::::::::::::::::
256
257         // onAccuracyChanged...............
258         /**
259          * Called by the system whenever the sensor's accuracy has changed
260          * @param sensor Reference to system hardware
261          * @param accuracy Accuracy code
262          */
263         @Override
264         public void onAccuracyChanged(Sensor sensor, int accuracy) {
265             // TODO: Do something here if sensor accuracy changes.  For now, I don't care
266
267             switch (accuracy) {
268                 case (SensorManager.SENSOR_STATUS_ACCURACY_LOW): {
269                     mMetaData.accuracy = Accuracy.LOW;
270                     mMetaData.accuracyString = "LOW";
271                     break;
272                 }
273                 case (SensorManager.SENSOR_STATUS_ACCURACY_MEDIUM): {
274                     mMetaData.accuracy = Accuracy.MEDIUM;
275                     mMetaData.accuracyString = "MEDIUM";
276                     break;
277                 }
278                 case (SensorManager.SENSOR_STATUS_ACCURACY_HIGH): {
279                     mMetaData.accuracy = Accuracy.HIGH;
280                     mMetaData.accuracyString = "HIGH";
281                     break;
282                 }
283                 case (SensorManager.SENSOR_STATUS_UNRELIABLE): {
284                     mMetaData.accuracy = Accuracy.UNRELIABLE;
285                     mMetaData.accuracyString = "UNRELIABLE";
```

```
                    break;
                }
                default: {
                    // TODO: error
                }
            }
        }

        // onSensorChanged...............
        /**
         * Called by the system when the sensor value changes
         * @param event Bundle of information regarding the sensor and its value change
         */
        @Override
        public void onSensorChanged(SensorEvent event) {
            if (mHistory.size() == 0) {
                onAccuracyChanged(event.sensor, event.accuracy);
                mHistory.add(event);
                return;
            }

            if (mSaveHistory) {
                mHistory.add(event);
            }
            else {
                mHistory.set(0, event);
            }
        }

        // toString...............
        /**
         * @return A string summarizing this sensor and its abilities/settings
         */
        @Override
        @NonNull
        public String toString() {
            String out = " \n";

            out += "\t" + "Sensor ID:                        ";
            if (mMetaData.id == null) {
                out += "NOT SUPPORTED";
```

```
        }
        else if (mMetaData.id == -1) {
            out += "N/A";
        }
        else {
            out += NumToString.number(mMetaData.id);
        }
        out += "\n";

        out += "\t" + "Sensor Name:                      " + mMetaData.name + "\n";
        out += "\t" + "Sensor Type:                      " + mMetaData.type + "\n";
        out += "\t" + "Sensor Vendor:                    " + mMetaData.vendor + "\n";
        out += "\t" + "Sensor Version:                   " + NumToString.number(mMetaData.
            ↪ version) + "\n";
        out += "\t" + "Sensor Current:                   " + NumToString.decimal(mMetaData.
            ↪ current) + " [mA]\n";

        out += "\t" + "Sensor Reporting Mode:            " + mMetaData.reportingModeString +
            ↪  "\n";

        out += "\t" + "Sensor Lowest Sampling Frequency: ";
        if (mMetaData.maxDelay == null) {
            out += "N/A";
        }
        else {
            float MHz = 1.f / mMetaData.maxDelay;
            out += NumToString.decimal(MHz) + " [MHz]\n";
        }

        out += "\t" + "Sensor Maximum Sampling Frequency: ";
        if (mMetaData.minDelay == null) {
            out += "N/A";
        }
        else {
            float MHz = 1.f / mMetaData.minDelay;
            out += NumToString.decimal(MHz) + " [MHz]\n";
        }

        out += "\t" + "Sensor Output Dimensionality:      " + NumToString.number(mDimensions
            ↪ ) + "\n";
```

```
        out += "\t" + "Sensor Maximum Value:              " + NumToString.decimal(mMetaData.maximumRange) + " [" + mUnits + "]\n";
        out += "\t" + "Sensor Resolution:                 " + NumToString.decimal(mMetaData.resolution) + " [" + mUnits + "]\n";

        out += "\t" + "Sensor Current Accuracy:           " + mMetaData.accuracyString + "\n";

        return out;
    }

}
```

Listing E.64: Humidity Sensor (`sensor/Humidity.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.hardware.Sensor;
import android.support.annotation.NonNull;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Low priority

/**
 * Ambient Humidity Sensors
 */
@TargetApi(21)
final class Humidity extends BasicSensor {

    // Private Class Constants
    //::::::::::::::::::::::

    private final static String mDescription = "Ambient relative humidity";
    private final static String mUnits       = "%";

    // Humidity is a scalar quantity (dimensionality = 1)
```

```
    private final static int mDimensions = 1;

    // Constructors
    //::::::::::::::::::::::

    // Humidity..............
    /**
     * Create new humidity sensor
     * @param sensor System hardware reference
     * @param saveHistory True to enable saving pressure history, false to disable
     */
    Humidity(@NonNull Sensor sensor, boolean saveHistory) {
        super(sensor, mDescription, mUnits, mDimensions, saveHistory);
    }

    // Public Class Methods
    //::::::::::::::::::::::

    // getDewPointTemperature..............
    /**
     * Compute the dew-point temperature
     * @param temperature [celsius]
     * @param relativeHumidity [%]
     * @return [celsius]
     */
    public static float getDewPointTemperature(float temperature, float relativeHumidity) {
        double m  = 17.62;  // [unitless]
        double Tn = 243.12; // [Celsius]

        double group1 = (float) Math.log(relativeHumidity);
        double group2 = m * temperature / (Tn + temperature);

        double numerator = group1 + group2;
        double denominator = m - numerator;

        return (float) ( Tn * numerator / denominator );
    }

    // getAbsoluteHumidity..............
    /**
     * Compute the absolute humidity
```

```
     * @param temperature [celsius]
     * @param relativeHumidity [%]
     * @return [grams / meter^3]
     */
    public static float getAbsoluteHumidity(float temperature, float relativeHumidity) {
        double m  = 17.62;  // [unitless]
        double Tn = 243.12; // [Celsius]
        double A  = 6.112;  // [hectoPascals]

        double group1 = m * temperature / (Tn + temperature);

        double numerator = relativeHumidity * A * Math.exp(group1);
        double denominator = 273.15 + temperature;

        return (float) (216.7 * numerator / denominator);
    }

}
```

Listing E.65: Light Sensor (`sensor/Light.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.hardware.Sensor;
import android.support.annotation.NonNull;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Low priority

/**
 * Ambient Light Sensors
 */
@TargetApi(21)
final class Light extends BasicSensor {

    // Private Class Constants
    //:::::::::::::::::::::::

    private final static String mDescription = "Ambient illuminance";
    private final static String mUnits       = "Lux";

    // Illuminance is a scalar quantity (dimensionality = 1)
```

```
    private final static int mDimensions = 1;

    // Constructors
    //::::::::::::::::::::::

    // Light..............
    /**
     * Create a new light sensor
     * @param sensor System hardware reference
     * @param saveHistory True to enable saving pressure history, false to disable
     */
    Light(@NonNull Sensor sensor, boolean saveHistory) {
        super(sensor, mDescription, mUnits, mDimensions, saveHistory);
    }

}
```

Listing E.66: Pressure Sensor (`sensor/Pressure.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.hardware.Sensor;
import android.support.annotation.NonNull;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Low priority

/**
 * Ambient Pressure Sensors
 */
@TargetApi(21)
final class Pressure extends BasicSensor {

    // Private Class Constants
    //:::::::::::::::::::::::

    private final static String mDescription = "Ambient air pressure";
    private final static String mUnits       = "millibar";

    // Pressure is a scalar quantity (dimensionality = 1)
```

```
    private final static int mDimensions = 1;

    // Constructors
    //::::::::::::::::::::::

    // Pressure..............
    /**
     * Create new pressure sensor
     * @param sensor System hardware reference
     * @param saveHistory True to enable saving pressure history, false to disable
     */
    Pressure(@NonNull Sensor sensor, boolean saveHistory) {
        super(sensor, mDescription, mUnits, mDimensions, saveHistory);
    }

}
```

Listing E.67: Temperature Sensor (`sensor/Temperature.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.sensor;

import android.annotation.TargetApi;
import android.hardware.Sensor;
import android.support.annotation.NonNull;

//////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
//////////////////////////
// Low priority

/**
 * Ambient Temperature Sensors
 */
@TargetApi(21)
final class Temperature extends BasicSensor {

    // Private Class Constants
    //::::::::::::::::::::::

    private final static String mDescription = "Ambient air temperature";
    private final static String mUnits       = "Celsius";

    // Temperature is a scalar quantity (dimensionality = 1)
```

```
    private final static int mDimensions = 1;

    // Constructors
    //::::::::::::::::::::::

    // Temperature..............
    /**
     * Create new temperature sensor
     * @param sensor System hardware reference
     * @param saveHistory True to enable saving pressure history, false to disable
     */
    Temperature(@NonNull Sensor sensor, boolean saveHistory) {
        super(sensor, mDescription, mUnits, mDimensions, saveHistory);
    }

}
```

Listing E.68: Asynchronous Response (`ssh/AsyncResponse.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.ssh;

////////////////////////////
//                    (TODO)    UNDER CONSTRUCTION    (TODO)
////////////////////////////
// This interface works well for transmitting data via SSH, but I've currently disabled that
// functionality.  I want to revisit this after I've done some work on StorageMedia

/**
 * Interface for AsyncTasks to send information back to the Activity.
 */
public interface AsyncResponse {
    /**
     * Called in the Activity once the AsyncTask finishes.
     * @param status a string of information to give back to the Activity.
     */
    void processFinish(String status);
}
```

Listing E.69: SSH Session (`ssh/SSHrampSession.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.ssh;

import android.os.AsyncTask;
import android.os.Environment;
import android.util.Log;

import com.jcraft.jsch.Channel;
import com.jcraft.jsch.ChannelExec;
import com.jcraft.jsch.JSch;
import com.jcraft.jsch.JSchException;
import com.jcraft.jsch.Session;

import java.io.File;
import java.io.FileInputStream;
import java.io.InputStream;
import java.io.OutputStream;
import java.text.SimpleDateFormat;
import java.util.Date;

//////////////////////////
//                    (TODO)    UNDER CONSTRUCTION    (TODO)
//////////////////////////
// This class works well for transmitting data via SSH, but I've currently disabled that
// functionality.  I want to revisit this after I've done some work on StorageMedia
```

```java

public class SSHrampSession extends AsyncTask<String, Void, String> {

    // This is a link back to the main activity
    public AsyncResponse mainactivity = null;

    /**
     * SSHrampSession operations to be done in the background asynchronously from the main thread.
     * @param filenames dummy name
     * @return returns the status of the SSHrampSession operation which gets passed back to the main activity
     */
    protected String doInBackground(String... filenames) {
        String filename = filenames[0];

        // status string for reporting back to the main activity
        String status = "";

        String user = "shramp";
        String host = "craydata.ps.uci.edu";
        //String knownhostsfile = Environment.getExternalStorageDirectory() + "/.ssh/known_hosts";
        String pubkeyfile = Environment.getExternalStorageDirectory() + "/.ssh/id_rsa";
        int port=22;

        try {
            JSch jsch = new JSch();
            //jsch.setKnownHosts(knownhostsfile);
            jsch.addIdentity(pubkeyfile);

            Session session = jsch.getSession(user, host, port);
            //session.setConfig("PreferredAuthentications", "publickey");
            session.setConfig("StrictHostKeyChecking", "no");
            session.setTimeout(10000);
            session.connect();

            //ChannelExec channel = (ChannelExec)session.openChannel("exec");
            //channel.setCommand("touch ShRAMP_was_here");

            String timestamp = new SimpleDateFormat("yyyyMMdd_HHmmss").format(new Date());
```

```
79              String outfile = "/data/shramp/" + timestamp + ".jpeg";
80
81              Channel channel = session.openChannel("exec");
82              ((ChannelExec)channel).setCommand("scp -t " + outfile);
83
84              try {
85                  OutputStream out = channel.getOutputStream();
86                  InputStream   in = channel.getInputStream();
87
88                  channel.connect();
89
90                  File file2upload = new File(filename);
91                  long filesize = file2upload.length();
92                  String command = "C0644 " + filesize + " ";
93                  if (filename.lastIndexOf('/') > 0) {
94                      command += filename.substring(filename.lastIndexOf('/') + 1);
95                  } else {
96                      command += filename;
97                  }
98                  command += "\n";
99
100                 out.write(command.getBytes());
101                 out.flush();
102
103                 FileInputStream fis = new FileInputStream(filename);
104                 byte[] buf = new byte[1024];
105                 while (true) {
106                     int len = fis.read(buf, 0, buf.length);
107                     if (len <= 0)
108                         break;
109                     out.write(buf, 0, len);
110                     out.flush();
111                 }
112                 fis.close();
113                 fis = null;
114
115                 // send '\0'
116                 buf[0] = 0;
117                 out.write(buf, 0, 1);
118                 out.flush();
119
```

```
            }
            catch (Exception e) {
                status = status.concat("fuck\n");
            }

            channel.disconnect();
            session.disconnect();
            status = status.concat("\tImage Uploaded!\n\n");
            status = status.concat("App finished, ready to close..");
        }
        catch(JSchException e) {
            status = status.concat("ERROR:\n");
            status = status.concat("\t");
            status = status.concat(e.getLocalizedMessage());
        }
        return status;
    }

    /**
     * Executed automatically when doInBackground finishes.
     * Passes status string back to the main activity.
     * @param status string to pass back
     */
    @Override
    protected void onPostExecute(String status) {
        mainactivity.processFinish(status);
    }

}
```

Listing E.70: Surface Controller (`surfaces/SurfaceController.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.surfaces;

import android.annotation.TargetApi;
import android.app.Activity;
import android.graphics.SurfaceTexture;
import android.media.ImageReader;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;
import android.util.Size;
import android.view.Surface;

import org.jetbrains.annotations.Contract;

import java.util.ArrayList;
import java.util.List;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.camera2.CameraController;

/**
 * This class is intended to be the public face of all surface operations, controlling
```

```
 * creation, updating, etc internally.
 */
@TargetApi(21)
final public class SurfaceController {

    // Private Class Constants
    //:::::::::::::::::::::::

    // mInstance..............
    // Reference to single instance
    private static final SurfaceController mInstance = new SurfaceController();

    // mImageReaderListener...............
    // Reference to single ImageReader surface for receiving camera frames
    private static final ImageReaderListener mImageReaderListener = new ImageReaderListener
        ↪ ();

    // mSurfaces..............
    // Master list of any and all open surfaces ready for use
    private static final List<Surface> mSurfaces = new ArrayList<>();

    // Private Instance Constants
    //:::::::::::::::::::::::

    // mTextureViewListener...............
    // Reference to single TextureView surface for displaying text or video, cannot be
        ↪ static
    // due to its link with the governing Activity
    private final TextureViewListener mTextureViewListener = new TextureViewListener();

    // Private Instance Fields
    //:::::::::::::::::::::::

    // mImageReaderIsReady...............
    // Status of ImageReader, true if ready for use, false if not
    private Boolean mImageReaderIsReady = false;

    // mTextureViewIsReady...............
    // Status of TextureView, true if ready for use, false if not
    private Boolean mTextureViewIsReady = false;

```

```
    // mOutputFormat...............
    // Output format, either ImageFormat.RAW or ImageFormat.YUV_420_888
    private Integer mOutputFormat;

    // mOutputSize...............
    // Output image dimensions (width, height) in pixels
    private Size mOutputSize;

    // mNextRunnable...............
    // After a surface is opened (asynchronously), execute this runnable on mNextHandler's thread
    private Runnable mNextRunnable;

    // mNextHandler...............
    // Handler of the thread to run mNextRunnable on after opening a surface asynchronously
    private Handler mNextHandler;

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // SurfaceController...............
    /**
     * Nothing special, just create single instance
     */
    private SurfaceController() {}

    // Public Class Methods
    //:::::::::::::::::::::::

    // getOpenSurfaces...............
    /**
     * @return Master list of open surfaces ready to use
     */
    @NonNull
    @Contract(pure = true)
    public static List<Surface> getOpenSurfaces() {
        return mSurfaces;
```

```
    }

    // getOutputSurfaceClasses...............
    /**
     * @return List of surface classes to be used, useful for determining output format /
         ↪ resolution
     */
    @NonNull
    public static List<Class> getOutputSurfaceClasses() {
        List<Class> classList = new ArrayList<>();

        // Video feed on screen
        if (GlobalSettings.TEXTURE_VIEW_SURFACE_ENABLED) {
            // The TextureView class itself isn't known to StreamConfigurationMap for
                ↪ determining
            // output format / resolution abilities, but TextureView turns out to use
            // SurfaceTexture, which is known to StreamConfigurationMap
            classList.add(SurfaceTexture.class);
        }

        // Image processing
        if (GlobalSettings.IMAGE_READER_SURFACE_ENABLED) {
            classList.add(ImageReader.class);
        }

        return classList;
    }

    // openSurfaces...............
    /**
     * Open all surfaces specified in GlobalSettings
     * @param activity The app-controlling activity
     * @param runnable Optional Runnable to run on handler's thread after asynchronous
         ↪ opening
     *                 all surfaces.  This method itself returns before the surfaces are
         ↪ open.
     * @param handler Handler to thread to run on after opening surfaces, defaults to main
         ↪ thread
     */
    public static void openSurfaces(@NonNull Activity activity,
```

```
                                    @Nullable Runnable runnable, @Nullable Handler handler) {

        mInstance.mOutputFormat = CameraController.getOutputFormat();
        mInstance.mOutputSize   = CameraController.getOutputSize();

        if (mInstance.mOutputFormat == null || mInstance.mOutputSize == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Output format/size cannot be null");
            MasterController.quitSafely();
            return;
        }

        if (handler == null) {
            mInstance.mNextHandler = new Handler(activity.getMainLooper());
        }
        mInstance.mNextHandler  = handler;
        mInstance.mNextRunnable = runnable;

        // Video feed on screen
        if (GlobalSettings.TEXTURE_VIEW_SURFACE_ENABLED) {
            mInstance.mTextureViewListener.openSurface(activity);
        }

        // Image processing
        if (GlobalSettings.IMAGE_READER_SURFACE_ENABLED) {
            mImageReaderListener.openSurface(mInstance.mOutputFormat, mInstance.mOutputSize);
        }
    }

    // Package-private Instance Methods
    //::::::::::::::::::::::

    // surfaceHasOpened...............
    /**
     * Called by other classes in this immediate package as their surfaces come online
     * @param surface Surface that has opened
     * @param klass Class of surface that has opened
     */
    static void surfaceHasOpened(@NonNull Surface surface, @NonNull Class klass) {
```

```
194         Log.e(Thread.currentThread().getName(), klass.getSimpleName() + " surface has opened
            ↪ ");
195         mSurfaces.add(surface);
196
197         if (klass == TextureViewListener.class) {
198             mInstance.mTextureViewIsReady = true;
199         }
200
201         if (klass == ImageReaderListener.class) {
202             mInstance.mImageReaderIsReady = true;
203         }
204
205         boolean allReady = true;
206         if (GlobalSettings.TEXTURE_VIEW_SURFACE_ENABLED) {
207             allReady = allReady && mInstance.mTextureViewIsReady;
208         }
209         if (GlobalSettings.IMAGE_READER_SURFACE_ENABLED) {
210             allReady = allReady && mInstance.mImageReaderIsReady;
211         }
212
213         if (allReady) {
214             if (mInstance.mNextRunnable != null) {
215                 mInstance.mNextHandler.post(mInstance.mNextRunnable);
216             }
217             mInstance.mNextHandler  = null;
218             mInstance.mNextRunnable = null;
219         }
220     }
221
222 }
```

Listing E.71: TextureView Listener (`surfaces/TextureViewListener.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.surfaces;

import android.annotation.TargetApi;
import android.app.Activity;
import android.graphics.SurfaceTexture;
import android.support.annotation.NonNull;
import android.util.Log;
import android.view.Surface;
import android.view.TextureView;

/**
 * A TextureView is useful for displaying text or a live camera feed.
 * The purpose of this class is to handle the creation and change of a TextureView surface.
 * TextureView implicitly runs on the main thread.
 */
@TargetApi(21)
final class TextureViewListener implements TextureView.SurfaceTextureListener {

    // Private Instance Fields
    //::::::::::::::::::::::

    // mSurface..............
    // Active TextureView surface
    private Surface mSurface;
```

```
41
42      // mSurfaceHeight...............
43      // Height dimension in pixels
44      private Integer mSurfaceHeight;
45
46      // mSurfaceWidth...............
47      // Width dimension in pixels
48      private Integer mSurfaceWidth;
49
50      // mTextureView...............
51      // Active TextureView object (good for displaying text or live camera images)
52      private TextureView mTextureView;
53
54      ///////////////////////////
55      //:::::::::::::::::::::::
56      ///////////////////////////
57
58      // Constructors
59      //:::::::::::::::::::::::
60
61      // TextureViewListener...............
62      /**
63       * Nothing special, just make it
64       */
65      TextureViewListener() {
66          super();
67      }
68
69      // Package-private Instance Methods
70      //:::::::::::::::::::::::
71
72      // openSurface...............
73      /**
74       * Build/open a new TextureView surface
75       * @param activity Activity in control of the app
76       */
77      void openSurface(@NonNull Activity activity) {
78          mTextureView = new TextureView(activity);
79          mTextureView.setSurfaceTextureListener(this);
80
81          // execution continues with onSurfaceTextureAvailable() listener below
```

```
        activity.setContentView(mTextureView);
    }

    // Public Overriding Instance Methods
    //::::::::::::::::::::::

    // onSurfaceTextureAvailable..............
    /**
     * Called once the system asynchronously configures a new TextureView surface.
     * @param texture Reference to the new surface
     * @param width Width (in pixels) of the surface
     * @param height Height (in pixels) of the surface
     */
    @Override
    public void onSurfaceTextureAvailable(@NonNull SurfaceTexture texture, int width, int
        ↪ height) {
        mSurfaceWidth  = width;
        mSurfaceHeight = height;
        mSurface = new Surface(texture);

        // return execution control to SurfaceController
        SurfaceController.surfaceHasOpened(mSurface, TextureViewListener.class);
    }

    // onSurfaceTextureUpdated...............
    /**
     * Called by the system every time something is written to the surface, so it's best to
     * keep this minimal if anything needs to be done.
     * @param texture Reference to the TextureView surface
     */
    @Override
    public void onSurfaceTextureUpdated(@NonNull SurfaceTexture texture) {
        // do nothing
    }

    // onSurfaceTextureDestroyed...............
    /**
     * Called by the system when the surface is destroyed
     * @param texture Reference to the TextureView surface
     * @return If returns true, no rendering should happen inside the surface texture after
        ↪ this
```

```
     * method is invoked. If returns false, the client needs to call SurfaceTexture.release
         ↪ ().
     * Most applications should return true.
     */
    @Override
    public boolean onSurfaceTextureDestroyed(@NonNull SurfaceTexture texture) {
        return true;
    }

    // onSurfaceTextureSizeChanged..............
    /**
     * Called by the system when the surface dimensions are changed
     * @param texture Reference to the TextureView surface
     * @param width New surface width (in pixels)
     * @param height New surface height (in pixels)
     */
    @Override
    public void onSurfaceTextureSizeChanged(@NonNull SurfaceTexture texture, int width, int
        ↪ height) {
        Log.e(Thread.currentThread().getName(), "TextureViewListener size has changed to: "
        + Integer.toString(width) + " x " + Integer.toString(height) + " pixels");
        mSurfaceWidth = width;
        mSurfaceHeight = height;
    }

}
```

Listing E.72: Image Reader Listener (`surfaces/ImageReaderListener.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.surfaces;

import android.media.ImageReader;
import android.os.Build;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.util.Log;
import android.util.Size;
import android.view.Surface;

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.analysis.AnalysisController;
import sci.crayfis.shramp.analysis.DataQueue;
import sci.crayfis.shramp.analysis.ImageWrapper;
import sci.crayfis.shramp.util.HandlerManager;
import sci.crayfis.shramp.util.HeapMemory;
import sci.crayfis.shramp.util.StopWatch;

/**
 * An ImageReader is useful for receiving camera image data.
 * The purpose of this class is to handle its creation and reception of image data.
 */
public final class ImageReaderListener implements ImageReader.OnImageAvailableListener {

```

```
    // Private Constants
    //::::::::::::::::::::::

    // THREAD_NAME..............
    // To maximize performance, the camera image data is received on its own thread
    private static final String THREAD_NAME = "ImageReaderThread";

    // mHandler...............
    // Handler to the ImageReaderThread
    private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
                                                        GlobalSettings.
                                                            ↪ IMAGE_READER_THREAD_PRIORITY);

    // LOCK...............
    // Synchronous lock to prevent the camera system thread from calling onImageAvailable()
        ↪ twice
    // (or more) in a row while ImageReaderThread is still processing the first call and
        ↪ from
    // getting the order of images messed up.. TODO: this might not be strictly necessary.
    private static final Object LOCK = new Object();

    // Private Instance Fields
    //::::::::::::::::::::::

    // mImageFormat...............
    // The output image format: ImageFormat.RAW or ImageFormat.YUV_420_888
    private Integer mImageFormat;

    // mImageHeight...............
    // Image height in pixels
    private Integer mImageHeight;

    // mImageWidth...............
    // Image width in pixels
    private Integer mImageWidth;

    // mImageReader...............
    // Reference to the ImageReader object that controls the surface
    private ImageReader mImageReader;

    // mSurface...............
```

```
    // The corresponding surface to the ImageReader object
    private Surface mSurface;

    // For now, monitor performance (TODO: remove in the future)
    private static abstract class StopWatches {
        final static StopWatch OnImageAvailable = new StopWatch("ImageReaderListener.
            ↪ onImageAvailable()");
        final static StopWatch AddImageWrapper  = new StopWatch("ImageReaderListener Queue
            ↪ ImageWrapper");
    }

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // ImageReaderListener...............
    /**
     * Nothing special, just make it
     */
    ImageReaderListener() {
        super();
    }

    // Package-private Instance Methods
    //:::::::::::::::::::::::

    // openSurface...............
    /**
     * Build/open a new ImageReader surface to receive camera image data
     *
     * @param imageFormat ImageFormat.RAW or ImageFormat.YUV_420_888
     * @param imageSize Image size width and height in pixels
     */
    void openSurface(@NonNull Integer imageFormat, @NonNull Size imageSize) {
        mImageFormat = imageFormat;
        mImageWidth  = imageSize.getWidth();
        mImageHeight = imageSize.getHeight();

```

```
        mImageReader = ImageReader.newInstance(mImageWidth, mImageHeight, mImageFormat,
                                                                GlobalSettings.
                                                                    ↪ MAX_SIMULTANEOUS_IMAGES);
        mImageReader.setOnImageAvailableListener(this, mHandler);

        SurfaceController.surfaceHasOpened(mImageReader.getSurface(), ImageReaderListener.
            ↪ class);
    }

    // Public Overriding Instance Methods
    //::::::::::::::::::::::

    // onImageAvailable..............
    /**
     * Called by the system every time a new image is ready from the camera
     * @param reader ImageReader buffer that holds the backlog of images
     */
    @Override
    public void onImageAvailable(@NonNull ImageReader reader) {
        StopWatches.OnImageAvailable.start();

        // TODO: Lock probably not necessary
        // onImageAvailable() runs on its own thread, so multiple calls from the system
            ↪ should
        // automatically queue..  Haven't tested yet
        synchronized (LOCK) {

            // Wait until there is enough memory to queue up an image for processing
            while (HeapMemory.isMemoryLow()) {

                Log.e(Thread.currentThread().getName(), ">> LOW MEMORY <<
                    ↪ ImageReaderListener is waiting for memory to clear >> LOW MEMORY <<")
                    ↪ ;
                HeapMemory.logAvailableMiB();

                try {
                    LOCK.wait(GlobalSettings.DEFAULT_WAIT_MS);
                }
                catch (InterruptedException e) {
                    // TODO: error?
                }
```

```

                // Try to free memory
                System.gc();
                if (Build.VERSION.SDK_INT > 27) {
                    reader.discardFreeBuffers();
                }

                // If images are not being processed, go ahead and queue this image up.
                // Sometimes the garbage collector just needs a kick.
                if (!AnalysisController.isBusy()) {
                    break;
                }
            }

            StopWatches.AddImageWrapper.start();
            DataQueue.add(new ImageWrapper(reader));
            StopWatches.AddImageWrapper.addTime();
        }

        StopWatches.OnImageAvailable.addTime();
    }

}
```

Listing E.73: Array to List (`util/ArrayToList.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;

import java.util.ArrayList;
import java.util.List;

/**
 * Helper for reading camera abilities, turns a primitive-type array (or object array) into
 * a List<Object> array.
 */
@TargetApi(21)
abstract public class ArrayToList {

    // Public Class Methods
    //::::::::::::::::::::::

    // convert..............
    /**
     * Turns a boolean[] array into a List<Boolean> array
     * @param array input
     * @return output
     */
```

```
    @NonNull
    public static List<Boolean> convert(@NonNull boolean[] array) {
        List<Boolean> list = new ArrayList<>();
        for (boolean val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns a byte[] array into a List<Byte> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Byte> convert(@NonNull byte[] array) {
        List<Byte> list = new ArrayList<>();
        for (byte val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns a char[] array into a List<Char> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Character> convert(@NonNull char[] array) {
        List<Character> list = new ArrayList<>();
        for (char val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
```

```
     * Turns a short[] array into a List<Short> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Short> convert(@NonNull short[] array) {
        List<Short> list = new ArrayList<>();
        for (short val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns an int[] array into a List<Integer> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Integer> convert(@NonNull int[] array) {
        List<Integer> list = new ArrayList<>();
        for (int val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns a long[] array into a List<Long> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Long> convert(@NonNull long[] array) {
        List<Long> list = new ArrayList<>();
        for (long val : array) {
            list.add(val);
        }
        return list;
```

```
    }

    // convert...............
    /**
     * Turns a float[] array into a List<Float> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Float> convert(@NonNull float[] array) {
        List<Float> list = new ArrayList<>();
        for (float val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns a double[] array into a List<Double> array
     * @param array input
     * @return output
     */
    @NonNull
    public static List<Double> convert(@NonNull double[] array) {
        List<Double> list = new ArrayList<>();
        for (double val : array) {
            list.add(val);
        }
        return list;
    }

    // convert...............
    /**
     * Turns an Object[] array into a List<Object> array
     * @param array input
     * @return output
     */
    @NonNull
    public static <T> List<T> convert(@NonNull T[] array) {
        List<T> list = new ArrayList<>();
```

```
        for (T val : array) {
            list.add(val);
        }
        return list;
    }

}
```

Listing E.74: Build String (`util/BuildString.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.os.Build;
import android.support.annotation.NonNull;
import android.util.Log;

/**
 * Translates Build.VERSION.SDK_INT into a string describing the Android APK version
 */
@TargetApi(21)
abstract public class BuildString {

    // Public Class Methods
    //::::::::::::::::::::::

    // get..............
    /**
     * Get a nice build string of the form: vX.X API XX Name (Date)
     * @return string
     */
    @NonNull
    public static String get() {
        int buildCode = Build.VERSION.SDK_INT;
```

```
41          String api = Integer.toString(buildCode);
42          String buildString;
43
44          switch (buildCode) {
45              case Build.VERSION_CODES.BASE: {
46                  buildString = "v1.0 API " + api + " \"Base\" (October 2008)";
47                  break;
48              }
49
50              case Build.VERSION_CODES.BASE_1_1: {
51                  buildString = "v1.1 API " + api + " \"Base 1.1\" (February 2009)";
52                  break;
53              }
54
55              case Build.VERSION_CODES.CUPCAKE: {
56                  buildString = "v1.5 API " + api + " \"Cupcake\" (May 2009)";
57                  break;
58              }
59
60              case Build.VERSION_CODES.DONUT: {
61                  buildString = "v1.6 API " + api + " \"Donut\" (September 2009)";
62                  break;
63              }
64
65              case Build.VERSION_CODES.ECLAIR: {
66                  buildString = "v2.0 API " + api + " \"Eclair\" (November 2009)";
67                  break;
68              }
69
70              case Build.VERSION_CODES.ECLAIR_0_1: {
71                  buildString = "v2.0.1 API " + api + " \"Eclair 0.1\" (December 2009)";
72                  break;
73              }
74
75              case Build.VERSION_CODES.ECLAIR_MR1: {
76                  buildString = "v2.1 API " + api + " \"Eclair MR1\" (January 2010)";
77                  break;
78              }
79
80              case Build.VERSION_CODES.FROYO: {
81                  buildString = "v2.2 API " + api + " \"Froyo\" (June 2010)";
```

```
                break;
            }

            case Build.VERSION_CODES.GINGERBREAD: {
                buildString = "v2.3 API " + api + " \"Gingerbread\" (November 2010)";
                break;
            }

            case Build.VERSION_CODES.GINGERBREAD_MR1: {
                buildString = "v2.3.3 API " + api + " \"Gingerbread MR1\" (February 2011)";
                break;
            }

            case Build.VERSION_CODES.HONEYCOMB: {
                buildString = "v3.0 API " + api + " \"Honeycomb\" (February 2011)";
                break;
            }

            case Build.VERSION_CODES.HONEYCOMB_MR1: {
                buildString = "v3.1 API " + api + " \"Honeycomb MR1\" (May 2011)";
                break;
            }

            case Build.VERSION_CODES.HONEYCOMB_MR2: {
                buildString = "v3.2 API " + api + " \"Honeycomb MR2\" (June 2011)";
                break;
            }

            case Build.VERSION_CODES.ICE_CREAM_SANDWICH: {
                buildString = "v4.0 API " + api + " \"Ice Cream Sandwich\" (October 2011)";
                break;
            }

            case Build.VERSION_CODES.ICE_CREAM_SANDWICH_MR1: {
                buildString = "v4.0.3 API " + api + " \"Ice Cream Sandwich MR1\" (December
                    ↪ 2011)";
                break;
            }

            case Build.VERSION_CODES.JELLY_BEAN: {
                buildString = "v4.1 API " + api + " \"Jelly Bean\" (June 2012)";
```

```
                    break;
                }

                case Build.VERSION_CODES.JELLY_BEAN_MR1: {
                    buildString = "v4.2 API " + api + " \"Jelly Bean MR1\" (November 2012)";
                    break;
                }

                case Build.VERSION_CODES.JELLY_BEAN_MR2: {
                    buildString = "v4.3 API " + api + " \"Jelly Bean MR2\" (July 2013)";
                    break;
                }

                case Build.VERSION_CODES.KITKAT: {
                    buildString = "v4.4 API " + api + " \"KitKat\" (October 2013)";
                    break;
                }

                case Build.VERSION_CODES.KITKAT_WATCH: {
                    buildString = "v4.4W API " + api + " \"KitKat\" (June 2014)";
                    break;
                }

                case Build.VERSION_CODES.LOLLIPOP: {
                    buildString = "v5.0 API " + api + " \"Lollipop\" (November 2014)";
                    break;
                }

                case Build.VERSION_CODES.LOLLIPOP_MR1: {
                    buildString = "v5.1 API " + api + " \"Lollipop MR1\" (March 2015)";
                    break;
                }

                case Build.VERSION_CODES.M: {
                    buildString = "v6.0 API " + api + " \"Marshmellow\" (October 2015)";
                    break;
                }

                case Build.VERSION_CODES.N: {
                    buildString = "v7.0 API " + api + " \"Nougat\" (August 2016)";
                    break;
```

```
163                 }
164
165                 case Build.VERSION_CODES.N_MR1: {
166                     buildString = "v7.1 API " + api + " \"Nougat MR1\" (October 2016)";
167                     break;
168                 }
169
170                 case Build.VERSION_CODES.O: {
171                     buildString = "v8.0 API " + api + " \"Oreo\" (August 2017)";
172                     break;
173                 }
174
175                 case Build.VERSION_CODES.O_MR1: {
176                     buildString = "v8.1 API " + api + " \"Oreo MR1\" (December 2017)";
177                     break;
178                 }
179
180                 case Build.VERSION_CODES.P: {
181                     buildString = "v9.0 API " + api + " \"Pie\" (August 2018)";
182                     break;
183                 }
184
185                 default: {
186                     if (buildCode > Build.VERSION_CODES.P) {
187                         buildString = "version is post v9.0: API " + api;
188                     }
189                     else {
190                         buildString = "unknown version code: API " + api;
191                     }
192                     break;
193                 }
194             }
195
196             return buildString;
197         }
198
199     }
```

Listing E.75: Datestamp (util/Datestamp.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.os.SystemClock;
import android.support.annotation.NonNull;
import android.util.Log;

import org.jetbrains.annotations.Contract;

import java.util.Calendar;
import java.util.Locale;
import java.util.TimeZone;

/**
 * Produces the current date and time as a String, all times are in Pacific Standard.
 * Also gives nanoseconds elapsed from start for sensor timestamps.
 */
@TargetApi(21)
public final class Datestamp {

    // Private Static Constants
    //::::::::::::::::::::::

    // mInstance..............
```

```
    // TODO: description
    private static final Datestamp mInstance = new Datestamp();

    // Private Instance Fields
    //:::::::::::::::::::::::

    // mFirstTimestamp..............
    // First sensor timestamp, all future timestamps are based off of this
    private Long mFirstTimestamp;

    // mStartDate..............
    // A String representation of the current date
    private String mStartDate;

    // mSystemStartNanos..............
    // Nanoseconds since the last boot at the time of this object's creation
    private Long mSystemStartNanos;

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //:::::::::::::::::::::::

    // Datestamp..............
    /**
     * Disabled
     */
    private Datestamp() {
        setStartDate();
    }

    // Private Instance Methods
    //:::::::::::::::::::::::

    // setStartDate..............
    /**
     * Sets the start date to the current time,
     * YYYY-MM-DD-HH-MM-SS-mmm (year-month-day-hour-minute-second-millisecond)
     */
```

```
    private void setStartDate() {
        mSystemStartNanos = SystemClock.elapsedRealtimeNanos();
        mFirstTimestamp   = 0L;
        mStartDate = getDate();
    }

    // Public Class Methods
    //::::::::::::::::::::::

    // getDate..............
    /**
     * Gets the current date and time without resetting the start date.
     * @return YYYY-MM-DD-HH-MM-SS-mmm (year-month-day-hour-minute-second-millisecond)
     */
    @NonNull
    public static String getDate() {

        // Make sure time zone is Pacific Standard Time (no daylight savings)
        TimeZone pst = TimeZone.getTimeZone("Etc/GMT+8");

        // Redundant check
        if (pst.useDaylightTime()) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> USING DAYLIGHT SAVINGS
                ↪ TIME <<\n ");
        }
        TimeZone.setDefault(pst);

        // Get time at this moment
        Calendar calendar = Calendar.getInstance(pst, Locale.US);
        int year          = calendar.get(Calendar.YEAR);
        int month         = calendar.get(Calendar.MONDAY);
        int day           = calendar.get(Calendar.DAY_OF_MONTH);
        int hour          = calendar.get(Calendar.HOUR_OF_DAY);
        int minute        = calendar.get(Calendar.MINUTE);
        int second        = calendar.get(Calendar.SECOND);
        int millisecond   = calendar.get(Calendar.MILLISECOND);

        return    Integer.toString(year)    + "-"
                + Integer.toString(month)   + "-"
                + Integer.toString(day)     + "-"
```

```
                + Integer.toString(hour)    + "-"
                + Integer.toString(minute)  + "-"
                + Integer.toString(second)  + "-"
                + Integer.toString(millisecond);
    }

    // resetStartDate...............
    /**
     * Resets the start date to now
     */
    public static void resetStartDate() {
        mInstance.setStartDate();
    }

    // getStartDate...............
    /**
     * @return A String representation of the start date (when object was created) YYYY-MM-DD-HH-MM-SS-mmm
     */
    @NonNull
    @Contract(pure = true)
    public static String getStartDate() {
        return mInstance.mStartDate;
    }

    // logStartDate...............
    /**
     * Displays the current date
     */
    public static void logStartDate() {
        Log.e(Thread.currentThread().getName(), " \n\n\t\t\t" + mInstance.mStartDate + "\n ");
    }

    // resetElapsedNanos...............
    /**
     * Sets sensor timestamp reference point and updates the current date
     * @param timestamp Sensor timestamp to base further timestamps off of
     */
    public static void resetElapsedNanos(long timestamp) {
        mInstance.setStartDate();
```

```
        mInstance.mFirstTimestamp = timestamp;
        logStartDate();
    }

    // getElapsedTimestampNanos...............
    /**
     * @param timestamp Sensor timestamp in nanoseconds
     * @return Nanoseconds from start date
     */
    public static long getElapsedTimestampNanos(long timestamp) {
        if (mInstance.mFirstTimestamp.equals(0L)) {
            resetElapsedNanos(timestamp);
            return 0L;
        }
        return timestamp - mInstance.mFirstTimestamp;
    }

    // getElapsedSystemNanos...............
    /**
     * @return System nanoseconds from start date
     */
    public static long getElapsedSystemNanos() {
        return SystemClock.elapsedRealtimeNanos() - mInstance.mSystemStartNanos;
    }

}
```

Listing E.76: Handler Manager (`util/HandlerManager.java`)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.os.Handler;
import android.os.HandlerThread;
import android.os.Process;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import java.util.ArrayList;
import java.util.List;

/**
 * Manages the creation and finish of all running threads.
 * Call newHandler() to start a new thread, and finish() to shut all threads down.
 */
@TargetApi(21)
abstract public class HandlerManager {

    // Private Class Constants
    //::::::::::::::::::::::

    // mHandlerHelpers..............
```

```
    // A list of all running threads
    private final static List<HandlerHelper> mHandlerHelpers = new ArrayList<>();

    // Private Class Fields
    //::::::::::::::::::::::

    // mUntitledThreadsCount..............
    // A count of threads without explicitly specified names
    private static Integer mUntitledThreadsCount = 0;

    // Private Inner Class
    //::::::::::::::::::::::

    /**
     * The HandlerHelper encapsulates a thread's Handler into a convenient bundle
     */
    private static class HandlerHelper {

        // nHandler..............
        // The thread's Handler contained by this helper instance
        private Handler nHandler;

        // nHandlerThread..............
        // The thread's HandlerThread contained by this helper instance
        private HandlerThread nHandlerThread;

        // Constructors
        //::::::::::::::::::::::

        // HandlerHelper..............
        /**
         * Start up a new thread with name 'name'
         * @param name Optional name for the thread
         * @param priority Optional priority for the thread
         */
        private HandlerHelper(@Nullable String name, @Nullable Integer priority) {
            if (name == null) {
                name = "Untitled thread: " + Integer.toString(mUntitledThreadsCount);
                mUntitledThreadsCount += 1;
            }
            Log.e(Thread.currentThread().getName(), "HandlerHelper HandlerHelper: " + name);
```

```
            if (priority == null) {
                priority = Process.THREAD_PRIORITY_DEFAULT;
            }

            nHandlerThread = new HandlerThread(name, priority);
            nHandlerThread.start();  // must start before calling .getLooper()
            nHandler = new Handler(this.nHandlerThread.getLooper());
        }

        // Instance Methods
        //::::::::::::::::::::::

        // finish..............
        /**
         * Shut down the thread
         */
        private void finish() {
            Log.e(Thread.currentThread().getName(), "HandlerHelper quit safely: " +
                ↪ nHandlerThread.getName());
            nHandlerThread.quitSafely();
        }

    }

    ////////////////////////////
    //::::::::::::::::::::::::
    ////////////////////////////

    // Public Class Methods
    //::::::::::::::::::::::

    // newHandler..............
    /**
     * Start up a new thread named 'name' with priority 'priority'
     * @param name Name of new thread
     * @param priority Priority of new thread
     * @return Handler to new thread
     */
    @NonNull
    public static Handler newHandler(@Nullable String name, @Nullable Integer priority) {
        Log.e(Thread.currentThread().getName(), "Handler newHandler: " + name);
```

```
        HandlerHelper helper = new HandlerHelper(name, priority);
        mHandlerHelpers.add(helper);
        return helper.nHandler;
    }

    // finish ..............
    /**
     * Shut down **all** running threads started by this class
     */
    public static void finish() {
        Log.e(Thread.currentThread().getName(), "Handler finish");
        for (HandlerHelper helper : mHandlerHelpers) {
            helper.finish();
        }
        mHandlerHelpers.clear();
    }

}
```

Listing E.77: Heap Memory (`util/HeapMemory.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.util.Log;

import sci.crayfis.shramp.GlobalSettings;

/**
 * Convenient monitor of available heap memory
 */
@TargetApi(21)
abstract public class HeapMemory {

    // Private Class Constants
    //::::::::::::::::::::::

    // MEBIBYTE..............
    // 1 Mebibyte is 2^20 bytes, memory returned from mRuntime is in bytes
    private static final long MEBIBYTE = 1048576L; // 2^20

    // mRuntime..............
    // Reference to Java Runtime object (the interface with the environment currently
        ↪ running)
    private static final Runtime mRuntime = Runtime.getRuntime();
```

```
40
41      // mStopWatch...............
42      // For now, monitoring performance -- (TODO) to be removed later
43      private static final StopWatch mStopWatch = new StopWatch("HeapMemory.getAvailableMiB()"
            ↪ );
44
45      ///////////////////////////
46      //:::::::::::::::::::::::
47      ///////////////////////////
48
49      // Public Class Methods
50      //:::::::::::::::::::::::
51
52      // getAvailableMiB...............
53      /**
54       * @return the amount of heap memory available to the application
55       */
56      public static long getAvailableMiB() {
57          mStopWatch.start();
58          long maxHeapMiB = mRuntime.maxMemory() / MEBIBYTE;
59          long usedMiB    = ( mRuntime.totalMemory() - mRuntime.freeMemory() ) / MEBIBYTE;
60          long available = maxHeapMiB - usedMiB;
61          mStopWatch.addTime();
62          return available;
63      }
64
65      // logAvailableMiB...............
66      /**
67       * Log the amount of heap memory available to the application
68       */
69      public static void logAvailableMiB() {
70          Log.e(Thread.currentThread().getName(), "Available Heap Memory: "
71                  + NumToString.number(getAvailableMiB()) + " [MiB]");
72      }
73
74      // isMemoryAmple...............
75      /**
76       * @return true if memory available is greater than GlobalSettings.AMPLE_MEMORY_MiB
77       */
78      public static boolean isMemoryAmple() {
79          return getAvailableMiB() > GlobalSettings.AMPLE_MEMORY_MiB;
```

```
    }

    // isMemoryLow...............
    /**
     * @return true if memory available is less than GlobalSettings.LOW_MEMORY_MiB
     */
    public static boolean isMemoryLow() {
        return getAvailableMiB() < GlobalSettings.LOW_MEMORY_MiB;
    }

}
```

Listing E.78: Number to String (`util/NumToString.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;

import java.text.DecimalFormat;
import java.text.NumberFormat;
import java.util.Locale;

/**
 * Convenient numeric to string formatting
 */
@TargetApi(21)
abstract public class NumToString {

    // Private Class Constants
    //:::::::::::::::::::::::

    // mDecimal...............
    // Format decimal numbers to two digits past zero, e.g. 9384857.23
    private static final DecimalFormat mDecimal = new DecimalFormat("#.##");

    // mSci...............
```

```java
    // Format decimal numbers into scientific notation with 3 significant figures, e.g. 6.02 E23
    private static final DecimalFormat mSci = new DecimalFormat("0.00E00");

    // mNumber...............
    // General number format e.g. 1,234,567.8901
    private static final DecimalFormat mNumber = (DecimalFormat) NumberFormat.getInstance(Locale.US);

    ///////////////////////////
    //:::::::::::::::::::::::
    ///////////////////////////

    // Public Class Decimal Conversions
    //:::::::::::::::::::::::

    // decimal...............
    /**
     * @param number Float number to convert to string
     * @return a two-digits-past-zero decimal, e.g. 23456.78
     */
    @NonNull
    public static String decimal(float number) {
        return mDecimal.format(number);
    }

    // decimal...............
    /**
     * @param number Double number to convert to string
     * @return a two-digits-past-zero decimal, e.g. 23456.78
     */
    @NonNull
    public static String decimal(double number) {
        return mDecimal.format(number);
    }

    // Public Class Scientific Notation Conversions
    //:::::::::::::::::::::::

    // sci...............
    /**
```

```
     * @param number Integer number to convert to string
     * @return a 3-significant-digit scientific notation String, e.g. 3.14E15
     */
    @NonNull
    public static String sci(int number) {
        return mSci.format(number);
    }

    // sci...............
    /**
     * @param number Long integer number to convert to string
     * @return a 3-significant-digit scientific notation String, e.g. 3.14E15
     */
    @NonNull
    public static String sci(long number) {
        return mSci.format(number);
    }

    // sci...............
    /**
     * @param number Floating point number to convert to string
     * @return a 3-significant-digit scientific notation String, e.g. 3.14E15
     */
    @NonNull
    public static String sci(float number) {
        return mSci.format(number);
    }

    // sci...............
    /**
     * @param number Double floating point number to convert to string
     * @return a 3-significant-digit scientific notation String, e.g. 3.14E15
     */
    @NonNull
    public static String sci(double number) {
        return mSci.format(number);
    }

    // Public Class General Number Conversions
    //:::::::::::::::::::::::

```

```
    // number...............
    /**
     * @param number Short integer number to convert to string
     * @return a general number formatted string, e.g. 1,234,567.8910
     */
    @NonNull
    public static String number(short number) {
        return mNumber.format(number);
    }

    // number...............
    /**
     * @param number Integer number to convert to string
     * @return a general number formatted string, e.g. 1,234,567.8910
     */
    @NonNull
    public static String number(int number) {
        return mNumber.format(number);
    }

    // number...............
    /**
     * @param number Long integer number to convert to string
     * @return a general number formatted string, e.g. 1,234,567.8910
     */
    @NonNull
    public static String number(long number) {
        return mNumber.format(number);
    }

    // number...............
    /**
     * @param number Floating point number to convert to string
     * @return a general number formatted string, e.g. 1,234,567.8910
     */
    @NonNull
    public static String number(float number) {
        return mNumber.format(number);
    }

    // number...............
```

```
    /**
     * @param number Double floating point number to convert to string
     * @return a general number formatted string, e.g. 1,234,567.8910
     */
    @NonNull
    public static String number(double number) {
        return mNumber.format(number);
    }

}
```

Listing E.79: Size-Sorted Set (`util/SizeSortedSet.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Size;

import org.jetbrains.annotations.Contract;

import java.util.ArrayList;
import java.util.Collection;
import java.util.Collections;
import java.util.Comparator;
import java.util.Iterator;
import java.util.List;
import java.util.SortedSet;

/**
 * Helper set to sort Size objects describing output surface resolutions.
 * List sorts unique resolutions by area (smallest to biggest).
 */
@TargetApi(21)
public final class SizeSortedSet implements SortedSet<Size> {

```

```
    // Private Instance Fields
    //::::::::::::::::::::::

    // mSortedSet..............
    // Container of Sizes
    private List<Size> mSortedSet = new ArrayList<>();

    // mSorter...............
    // Sort algorithm
    private Sorter mSorter = new Sorter();

    // Private Inner Classes
    //::::::::::::::::::::::

    // SortByArea..............
    /**
     * Sort sizes by area from smallest to biggest, primary sorting method
     */
    private class SortByArea implements Comparator<Size> {

        // compare...............
        /**
         * @param s1 first Size to be compared
         * @param s2 second Size to be compared
         * @return a negative integer, zero, or a positive integer as the first argument is less
         * than, equal to, or greater than the second.
         */
        @Override
        public int compare(@NonNull Size s1, @NonNull Size s2) {
            long area1 = s1.getHeight() * s1.getWidth();
            long area2 = s2.getHeight() * s2.getWidth();
            return Long.compare(area1, area2);
        }
    }

    // SortByLongestSide..............
    /**
     * Sort sizes by longest side from shortest to longest, if SortByArea ends in a tie, this is the
     * tie breaker
```

```
     */
    private class SortByLongestSide implements Comparator<Size> {

        // compare...............
        /**
         * @param s1 first Size to be compared
         * @param s2 second Size to be compared
         * @return a negative integer, zero, or a positive integer as the first argument is less
         * than, equal to, or greater than the second
         */
        @Override
        public int compare(@NonNull Size s1, @NonNull Size s2) {
            int longest1 = Math.max(s1.getHeight(), s1.getWidth());
            int longest2 = Math.max(s2.getHeight(), s2.getWidth());
            return Integer.compare(longest1, longest2);
        }
    }

    // Sorter...............
    /**
     * Master sorter, calls on SortByArea and SortByLongestSide as needed
     */
    private class Sorter implements Comparator<Size> {

        // compare...............
        /**
         * @param s1 first Size to be compared
         * @param s2 second Size to be compared
         * @return a negative integer, zero, or a positive integer as the first argument is less
         * than, equal to, or greater than the second
         */
        @Override
        public int compare(@NonNull Size s1, @NonNull Size s2) {
            SortByArea        sortByArea        = new SortByArea();
            SortByLongestSide sortByAspectRatio = new SortByLongestSide();

            int areaResult = sortByArea.compare(s1, s2);
            if (areaResult != 0) {
                return areaResult;
```

```
            }
            return sortByAspectRatio.compare(s1, s2);
        }
    }

    ///////////////////////////
    //::::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //::::::::::::::::::::::::

    // SizeSortedSet...............
    /**
     * Create a new SizeSortedSet
     */
    public SizeSortedSet() { super(); }

    // Public Instance Methods
    //::::::::::::::::::::::::

    // add...............
    /**
     * Add an element to the set (only unique Sizes are kept)
     * @param size Size object to add
     * @return true if added to the set, false if a Size like size is already contained in
         ↪ the set
     */
    @Override
    public boolean add(Size size) {
        if (mSortedSet.contains(size)) {
            return false;
        }
        mSortedSet.add(size);
        Collections.sort(mSortedSet, comparator());
        return true;
    }

    // addAll...............
    /**
     * Adds a collection to the set (keeping only unique Sizes)
```

```
159         * @param c Any collection that is a Size object or a subclass
160         * @return true if at least one element has been added, false if at least one element
                ↪ hasn't
161         */
162        @Override
163        public boolean addAll(@NonNull Collection<? extends Size> c) {
164            boolean val = false;
165            for (Size s : c) {
166                if (mSortedSet.contains(s)) {
167                    continue;
168                }
169                mSortedSet.add(s);
170                val = true;
171            }
172            Collections.sort(mSortedSet, comparator());
173            return val;
174        }
175
176        // clear...............
177        /**
178         * Clear the set and start over from scratch
179         */
180        @Override
181        public void clear() {
182            mSortedSet.clear();
183        }
184
185        // comparator...............
186        /**
187         * @return Comparator used in sorting
188         */
189        @NonNull
190        @Override
191        @Contract(pure = true)
192        public Comparator<? super Size> comparator() {
193            return mSorter;
194        }
195
196        // contains...............
197        /**
198         * @param o Object under test if it is contained in the set
```

```
199         * @return true if Size object already in the set, false if not
200         */
201        @Override
202        @Contract(pure = true)
203        public boolean contains(@Nullable Object o) {
204            return mSortedSet.contains(o);
205        }
206
207        // containsAll...............
208        /**
209         * @param c A collection of objects under test if they are contained in the set
210         * @return true if all objects in the collection are also in the set, false otherwise
211         */
212        @Override
213        public boolean containsAll(@NonNull Collection<?> c) {
214            return mSortedSet.containsAll(c);
215        }
216
217        // first...............
218        /**
219         * @return first element in the set (null if set is empty)
220         */
221        @Nullable
222        @Override
223        @Contract(pure = true)
224        public Size first() {
225            if (mSortedSet.size() > 0) {
226                return mSortedSet.get(0);
227            }
228            return null;
229        }
230
231        // headSet...............
232        /**
233         * @param toElement Reference Size
234         * @return a set of all Sizes less than (not including) the reference Size
235         */
236        @NonNull
237        @Override
238        public SortedSet<Size> headSet(@NonNull Size toElement) {
239            SizeSortedSet headSet = new SizeSortedSet();
```

```
240
241         for (Size s : mSortedSet) {
242             if (mSorter.compare(s, toElement) < 0) {
243                 headSet.add(s);
244             }
245         }
246         return headSet;
247     }
248
249     // isEmpty...............
250     /**
251      * @return true if set is empty, false if set has elements
252      */
253     @Override
254     @Contract(pure = true)
255     public boolean isEmpty() {
256         return mSortedSet.size() == 0;
257     }
258
259     // iterator...............
260     /**
261      * @return Set iterator
262      */
263     @NonNull
264     @Override
265     public Iterator<Size> iterator() {
266         return mSortedSet.iterator();
267     }
268
269     // last...............
270     /**
271      * @return last Size in set (null if empty)
272      */
273     @Nullable
274     @Override
275     @Contract(pure = true)
276     public Size last() {
277         if(isEmpty()) {
278             return null;
279         }
280         return mSortedSet.get(mSortedSet.size() - 1);
```

```
    }

    // remove...............
    /**
     * @param o Size element to remove from set
     * @return true if successfully removed, false if wasn't found / removed
     */
    @Override
    public boolean remove(@Nullable Object o) {
        return mSortedSet.remove(o);
    }

    // removeAll...............
    /**
     * @param c Collection of Size (or subclass) objects to remove from set
     * @return true if all were removed, false if not all were removed
     */
    @Override
    public boolean removeAll(@NonNull Collection<?> c) {
        return mSortedSet.removeAll(c);
    }

    // retainAll...............
    /**
     * @param c Collection of Size objects to retain if present, discarding all the rest
     * @return true if at least one object has been retained
     */
    @Override
    public boolean retainAll(@NonNull Collection<?> c) {
        return mSortedSet.retainAll(c);
    }

    // size...............
    /**
     * @return Get the size (length) of the set of Size objects
     */
    @Override
    public int size() {
        return mSortedSet.size();
    }

```

```
    // subSet...............
    /**
     * @param fromElement Non-inclusive start Size
     * @param toElement Non-inclusive stop Size
     * @return All Size objects between from and to
     */
    @NonNull
    @Override
    public SortedSet<Size> subSet(@NonNull Size fromElement, @NonNull Size toElement) {
        SizeSortedSet subSet = new SizeSortedSet();

        for (Size s : mSortedSet) {
            if (mSorter.compare(fromElement, s) < 0
             && mSorter.compare(s, toElement)   < 0) {
                subSet.add(s);
            }
        }
        return subSet;
    }

    // tailSet...............
    /**
     * @param fromElement Reference Size
     * @return the set of elements greater than (not including) the reference Size
     */
    @NonNull
    @Override
    public SortedSet<Size> tailSet(@NonNull Size fromElement) {
        SizeSortedSet tailSet = new SizeSortedSet();

        for (Size s : mSortedSet) {
            if (mSorter.compare(fromElement, s) < 0) {
                tailSet.add(s);
            }
        }
        return tailSet;
    }

    // toArray...............
    /**
     * @return The sorted Size set as an Object[] array
```

```
     */
    @Nullable
    @Override
    public Object[] toArray() {
        return mSortedSet.toArray();
    }

    // toArray...............
    /**
     * @param a Array object to populate
     * @param <T> Object type for the return array
     * @return Sorted Size set as a T[] array
     */
    @Nullable
    @Override
    public <T> T[] toArray(@Nullable T[] a) {
        return mSortedSet.toArray(a);
    }

}
```

Listing E.80: Stop Watch (`util/StopWatch.java`)

```java
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.os.SystemClock;
import android.support.annotation.NonNull;

import org.jetbrains.annotations.Contract;

import java.util.ArrayList;
import java.util.Collections;
import java.util.Comparator;
import java.util.List;

/**
 * Convenient stop watch class for benchmarking performance
 */
@TargetApi(21)
public final class StopWatch {

    // Private Class Constants
    //::::::::::::::::::::::

    // mLabeledStopWatches..............
    // An array of every stop watch ever created (with a label)
```

```
    private static final List<StopWatch> mLabeledStopWatches = new ArrayList<>();

    // Private Instance Fields
    //::::::::::::::::::::::

    // mStartNanos..............
    // System nanosecond time epoch when stopwatch is started
    private long mStartNanos;

    // mStopNanos...............
    // System nanosecond time epoch when stopwatch is stopped/sampled
    private long mStopNanos;

    // mSum.............
    // Ever-growing sum of total elapsed time when addTime() is called
    private long mSum;

    // mCount...............
    // The number of entries contained in mSum (number of times stop watch is stopped/
        ↪ sampled)
    private long mCount;

    // mLongest...............
    // The longest elapsed time measured so far
    private long mLongest;

    // mShortest...............
    // The shortest elapsed time measured so far
    private long mShortest;

    // mLabel...............
    // A short label describing this StopWatch
    private String mLabel;

    ///////////////////////////
    //::::::::::::::::::::::
    ///////////////////////////

    // Constructors
    //::::::::::::::::::::::

```

```
    // StopWatch...............
    /**
     * Create a new stop watch, mark current system nanosecond time as start epoch
     * (Not kept in master list of stopwatches)
     */
    public StopWatch() {
        mLabel = null;
        reset();
    }

    // StopWatch...............
    /**
     * Create a new stop watch, mark current system nanosecond time as start epoch
     * (A reference is kept in the master list of stopwatches)
     * @param label A short string labeling this StopWatch
     */
    public StopWatch(@NonNull String label) {
        mLabel = label;
        mLabeledStopWatches.add(this);
        reset();
    }

    // Public Class Methods
    //:::::::::::::::::::::::

    // getLabeledPerformances...............
    /**
     * @return A String summarizing performance of all stop watches with labels of the
       ↪ format:
     *          "Label:
     *             Count = www, Shortest = zzzzzz [ns], Mean = xxxxx [ns], Longest = yyyyy [
       ↪ ns]"
     */
    @NonNull
    public static String getLabeledPerformances() {
        // Sort longest mean to shortest mean
        Comparator<StopWatch> comparator = new Comparator<StopWatch>() {
            @Override
            public int compare(StopWatch o1, StopWatch o2) {
                if (o1.mCount == 0 || o2.mCount == 0) {
                    return Double.compare(o2.mCount, o1.mCount);
```

```
                }
                return Double.compare(o2.getMean(), o1.getMean());
            }
        };
        Collections.sort(mLabeledStopWatches, comparator);
        String out = " \n Stop watch results: \n\n ";
        for (StopWatch stopwatch : mLabeledStopWatches) {
            out += stopwatch.mLabel + ":\n" + stopwatch.getPerformance() + "\n\n";
        }
        return out + " ";
    }

    // resetLabeled...............
    /**
     * Resets all stopwatches with labels
     */
    public static void resetLabeled() {
        for (StopWatch stopWatch : mLabeledStopWatches) {
            stopWatch.reset();
        }
    }

    // Public Instance Methods
    //:::::::::::::::::::::::

    // start...............
    /**
     * Start a new measurement interval
     */
    public void start() {
        mStartNanos = SystemClock.elapsedRealtimeNanos();
        mStopNanos  = mStartNanos;
    }

    // stop...............
    /**
     * Stop current measurement interval
     * @return elapsed nanoseconds
     */
    public long stop() {
        mStopNanos = SystemClock.elapsedRealtimeNanos();
```

```
        long elapsed = mStopNanos - mStartNanos;
        mStartNanos = mStopNanos;
        return elapsed;
    }

    // addTime...............
    /**
     * Stop current measurement interval and add the elapsed time to the running total
     */
    public void addTime() {
        addTime(stop());
    }

    // addTime...............
    /**
     * Add an elapsed time to the running total
     * @param time Time to add to the running total
     */
    public void addTime(long time) {
        mSum   += time;
        mCount += 1;
        if (time > mLongest) {
            mLongest = time;
        }

        if (mShortest == 0L) {
            mShortest = time;
        }
        else if (time < mShortest) {
            mShortest = time;
        }
    }

    // getMean...............
    /**
     * @return Average elapsed time from addTime() calls
     */
    @Contract(pure = true)
    public double getMean() {
        return mSum / (double) mCount;
    }
```

```

    // reset...............
    /**
     * Reset/clear this stop watch
     */
    public void reset() {
        mSum   = 0L;
        mCount = 0L;
        mLongest  = 0L;
        mShortest = 0L;
        start();
    }

    // getLongest...............
    /**
     * @return The longest recorded elapsed time from addTime()
     */
    @Contract(pure = true)
    public long getLongest() {
        return mLongest;
    }

    // getShortest...............
    /**
     * @return The shortest recorded elapsed time from addTime()
     */
    @Contract(pure = true)
    public long getShortest() {
        return mShortest;
    }

    // getPerformance...............
    /**
     * @return A String summarizing performance from addTime() of the format:
     *          "Count = www, Shortest = zzzzzz [ns], Mean = xxxxx [ns], Longest = yyyyy [ns
        ↪ ]"
     */
    @NonNull
    public String getPerformance() {
        String out = "\t";
        out += "Count = " + NumToString.number(mCount)
```

```
                    + ", Shortest = " + NumToString.number(mShortest) + " [ns]"
                    + ", Mean = " + NumToString.number(Math.round(getMean())) + " [ns]"
                    + ", Longest = " + NumToString.number(mLongest) + " [ns]";
            return out;
        }

    }
```

Listing E.81: Storage Media (util/StorageMedia.java)

```
/*
 * @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
 * @version: ShRAMP v0.0
 *
 * @objective: To detect extensive air shower radiation using smartphones
 *             for the scientific study of ultra-high energy cosmic rays
 *
 * @institution: University of California, Irvine
 * @department:  Physics and Astronomy
 *
 * @author: Eric Albin
 * @email:  Eric.K.Albin@gmail.com
 *
 * @updated: 3 May 2019
 */

package sci.crayfis.shramp.util;

import android.annotation.TargetApi;
import android.os.Environment;
import android.os.Handler;
import android.support.annotation.NonNull;
import android.support.annotation.Nullable;
import android.util.Log;

import org.jetbrains.annotations.Contract;

import java.io.File;
import java.io.FileNotFoundException;
import java.io.FileOutputStream;
import java.io.FilenameFilter;
import java.io.IOException;
import java.text.ParseException;
import java.text.SimpleDateFormat;
import java.util.Collections;
import java.util.Comparator;
import java.util.Date;
import java.util.List;
import java.util.Locale;
import java.util.concurrent.atomic.AtomicInteger;
```

```

import sci.crayfis.shramp.GlobalSettings;
import sci.crayfis.shramp.MasterController;
import sci.crayfis.shramp.analysis.OutputWrapper;


///////////////////////////
//                        (TODO)      UNDER CONSTRUCTION      (TODO)
///////////////////////////
// Mostly complete, I think I'll have this operate the SSH interface in the future ..


/**
 * This class controls all disk actions on the ShRAMP data directory
 */
@TargetApi(21)
abstract public class StorageMedia {

    // Private Class Constants
    //::::::::::::::::::::::::

    // THREAD_NAME..............
    // Thread for handling output writing and storage management
    private static final String THREAD_NAME = "StorageMediaThread";

    // mHandler...............
    // Reference to storage media thread Handler
    private static final Handler mHandler = HandlerManager.newHandler(THREAD_NAME,
                                                GlobalSettings.
                                                    ↪ STORAGE_MEDIA_THREAD_PRIORITY);

    // mBacklog...............
    // Thread-safe count of files to be written
    private static final AtomicInteger mBacklog = new AtomicInteger();

    /**
     * Runnable for saving files on the Storage Media Thread
     */
    private static class DataSaver implements Runnable {

        // Payload
```

```
        private String mPath;
        private OutputWrapper mOutputWrapper;

        // Constructor
        private DataSaver(@NonNull String path, @NonNull OutputWrapper wrapper) {
            mPath = path;
            mOutputWrapper = wrapper;
        }

        // Action
        public void run() {

            if (mOutputWrapper.getByteBuffer() == null) {
                Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> BYTE BUFFER IS NULL FOR: " + mPath
                        + File.separator + mOutputWrapper.getFilename() + " <<\n ");
                mBacklog.decrementAndGet();
                return;
            }

            if (GlobalSettings.DEBUG_DISABLE_ALL_SAVING) {
                Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> WRITING DISABLED FOR: " + mPath
                        + File.separator + mOutputWrapper.getFilename() + " <<\n ");
                mBacklog.decrementAndGet();
                return;
            }

            Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> WRITING: " + mPath
                    + File.separator + mOutputWrapper.getFilename() + " <<\n ");

            // Check for enough disk space
            File file = new File(mPath);
            long freeSpace  = file.getFreeSpace();
            long totalSpace = file.getTotalSpace();
            float usage = 1.f - (freeSpace / (float) totalSpace);

            if (usage > 0.9) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> ERROR: OUT OF MEMORY, CANNOT SAVE DATA <<\n ");
```

```
                MasterController.quitSafely();
                return;
            }

            // Make sure the full buffer is getting written
            mOutputWrapper.getByteBuffer().position(0);
            mOutputWrapper.getByteBuffer().limit(mOutputWrapper.getByteBuffer().capacity());

            FileOutputStream outputStream = null;
            try {
                outputStream = new FileOutputStream(mPath + File.separator + mOutputWrapper.
                    ↪ getFilename());
                outputStream.getChannel().write(mOutputWrapper.getByteBuffer());
            }
            catch (FileNotFoundException e) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> ERROR: INVALID PATH,
                    ↪ CANNOT SAVE DATA <<\n ");
                MasterController.quitSafely();
                return;
            }
            catch (IOException e) {
                // TODO: error
                Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> ERROR: IO EXCEPTION,
                    ↪ CANNOT SAVE DATA <<\n ");
                MasterController.quitSafely();
                return;
            }
            finally {
                if (outputStream != null) {
                    try {
                        outputStream.close();
                    }
                    catch (IOException e) {
                        // TODO: error
                        Log.e(Thread.currentThread().getName(), " \n\n\t\t\t>> ERROR: IO
                            ↪ EXCEPTION, CANNOT CLOSE OUTPUT STREAM <<\n ");
                        MasterController.quitSafely();
                    }
                }
            }
```

```
156                 mBacklog.decrementAndGet();
157             }
158         }
159
160         // Path...............
161         // Handy absolute path links
162         abstract private static class Path {
163             static final String Home = Environment.getExternalStorageDirectory() + File.
                    ↪ separator + "ShRAMP";
164             static String Transmittable;
165             static String InProgress;
166             static String Calibrations;
167             static String WorkingDirectory;
168         }
169
170         ///////////////////////////
171         //:::::::::::::::::::::::
172         ///////////////////////////
173
174         // Public Class Methods
175         //:::::::::::::::::::::::
176
177         // homePath...............
178         /**
179          * @return ShRAMP home path
180          */
181         @Contract(pure = true)
182         public static String homePath() { return Path.Home; }
183
184         // transmittablePath...............
185         /**
186          * @return Transmittable path
187          */
188         @Contract(pure = true)
189         public static String transmittablePath() { return Path.Transmittable; }
190
191         // workInProgressPath...............
192         /**
193          * @return Work in progress path
194          */
195         @Contract(pure = true)
```

```
    public static String workInProgressPath() { return Path.InProgress; }

    // calibrationPath ..............
    /**
     * @return Calibration path
     */
    @Contract(pure = true)
    public static String calibrationPath() { return Path.Calibrations; }

    // setUpShrampDirectory ..............
    /**
     * Check if ShRAMP data directory exists, if not initialize it
     */
    public static void setUpShrampDirectory() {
        // TODO: consider using SD-card memory in addition to onboard memory
        String Home = createDirectory(null);
        if (Home == null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Unable to create home directory");
            MasterController.quitSafely();
            return;
        }

        Path.Transmittable  = createDirectory("Transmittable");
        Path.InProgress     = createDirectory("WorkInProgress");
        Path.Calibrations   = createDirectory("Calibrations");
        if (Path.Transmittable == null || Path.InProgress == null || Path.Calibrations ==
            ↪ null) {
            // TODO: error
            Log.e(Thread.currentThread().getName(), "Unable to create directory hierarchy");
            MasterController.quitSafely();
        }
    }

    // cleanSlate ..............
    /**
     * Wipes out all files and directories under ShRAMP/, but does not delete ShRAMP/
     */
    public static void cleanSlate() {
        cleanDir(null);
    }
```

```
236
237     // createDirectory...............
238     /**
239      * Creates a sub-directory for depositing data (could be a hierarchy, e.g. parent/parent
         ↪ /dir)
240      * @param name Name of the sub-directory, usually meant to be a timestamp in string form
         ↪ ,
241      *             the ShRAMP home directory is implied if not part of the name, i.e. this
         ↪ name is
242      *             then understood as home/name.  If name is null, creates home directory.
243      * @return The full path of the new directory as a string, null if unsuccessful
244      */
245     @Nullable
246     public static String createDirectory(@Nullable String name) {
247         String path;
248         if (name == null) {
249             path = Path.Home;
250         }
251         else if (!name.contains(Path.Home)) {
252             path = Path.Home + File.separator + name;
253         }
254         else {
255             path = name;
256         }
257         File newDirectory = new File(path);
258
259         // Check if media is available
260         if (!Environment.getExternalStorageState().equals(Environment.MEDIA_MOUNTED)) {
261             // TODO: error
262             Log.e(Thread.currentThread().getName(),"ERROR: Media unavailable");
263             MasterController.quitSafely();
264             return null;
265         }
266
267         // Check if data directory already exists
268         if (newDirectory.exists()) {
269             if (newDirectory.isDirectory()) {
270                 Log.e(Thread.currentThread().getName(),"WARNING: " + path + " already exists
                    ↪ , no action taken");
271                 return path;
272             }
```

```
            else {
                // someone saved a file with the name of this directory request
                Log.e(Thread.currentThread().getName(),"ERROR: Existing file \"" + name + "
                    ↪ \" where this directory should be: " + path);
                return null;
            }
        }

        // By this point, we're clear to make the directory
        if (!newDirectory.mkdirs()) {
            // TODO: error
            Log.e(Thread.currentThread().getName(),"ERROR: Failed to make directory: " +
                ↪ path);
            MasterController.quitSafely();
            return null;
        }

        return path;
    }

    // cleanDir...............
    /**
     * Clean a directory of all it's files and subfolders, but does not delete the directory
         ↪ itself.
     * @param name If null, clears everything under ShRAMP/, if not an absolute path assumes
         ↪ its
     *             relative to ShRAMP/.
     */
    public static void cleanDir(@Nullable String name) {
        String path;
        if (name == null) {
            path = Path.Home;
        }
        else if (!name.contains(Path.Home)) {
            path = Path.Home + File.separator + name;
        }
        else {
            path = name;
        }
        File directoryToClean = new File(path);

```

```
        if (!directoryToClean.exists()) {
            Log.e(Thread.currentThread().getName(), "Directory " + path + " does not exist, cannot clean");
            return;
        }

        for (File file : directoryToClean.listFiles()) {
            if (file.isDirectory()) {
                cleanDir(file.getAbsolutePath());
            }
            if (!file.delete()) {
                Log.e(Thread.currentThread().getName(), "Unable to delete " + file.getAbsolutePath());
            }
        }
    }

    // removeDir...............
    /**
     * Remove a directory and all of it's files and subfolders.
     * @param name If null, removes everything under ShRAMP/ including ShRAMP/ itself.  If not an
     *             absolute path, assumes its relative to ShRAMP/
     */
    public static void removeDir(@Nullable String name) {
        String path;
        if (name == null) {
            path = Path.Home;
        }
        else if (!name.contains(Path.Home)) {
            path = Path.Home + File.separator + name;
        }
        else {
            path = name;
        }
        File directoryToRemove = new File(path);

        if (!directoryToRemove.exists()) {
            Log.e(Thread.currentThread().getName(), "Directory " + path + " does not exist, cannot clean");
            return;
```

```
        }

        cleanDir(path);

        if (!directoryToRemove.delete()) {
            Log.e(Thread.currentThread().getName(), "Unable to delete " + directoryToRemove.
                ↪ getAbsolutePath());
        }
    }

    // removeEmptyDirs...............
    /**
     * Wipes out any empty directories under startDirectory
     * @param startDirectory empty directories under this, if null, startDirectory = ShRAMP/
     */
    public static void removeEmptyDirs(@Nullable String startDirectory) {
        String path;
        if (startDirectory == null) {
            path = Path.Home;
        }
        else if (!startDirectory.contains(Path.Home)) {
            path = Path.Home + File.separator + startDirectory;
        }
        else {
            path = startDirectory;
        }
        File directoryToClean = new File(path);

        if (!directoryToClean.exists()) {
            Log.e(Thread.currentThread().getName(), "Directory " + path + " does not exist,
                ↪ cannot clean");
            return;
        }

        if (directoryToClean.listFiles().length == 0) {
            removeDir(path);
        }
        else {
            for (File file : directoryToClean.listFiles()) {
                if (file.isDirectory()) {
                    removeEmptyDirs(file.getAbsolutePath());
```

```
                }
            }
        }
    }

    // newInProgress...............
    /**
     * Create a new directory under ShRAMP/InProgress/ and sets WorkingDirectory to this.
     * @param name If null, makes a new directory with the current date Datestamp.
     *             If not an absolute path, assumes its relative to ShRAMP/InProgress/.
     *             If directory already exists, takes no action besides setting
       ↪ WorkingDirectory to this.
     */
    public static void newInProgress(@Nullable String name) {
        String path;
        if (name == null) {
            path = Path.InProgress + File.separator + Datestamp.getDate();
        }
        else if (!name.contains(Path.InProgress)) {
            path = Path.InProgress + File.separator + name;
        }
        else {
            path = name;
        }
        File newDirectory = new File(path);

        if (newDirectory.exists()) {
            Log.e(Thread.currentThread().getName(), "Directory " + name + " already exists,
                ↪ making it the working directory");
            Path.WorkingDirectory = path;
            return;
        }

        Path.WorkingDirectory = createDirectory(path);
    }

    // TODO: method for moving/tarballing directory or files to Transmittable
    //public static void makeTransmittable(...)

    // isBusy...............
    /**
```

```
425         * @return True if files are currently being written, false if in idle
426         */
427        public static boolean isBusy() {
428            return mBacklog.get() > 0;
429        }
430
431        // getBacklog...............
432        /**
433         * @return The number of files in backlog to be / are being written
434         */
435        public static int getBacklog() {
436            return mBacklog.get();
437        }
438
439        // writeCalibration...............
440        /**
441         * Writes a new calibration file to the Calibrations directory
442         * @param wrapper Calibration data (e.g. mean, stddev, etc)
443         */
444        public static void writeCalibration(@NonNull OutputWrapper wrapper) {
445            mBacklog.incrementAndGet();
446            mHandler.post(new DataSaver(Path.Calibrations, wrapper));
447        }
448
449        /**
450         * Writes OutputWrapper in the current working directory (if path is null), or to the
             ↪ specified path.
451         * Path can be relative to /ShRAMP (i.e. "mydir" translates to /ShRAMP/mydir).
452         * Caution: existing files with the same name will be overwritten.
453         * Note: writing occurs on the storage media thread, so the calling thread will not be
             ↪ burdened.
454         * @param wrapper OutputWrapper to be written
455         * @param path (Optional) If null, writes to working directory, if specified, writes to
             ↪ that
456         */
457        public static void writeInternalStorage(@NonNull OutputWrapper wrapper, @Nullable String
            ↪  path) {
458            mBacklog.incrementAndGet();
459
460            String outpath;
461            if (path == null) {
```

```
            outpath = Path.WorkingDirectory;
        }
        else if (!path.contains(Path.Home)) {
            outpath = Path.Home + File.separator + path;
        }
        else {
            outpath = path;
        }

        File outfile = new File(outpath + File.separator + wrapper.getFilename());
        if (outfile.exists()) {
            Log.e(Thread.currentThread().getName(), "WARNING: " + outfile.getAbsolutePath()
                ↪ + " already exists and will be OVERWRITTEN");
        }

        mHandler.post(new DataSaver(outpath, wrapper));
    }

    /**
     * @param head options include "cold_fast", "cold_slow", "hot_fast", "hot_slow",
     *             "mean", "stddev", "stderr", and "mask"
     * @param extension options include "mean", "stddev", "stderr", and "mask"
     * @return Returns the absolute path of the most recent calibration file matching the
         ↪ parameters,
     *         or null if one cannot be found
     */
    // TODO: (PRIORITY) double check it's sorting correctly
    @Nullable
    @Contract(pure = true)
    public static String findRecentCalibration(@NonNull String head, @NonNull String
        ↪ extension) {
        if (!head.equals("cold_fast") && !head.equals("cold_slow") && !head.equals("hot_fast
            ↪ ")
                && !head.equals("hot_slow") && !head.equals("mean") && !head.equals("stddev"
                    ↪ )
                && !head.equals("stderr") && !head.equals("mask")) {
            Log.e(Thread.currentThread().getName(), "Unable to find calibration by this
                ↪ heading: " + head);
            return null;
        }

```

```
497         if (!extension.equals(GlobalSettings.MEAN_FILE) && !extension.equals(GlobalSettings.
                ↪ STDDEV_FILE)
498                 && !extension.equals(GlobalSettings.STDERR_FILE) && !extension.equals(
                        ↪ GlobalSettings.MASK_FILE)) {
499             Log.e(Thread.currentThread().getName(), "Unable to find calibration by this
                    ↪ extension: " + extension);
500             return null;
501         }
502
503         File calibrations = new File(Path.Calibrations);
504
505         // Filename filter
506         class CalibrationFilter implements FilenameFilter {
507             private String Head;
508             private String Extension;
509
510             private CalibrationFilter(@NonNull String head, @NonNull String extension) {
511                 Head = head;
512                 Extension = extension;
513             }
514
515             @Override
516             public boolean accept(File dir, String name) {
517                 return name.startsWith(Head) && name.endsWith(Extension);
518             }
519         }
520
521         // Order files by datestamp
522         class LatestDateFirst implements Comparator<String> {
523             private int HeadLen;
524             private int ExtLen;
525             private SimpleDateFormat format = new SimpleDateFormat("yyyy-MM-dd-HH-mm-ss-SSS"
                    ↪ , Locale.US);
526
527             private LatestDateFirst(@NonNull String head, @NonNull String extension) {
528                 HeadLen = head.length() + 1;
529                 ExtLen  = extension.length();
530             }
531
532             @Override
533             public int compare(String o1, String o2) {
```

```
                try {
                    Date date1 = format.parse(o1.substring(HeadLen, o1.length() - ExtLen));
                    Date date2 = format.parse(o2.substring(HeadLen, o2.length() - ExtLen));
                    return date1.compareTo(date2);
                }
                catch (ParseException e) {
                    // TODO: error
                    Log.e(Thread.currentThread().getName(), "Parse exception, cannot sort files");
                    return 0;
                }
            }
        }

        // Sort found files
        List<String> sortedFiles = ArrayToList.convert(calibrations.list(new CalibrationFilter(head, extension)));
        Collections.sort( sortedFiles, new LatestDateFirst(head, extension) );

        if (sortedFiles.size() == 0) {
            return null;
        }

        File foundFile = new File(Path.Calibrations + File.separator + sortedFiles.get(0));
        return foundFile.getAbsolutePath();
    }

}
```

Listing E.82: Live Processing (`renderscript/LiveProcessing.rs`)

```
//
// @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
// @version: ShRAMP v0.0
//
// @objective: To detect extensive air shower radiation using smartphones
//             for the scientific study of ultra-high energy cosmic rays
//
// @institution: University of California, Irvine
// @department:  Physics and Astronomy
//
// @author: Eric Albin
// @email:  Eric.K.Albin@gmail.com
//
// @updated: 3 May 2019
//

#pragma version(1)
#pragma rs java_package_name(sci.crayfis.shramp)

// TODO: check if there is substantial performance increase with relaxed
#pragma rs_fp_full
//#pragma rs_fp_relaxed

// Enable debugging
//#include "rs_debug.rsh"

// Global Variables
//::::::
```

```
rs_allocation gMask;
rs_allocation gSignificance;

// gMax8bitValue / gMax16bitValue..................
// Statistics (mean, stddev) are saved as normalized values, i.e. mean = gMean *
    ↪ gMax_bitValue
const float gMax8bitValue  = 255.;
const float gMax16bitValue = 1023.;

// gEnableSignificance.............................
// "1" for pixel statistical significance testing, "0" for no testing
int gEnableSignificance;

// gSignificanceThreshold..........................
// Pixels with significance above this theshold are considered "actually significant"
float gSignificanceThreshold;

// gCountAboveThreshold............................
// Number of pixels with significance above threshold ("actually significant")
rs_allocation gCountAboveThreshold;

// RenderScript Kernels
//::::::::::::::::::::::::::::::::::::::::::::::::
    ↪ ::::::::::::::::::::::::::::::::::::::::::::::::

// TODO: figure out a way to write one processData kernel?

// process8bitData.................................
// Updates running sums and computes significance if enabled (exact same as process16bitData
    ↪ )
// @param val 8-bit depth pixel value
// @param x row pixel coordinate
// @param y column pixel coordinate
void RS_KERNEL process8bitData(uchar val, uint32_t x, uint32_t y) {
    // Value Sum
    uint old_val_sum = rsGetElementAt_uint(gValueSum, x, y);
    uint this_val    = (uint) val;
    uint new_val_sum = old_val_sum + this_val;
    rsSetElementAt_uint(gValueSum, new_val_sum, x, y);

    // Value**2 Sum
```

```
    uint old_val2_sum = rsGetElementAt_uint(gValue2Sum, x, y);
    uint this_val2    = this_val * this_val;
    uint new_val2_sum = old_val2_sum + this_val2;
    rsSetElementAt_uint(gValue2Sum, new_val2_sum, x, y);

    // Statistical Significance
    float significance;
    if (gEnableSignificance == 0) {
        // Disabled
        significance = 0.f;
    }
    else { // Enabled
        //                                                  this is the only difference
        float mean   = rsGetElementAt_float(gMean,   x, y) * gMax8bitValue;
        float stddev = rsGetElementAt_float(gStdDev, x, y) * gMax8bitValue;

        if (stddev == 0.f) {
            // positive infinity, avoid 0./0.
            significance = 1./0.;
        }
        else {
            significance = ( ((float) val) - mean ) / stddev;

            uchar mask = rsGetElementAt_uchar(gMask, x, y);
            if (mask == 1 && significance >= gSignificanceThreshold) {
                long count = rsGetElementAt_long(gCountAboveThreshold, 0, 0);
                rsSetElementAt_long(gCountAboveThreshold, count + 1, 0, 0);
            }
        }
    }
    rsSetElementAt_float(gSignificance, significance, x, y);
}

// process16bitData.................................
// Updates running sums and computes significance if enabled (exact same as process8bitData)
// @param val 16-bit depth pixel value
// @param x row pixel coordinate
// @param y column pixel coordinate
void RS_KERNEL process16bitData(ushort val, uint32_t x, uint32_t y) {
    // Value Sum
    uint old_val_sum = rsGetElementAt_uint(gValueSum, x, y);
```

```
    uint this_val    = (uint) val;
    uint new_val_sum = old_val_sum + this_val;
    rsSetElementAt_uint(gValueSum, new_val_sum, x, y);

    // Value**2 Sum
    uint old_val2_sum = rsGetElementAt_uint(gValue2Sum, x, y);
    uint this_val2    = this_val * this_val;
    uint new_val2_sum = old_val2_sum + this_val2;
    rsSetElementAt_uint(gValue2Sum, new_val2_sum, x, y);

    // Statistical Significance
    float significance;
    if (gEnableSignificance == 0) {
        // Disabled
        significance = 0.f;
    }
    else { // Enabled
        //                                                  this is the only difference
        float mean   = rsGetElementAt_float(gMean,   x, y) * gMax16bitValue;
        float stddev = rsGetElementAt_float(gStdDev, x, y) * gMax16bitValue;

        if (stddev == 0.f) {
            // positive infinity, avoid 0./0.
            significance = 1./0.;
        }
        else {
            significance = ( ((float) val) - mean ) / stddev;

            uchar mask = rsGetElementAt_uchar(gMask, x, y);
            if (mask == 1 && significance >= gSignificanceThreshold) {
                long count = rsGetElementAt_long(gCountAboveThreshold, 0, 0);
                rsSetElementAt_long(gCountAboveThreshold, count + 1, 0, 0);
            }
        }
    }
    rsSetElementAt_float(gSignificance, significance, x, y);
}

////////////
```

```
// getValueSum ....................................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return pixel value sum
uint RS_KERNEL getValueSum(uint32_t x, uint32_t y) {
    return rsGetElementAt_uint(gValueSum, x, y);
}

// getValue2Sum ...................................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return pixel value**2 sum
uint RS_KERNEL getValue2Sum(uint32_t x, uint32_t y) {
    return rsGetElementAt_uint(gValue2Sum, x, y);
}

// getSignificance ................................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return pixel significance
float RS_KERNEL getSignificance(uint32_t x, uint32_t y) {
    return rsGetElementAt_float(gSignificance, x, y);
}

// getCountAboveThreshold .........................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return number of pixels above threshold
ulong RS_KERNEL getCountAboveThreshold(uint32_t x, uint32_t y) {
    return rsGetElementAt_long(gCountAboveThreshold, 0, 0);
}

////////////////////////////////////////////////////
    ↪ ////////////////////////////////////////////

// zeroUIntAllocation .............................
// @param x row pixel coordinate
```

```
// @param y column pixel coordinate
// @return 0
uint RS_KERNEL zeroUIntAllocation(uint32_t x, uint32_t y) {
    return 0;
}

// zeroFloatAllocation ..............................
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return 0.f
float RS_KERNEL zeroFloatAllocation(uint32_t x, uint32_t y) {
    return 0.f;
}

// zeroDoubleAllocation .............................
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return 0.
double RS_KERNEL zeroDoubleAllocation(uint32_t x, uint32_t y) {
    return 0.;
}

// oneFloatAllocation ...............................
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return 1.f
float RS_KERNEL oneFloatAllocation(uint32_t x, uint32_t y) {
    return 1.f;
}

// oneCharAllocation ................................
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return 1
uchar RS_KERNEL oneCharAllocation(uint32_t x, uint32_t y) {
    return 1;
}
```

Listing E.83: Post Processing (`renderscript/PostProcessing.rs`)

```
//
// @project: (Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones
// @version: ShRAMP v0.0
//
// @objective: To detect extensive air shower radiation using smartphones
//             for the scientific study of ultra-high energy cosmic rays
//
// @institution: University of California, Irvine
// @department:  Physics and Astronomy
//
// @author: Eric Albin
// @email:  Eric.K.Albin@gmail.com
//
// @updated: 3 May 2019
//

#pragma version(1)
#pragma rs java_package_name(sci.crayfis.shramp)

// TODO: check if there is substantial performance increase with relaxed
#pragma rs_fp_full
//#pragma rs_fp_relaxed

// Enable debugging
//#include "rs_debug.rsh"

// Global Variables
//::::::
```

```
// gNframes.......................................
// Total number of image frames
long gNframes;

// Running Sums...................................
// Sum of pixel value (for mean computation)
// Sum of pixel value**2 (for standard deviation computation)
rs_allocation gValueSum;
rs_allocation gValue2Sum;

// Statistics.....................................
// gMean:   average pixel value
// gStdDev: standard deviation of the pixel value
// gStdErr: standard deviation / sqrt(N frames)
rs_allocation gMean;
rs_allocation gStdDev;
rs_allocation gStdErr;

// gAnomalousStdDev...............................
// In the process of determining the mean and standard deviation, an unlikely overflow in
// the summing variables might have occured under extreme conditions, if this happens the number of
// pixels with this problem are recorded in this variable.
rs_allocation gAnomalousStdDev;

// RenderScript Kernels
//::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

// getMean........................................
// Actually computes all the statistics at once, but returns only the mean back to Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return normalized pixel mean value (mean / gMax_bitValue)
float RS_KERNEL getMean(uint32_t x, uint32_t y) {

    // Max pixel value to normalize to
    float maxValue = gMax8bitValue;
    if (gIs8bit == 0) {
        maxValue = gMax16bitValue;
    }
```

```
    // Mean Pixel
    //::::::
```

```
    return (float) mean_pixel_val / maxValue;
}

// getStdDev ........................................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return normalized pixel standard deviation (standard deviation / gMax_bitValue)
float RS_KERNEL getStdDev(uint32_t x, uint32_t y) {
    return rsGetElementAt_float(gStdDev, x, y);
}

// getStdErr ........................................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return normalized pixel standard error (standard error / gMax_bitValue)
float RS_KERNEL getStdErr(uint32_t x, uint32_t y) {
    return rsGetElementAt_float(gStdErr, x, y);
}

// getAnomalousStdDev ...............................
// Transfer RenderScript Allocation back into Java
// @param x row pixel coordinate
// @param y column pixel coordinate
// @return number of pixels that experianced an overflow in their running sums
ulong RS_KERNEL getAnomalousStdDev(uint32_t x, uint32_t y) {
    return rsGetElementAt_long(gAnomalousStdDev, 0, 0);
}
```

Listing E.84: ShRAMP module (`shramp/python/__init__.py`)

```
#!/usr/bin/env python3

"""Functions to operate on ShRAMP-generated data files
"""

__project__     = '(Sh)ower (R)econstructing (A)pplication for (M)obile (P)hones'
__version__     = 'ShRAMP v0.0'
__objective__   = 'To detect extensive air shower radiation using smartphones '\
                  'for the scientific study of ultra-high energy cosmic rays'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '3 May 2019'

from . import read
```

Listing E.85: ShRAMP read tool (`shramp/python/read.py`)

```
#!/usr/bin/env python3

"""Functions to read ShRAMP-generated data files
"""

import numpy as np
import struct

__author__  = 'Eric Albin'
__email__   = 'Eric.K.Albin@gmail.com'
__updated__ = '3 May 2019'

##########################################################################################

def image(filename, reshape=False, dictionary=False):
    """Reads in a ShRAMP-generated file with extension .frame

        Parameters
        ----------

            filename : String
                        A file path to the file you want to read in

            reshape : True or False
                      When False (default) return pixel values as a 1-D array, npixels long.
                      When True, return pixel values as a 2-D array, shape = (rows x columns).
                      In this latter case, (0,0) cooresponds to the upper left corner of the
                          ↪ image.

            dictionary : True or False
                         When False a tuple (described below) is returned.
                         When True, a dictionary is returned.

        Returns
        -------

             out : B, R, C, E, T, V  (applies if dictionary=False, default)
                   A tuple in this order: (B) bits-per-pixel (8 = YUV, 16 = RAW),
                                          (R) number of pixel rows,
                                          (C) number of pixel columns,
```

```
                                        (E) sensor exposure in nanoseconds (if available, otherwise 0)
                                        (T) battery temperature when this was made in Celsius
                                        (V) np.array() of length n-pixels = (R)x(C) of pixel values

            out : A dictionary (applies if dictionary=True)
                  Keys: 'bits', 'rows', 'cols', 'exposure', 'temperature', 'values'

        See Also
        --------
        mask : read in .mask files (pixel mask)
        statistic : read in .mean/.stddev/.stderr/.signif files (pixel statistics)
        histogram : read in .hist files (1-D histograms)

        Examples
        --------
        >>> B, R, C, E, T, V = shramp.read.image('foo/bar/filename.frame', reshape=True)

        >>> dictionary = shramp.read.image('foo/bar/filename.frame', dictionary=True)
    """
    if ( not ( filename.endswith('.frame') ) ):
        print('Incorrect file extension: "' + filename.split('.')[-1] + '", cannot open with this function')
        return;

    with open(filename, 'rb') as file:
        bits    = int.from_bytes(file.read(1), byteorder='big')
        rows    = int.from_bytes(file.read(4), byteorder='big')
        cols    = int.from_bytes(file.read(4), byteorder='big')
        expo    = int.from_bytes(file.read(8), byteorder='big')
        temp    = struct.unpack('>f', file.read(4))[0]
        npixels = rows * cols
        if (bits == 8):
            values = np.asarray( struct.unpack('>' + 'b'*npixels, file.read(npixels)) )
        elif (bits == 16):
            values = np.asarray( struct.unpack('>' + 'h'*npixels, file.read(2*npixels)) )
        else:
            print('Unexpected image format, pixel depth is: ' + str(bits) + ', cannot read at this time')
```

```
            return;
        if (reshape):
            values = values.reshape(rows, cols)
        if (dictionary):
            return {'bits':bits, 'rows':rows, 'cols':cols, 'exposure':expo, 'temperature':temp, 'values':values}
        else:
            return bits, rows, cols, expo, temp, values

##########################################################################################

def mask(filename, reshape=False, dictionary=False):
    """Reads in a ShRAMP-generated file with extension .mask

        Parameters
        ----------

            filename :  String
                        A file path to the file you want to read in

            reshape : True or False
                      When False (default) return pixel values as a 1-D array, npixels long.
                      When True, return pixel values as a 2-D array, shape = (rows x columns).
                      In this latter case, (0,0) cooresponds to the upper left corner of the image.

            dictionary : True or False
                         When False a tuple (described below) is returned.
                         When True, a dictionary is returned.

        Returns
        -------

            out : B, R, C, M (applies if dictionary=False, default)
                  A tuple in this order: (B) bits-per-pixel (8 = YUV, 16 = RAW),
                                         (R) number of pixel rows,
                                         (C) number of pixel columns,
                                         (M) np.array() of length n-pixels = (R)x(C) of mask values

```

```
            out : A dictionary (applies if dictionary=True)
                  Keys: 'bits', 'rows', 'cols', 'mask'

        See Also
        --------
        image : read in .frame files (images)
        statistic : read in .mean/.stddev/.stderr/.signif files (pixel statistics)
        histogram : read in .hist files (1-D histograms)

        Examples
        --------
        >>> B, R, C, M = shramp.read.mask('foo/bar/filename.mask', reshape=True)

        >>> dictionary = shramp.read.mask('foo/bar/filename.mask', dictionary=True)
    """
    if ( not ( filename.endswith('.mask') ) ):
        print('Incorrect file extension: "' + filename.split('.')[-1] + '", cannot open with this function')
        return;

    with open(filename, 'rb') as file:
        bits    = int.from_bytes(file.read(1), byteorder='big')
        rows    = int.from_bytes(file.read(4), byteorder='big')
        cols    = int.from_bytes(file.read(4), byteorder='big')
        npixels = rows * cols
        mask    = np.asarray( struct.unpack('>' + 'b'*npixels, file.read(npixels)) )
        if (reshape):
            mask = mask.reshape(rows, cols)
        if (dictionary):
            return {'bits':bits, 'rows':rows, 'cols':cols, 'mask':mask}
        else:
            return bits, rows, cols, mask

##########################################################################################

def statistic(filename, reshape=False, dictionary=False):
    """Reads in a ShRAMP-generated file with extension .mean, .stddev, .stderr or .signif

        Parameters
        ----------

```

```
            filename : String
                       A file path to the file you want to read in

            reshape : True or False
                      When False (default) return pixel values as a 1-D array, npixels long.
                      When True, return pixel values as a 2-D array, shape = (rows x columns) .
                      In this latter case, (0,0) cooresponds to the upper left corner of the image.

            dictionary : True or False
                         When False a tuple (described below) is returned.
                         When True, a dictionary is returned.

        Returns
        -------

            out : B, R, C, F, T, S (applies if dictionary=False, default)
                  A tuple in this order: (B) bits-per-pixel (8 = YUV, 16 = RAW),
                                         (R) number of pixel rows,
                                         (C) number of pixel columns,
                                         (F) number of image frames that went into this statistic,
                                         (T) battery temperature when this was made in Celsius
                                         (S) np.array() of length n-pixels = (R)x(C) of statistic values

            out : A dictionary (applies if dictionary=True)
                  Keys: 'bits', 'rows', 'cols', 'frames', 'temperature', 'values'

        See Also
        --------
        image : read in .frame files (images)
        mask : read in .mask files (pixel mask)
        histogram : read in .hist files (1-D histograms)

        Examples
        --------
        >>> B, R, C, F, T, S = shramp.read.statistic('foo/bar/filename.stddev', reshape=True )
```

```

        >>> dictionary = shramp.read.statistic('foo/bar/filename.stddev', dictionary=True)
    """
    if ( not ( filename.endswith('.mean') or filename.endswith('.stddev')
               or filename.endswith('.stderr') or filename.endswith('.signif') ) ):
        print('Incorrect file extension: "' + filename.split('.')[-1] + '", cannot open with this function')
        return;

    with open(filename, 'rb') as file:
        bits    = int.from_bytes(file.read(1), byteorder='big')
        rows    = int.from_bytes(file.read(4), byteorder='big')
        cols    = int.from_bytes(file.read(4), byteorder='big')
        frames  = int.from_bytes(file.read(8), byteorder='big')
        temp    = struct.unpack('>f', file.read(4))[0]
        npixels = rows * cols
        stats   = np.asarray( struct.unpack('>' + 'f'*npixels, file.read(4*npixels)) )
        if (reshape):
            stats = stats.reshape(rows, cols)
        if (dictionary):
            return {'bits':bits, 'rows':rows, 'cols':cols, 'frames':frames, 'temperature': temp, 'values':stats}
        else:
            return bits, rows, cols, frames, temp, stats

##########################################################################################

def histogram(filename, dictionary=False):
    """Reads in a ShRAMP-generated file with extension .hist

        Parameters
        ----------

            filename : String
                       A file path to the file you want to read in

            dictionary : True or False
                         When False a tuple (described below) is returned.
                         When True, a dictionary is returned.

        Returns
```

```
        -------

            out : N, U, O, L, H, C, V (applies if dictionary=False, default)
                  A tuple in this order: (N) Number of bins,
                                         (U) Underflow bin value,
                                         (O) Overflow bin value,
                                         (L) If cuts were applied, low bound for the cut (NaN otherwise)
                                         (H) If cuts were applied, high bound for the cut (NaN otherwise)
                                         (C) np.array() of length N of bin centers
                                         (V) np.array() of length N of bin values

            out : A dictionary (applies if dictionary=True)
                  Keys: 'nbins', 'underflow', 'overflow', 'cut_low', 'cut_high', 'centers', 'values'

        See Also
        --------
        image : read in .frame files (images)
        mask : read in .mask files (pixel mask)
        statistic : read in .mean/.stddev/.stderr/.signif files (pixel statistics)

        Examples
        --------
        >>> N, U, O, L, H, C, V = shramp.read.histogram('foo/bar/filename.hist')

        >>> dictionary = shramp.read.histogram('foo/bar/filename.hist', dictionary=True)
    """
    if ( not ( filename.endswith('.hist') ) ):
        print('Incorrect file extension: "' + filename.split('.')[-1] + '", cannot open with this function')
        return;

    with open(filename, 'rb') as file:
        bins      = int.from_bytes(file.read(4), byteorder='big')
        underflow = int.from_bytes(file.read(4), byteorder='big')
        overflow  = int.from_bytes(file.read(4), byteorder='big')
        cut_low   = struct.unpack('>f', file.read(4))[0]
        cut_high  = struct.unpack('>f', file.read(4))[0]
        centers   = np.asarray( struct.unpack('>' + 'f'*bins, file.read(4*bins)) )
```

```
        values    = np.asarray( struct.unpack('>' + 'i'*bins, file.read(4*bins)) )
        if (dictionary):
            return {'nbins':bins, 'underflow':underflow, 'overflow':overflow, 'cut_low':
                ↪ cut_low, 'cut_high':cut_high, 'centers':centers, 'values':values}
        else:
            return bins, underflow, overflow, cut_low, cut_high, centers, values
```

Appendix F

Gerizimosa-Zatsepin Kinematics

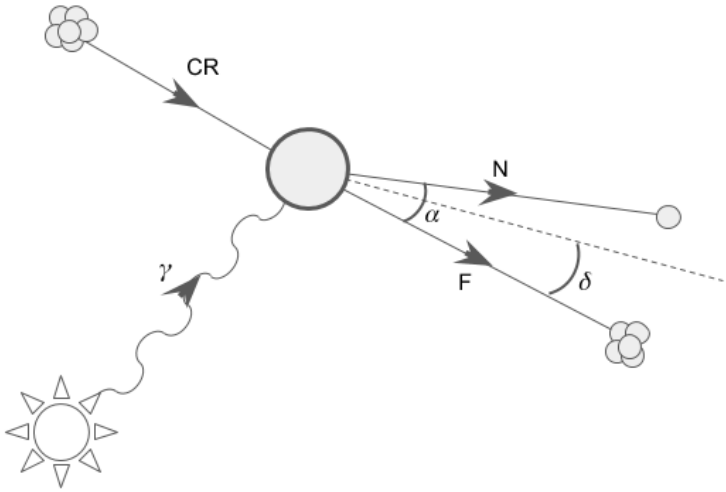


Figure F.1: Kinematic diagram of photodissintegration via the Giant Dipole Resonance. CR=incident UHECR, γ=incident solar photon, N=outgoing nucleon, F=outgoing nuclear fragment. The net outgoing momentum direction is represented by the dotted line. The incident plane containing CR and γ need not be coplanar with the outgoing plane containing N and F.

Working in the solar frame of reference, the total incident momentum is,

$$\vec{p}_{\text{tot}} = \vec{p}_{\text{CR}} + \vec{p}_{\gamma} \tag{F.1}$$

Likewise, the total outgoing momentum (the dotted line in Fig. F.1) is,

$$\vec{p}_{\text{tot}} = \vec{p}_{\text{N}} + \vec{p}_{\text{F}} \tag{F.2}$$

Squaring both sides of Eq. (F.2),

$$\begin{aligned} \vec{p}_{\text{tot}} \cdot \vec{p}_{\text{tot}} &= (\vec{p}_{\text{N}} + \vec{p}_{\text{F}}) \cdot (\vec{p}_{\text{N}} + \vec{p}_{\text{F}}) \\ p_{\text{tot}}^2 &= p_{\text{N}}^2 + p_{\text{F}}^2 + 2\, p_{\text{N}}\, p_{\text{F}} \cos\alpha \\ \cos\alpha &= \frac{p_{\text{tot}}^2 - p_{\text{N}}^2 - p_{\text{F}}^2}{2\, p_{\text{N}}\, p_{\text{F}}} \end{aligned} \tag{F.3}$$

All that remains is to substitute reasonable values for each right-side term. The energies of UHECRs of interest are in excess of 10^{14} eV, with masses between roughly 10^9 and 10^{11} eV/c^2 (approximately that of Hydrogen and Uranium respectively). The relativistic energy–momentum relationship,

$$E^2 = (p\, c)^2 + (m\, c^2)^2 \tag{F.4}$$

establishes for that to at least 6 digits of precision,

$$E_{\text{CR}} = p_{\text{CR}}\, c \tag{F.5}$$

Further, the incident solar photon energy is on average 1 eV; therefore, Eq. (F.1) is, to great accuracy,

$$\vec{p}_{\text{tot}} = \vec{p}_{\text{CR}} \tag{F.6}$$

with magnitude E_{CR}/c.

With the expected energy-transfer behavior of a GDR photodissintegration, Eq. (F.3) gives,

$$\begin{aligned} \cos\alpha &= \frac{E_{\text{CR}}^2 - \left(\frac{1}{A}\right)^2 E_{\text{CR}}^2 - \left(\frac{A-1}{A}\right)^2 E_{\text{CR}}^2}{2\ \left(\frac{1}{A}\right) E_{\text{CR}}\ \left(\frac{A-1}{A}\right) E_{\text{CR}}} \\ &= 1 \end{aligned} \tag{F.7}$$

Therefore, to excellent approximation, $\alpha = 0$.

Appendix G

Gerizimosa-Zatsepin Effect Simulation Module

The following code listings were developed for simulating the Gerizimosa-Zatsepin Effect. The complete listing can be downloaded from `https://github.com/ealbin/GZ`.

Listing G.1: GZ Effect simulation module (`__init__.py`)

```python
#!/usr/bin/env python3

"""GZ-Effect Simulation package
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

from . import coordinates
from . import cross_section
from . import earth
from . import heliosphere_model
from . import magnetic_field
from . import path
from . import photon_field
from . import probability
from . import relativity
from . import results
from . import units
```

Listing G.2: Coordinate Transformations (`coordinates.py`)

```python
#!/usr/bin/env python3

"""Transformations between coordinate systems.
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

import numpy as np


def cartesian2polar( xyz, vec=np.array([0,0,0]) ):
    """Transform from cartesian x-y-z coordinates to polar rho-theta-z.
    Optionally also transform a cartesian vector into a polar one.
    returns dictionary 'rtz':(position) and 'vec':(transformed vector)
    """
    x = xyz[0] # [distance units]
    y = xyz[1] # [distance units]
    z = xyz[2] # [distance units]

    vec_x = vec[0] # [any unit]
    vec_y = vec[1] # [any unit]
    vec_z = vec[2] # [any unit]

    ### convert to polar
    rho   = np.sqrt( x**2 + y**2 ) # [distance units]
    theta = np.arctan2(y, x)       # [radians]
    z     = z                      # [distance units]

    vec_rho   =  vec_x * np.cos(theta) + vec_y * np.sin(theta)
    vec_theta = -vec_x * np.sin(theta) + vec_y * np.cos(theta)
    vec_z     =  vec_z

    return { 'rtz':np.array([ rho, theta, z ]),
```

```
            'vec':np.array([ vec_rho, vec_theta, vec_z ]) }

def polar2cartesian( rtz, vec=np.array([0,0,0]) ):
    """Transform from polar rho-theta-z coordinates to cartesian x-y-z.
    Optionally also transform a polar vector into a cartesian one.
    returns dictionary 'xyz':(position) and 'vec':(transformed vector)
    """
    rho   = rtz[0] # [distance units]
    theta = rtz[1] # [radians]
    z     = rtz[2] # [distance units]

    vec_rho   = vec[0] # [any unit]
    vec_theta = vec[1] # [any unit]
    vec_z     = vec[2] # [any unit]

    ### convert to cartesian
    x = rho * np.cos(theta) # [distance units]
    y = rho * np.sin(theta) # [distance units]
    z = z                   # [distance units]

    vec_x = vec_rho * np.cos(theta) - vec_theta * np.sin(theta)
    vec_y = vec_rho * np.sin(theta) + vec_theta * np.cos(theta)
    vec_z = vec_z

    return { 'xyz':np.array([ x, y, z ]),
             'vec':np.array([ vec_x, vec_y, vec_z ]) }

class Cartesian:
    sun   = np.asarray([0,0,0]) # [AU, AU, AU]
    earth = np.asarray([1,0,0]) # [AU, AU, AU]

class Polar:
    sun   = cartesian2polar(Cartesian.sun)['rtz']   # [AU, radian, AU]
    earth = cartesian2polar(Cartesian.earth)['rtz'] # [AU, radian, AU]

class Spherical:
    def toCartesian(vector, theta, phi):
        """Vector in r-hat, theta-hat, phi-hat for r-hat directed in
        theta, phi direction
        """
        vector = np.asarray(vector, dtype=np.float64)
```

```
        txfm_x = np.asarray([np.sin(theta) * np.cos(phi),  np.cos(theta) * np.cos(phi), -np.sin(phi)])
        txfm_y = np.asarray([np.sin(theta) * np.sin(phi),  np.cos(theta) * np.sin(phi),  np.cos(phi)])
        txfm_z = np.asarray([np.cos(theta),                -np.sin(theta),                0.         ])

        x = np.dot(txfm_x, vector)
        y = np.dot(txfm_y, vector)
        z = np.dot(txfm_z, vector)
        return np.asarray([x, y, z])
```

Listing G.3: Cross Sections (`cross_section.py`)

```python
#!/usr/bin/env python3

"""Compute the interaction cross section for photodissintegration
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'


import numpy as np

from . import units


class Photodissociation:

    # TODO: use nuclear data instead of a model

    def singleNucleon(proton_number, photon_energy_eV, mass_number=None):
        """Returns the photodisintegration cross section [cm**2] for losing one nucleon by a nucleus
        of mass_number [unit-less] (a.k.a. "A") through interaction with a photon with energy
        photon_energy [eV] in the nucleus' frame of reference.
        Reference 1999 Epele, Mollerach and Roulet.
        If mass_number is None, uses average mass number from units module.
        """

        if (mass_number == None):
            mass_number = units.Nuclide.mass_number(proton_number)

        if (mass_number == 1):
            print("Proton cross-section is not modeled")
            return
```

```python

def giantDipoleResonance(A, E_MeV):
    """Returns cross section model for GDR interaction [cm**2].
    """
    sigma0 = 1.45e-27 * A # [cm**2], cross section scale factor
    T      = 8.           # [MeV], GDR energy bandwidth
    if (A <= 4):
        epsilon0 = 0.925 * A**2.433 # [MeV], peak energy of GDR resonance
    else:
        epsilon0 = 42.65 * A**-0.21 # [MeV]

    numerator   = (E_MeV * T)**2
    denominator = (E_MeV**2 - epsilon0**2)**2 + (E_MeV * T)**2
    shapefactor = numerator / float(denominator) # [unit-less] peak shape factor

    return sigma0 * shapefactor # [cm**2]


def prePionProduction(A, E_MeV):
    """Returns cross section model for energies between 30 and 150 MeV.
    note: quasi-deuteron or multiple nucleon ejection turns on in this regeme.
    This cross section represents single nucleon ejection only.  Proceed with caution.
    """
    low_bound = A / 8. * 1e-27 # [cm**2]
    gdr_bound = giantDipoleResonance(A, E_MeV) # [cm**2]
    return max([gdr_bound, low_bound])


def postPionProduction(A, E_MeV):
    """Returns cross section model for energies above 150 MeV.
    note: pion production turns on around 150 MeV and nucleons are knocked out
    via photon-absorption with nearest resonance at the Delta baryon mass 1232 MeV
    (proton ~938 MeV + ~300 MeV photon).
    Multiple nucleon emission is increasing likely.. use caution with results.
    """
    S  = 0.3
    nu = 1.8
    epsilon1  = 180 # [MeV]
    epsilon_t = (E_MeV - 150.) / epsilon1

```

```
            piece_1 = A / 8.
            piece_2 = A * S * epsilon_t * np.exp( (1 - epsilon_t**nu) / nu )
            return (piece_1 + piece_2) * 1e-27 # [cm**2]


        photon_energy_MeV = photon_energy_eV / 1e6

        if (photon_energy_MeV <= 30.):  # i.e. 30 [MeV]
            return giantDipoleResonance(mass_number, photon_energy_MeV)
        elif (photon_energy_MeV <= 150.): # i.e. 150 [MeV]
            return prePionProduction(mass_number, photon_energy_MeV)
        else:
            return postPionProduction(mass_number, photon_energy_MeV)
```

Listing G.4: Job Generation (`earth.py`)

```python
#!/usr/bin/env python3

"""Earth
"""

__project__      = 'GZ Paper'
__version__      = 'v1.0'
__objective__    = 'Phenominology'
__institution__  = 'University of California, Irvine'
__department__   = 'Physics and Astronomy'
__author__       = 'Eric Albin'
__email__        = 'Eric.K.Albin@gmail.com'
__updated__      = '13 May 2019'

import datetime
import numpy as np
import os
import platform

import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

from . import coordinates
from . import probability
from . import units

class Patch:

    def __init__(self, phi_lo, phi_hi, theta_lo, theta_hi):
        """phi = azimuthal angle = 0 to 360 deg from x axis
        theta = polar angle = 0 to 180 deg from z axis
        """
        self.phi_lo = phi_lo
        self.phi_hi = phi_hi
        self.theta_lo = theta_lo
        self.theta_hi = theta_hi

        self.phi_mid = (phi_lo + phi_hi) / 2.
        self.theta_mid = (theta_lo + theta_hi) / 2.

```

```
        p = self.phi_mid * (np.pi / 180.)
        t = self.theta_mid * (np.pi / 180.)
        x = np.sin(t) * np.cos(p)
        y = np.sin(t) * np.sin(p)
        z = np.cos(t)
        self.zenith = np.asarray([x, y, z])


class Earth:

    OUT_JOB_PATH = './out_jobs'
    IN_JOB_PATH  = './in_jobs'

    def randomThetaPhi(size, theta_hi=180):
        x = np.deg2rad( np.linspace(0, theta_hi, theta_hi + 1) )
        pdf = np.sin(x)
        theta = probability.random(x, pdf, size)
        phi = 2. * np.pi * np.random.random(size)
        return theta, phi

    def outgoing_batch(Zlist=[2, 8, 26, 92],
                       Elist=[1e15, 10e15, 100e15, 1_000e15, 10_000e15, 100_000e15],
                       max_step=.01, R_limit=None, runs=100_000, cone=90.,
                       seed=None, out_path=None, job_path=None,
                       B_override=None):
        if (seed is not None):
            np.random.seed(seed)

        if (job_path is None):
            job_path = Earth.OUT_JOB_PATH

        if (not os.path.isdir(job_path)):
            os.makedirs(job_path)

        eTheta, ePhi = Earth.randomThetaPhi(runs)
        zTheta, zPhi = Earth.randomThetaPhi(runs, theta_hi=cone)

        zx = np.sin(eTheta) * np.cos(ePhi)
        zy = np.sin(eTheta) * np.sin(ePhi)
        zz = np.cos(eTheta)
        zenith = np.asarray([zx, zy, zz]).T
```

```
        r  = np.cos(zTheta)
        th = np.sin(zTheta) * np.cos(zPhi)
        ph = np.sin(zTheta) * np.sin(zPhi)
        beta = np.zeros((len(zTheta), 3))
        for _ in range(len(zTheta)):
            beta[_] = coordinates.Spherical.toCartesian([r[_], th[_], ph[_]], eTheta[_], ePhi[_])

        Re = units.SI.radius_earth * units.Change.meter_to_AU
        position = coordinates.Cartesian.earth + (Re * zenith)

        for run in range(runs):
            filename = 'job{:06}'.format(run + 1)

            eTh = eTheta[run]
            ePh = ePhi[run]
            zTh = zTheta[run]
            zPh = zPhi[run]

            pos = position[run]
            bet = beta[run]

            A = None
            step_override = None
            algorithm = 'dop853'
            with open(os.path.join(job_path, filename + '.py'), 'w') as f:
                f.write('#!/usr/bin/env python3\n')
                f.write('#\n')
                f.write('# Outgoing propagation job: ' + __version__ + '\n')
                f.write('# Time of writing: ' + str(datetime.datetime.now()) + '\n')
                f.write('#\n')
                f.write('# Platform\n')
                uname = platform.uname()
                f.write('# Node=' + uname.node + '\n')
                f.write('# Machine=' + uname.machine + '\n')
                f.write('# System=' + uname.system + '\n')
                f.write('# Version=' + uname.version + '\n')
                f.write('# Release=' + uname.release + '\n')
                f.write('# Processor=' + uname.processor + '\n')
                f.write('#\n')
```

```
                f.write('# Setup\n')
                f.write('# Zlist=' + str(Zlist) + '\n')
                f.write('# Elist=' + str(Elist) + '\n')
                f.write('# Runs=' + str(runs) + '\n')
                f.write('# Cone=' + str(cone) + ' [deg]\n')
                f.write('# Seed=' + str(seed) + '\n')
                f.write('#\n')
                f.write('# Parameters\n')
                f.write('# Earth_Theta=' + str(np.rad2deg(eTh)) + ' [deg]\n')
                f.write('# Earth_Phi=' + str(np.rad2deg(ePh)) + ' [deg]\n')
                f.write('# Zenith_Theta=' + str(np.rad2deg(zTh)) + ' [deg]\n')
                f.write('# Zenith_Phi=' + str(np.rad2deg(zPh)) + ' [deg]\n')
                f.write('# Zenith=' + str(zenith[run]) + '\n')
                f.write('# A=' + str(A) + ' [atomic mass units]\n')
                f.write('# Max_Step=' + str(max_step) + ' [AU]\n')
                f.write('# R_Limit=' + str(R_limit) + ' [AU]\n')
                f.write('# B_Override=' + str(B_override) + ' [T]\n')
                f.write('# Step_Override=' + str(step_override) + ' [AU]\n')
                f.write('# Algorithm=' + str(algorithm) + '\n')
                f.write('#\n')
                f.write('# Script\n\n')
                f.write('import gz\n\n')

                for z in Zlist:
                    for e in Elist:

                        args  = '[' + str(pos[0]) + ', ' + str(pos[1]) + ', ' + str(pos[2]) + '], '
                        args += '[' + str(bet[0]) + ', ' + str(bet[1]) + ', ' + str(bet[2]) + '], '
                        args += str(z) + ', '
                        args += str(e) + ', '
                        args += 'A=' + str(A) + ', '
                        args += 'max_step=' + str(max_step) + ', '
                        if (R_limit is not None):
                            args += 'R_limit=' + str(R_limit) + ', '
                        args += 'save_path=' + str(out_path) + ', '
                        outname = filename + '_' + str(z) + '_' + str(int(e/1e15))
                        args += 'filename=' + "'" + outname + "'"
                        f.write('outgoing = gz.path.Outgoing(' + args + ')\n')
                        args = ''
```

```
                        if (B_override is not None):
                            b_str = '[' + str(B_override[0]) + ', ' + str(B_override[1]) + ', ' + str(B_override[2]) + ']'
                            args += 'B_override=' + b_str + ', '
                        if (step_override is not None):
                            args += 'step_override=' + str(step_override) + ', '
                        args += "algorithm='" + str(algorithm) + "'"
                        f.write('outgoing.propagate(' + args + ')\n\n')

def incoming_jobs(directory=None, filelist=None, runs=100, seed=None, quick_dist=False,
                    out_path=None, job_path=None, plot=False, histograms=True):

    if (seed is not None):
        np.random.seed(seed)

    if (job_path is None):
        job_path = Earth.IN_JOB_PATH

    if (not os.path.isdir(job_path)):
        os.makedirs(job_path)

    if (directory is not None):
        filelist = []
        for file in os.listdir(directory):
            if (file.endswith('.outgoing')):
                filelist.append(os.path.join(directory, file))

    if (plot):
        plt.figure(figsize=[15,15])

    total_probability = 0.
    for file in filelist:
        with open(file, 'r') as f:
            Z = None
            A = None
            E = None
            algorithm = None
            max_step = None
            R_limit = None
            B_override = None
            step_override = None
```

```
                telemetry = []
                seek = 0
                for _, line in enumerate(f.readlines()):

                    search = '# Z='
                    if (line.startswith(search)):
                        Z = int( line[len(search):].split()[0] )
                        continue

                    search = '# A='
                    if (line.startswith(search)):
                        A = line[len(search):].split()[0]
                        try:
                            A = float(A)
                        except ValueError:
                            A = None
                        continue

                    search = '# E='
                    if (line.startswith(search)):
                        E = float( line[len(search):].split()[0] )
                        continue

                    search = '# Algorithm='
                    if (line.startswith(search)):
                        algorithm = line[len(search):].split()[0]
                        continue

                    search = '# Max_Step='
                    if (line.startswith(search)):
                        max_step = line[len(search):].split()[0]
                        try:
                            max_step = float(max_step)
                        except ValueError:
                            max_step = None
                        continue

                    search = '# R_Limit='
                    if (line.startswith(search)):
                        R_limit = line[len(search):].split()[0]
                        try:
```

```
                R_limit = float(R_limit)
            except ValueError:
                R_limit = None
            continue

        search = '# B_Override='
        if (line.startswith(search)):
            B_override = line[len(search):].split()
            try:
                B_override = np.asarray(B_override[:3], dtype=np.float64)
            except ValueError:
                B_override = None
            continue

        search = '# Step_Override='
        if (line.startswith(search)):
            step_override = line[len(search):].split()[0]
            try:
                step_override = float(step_override)
            except ValueError:
                step_override = None
            continue

        search = '# Telemetry'
        if (line.startswith(search)):
            f.seek(0)
            seek = _
            break

    for line in f.readlines()[seek + 1:]:
        if (line.strip() == ''):
            break
        telemetry.append(np.asarray(line.split(), dtype=np.float64))

    origin = telemetry[0][:3]
    position = telemetry[-1][:3]
    beta = -1. * telemetry[-1][3:6]

    if (quick_dist):
        cdf = [1.]
        rand_dists = telemetry[-1][6] * np.random.random(runs)
```

```
            if (runs == 1):
                rand_dists = rand_dists[0]
        else:
            edist = []
            dists = []
            probs = []
            max_dist = telemetry[-1][6]
            length = len(telemetry)
            for _ in range(length):
                if (_ == 0):
                    dists.append(0.)
                    probs.append(0.)
                    continue
                t = telemetry[length - _ - 1]
                pos = t[:3]
                bet = -1. * t[3:6]
                epos = pos - coordinates.Cartesian.earth
                edist.append(np.sqrt(np.dot(epos, epos)))
                dis = max_dist - t[6]
                step = np.abs(telemetry[length - _][6] - t[6])
                atten = probability.Solar.attenuation(pos, bet, Z, E, mass_number=A)
                probs.append(probability.oneOrMore(atten, step))
                dists.append(dis)
            rand_dists, x, pdf, cdf = probability.random(dists, probs, runs, seed=seed, plottables=True, CDF=True)
            total_probability += cdf[-1]
            bins = np.linspace(0., max_dist, 50)
            if (plot):
                color = tuple(np.random.random(3))
                if (histograms):
                    plt.hist(rand_dists, bins=bins, log=True, density=True, color=color + (.3,))
                plt.plot(x, pdf, color=color)
                plt.xlim(x[0], x[-1])
                plt.yscale('log')
                continue

        filename = os.path.basename(file).rstrip('.outgoing') + '.pdf'
        with open(os.path.join(job_path, filename), 'w') as g:
            g.write('# dist from earth [AU], return path dist [AU], pdf, cdf\n')
            for e, d, p, c in zip(edist, x, pdf, cdf):
```

```
                g.write('{}  {}  {}  {}\n'.format(e, d, p, c))

            filename = os.path.basename(file).rstrip('.outgoing') + '.py'
            with open(os.path.join(job_path, filename), 'w') as g:
                print('writing ' + filename, flush=True)
                g.write('#!/usr/bin/env python3\n')
                g.write('#\n')
                g.write('# Incoming propagation job: ' + __version__ + '\n')
                g.write('# Time of writing: ' + str(datetime.datetime.now()) + '\n')
                g.write('#\n')
                g.write('# Platform\n')
                uname = platform.uname()
                g.write('# Node=' + uname.node + '\n')
                g.write('# Machine=' + uname.machine + '\n')
                g.write('# System=' + uname.system + '\n')
                g.write('# Version=' + uname.version + '\n')
                g.write('# Release=' + uname.release + '\n')
                g.write('# Processor=' + uname.processor + '\n')
                g.write('#\n')
                g.write('# Setup\n')
                g.write('# Runs=' + str(runs) + '\n')
                g.write('# Seed=' + str(seed) + '\n')
                g.write('# Outgoing_File=' + str(file) + '\n')
                g.write('#\n')
                g.write('# Parameters\n')
                g.write('# Z=' + str(np.abs(Z)) + ' [proton number]\n')
                g.write('# A=' + str(A) + ' [atomic mass units]\n')
                g.write('# E=' + str(E) + ' [electron volts]\n')
                g.write('# Algorithm=' + str(algorithm) + '\n')
                g.write('# Max_Step=' + str(max_step) + ' [AU]\n')
                g.write('# R_Limit=' + str(R_limit) + ' [AU]\n')
                g.write('# B_Override=' + str(B_override) + ' [T]\n')
                g.write('# Step_Override=' + str(step_override) + ' [AU]\n')
                g.write('# Origin=' + str(origin) + ' [AU]\n')
                g.write('# Position=' + str(position) + ' [AU]\n')
                g.write('# Beta=' + str(beta) + '\n')
                g.write('# CDF=' + str(cdf[-1]) + '\n')
                g.write('#\n')
                g.write('# Script\n\n')
                g.write('import gz\n\n')

```

```
                    if (runs == 1):
                        rand_dists = [rand_dists]
                    for _, dist in enumerate(rand_dists):

                        out_name = os.path.basename(filename).rstrip('.py') + '_{:04}'.format(_)

                        args  = '[' + str(origin[0])   + ', ' + str(origin[1])   + ', ' + str(origin[2])   + '], '
                        args += '[' + str(position[0]) + ', ' + str(position[1]) + ', ' + str(position[2]) + '], '
                        args += '[' + str(beta[0])     + ', ' + str(beta[1])     + ', ' + str(beta[2])     + '], '
                        args += str(Z) + ', '
                        args += str(A) + ', '
                        args += str(E) + ', '
                        args += str(dist) + ', '
                        args += 'max_step=' + str(max_step) + ', '
                        if (R_limit is not None):
                            args += 'R_limit=' + str(R_limit) + ', '
                        args += 'save_path=' + str(out_path) + ', '
                        args += 'filename=' + "'" + out_name + "'"
                        g.write('incoming = gz.path.Incoming(' + args + ')\n')
                        args = ''
                        if (B_override is not None):
                            b_str = '[' + str(B_override[0]) + ', ' + str(B_override[1]) + ', ' + str(B_override[2]) + ']'
                            args += 'B_override=' + b_str + ', '
                        if (step_override is not None):
                            args += 'step_override=' + str(step_override) + ', '
                        args += "algorithm='" + str(algorithm) + "'"
                        g.write('incoming.propagate(' + args + ')\n\n')

        print('Average probability to disinitegrate: ' + str(total_probability / float(len(filelist))), flush=True)


    ################################################################################


    # OBSOLETE
```

```
    def run(wedges=4, bands=3, Zlist=[2, 26, 92], Elist=[2e18, 20e18, 200e18], runs=1000):
        earth = Earth(wedges=wedges, bands=bands)
        for z in Zlist:
            for e in Elist:
                earth.outgoing_jobs(z, e, max_step=.01, runs=runs)#, cone=90., B_override
                    ↪ =[0,0,0], name_header='try90')

    # OBSOLETE
    def __init__(self, wedges=4, bands=3):
        self.wedges = wedges
        self.bands = bands

        self.phi_sep = 360. / wedges
        self.theta_sep = 180. / bands

        self.phi_offset = self.phi_sep / 2.
        self.theta_offset = 0.

        self.patches = []
        for w in range(wedges):
            for b in range(bands):
                phi_lo = self.phi_offset + w * self.phi_sep
                phi_hi = phi_lo + self.phi_sep
                theta_lo = self.theta_offset + b * self.theta_sep
                theta_hi = theta_lo + self.theta_sep
                self.patches.append(Patch(phi_lo, phi_hi, theta_lo, theta_hi))

    # OBSOLETE
    def draw(self, ax=None):
        if (ax is None):
            fig = plt.figure(figsize=[16,16])
            ax = plt.axes(projection='3d')

        for patch in self.patches:
            phi_lo = patch.phi_lo * np.pi / 180.
            phi_hi = patch.phi_hi * np.pi / 180.
            theta_lo = patch.theta_lo * np.pi / 180.
            theta_hi = patch.theta_hi * np.pi / 180.

            u, v = np.mgrid[phi_lo:phi_hi:10j, theta_lo:theta_hi:10j]
            r = units.SI.radius_earth * units.Change.meter_to_AU
```

```
            x = r * np.cos(u)*np.sin(v)
            y = r * np.sin(u)*np.sin(v)
            z = r * np.cos(v)
            x += coordinates.Cartesian.earth[0]
            y += coordinates.Cartesian.earth[1]
            z += coordinates.Cartesian.earth[2]
            ax.plot_surface(x, y, z, color=tuple(np.random.rand(3)))

    # OBSOLETE
    def outgoing_jobs(self, Z, E, max_step=.01, A=None, R_limit=None, runs=100, cone=90.,
                      seed=None, out_path=None, job_path=None, name_header=None, name_tail=None,
                      B_override=None, step_override=None, algorithm='dop853'):
        if (seed is not None):
            np.random.seed(seed)

        if (job_path is None):
            job_path = Earth.OUT_JOB_PATH

        if (not os.path.isdir(job_path)):
            os.makedirs(job_path)

        for patch in self.patches:
            p_mid = int(patch.phi_mid)
            t_mid = int(patch.theta_mid)

            if (name_header is not None):
                filename = name_header + '_'
            else:
                filename = ''
            filename += str(t_mid) + '_' + str(p_mid)

            if (name_tail is not None):
                filename += '_' + name_tail
            else:
                filename += '_' + str(Z) + '_' + str(int(E/1e18))
            filename += '.py'

            position = coordinates.Cartesian.earth
            position = position + patch.zenith * units.SI.radius_earth * units.Change.meter_to_AU
```

```

        with open(os.path.join(job_path, filename), 'w') as f:
            f.write('#!/usr/bin/env python3\n')
            f.write('#\n')
            f.write('# Outgoing propagation job: ' + __version__ + '\n')
            f.write('# Time of writing: ' + str(datetime.datetime.now()) + '\n')
            f.write('#\n')
            f.write('# Platform\n')
            uname = platform.uname()
            f.write('# Node=' + uname.node + '\n')
            f.write('# Machine=' + uname.machine + '\n')
            f.write('# System=' + uname.system + '\n')
            f.write('# Version=' + uname.version + '\n')
            f.write('# Release=' + uname.release + '\n')
            f.write('# Processor=' + uname.processor + '\n')
            f.write('#\n')
            f.write('# Setup\n')
            f.write('# Wedges=' + str(self.wedges) + '\n')
            f.write('# Bands=' + str(self.bands) + '\n')
            f.write('# Runs=' + str(runs) + '\n')
            f.write('# Cone=' + str(cone) + ' [deg]\n')
            f.write('# Seed=' + str(seed) + '\n')
            f.write('#\n')
            f.write('# Patch\n')
            f.write('# Phi_lo=' + str(patch.phi_lo) + ' [deg]\n')
            f.write('# Phi_mid=' + str(patch.phi_mid) + ' [deg]\n')
            f.write('# Phi_hi=' + str(patch.phi_hi) + ' [deg]\n')
            f.write('# Theta_lo=' + str(patch.theta_lo) + ' [deg]\n')
            f.write('# Theta_mid=' + str(patch.theta_mid) + ' [deg]\n')
            f.write('# Theta_hi=' + str(patch.theta_hi) + ' [deg]\n')
            f.write('# Zenith=' + str(patch.zenith) + '\n')
            f.write('#\n')
            f.write('# Parameters\n')
            f.write('# Z=' + str(np.abs(Z)) + ' [proton number]\n')
            f.write('# A=' + str(A) + ' [atomic mass units]\n')
            f.write('# E=' + str(E) + ' [electron volts]\n')
            f.write('# Max_Step=' + str(max_step) + ' [AU]\n')
            f.write('# R_Limit=' + str(R_limit) + ' [AU]\n')
            f.write('# B_Override=' + str(B_override) + ' [T]\n')
            f.write('# Step_Override=' + str(step_override) + ' [AU]\n')
            f.write('# Algorithm=' + str(algorithm) + '\n')
```

```
518                 f.write('#\n')
519                 f.write('# Script\n\n')
520                 f.write('import gz\n\n')
521
522                 phis = 2.*np.pi * np.random.random(runs)
523                 thetas = np.ones(runs) * 89. * np.pi/180. #cone * np.pi / 180. * np.random.
                        ↪ random(runs)
524                 for t, p in zip(thetas, phis):
525                     r  = np.cos(t)
526                     th = np.sin(t) * np.cos(p)
527                     ph = np.sin(t) * np.sin(p)
528                     theta = np.arccos(patch.zenith[2])
529                     phi   = np.arctan2(patch.zenith[1], patch.zenith[0])
530                     beta = coordinates.Spherical.toCartesian([r, th, ph], theta, phi)
531
532                     if (name_header is not None):
533                         out_name = name_header + '_'
534                     else:
535                         out_name = ''
536                     out_name += str(t_mid) + '_' + str(p_mid) + '_'
537                     out_name += str(Z) + '_' + str(int(E/1e18)) + '_'
538                     out_name += str(int(t * 180. / np.pi)) + '_' + str(int(p * 180./np.pi))
539
540                     args  = '[' + str(position[0]) + ', ' + str(position[1]) + ', ' + str(
                            ↪ position[2]) + '], '
541                     args += '[' + str(beta[0])     + ', ' + str(beta[1])     + ', ' + str(
                            ↪ beta[2])     + '], '
542                     args += str(Z) + ', '
543                     args += str(E) + ', '
544                     args += 'A=' + str(A) + ', '
545                     args += 'max_step=' + str(max_step) + ', '
546                     if (R_limit is not None):
547                         args += 'R_limit=' + str(R_limit) + ', '
548                     args += 'save_path=' + str(out_path) + ', '
549                     args += 'filename=' + "'" + out_name + "'"
550                     f.write('outgoing = gz.path.Outgoing(' + args + ')\n')
551                     args = ''
552                     if (B_override is not None):
553                         b_str = '[' + str(B_override[0]) + ', ' + str(B_override[1]) + ', '
                                ↪ + str(B_override[2]) + ']'
554                         args += 'B_override=' + b_str + ', '
```

```
                        if (step_override is not None):
                            args += 'step_override=' + str(step_override) + ', '
                        args += "algorithm='" + str(algorithm) + "'"
                        f.write('outgoing.propagate(' + args + ')\n\n')
```

Listing G.5: HMF (`heliosphere_model.py`)

```python
#!/usr/bin/env python3

"""Compute the solar magnetic field as modeled in:
Akasofu, S.-I., Gray, P., & Lee, L. 1980, Planetary Space Science, 28, 609
(1) Solar Dipole
(2) Sunspot Dipoles
(3) Solar Dynamo
(4) Ring Current
Coordinate system: (x,y,z) Sun == (0,0,0), Earth == (1,0,0)
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

import numpy as np

from . import coordinates
from . import units


################################################################################

### parametric constants, ref. Akasofu, Gray & Lee (1980):
Bs = 2.      # [Gauss]
Bo = -3.5e-5 # [Gauss]
Bt =  3.5e-5 # [Gauss]
Bd = 1000.   # [Gauss]
Ro = 0.00465 # Radius of the Sun [astronomical units]
Rd = 0.1*Ro  # Sunspot dipole radius [astronomical units]
po = 1.      # [astronomical units]

################################################################################

def solarDipole(cartesian_pos):
```

```
    """Compute the solar dipole component of the field model given
    cartesian position in [astronomical units].
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    polar_pos = coordinates.cartesian2polar(cartesian_pos)['rtz']
    rho       = polar_pos[0] # [astronomical units]
    theta     = polar_pos[1] # [radians]
    z         = polar_pos[2] # [astronomical units]

    ## B_rho [Gauss]
    B_rho = 0
    if np.abs(z) > 0:
        B_rho = -(3./2.) * (Bs * Ro**3) * rho * z * (z**2 + rho**2)**(-5./2.)

    ## B_theta [Gauss]
    B_theta  = 0

    ## B_z [Gauss]
    B_z  = 0
    if np.abs(rho) > 0:
       B_z = (1./2.) * (Bs * Ro**3) * (rho**2 - 2*(z**2)) * (z**2 + rho**2)**(-5./2.)

    polar_B     = np.array([ B_rho, B_theta, B_z ])
    cartesian_B = coordinates.polar2cartesian(polar_pos, vec=polar_B)['vec']
    return cartesian_B # [Gauss]


def solarSunspot(cartesian_pos):
    """Compute the solar sunspot component of the field model given
    cartesian position in [astronomical units].
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    x = cartesian_pos[0] # [astronomical units]
    y = cartesian_pos[1] # [astronomical units]
    z = cartesian_pos[2] # [astronomical units]

    N_dipoles = 180
    dipole_thetas = np.linspace(0, 360, N_dipoles, endpoint=False) * np.pi / 180. # [radians
        ↪ ]
    sumB_x = 0
    sumB_y = 0
```

```
    sumB_z = 0
    for dipole_theta in dipole_thetas:
        dipole_x = Rd * np.cos(dipole_theta) # [astronomical units]
        dipole_y = Rd * np.sin(dipole_theta) # [astronomical units]
        dipole_z = 0                         # [astronomical units]

        ## relative distance from dipole to field point
        rel_x = x - dipole_x # [astronomical units]
        rel_y = y - dipole_y # [astronomical units]
        rel_z = z - dipole_z # [astronomical units]

        rel_cartesian = np.array([ rel_x, rel_y, rel_z ])
        rel_polar     = coordinates.cartesian2polar(rel_cartesian)['rtz']
        rho   = rel_polar[0] # [astronomical units]
        theta = rel_polar[1] # [radians]
        z     = rel_polar[2] # [astronomical units]

        ## B_rho [Gauss]
        B_rho = 0
        if np.abs(z) > 0:
            B_rho = -(3./2.) * (Bd * Rd**3) * rho * z * (z**2 + rho**2)**(-5./2.)

        ## B_theta [Gauss]
        B_theta  = 0

        ## B_z [Gauss]
        B_z  = 0
        if np.abs(rho) > 0:
           B_z = (1./2.) * (Bd * Rd**3) * (rho**2 - 2*(z**2)) * (z**2 + rho**2)**(-5./2.)

        polar_B     = np.array([ B_rho, B_theta, B_z ])
        cartesian_B = coordinates.polar2cartesian(rel_polar, vec=polar_B)['vec']

        sumB_x += cartesian_B[0]
        sumB_y += cartesian_B[1]
        sumB_z += cartesian_B[2]

    return np.array([ sumB_x, sumB_y, sumB_z ]) # [Gauss]


def solarDynamo(cartesian_pos):
```

```
    """Compute the solar dynamo component of the field model given
    cartesian position in [astronomical units].
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    polar_pos = coordinates.cartesian2polar(cartesian_pos)['rtz']
    rho       = polar_pos[0] # [astronomical units]
    theta     = polar_pos[1] # [radians]
    z         = polar_pos[2] # [astronomical units]

    ## B_rho [Gauss]
    B_rho = 0

    ## B_theta [Gauss]
    B_theta  = 0
    if np.abs(rho) > 0:
        B_theta  = (Bt * po) / float(rho)
    if z < 0:
        B_theta *= -1.

    ## B_z [Gauss]
    B_z = 0

    polar_B     = np.array([ B_rho, B_theta, B_z ])
    cartesian_B = coordinates.polar2cartesian(polar_pos, vec=polar_B)['vec']
    return cartesian_B # [Gauss]


### OPTIONAL TODO
def solarRingAGL(cartesian_pos):
    """Compute the solar ring component of the field model given
    cartesian position in [astronomical units].
    Follows the approximation made in Akasofu, Gray & Lee (1980).
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    polar_pos = coordinates.cartesian2polar(cartesian_pos)['rtz']
    rho       = polar_pos[0] # [astronomical units]
    theta     = polar_pos[1] # [radians]
    z         = polar_pos[2] # [astronomical units]

    print("DON'T CALL ME - I'M NOT IMPLEMENTED YET")
    #return np.array([ 0, 0, 0 ])
```

```python


def solarRingEMR(cartesian_pos):
    """Compute the solar ring component of the field model given
    cartesian position in [astronomical units].
    Follows the approximation made in Epele, Mollerach & Roulet (1999).
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    polar_pos = coordinates.cartesian2polar(cartesian_pos)['rtz']
    rho       = polar_pos[0] # [astronomical units]
    theta     = polar_pos[1] # [radians]
    z         = polar_pos[2] # [astronomical units]
    ## B_rho [Gauss]
    B_rho = 0
    if np.abs(rho) > 0:
        B_rho = (Bo * po**2) * rho * (z**2 + rho**2)**(-3./2.)
    if z < 0:
        B_rho *= -1.

    ## B_theta [Gauss]
    B_theta = 0

    ## B_z [Gauss]
    B_z = 0
    if np.abs(rho) > 0:
       B_z = (Bo * po**2) * np.abs(z) * (z**2 + rho**2)**(-3./2.)

    polar_B     = np.array([ B_rho, B_theta, B_z ])
    cartesian_B = coordinates.polar2cartesian(polar_pos, vec=polar_B)['vec']
    return cartesian_B # [Gauss]


### OPTIONAL TODO
def solarRingExact(cartesian_pos):
    """Compute the solar ring component of the field model given
    cartesian position in [astronomical units].
    Follows the exact integral formulation in Akasofu, Gray & Lee (1980).
    returns a magnetic field density vector in cartesian coordinates in Gauss.
    """
    polar_pos = coordinates.cartesian2polar(cartesian_pos)['rtz']
    rho       = polar_pos[0] # [astronomical units]
```

```
    theta     = polar_pos[1] # [radians]
    z         = polar_pos[2] # [astronomical units]

    print("DON'T CALL ME - I'M NOT IMPLEMENTED YET")
    #return np.array([ 0, 0, 0 ])


def sumBfieldGauss(cartesian_pos):
    """Compute the total cartesian compoents of the solar magnetic field
    given cartesian position in [astronomical units].
    Uses the EMR approximation for the solar ring field.
    returns a magnetic field density vector in Gauss.
    """
    B_dipole  = solarDipole(cartesian_pos)    # [Gauss]
    B_sunspot = solarSunspot(cartesian_pos)   # [Gauss]
    B_dynamo  = solarDynamo(cartesian_pos)    # [Gauss]
    B_ring    = solarRingEMR(cartesian_pos)   # [Gauss]
    B_total   = B_dipole + B_sunspot + B_dynamo + B_ring
    return B_total # [Gauss]

def sumBfieldTesla(cartesian_pos):
    """Compute the total cartesian compoents of the solar magnetic field
    given cartesian position in [astronomical units].
    Uses the Epele approximation for the solar ring field.
    returns a magnetic field density vector in Tesla.
    """
    B_total = sumBfieldGauss(cartesian_pos) # [Gauss]
    return B_total * units.Change.gauss_to_tesla # [Tesla]
```

Listing G.6: Magnetic Field (`magnetic_field.py`)

```
#!/usr/bin/env python3

"""Precompute the total magnetic field, store to disk
and use it as an interpolated look-up table to profoundly accelerate
numeric integration.
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

import numpy as np
import os
import sys
import tarfile
import time

from scipy import interpolate

from . import heliosphere_model


# global field values in memory
#-----------------------------
__spacelimit = None
__resolution = None
__x  = None
__y  = None
__z  = None
__BX = None
__BY = None
__BZ = None
__InterpolateBx = None
__InterpolateBy = None
__InterpolateBz = None
```

```python

def precompute(spacelimit=6, resolution=60, autoload=True, directory='tables', b_fname='cartesianBfield.Tesla'):
    """Returns total magnetic field x, y, z, BX, BY, BZ meshes by
    by disk-read or re-generation.  Field density in Teslas.

    spacelimit : radial reach (r) of the space volume
                 (x, y, z) === (-r to r) by (-r to r) by (-r to r) [astronomical units]

    resolution : the number of samples taken between (-r to r) along each dimension.
                 In addition, there are another resolution's-worth of samples added to
                 that set between (-r/10 to r/10) to resolve near the Sun better.
                 resolution = 60 takes around 5 hours to regenerate.

    autoload   : if True, look FIRST to disk for existing table.
                    if (no preexisting) or (has different spacelimit or resolution):
                        regenerate from scratch and overwrite existing.
                 if False, force regenerate from scratch and overwrite existing.

    directory  : subdirectory with magnetic field text file

    b_fname    : filename for magnetic field text file

    returns dictionary { 'x', 'y', 'z', 'BX', 'BY', 'BZ' }
                 x, y, z have shape (<=2*resolution,)
                 BX, BY, BZ have shape (<=2*resolution, <=2*resolution, <=2*resolution)
                 The <=2 is because some points are common to both (-r to r) and
                 (-r/10 to r/10), thus the shape is between (1 to 2)*resolution.

    """
    # check if already loaded in memory, return and exit if so
    #-------------------------------------------------------------
    global __spacelimit, __resolution
    global __x, __y, __z, __BX, __BY, __BZ

    if ( (__spacelimit == spacelimit) and (__resolution == resolution) and
         (__x is not None)  and (__y is not None)  and (__z is not None) and
         (__BX is not None) and (__BY is not None) and (__BZ is not None) ):
        return {'x':__x, 'y':__y, 'z':__z, 'BX':__BX, 'BY':__BY, 'BZ':__BZ}


```

```
    # configure x,y,z and bx,by,bz
    #-----------------------------
    spacelimit = int( spacelimit ) # [astronomical units] (integer for easy file read)
    resolution = int( resolution ) # N divisions (integer for easy file read)

    x = np.linspace(-spacelimit, spacelimit, resolution) # [astronomical units]
    y = np.linspace(-spacelimit, spacelimit, resolution) # [astronomical units]
    z = np.linspace(-spacelimit, spacelimit, resolution) # [astronomical units]
    ## add extra points around the sun:
    x = np.union1d(x, np.linspace(-spacelimit/10., spacelimit/10., resolution) )
    y = np.union1d(y, np.linspace(-spacelimit/10., spacelimit/10., resolution) )
    z = np.union1d(z, np.linspace(-spacelimit/10., spacelimit/10., resolution) )

    spacelimit = np.array([spacelimit])
    resolution = np.array([resolution])

    X, Y, Z = np.meshgrid(x, y, z, indexing='ij')
    shape = np.array(X.shape)
    size = X.flatten().size

    bx = np.zeros(size) # [Tesla]
    by = np.zeros(size) # [Tesla]
    bz = np.zeros(size) # [Tesla]

    # load from file or regenerate
    #-----------------------------
    regen = False
    if not autoload:
        regen = True

    text_sep = ', '
    # TODO: update path
    base_dir  = os.path.dirname( os.path.abspath( heliosphere_model.__file__ ) )
    directory = 'tables'
    b_fname   = 'cartesianBfield.Tesla'
    b_fnameZip= b_fname + '.tar.gz'
    b_path    = os.path.abspath( os.path.join( base_dir, directory, b_fname ) )
    b_exists  = os.path.isfile(b_path)
    if (not b_exists):
        zip_path = os.path.abspath( os.path.join( base_dir, directory, b_fnameZip ) )
        if os.path.isfile(zip_path):
```

```
            with tarfile.open(zip_path, 'r:gz') as tf:
                tf.extractall( os.path.abspath( os.path.join( base_dir, directory) ) )
                return precompute(spacelimit=spacelimit, resolution=resolution, autoload=
                    ↪ autoload, directory=directory, b_fname=b_fname)
        else:
            regen = True

    # load from file if the file is good
    if (not regen):
        with open(b_path) as b_f:
            header = b_f.readline()
            f_spacelimit = int( b_f.readline() )
            f_resolution = int( b_f.readline() )
            f_shape      = np.fromstring( b_f.readline(), sep=text_sep )
            if ( f_spacelimit == spacelimit and
                 f_resolution == resolution and
                 f_shape == shape).all():
                x  = np.fromstring( b_f.readline(), sep=text_sep)
                y  = np.fromstring( b_f.readline(), sep=text_sep)
                z  = np.fromstring( b_f.readline(), sep=text_sep)
                bx = np.fromstring( b_f.readline(), sep=text_sep)
                by = np.fromstring( b_f.readline(), sep=text_sep)
                bz = np.fromstring( b_f.readline(), sep=text_sep)
            else:
                regen = True

    # regenerate and overwrite
    if regen:
        i_max  = X.flatten().size
        target = 0.
        start  = time.time()
        for i, (ix, iy, iz) in enumerate( zip( X.flatten(), Y.flatten(), Z.flatten() ) ):
            b_solar = heliosphere_model.sumBfieldTesla( np.array([ ix, iy, iz ]) )
            bx[i] = b_solar[0] # [Tesla]
            by[i] = b_solar[1] # [Tesla]
            bz[i] = b_solar[2] # [Tesla]
            # progress report for long regenerations
            if ( i / float(i_max) ) >= ( target / 100. ):
                print('\r                                                                    \r',)
                print('  progress: {:.1f}%   elapsed: {:.2f} [sec]'.format(target, time.time
                    ↪ () - start ),)
```

```
                sys.stdout.flush()
                target += .1
        print

        with open(b_path, 'w') as b_f:
            header = ( 'rows: 0:this header, 1:spacelimit [AU], 2:resolution, 3:shape, '
                       '4:x [AU], 5:y [AU], 6:z [AU], 7:BX [T], 8:BY [T], 9:BZ [T]' )

            # header and parameters
            b_f.write(header + '\n')
            spacelimit.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            resolution.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            shape.tofile(b_f, sep=text_sep)
            b_f.write('\n')

            # x, y, z
            x.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            y.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            z.tofile(b_f, sep=text_sep)
            b_f.write('\n')

            # bx, by, bz
            bx.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            by.tofile(b_f, sep=text_sep)
            b_f.write('\n')
            bz.tofile(b_f, sep=text_sep)
            b_f.write('\n')

            #### OPTIONAL TODO:
            # make tar.gz file

    # load into memory
    #-----------------
    BX = bx.reshape(shape)
    BY = by.reshape(shape)
    BZ = bz.reshape(shape)
```

```
    __spacelimit = spacelimit
    __resolution = resolution
    __x  = x
    __y  = y
    __z  = z
    __BX = BX
    __BY = BY
    __BZ = BZ

    return {'x':__x, 'y':__y, 'z':__z, 'BX':__BX, 'BY':__BY, 'BZ':__BZ}


def cartesianTesla( cartesian_pos, close2sun=0.01 ):
    """Returns cartesian [Tesla] values (Bx, By, Bz) for cartesian_pos = (x, y, z).
    If position is within close2sun radius [AU], do not interpolate, return exact (slow).
    For spacelimit==6 and resolution==60, interpolation is acceptable up to close2sun==0.01.
    """
    cartesian_pos = np.array(cartesian_pos)
    distance = np.sqrt(np.dot(cartesian_pos, cartesian_pos))
    if distance < close2sun:
        return heliosphere_model.sumBfieldTesla(cartesian_pos)

    global __spacelimit
    global __InterpolateBx, __InterpolateBy, __InterpolateBz
    if ( (__InterpolateBx is not None) and (__InterpolateBy is not None) and
         (__InterpolateBz is not None) ):

        if distance > __spacelimit:
            return heliosphere_model.sumBfieldTesla(cartesian_pos)
        else:
            Bx = __InterpolateBx(cartesian_pos)
            By = __InterpolateBy(cartesian_pos)
            Bz = __InterpolateBz(cartesian_pos)
            return np.array([ Bx, By, Bz ]).flatten()
    else:
        meshes = precompute()
        x  = meshes['x']
        y  = meshes['y']
        z  = meshes['z']
        BX = meshes['BX']
```

```
        BY = meshes['BY']
        BZ = meshes['BZ']

        __InterpolateBx = interpolate.RegularGridInterpolator((x,y,z), BX, bounds_error=False, fill_value=0) # [Tesla]
        __InterpolateBy = interpolate.RegularGridInterpolator((x,y,z), BY, bounds_error=False, fill_value=0) # [Tesla]
        __InterpolateBz = interpolate.RegularGridInterpolator((x,y,z), BZ, bounds_error=False, fill_value=0) # [Tesla]

        return cartesianTesla(cartesian_pos)
```

Listing G.7: Propagation (path.py)

```
#!/usr/bin/env python3

"""
Description
"""

__project__      = 'GZ Paper'
__version__      = 'v1.0'
__objective__    = 'Phenominology'
__institution__  = 'University of California, Irvine'
__department__   = 'Physics and Astronomy'
__author__       = 'Eric Albin'
__email__        = 'Eric.K.Albin@gmail.com'
__updated__      = '13 May 2019'

import datetime
import numpy as np
import os
import platform
import time

from scipy import integrate

from . import coordinates
from . import magnetic_field
from . import probability
from . import relativity
from . import units

class Path:

    EULER_DIVISOR  = 1e4
    DOP853_DIVISOR = 1e2

    def __init__(self, position, beta, Z, E, max_step=1.):
        """
        position: np.array(x,y,z) start position
        beta: np.array(bx,by,bz) start beta (direction of propagation)
        Z: atomic number
        E: energy in eV
```

```
        """
        self.position = np.asarray(position, dtype=np.float64)
        self.beta = np.asarray(beta, dtype=np.float64)
        self.beta = self.beta / np.sqrt(np.dot(self.beta, self.beta))
        self.Z = Z
        self.E = E
        self.ratio = Z / E

        self.max_step = max_step
        self.distance = 0.
        self._set_dist_earth()
        self._set_dist_sun()

    def _set_dist_earth(self):
        r = self.position - coordinates.Cartesian.earth
        self.dist_earth = np.sqrt(np.dot(r, r))

    def _set_dist_sun(self):
        r = self.position - coordinates.Cartesian.sun
        self.dist_sun = np.sqrt(np.dot(r, r))

    def _set_stepsize(self):
        if (self.ratio == 0. or np.sqrt(np.dot(self.B, self.B)) == 0.):
            self.step = self.max_step
        else:
            B = np.sqrt(np.dot(self.B, self.B))
            gyro_radius  = 1. / units.SI.lightspeed / np.abs(self.ratio) / B
            gyro_radius *= units.Change.meter_to_AU
            self.step    = min(self.max_step, gyro_radius / self.step_divisor)


    def propagate(self, B_override=None, step_override=None, algorithm='dop853'):
        """
        Propagates one step
        B_override: use this B instead of Bfield [tesla]
        step_override: use this step instead of step()
        """
        if (B_override is not None):
            self.B = np.asarray(B_override, dtype=np.float64)
        else:
            self.B = magnetic_field.cartesianTesla(self.position)
```

```
        if (step_override is not None):
            self.step = step_override
        else:
            if (algorithm == 'euler'):
                self.step_divisor = Path.EULER_DIVISOR
            elif (algorithm == 'dop853'):
                self.step_divisor = Path.DOP853_DIVISOR
            self._set_stepsize()

        if (algorithm == 'euler'):
            dbeta_ds  = units.Change.AU_to_meter
            dbeta_ds *= self.ratio
            dbeta_ds *= np.cross(self.beta, units.SI.lightspeed * self.B)

            self.beta += dbeta_ds * self.step
            self.beta = self.beta / np.sqrt(np.dot(self.beta, self.beta))
            self.position += self.beta * self.step

        else:
            def ode(t, Y):
                beta = Y[3:]
                dbeta_ds  = units.Change.AU_to_meter
                dbeta_ds *= self.ratio
                dbeta_ds *= np.cross(beta, units.SI.lightspeed * self.B)
                return np.concatenate([beta, dbeta_ds])
            try:
                self.integrator
            except (AttributeError, NameError):
                if (algorithm == 'dop853'):
                    self.integrator = integrate.ode(ode).set_integrator('dop853')

            initial_conditions = np.concatenate([self.position, self.beta])
            self.integrator.set_initial_value(initial_conditions, 0.)
            self.integrator.integrate(self.integrator.t + self.step)
            self.position = self.integrator.y[:3]
            self.beta = self.integrator.y[3:]
            self.beta = self.beta / np.sqrt(np.dot(self.beta, self.beta))

        self.distance += self.step
        self._set_dist_earth()
```

```
        self._set_dist_sun()


class Outgoing(Path):

    LIMIT_BUFFER  = 2. # AU
    DEFAULT_SAVE_PATH = './telemetry'

    def __init__(self, position, beta, Z, E,
                 A=None, max_step=None, R_limit=6., zigzag=False,
                 save=True, save_path=None, filename=None):
        """
        position: np.array(x,y,z) AU start position on earth
        beta: np.array(bx,by,bz) start beta (away from earth)
        Z: atomic number
        A: atomic mass if none then auto assign
        E: energy in eV
        R_limit: radius [AU] of maximum propagation
        """
        if (max_step is None):
            Path.__init__(self, position, beta, -Z, E)
        else:
            Path.__init__(self, position, beta, -Z, E, max_step=max_step)

        self.A = A
        self.R_limit = R_limit

        self.telemetry = [np.concatenate([self.position, self.beta, [self.distance]])]
        self.last_save = self.distance
        self.save_distance = self.max_step / 10.

        self.zigzag = zigzag
        self.save = save
        self.save_path = save_path
        self.filename = filename

    def _add_telemetry(self):
        near_sun   = units.SI.radius_sun   * 10. * units.Change.meter_to_AU
        near_earth = units.SI.radius_earth * 10. * units.Change.meter_to_AU

        if (self.dist_sun < near_sun or self.dist_earth < near_earth
```

```
            or self.distance - self.last_save >= self.save_distance):

            self.telemetry.append(np.concatenate([self.position, self.beta, [self.distance ]]))
            self.last_save = self.distance

    def _set_B(self, B_override=None):
        if (B_override is not None):
            self.B = np.asarray(B_override, dtype=np.float64)
        else:
            if (self.interpolate_B):
                self.B = magnetic_field.cartesianTesla(self.position)
            else:
                self.B = magnetic_field.cartesianTesla(self.position, close2sun=100.)

    def _set_stepsize(self):
        # any special needs here
        Path._set_stepsize(self)

    def propagate(self, B_override=None, interpolate_B=True, step_override=None, algorithm='dop853'):
        """
        Propagates one step
        B_override: use this B instead of Bfield
        step_override: use this step instead of step()
        """
        self.B_override = B_override
        self.interpolate_B = interpolate_B
        self.step_override = step_override

        self._set_B(B_override=B_override)

        if (step_override is not None):
            self.step = step_override
        else:
            if (algorithm == 'euler'):
                self.step_divisor = Path.EULER_DIVISOR
            elif (algorithm == 'dop853'):
                self.step_divisor = Path.DOP853_DIVISOR
            self._set_stepsize()

```

```
        if (self.zigzag):
            def stop_condition():
                if (self.distance + self.step > self.R_limit + Outgoing.LIMIT_BUFFER):
                    self.step = self.R_limit + Outgoing.LIMIT_BUFFER - self.distance
                return self.distance < self.R_limit + Outgoing.LIMIT_BUFFER
        else:
            def stop_condition():
                return self.distance < self.R_limit + Outgoing.LIMIT_BUFFER and self.dist_sun < self.R_limit

        start = time.time()
        while (stop_condition()):
            Path.propagate(self, B_override=self.B, step_override=self.step, algorithm=algorithm)
            self._set_B(B_override=B_override)
            self._add_telemetry()
            if (step_override is None):
                self._set_stepsize()
        self.elapsed_sec = time.time() - start

        if (self.last_save < self.distance):
            self.telemetry.append(np.concatenate([self.position, self.beta, [self.distance]]))

        if (self.save):
            self.algorithm = algorithm
            self.save_telemetry()

    def save_telemetry(self):
        if (self.save_path is None):
           self.save_path = Outgoing.DEFAULT_SAVE_PATH

        subdir = str(np.abs(self.Z)) + '_' + str(int(self.E/1e15))
        self.save_path = os.path.join(self.save_path, subdir)
        if (not os.path.isdir(self.save_path)):
            os.makedirs(self.save_path)

        if (self.filename is None):
            self.filename  = str(np.abs(self.Z))
            self.filename += '_'
            self.filename += str(int(self.E / 1e15))
```

```
        test_name = self.filename
        full_path = os.path.join(self.save_path, test_name + '.outgoing')
        _ = 1
        while (os.path.exists(full_path)):
            test_name = self.filename + '_' + str(_)
            full_path = os.path.join(self.save_path, test_name + '.outgoing')
            _ += 1
        self.filename = test_name + '.outgoing'

        with open(os.path.join(self.save_path, self.filename), 'w') as f:
            f.write('# Outgoing propagation: ' + __version__ + '\n')
            f.write('# Time of writing: ' + str(datetime.datetime.now()) + '\n')
            f.write('# Run time [sec]: ' + str(self.elapsed_sec) + '\n')
            f.write('#\n')
            f.write('# Platform\n')
            uname = platform.uname()
            f.write('# Node=' + uname.node + '\n')
            f.write('# Machine=' + uname.machine + '\n')
            f.write('# System=' + uname.system + '\n')
            f.write('# Version=' + uname.version + '\n')
            f.write('# Release=' + uname.release + '\n')
            f.write('# Processor=' + uname.processor + '\n')
            f.write('#\n')
            f.write('# Parameters\n')
            f.write('# Z=' + str(np.abs(self.Z)) + ' [proton number]\n')
            f.write('# A=' + str(self.A) + ' [atomic mass units]\n')
            f.write('# E=' + str(self.E) + ' [electron volts]\n')
            f.write('# Algorithm=' + self.algorithm + '\n')
            f.write('# Max_Step=' + str(self.max_step) + ' [AU]\n')
            f.write('# R_Limit=' + str(self.R_limit) + ' [AU]\n')
            B_str = str(self.B_override)
            if (self.B_override is not None):
                B_str = str(self.B_override[0]) + ' ' + str(self.B_override[1]) + ' ' + str(
                    ↪ self.B_override[2])
            f.write('# B_Override=' + B_str + ' [T]\n')
            f.write('# Step_Override=' + str(self.step_override) + '\n')
            f.write('#\n')
            f.write('# Key\n')
            f.write('# position_x, position_y, position_z, beta_x, beta_y, beta_z,
                ↪ path_distance\n')
```

```
            f.write('# units: positions=AU, beta=unitless, distance=AU\n')
            f.write('#\n')
            f.write('# Telemetry\n')
            for _ in self.telemetry:
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('\n')
            f.write('# Finished\n')


class Incoming(Outgoing):

    def __init__(self, origin, position, beta, Z, A, E, decay_dist,
                 max_step=None, R_limit=6., save=True, save_path=None, filename=None):

        if (max_step is None):
            Path.__init__(self, position, beta, Z, E)
        else:
            Path.__init__(self, position, beta, Z, E, max_step=max_step)

        self.origin = np.asarray(origin)
        self.decay_dist = decay_dist
        self.R_limit = R_limit

        if (A is None):
            self.A = units.Nuclide.mass_number(Z)
        else:
            self.A = A

        self.telemetry = [np.concatenate([self.position, self.beta, [self.distance]])]
        self.last_save = self.distance
        self.save_distance = self.max_step / 10.
        self.near_earth = False

        self.save = save
        self.save_path = save_path
        self.filename = filename

    def _add_telemetry(self):
        # add anything custom
```

```
        Outgoing._add_telemetry(self)

    def _set_stepsize(self):
        if (self.near_earth or self.dist_earth <= self.max_step):
            self.near_earth = True
            if (self.dist_earth > self.max_step):
                self.near_earth = False
            self.save_distance = 10. * units.SI.radius_earth * units.Change.meter_to_AU
            if (self.dist_earth > 2 * units.SI.radius_earth * units.Change.meter_to_AU):
                self.step = units.SI.radius_earth * units.Change.meter_to_AU / 5.
            else:
                self.step = units.SI.radius_earth * units.Change.meter_to_AU / 50.
        else:
            Path._set_stepsize(self)

    def propagate(self, B_override=None, interpolate_B=True, step_override=None, algorithm='
        ↪ dop853', seed=None):
        """
        Propagates one step
        B_override: use this B instead of Bfield
        step_override: use this step instead of step()
        """
        self.B_override = B_override
        self.interpolate_B = interpolate_B
        self.step_override = step_override

        Outgoing._set_B(self, B_override=B_override)

        if (step_override is not None):
            self.step = step_override
        else:
            if (algorithm == 'euler'):
                self.step_divisor = Path.EULER_DIVISOR
            elif (algorithm == 'dop853'):
                self.step_divisor = Path.DOP853_DIVISOR
            Path._set_stepsize(self)
            self._set_stepsize()

        def remaining():
            return self.decay_dist - self.distance

```

```
        # Propogate nucleus until time to dissintegrate
        start = time.time()
        while (remaining() > 0):
            if (remaining() < self.step):
                self.step = remaining()
            Path.propagate(self, B_override=self.B, step_override=self.step, algorithm=
                ↪ algorithm)
            Outgoing._set_B(self, B_override=B_override)
            self._add_telemetry()
            if (step_override is None):
                self._set_stepsize()
        if (self.last_save < self.distance):
            self.telemetry.append(np.concatenate([self.position, self.beta, [self.distance
                ↪ ]]))

        # Photodissintegration
        # "1" = original nucleus
        # "2" = solar photon
        # "3" = proton or neutron
        # "4" = daughter nucleus
        e1 = self.E
        p1 = relativity.momentum(e1, self.A * units.Change.amu_to_eV, self.beta)
        e2 = probability.Solar.get_photon(self.position, self.beta, self.Z, self.E, seed=
            ↪ seed) # seed is set here
        p2 = relativity.momentum(e2, 0., self.position / self.dist_sun)

        Epn =  1.          / self.A * (self.E + e2) # proton/neutron energy
        Ed  = (self.A - 1) / self.A * (self.E + e2) # daugter nucleous energy
        Zp  = 1 # proton charge
        Zn  = 0 # neutron charge
        Zdp = self.Z - 1 # daughter (proton ejection) charge
        Zdn = self.Z     # daughter (neutron ejection) charge

        e3 = Epn
        m3 = 1. * units.Change.amu_to_eV
        e4 = Ed
        m4 = (self.A - 1) * units.Change.amu_to_eV

        # "p" is the net 3-momentum
        p       = p1 + p2
        p_mag   = np.sqrt(np.dot(p, p))
```

```
        p_hat   = p / p_mag
        p_theta = np.arccos(p_hat[2])
        p_phi   = np.arctan2(p_hat[1], p_hat[0])

        p3_mag = relativity.momentum_mag(e3, m3)
        p4_mag = relativity.momentum_mag(e4, m4)

        # Angle between p3 and p4
        theta = relativity.theta(e1, p1, e2, p2, e3, m3, e4, m4)
        # Angle between p3 and p
        cosTheta = (p3_mag * p4_mag * np.cos(theta) + p3_mag**2) / (p3_mag * p_mag)
        if (cosTheta > 1. and np.isclose(cosTheta, 1.)):
            cosTheta = 1.
        if (cosTheta < -1. and np.isclose(cosTheta, -1.)):
            cosTheta = -1.
        theta3 = np.arccos(cosTheta)
        # Azimuthal angle around p
        phi3 = 2. * np.pi * np.random.random()

        p3_r = p3_mag * np.cos(theta3)
        p3_t = p3_mag * np.sin(theta3) * np.cos(phi3)
        p3_p = p3_mag * np.sin(theta3) * np.sin(phi3)
        p3 = coordinates.Spherical.toCartesian(np.asarray([p3_r, p3_t, p3_p]), p_theta, p_phi)
        p4 = p - p3

        beta_3 = p3 / p3_mag
        beta_4 = p4 / p4_mag

        self.p_path  = Incoming(None, self.position, beta_3, Zp,  None, e3, None, max_step=self.max_step) # ejected proton
        self.n_path  = Incoming(None, self.position, beta_3, Zn,  None, e3, None, max_step=self.max_step) # ejected neutron
        self.dp_path = Incoming(None, self.position, beta_4, Zdp, None, e4, None, max_step=self.max_step) # Z-1 nucleus
        self.dn_path = Incoming(None, self.position, beta_4, Zdn, None, e4, None, max_step=self.max_step) # A-1 nucleus

        for subpath in [self.p_path, self.n_path, self.dp_path, self.dn_path]:
            subpath.sub_propogate(B_override=B_override, interpolate_B=self.interpolate_B, step_override=None, algorithm=algorithm)
```

```python

        self.elapsed_sec = time.time() - start

        if (self.save):
            self.algorithm = algorithm
            self.save_telemetry()

    # Sub-propogate children
    def sub_propogate(self, B_override=None, interpolate_B=True, step_override=None, algorithm='dop853'):

        self.B_override = B_override
        self.interpolate_B = interpolate_B
        self.step_override = step_override

        Outgoing._set_B(self, B_override=B_override)

        if (step_override is not None):
            self.step = step_override
        else:
            if (algorithm == 'euler'):
                self.step_divisor = Path.EULER_DIVISOR
            elif (algorithm == 'dop853'):
                self.step_divisor = Path.DOP853_DIVISOR
            Path._set_stepsize(self)
            self._set_stepsize()

        dist_earth_init = self.dist_earth

        def keep_going():
            if (self.dist_earth > (1.01) * units.SI.radius_earth * units.Change.meter_to_AU
                and self.distance < dist_earth_init + Outgoing.LIMIT_BUFFER):
                return True
            return False

        while (keep_going()):
            Path.propagate(self, B_override=self.B, step_override=self.step, algorithm=algorithm)
            Outgoing._set_B(self, B_override=B_override)
            self._add_telemetry()
            if (step_override is None):
```

```
                self._set_stepsize()
        if (self.last_save < self.distance):
            self.telemetry.append(np.concatenate([self.position, self.beta, [self.distance
                ↪ ]]))


    def save_telemetry(self):
        if (self.save_path is None):
            self.save_path = Outgoing.DEFAULT_SAVE_PATH

        subdir = str(np.abs(self.Z)) + '_' + str(int(self.E/1e15))
        self.save_path = os.path.join(self.save_path, subdir)
        if (not os.path.isdir(self.save_path)):
            os.makedirs(self.save_path)

        if (self.filename is None):
            self.filename  = str(np.abs(self.Z))
            self.filename += '_'
            self.filename += str(int(self.E / 1e15))

        test_name = self.filename
        full_path = os.path.join(self.save_path, test_name + '.incoming')
        _ = 1
        while (os.path.exists(full_path)):
            test_name = self.filename + '_' + str(_)
            full_path = os.path.join(self.save_path, test_name + '.incoming')
            _ += 1
        self.filename = test_name + '.incoming'

        with open(os.path.join(self.save_path, self.filename), 'w') as f:
            f.write('# Incoming propagation: ' + __version__ + '\n')
            f.write('# Time of writing: ' + str(datetime.datetime.now()) + '\n')
            f.write('# Run time [sec]: ' + str(self.elapsed_sec) + '\n')
            f.write('#\n')
            f.write('# Platform\n')
            uname = platform.uname()
            f.write('# Node=' + uname.node + '\n')
            f.write('# Machine=' + uname.machine + '\n')
            f.write('# System=' + uname.system + '\n')
            f.write('# Version=' + uname.version + '\n')
            f.write('# Release=' + uname.release + '\n')
```

```
            f.write('# Processor=' + uname.processor + '\n')
            f.write('#\n')
            f.write('# Parameters\n')
            f.write('# Z=' + str(np.abs(self.Z)) + ' [proton number]\n')
            f.write('# A=' + str(self.A) + ' [atomic mass units]\n')
            f.write('# E=' + str(self.E) + ' [electron volts]\n')
            f.write('# Origin=' + str(self.origin[0]) + ' ' + str(self.origin[1]) + ' ' + str(self.origin[2]) + ' [AU]\n')
            f.write('# Decay_Dist=' + str(self.decay_dist) + ' [AU]\n')
            f.write('# Algorithm=' + self.algorithm + '\n')
            f.write('# Max_Step=' + str(self.max_step) + ' [AU]\n')
            f.write('# R_Limit=' + str(self.R_limit) + ' [AU]\n')
            B_str = str(self.B_override)
            if (self.B_override is not None):
                B_str = str(self.B_override[0]) + ' ' + str(self.B_override[1]) + ' ' + str(self.B_override[2])
            f.write('# B_Override=' + B_str + ' [T]\n')
            f.write('# Step_Override=' + str(self.step_override) + '\n')
            f.write('#\n')
            f.write('# Key\n')
            f.write('# position_x, position_y, position_z, beta_x, beta_y, beta_z, path_distance\n')
            f.write('# units: positions=AU, beta=unitless, distance=AU\n')
            f.write('#\n')

            f.write('# Start Telemetry\n')
            for _ in self.telemetry:
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('#\n')

            f.write('# Proton Telemetry\n')
            for _ in self.p_path.telemetry:
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('#\n')

            f.write('# Z-1 Daughter Telemetry\n')
            for _ in self.dp_path.telemetry:
```

```
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('#\n')

            f.write('# Neutron Telemetry\n')
            for _ in self.n_path.telemetry:
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('#\n')

            f.write('# Z Daughter Telemetry\n')
            for _ in self.dn_path.telemetry:
                for val in _:
                    f.write(str(val) + ' ')
                f.write('\n')
            f.write('\n')
            f.write('# Finished\n')
```

Listing G.8: Photon Field (`photon_field.py`)

```
#!/usr/bin/env python3

"""Computes the photon field density in [number / (eV * cm**3)]
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'


import numpy as np

from . import coordinates
from . import units

class Solar:

    def earthShadow(position):
        Re = units.SI.radius_earth * units.Change.meter_to_AU
        Rs = units.SI.radius_sun * units.Change.meter_to_AU

        earth = coordinates.Cartesian.earth
        sun = coordinates.Cartesian.sun

        p2earth = earth - position
        p2sun = sun - position

        p2earth_dist = np.sqrt(np.dot(p2earth, p2earth))
        p2sun_dist = np.sqrt(np.dot(p2sun, p2sun))

        # Inside Earth
        if (p2earth_dist < Re):
            return 0.

        # On the darkside of the Earth
```

```
        if (p2earth_dist <= Re and position[0] > earth[0]):
            return 0.

        # Earth is behind the Sun
        if (p2earth_dist > p2sun_dist):
            return 1.

        earth_sun_angle = np.arccos( np.dot(p2earth, p2sun) / ( p2earth_dist * p2sun_dist )
            ↪ )
        earth_angle = np.arcsin(Re / p2earth_dist)
        sun_angle = np.arcsin(Rs / p2sun_dist)

        # Apparent Earth radius
        re = Re

        # Apparent Sun radius
        rs = p2earth_dist * np.sin(sun_angle)

        # Apparent distance between Earth and Sun objects
        d = p2earth_dist * np.sqrt(2. * (1. - np.cos(earth_sun_angle)) )

        # Earth is not obscuring the Sun
        if (re <= d - rs):
            return 1.

        # Earth and Sun perfectly aligned
        if (earth_sun_angle == 0.):
            if (re > rs):
                return 0.
            else:
                return 1. - (re*re)/(rs*rs)

        # Earth fully inside Sun, or vise-versa
        if (rs > re):
            rbig = rs
            rsmall = re
        else:
            rbig = re
            rsmall = rs
        if (d + rsmall <= rbig):
            if (re > rs):
```

```
                return 0.
            else:
                return 1. - (re*re)/(rs*rs)

        # Area overlapping
        def arg(r1, r2):
            out = (d*d + r1*r1 - r2*r2) / (2. * d * r1)
            return out

        a1 = re*re * np.arccos(arg(re, rs))
        a2 = rs*rs * np.arccos(arg(rs, re))
        a3 = (-d + re + rs) * (d + re - rs) * (d - re + rs) * (d + re + rs)
        a3 = .5 * np.sqrt(a3)
        A = a1 + a2 - a3

        # Fraction of Sun showing
        Asun = np.pi * rs*rs
        return 1. - (A / Asun)


    def dNdE(distance_AU, energy_eV, position=None):
        """Returns the differential solar photon number density dn/dE in
        [number / eV * cm**3] given a radial distance from the Sun, distance_AU in
        [astronomical units] and solar photon energy energy_eV in [electronVolts]
        as measured in the reference frame of the Sun.
        Black body spectrum with T = 5770 K.
        """
        if (energy_eV == 0.):
            return 0.
        scale = 7.8e7
        r_dependence = 1. / distance_AU**2
        exponent = energy_eV / .5
        if (np.abs(exponent) > 100.):
            return 0.
        e_dependence = energy_eV**2 / ( np.exp(exponent) - 1. )

        shadow = 1.
        if (position is not None):
            shadow = Solar.earthShadow(position)
        return shadow * scale * r_dependence * e_dependence

```

```python

class CMB:

    def dNdE(energy_eV):
        if (energy_eV == 0.):
            return 0.
        energy_J = energy_eV * units.Change.eV_to_joules
        scale = 8.*np.pi / (units.SI.planck * units.SI.lightspeed)**3
        kT = units.SI.boltzmann * 2.725
        exponent = energy_J / kT
        if (np.abs(exponent) > 100.):
            return 0.
        e_dependence = energy_J**2 / ( np.exp(exponent) - 1. )
        si = scale * e_dependence # number / meters^3 / joules
        return si * units.Change.eV_to_joules * (1./100.)**3 # number / (cm^3  eV)
```

Listing G.9: Probability (`probability.py`)

```python
#!/usr/bin/env python3

"""Computes the attenuation length [AU] of photodissentegration.
Coordinate system: (x,y,z) Sun === (0,0,0), Earth === (1,0,0)
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'


import numpy as np

from scipy import integrate
from scipy import interpolate
from scipy import optimize

from . import units
from . import cross_section
from . import photon_field


def oneOrMore(atten_length, distance):
    """Returns the probability of a process with attenuation length [AU] over
    a distance [AU].
    """
    p0 = np.exp(-distance / atten_length)
    return 1. - p0


def random(x, pdf, size, algorithm='akima', seed=None, plottables=False, CDF=False):
    x = np.asarray(x)
    pdf = np.asarray(pdf)
    cdf = np.zeros(x.size)

```

```
    if (algorithm == 'simps'):
        for i in range(x.size):
            if (i == 0):
                continue
            cdf[i-1] = integrate.simps(pdf[:i], x=x[:i])
        cdf[-1] = cdf[-2]
    else:
        pdf_akima = interpolate.Akima1DInterpolator(x, pdf)
        for i in range(x.size):
            cdf[i] = np.asscalar(pdf_akima.integrate(x[0], x[i]))

    cdf_akima = interpolate.Akima1DInterpolator(x, cdf)

    if (seed is not None):
        np.random.seed(seed)
    val = (cdf[-1] - cdf[0]) * np.random.random(size) + cdf[0]

    out = []
    for v in val:
        out.append(np.asscalar(cdf_akima.solve(v)))

    if (size == 1):
        out = out[0]

    if (plottables):
        if (CDF):
            out = out, x, pdf / cdf[-1], cdf
        else:
            out = out, x, pdf / cdf[-1]
    elif (CDF):
        out = out, x, cdf

    return out


class Solar:

    ENERGY_LOW_EXPONENT  = -15.
    ENERGY_HIGH_EXPONENT = 3.
    ENERGY_SAMPLES       = 2000

```

```python
def integrand(photon_energy, lorentz_gamma, mass_number, dist_sun, geo_factor, cross_section):
    """Returns the integrand of the energy integral for computing the attenuation.
    See "attenuation()" below.
    """
    density = photon_field.Solar.dNdE(dist_sun, photon_energy)
    x_section = cross_section(None, lorentz_gamma * geo_factor * photon_energy, mass_number=mass_number)
    return density * x_section * geo_factor # [probability / centimeter * electronVolt]


def attenuation(position, beta, proton_number, nuclide_energy,
        cross_section=cross_section.Photodissociation.singleNucleon,
        mass_number=None, algorithm='simps'):
    """Returns the attenuation length [AU] for process specified by
    cross_section parameter (single nucleon ejection by default) for
    cartesian position (x, y, z) [AU] from parent nucleide (proton_number or mass_number)
    traveling with energy (nuclide_eV) heading in direction beta (bx, by ,bz).
    See comments below regarding 'algorithm'.  In short, 'simps' is 10x slower but accurate,
    'quad' is 10x faster but less accurate.
    """

    if (algorithm != 'simps' and algorithm != 'quad'):
        print('invalid algorithm: choose "simps" or "quad"')
        return

    if (mass_number == None):
        mass_number = units.Nuclide.mass_number(proton_number)

    mass_eV = mass_number * units.Change.amu_to_eV # [eV / c**2]
    lorentz_gamma = nuclide_energy / mass_eV

    dist_sun = np.sqrt( np.dot(position, position) )
    r_hat = position / dist_sun
    beta = beta / np.sqrt( np.dot(beta, beta) )

    dot = np.dot( -r_hat, beta)
    if (dot > 1. and np.isclose(dot, 1.)):
        dot = 1.
```

```
        if (dot < -1. and np.isclose(dot, -1.)):
            dot = -1.
        alpha_radians = np.arccos(dot)
        geo_factor = 2. * np.cos(alpha_radians / 2.)**2

        # Analytical limits of integration are 0 to infinity [electronVolts], however the solar blackbody
        # spectrum is negligible by 10 [eV].  An upper limit of 100 [eV] is performed.
        # Using an algorithm such as quad produces very similar (within ~20%) results to a sampled algorithm
        # like simps, however I believe a well sampled simps result is closer to the true value as quad (et al)
        # tends to undersample the integrand between 0 and 1 [eV] (aka the most important part).
        # The downside is it is a few orders of magnitude slower than quad.
        if (algorithm == 'simps'):
            # good 5 digit precision at 1000 samples
            e_samples = np.logspace(Solar.ENERGY_LOW_EXPONENT, Solar.ENERGY_HIGH_EXPONENT, Solar.ENERGY_SAMPLES)
            i_samples = np.zeros(e_samples.size)

            for i, e in enumerate(e_samples):
                i_samples[i] = Solar.integrand(e, lorentz_gamma, mass_number, dist_sun, geo_factor, cross_section)
                # [probability / centimeter * electronVolt]

            atten_cm = 1. / integrate.simps( i_samples, x=e_samples ) # [centimeters]

        else: # algorithm == 'quad'
            # upper limit capped at 100 eV instead of infinity to avoid undersampling:
            atten_cm, err = integrate.quad( Solar.integrand, 0, 100,
                                            args=(lorentz_gamma, mass_number, dist_sun, geo_factor, cross_section) )
            atten_cm = 1. / atten_cm # [centimeters]

        atten_m = atten_cm / 100. # [meters]
        return atten_m * units.Change.meter_to_AU # [AU]


    def get_photon(position, beta, proton_number, nuclide_energy,
                   cross_section=cross_section.Photodissociation.singleNucleon,
```

```
                    mass_number=None, seed=None, size=1, plottables=False, CDF=False):

        if (mass_number == None):
            mass_number = units.Nuclide.mass_number(proton_number)

        mass_eV = mass_number * units.Change.amu_to_eV # [eV / c**2]
        lorentz_gamma = nuclide_energy / mass_eV

        dist_sun = np.sqrt( np.dot(position, position) )
        r_hat = position / dist_sun
        beta = beta / np.sqrt( np.dot(beta, beta) )

        dot = np.dot( -r_hat, beta)
        if (dot > 1. and np.isclose(dot, 1.)):
            dot = 1.
        if (dot < -1. and np.isclose(dot, -1.)):
            dot = -1.
        alpha_radians = np.arccos(dot)
        geo_factor = 2. * np.cos(alpha_radians / 2.)**2

        e_samples = np.logspace(Solar.ENERGY_LOW_EXPONENT, Solar.ENERGY_HIGH_EXPONENT, Solar
            ↪ .ENERGY_SAMPLES)
        i_samples = np.zeros(e_samples.size)
        for i, e in enumerate(e_samples):
            i_samples[i] = Solar.integrand(e, lorentz_gamma, mass_number, dist_sun,
                ↪ geo_factor, cross_section)

        return random(e_samples, i_samples, size, seed=seed, plottables=plottables, CDF=CDF)
```

Listing G.10: Relativity (`relativity.py`)

```python
#!/usr/bin/env python3

"""Special relativity
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

import numpy as np

def gamma(energy, mass):
    """ Energy in eV, mass in eV/c*2
    """
    return energy / mass

def beta(gamma):
    return np.sqrt(1. - 1. / gamma)

def momentum_mag(energy, mass):
    return np.sqrt(energy*energy - mass*mass)

def momentum(energy, mass, direction):
    """ direction is a unit vector
    """
    return momentum_mag(energy, mass) * np.asarray(direction)

def theta(e1, p1, e2, p2, e3, m3, e4, m4):
    p1 = np.asarray(p1)
    p2 = np.asarray(p2)

    e12 = (e1 + e2)**2
    p12 = np.dot(p1 + p2, p1 + p2)

    e34 = (e3 + e4)**2
```

```
    p3_mag = momentum_mag(e3, m3)
    p4_mag = momentum_mag(e4, m4)

    cosTheta = ( e34 - (e12 - p12) - p3_mag**2 - p4_mag**2 ) / (2. * p3_mag * p4_mag)
    if (cosTheta > 1. and np.isclose(cosTheta, 1.)):
        cosTheta = 1.
    if (cosTheta < -1. and np.isclose(cosTheta, -1.)):
        cosTheta = -1.
    return np.arccos(cosTheta)
```

Listing G.11: Results (`results.py`)

```python
#!/usr/bin/env python3

"""
Description
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'

import matplotlib.pyplot as plt
import matplotlib as mpl
import numpy as np
import os

from . import coordinates
from . import units

class Result:

    def __init__(self, filename, full_telemetry=False):
        self.dirname = os.path.dirname(filename)
        self.filename = os.path.basename(filename)
        self.full_telemetry = full_telemetry

    def setZ(self, Z):
        self.Z = Z

    def setA(self, A):
        self.A = A

    def setE(self, E):
        self.E = E

    def setOrigin(self, origin):
```

```
        self.origin = origin

    def setDist(self, dist):
        self.dist = dist

    def setAlgorithm(self, algorithm):
        self.algorithm = algorithm

    def setMaxStep(self, max_step):
        self.max_step = max_step

    def setRlimit(self, R_limit):
        self.R_limit = R_limit

    def setBOverride(self, B_override):
        self.B_override = B_override

    def setStepOverride(self, step_override):
        self.step_override = step_override

    def setInTelemetry(self, telemetry):
        if (self.full_telemetry):
            self.in_telemetry = telemetry
        else:
            self.in_telemetry = (telemetry[0], telemetry[-1])

    def setProtonTelemetry(self, telemetry):
        if (self.full_telemetry):
            self.p_telemetry = telemetry
        else:
            self.p_telemetry = (telemetry[0], telemetry[-1])

    def setPDaughterTelemetry(self, telemetry):
        if (self.full_telemetry):
            self.dp_telemetry = telemetry
        else:
            self.dp_telemetry = (telemetry[0], telemetry[-1])

    def setNeutronTelemetry(self, telemetry):
        if (self.full_telemetry):
            self.n_telemetry = telemetry
```

```
        else:
            self.n_telemetry = (telemetry[0], telemetry[-1])

    def setNDaughterTelemetry(self, telemetry):
        if (self.full_telemetry):
            self.dn_telemetry = telemetry
        else:
            self.dn_telemetry = (telemetry[0], telemetry[-1])

    def getEarthRadii(self, telemetry):
        pos = telemetry[:3]
        from_earth = pos - coordinates.Cartesian.earth
        dist_Re = np.sqrt(np.dot(from_earth, from_earth)) / (units.SI.radius_earth * units.
            ↪ Change.meter_to_AU)
        return dist_Re

    def getSummary(self):
        p_dist  = self.getEarthRadii(self.p_last)
        dp_dist = self.getEarthRadii(self.dp_last)
        n_dist  = self.getEarthRadii(self.n_last)
        dn_dist = self.getEarthRadii(self.dn_last)
        return (p_dist, dp_dist, n_dist, dn_dist)

    def fix(self, telemetry):
        Re = units.SI.radius_earth * units.Change.meter_to_AU

        pvec = telemetry[:3] - coordinates.Cartesian.earth
        pmag = np.sqrt(np.dot(pvec, pvec))
        phat = pvec / pmag
        if (pmag == Re):
            return telemetry[:3]

        bhat = telemetry[3:6]
        bhat = bhat / np.sqrt(np.dot(bhat,bhat))

        cosTheta = np.dot(phat, bhat)
        discriminant = Re*Re - pmag*pmag * (1. - cosTheta*cosTheta)
        if (discriminant < 0.):
            return telemetry[:3]

        cplus  = -1. * pmag * cosTheta + np.sqrt(discriminant)
```

```
        cminus = -1. * pmag * cosTheta - np.sqrt(discriminant)
        c = np.asarray([cplus, cminus])

        if (pmag > Re):
            if (cosTheta > 0.):
                c = c[c < 0.]
                c = -1. * np.min(np.abs(c))
            else:
                c = c[c > 0.]
                c = np.min(c)
        else:
            c = c[c < 0.]
            if (cosTheta > 0.):
                c = -1. * np.max(np.abs(c))
            else:
                c = -1. * np.min(np.abs(c))

        pvec = (pvec + c * bhat) + coordinates.Cartesian.earth
        return pvec

    def findLastPos(self):
        self.p_last  = self.fix(self.p_telemetry[-1])
        self.dp_last = self.fix(self.dp_telemetry[-1])
        self.n_last  = self.fix(self.n_telemetry[-1])
        self.dn_last = self.fix(self.dn_telemetry[-1])
        return


class Results:

    def __init__(self, directory=None, filelist=None, full_telemetry=False, cone=None):

        if (directory is not None):
            filelist = []
            for file in os.listdir(directory):
                if (file.endswith('.incoming')):
                    if (cone is not None):
                        tokens = file.split('_')
                        if (tokens[0][0].isalpha()):
                            tokens = tokens[1:]
                        theta = float(tokens[4])
```

```
                        if (theta < cone):
                            filelist.append(os.path.join(directory, file))
                    else:
                        filelist.append(os.path.join(directory, file))

        self.directory = directory
        self.filelist = filelist
        self.results = []

        tot = float(len(filelist))
        for i, file in enumerate(filelist):
            print('\r' + (" "*20) + '\rloading... {:.2f}%'.format((i+1.)/tot*100.), flush=
                ↪ True, end='')
            with open(file, 'r') as f:
                Z = None
                A = None
                E = None
                origin = None
                dist = None
                algorithm = None
                max_step = None
                R_limit = None
                B_override = None
                step_override = None
                in_telemetry = []
                p_telemetry  = []
                dp_telemetry = []
                n_telemetry  = []
                dn_telemetry = []
                seek = 0
                lines = f.readlines()
                if (not lines[-1].startswith('# Finished')):
                    continue
                lines = lines[:-2]

                for _, line in enumerate(lines):

                    search = '# Z='
                    if (line.startswith(search)):
                        Z = int( line[len(search):].split()[0] )
                        continue
```

```
                search = '# A='
                if (line.startswith(search)):
                    A = line[len(search):].split()[0]
                    try:
                        A = float(A)
                    except ValueError:
                        A = None
                    continue

                search = '# E='
                if (line.startswith(search)):
                    E = float( line[len(search):].split()[0] )
                    continue

                # TODO UPDATE TO NEW FORMAT
                search = '# Origin=['
                if (line.startswith(search)):
                    tokens = line[len(search):].split()
                    x = float(tokens[0])
                    y = float(tokens[1])
                    z = float(tokens[2].strip(']'))
                    origin = np.asarray([x, y ,z])

                search = '# Decay_Dist='
                if (line.startswith(search)):
                    dist = float( line[len(search):].split()[0] )
                    continue

                search = '# Algorithm='
                if (line.startswith(search)):
                    algorithm = line[len(search):].split()[0]
                    continue

                search = '# Max_Step='
                if (line.startswith(search)):
                    max_step = line[len(search):].split()[0]
                    try:
                        max_step = float(max_step)
                    except ValueError:
                        max_step = None
```

```
                continue

            search = '# R_Limit='
            if (line.startswith(search)):
                R_limit = line[len(search):].split()[0]
                try:
                    R_limit = float(R_limit)
                except ValueError:
                    R_limit = None
                continue

            search = '# B_Override='
            if (line.startswith(search)):
                B_override = line[len(search):].split()
                try:
                    B_override = np.asarray(B_override[:3], dtype=np.float64)
                except ValueError:
                    B_override = None
                continue

            search = '# Step_Override='
            if (line.startswith(search)):
                step_override = line[len(search):].split()[0]
                try:
                    step_override = float(step_override)
                except ValueError:
                    step_override = None
                continue

            search = '# Start Telemetry'
            if (line.startswith(search)):
                seek = _
                break

        lines = lines[seek + 1:]
        seek = 0
        for _, line in enumerate(lines):
            search = '#'
            if (line.startswith(search)):
                seek = _
                break
```

```
                in_telemetry.append(np.asarray(line.split(), dtype=np.float64))

            if (not lines[seek + 1].startswith('# Proton Telemetry')):
                print('FORMAT MIS-MATCH')
                return

            lines = lines[seek + 2:]
            seek = 0
            for _, line in enumerate(lines):
                search = '#'
                if (line.startswith(search)):
                    seek = _
                    break
                p_telemetry.append(np.asarray(line.split(), dtype=np.float64))

            if (not lines[seek + 1].startswith('# Z-1')):
                print('FORMAT MIS-MATCH')
                return

            lines = lines[seek + 2:]
            seek = 0
            for _, line in enumerate(lines):
                search = '#'
                if (line.startswith(search)):
                    seek = _
                    break
                dp_telemetry.append(np.asarray(line.split(), dtype=np.float64))

            if (not lines[seek + 1].startswith('# Neutron Telemetry')):
                print('FORMAT MIS-MATCH')
                return

            lines = lines[seek + 2:]
            seek = 0
            for _, line in enumerate(lines):
                search = '#'
                if (line.startswith(search)):
                    seek = _
                    break
                n_telemetry.append(np.asarray(line.split(), dtype=np.float64))

```

```
                if (not lines[seek + 1].startswith('# Z Daughter')):
                    print('FORMAT MIS-MATCH')
                    return

                lines = lines[seek + 2:]
                for line in lines:
                    dn_telemetry.append(np.asarray(line.split(), dtype=np.float64))

                result = Result(file, full_telemetry=full_telemetry)
                result.setZ(Z)
                result.setA(A)
                result.setE(E)
                result.setOrigin(origin)
                result.setDist(dist)
                result.setAlgorithm(algorithm)
                result.setMaxStep(max_step)
                result.setRlimit(R_limit)
                result.setBOverride(B_override)
                result.setStepOverride(step_override)
                result.setInTelemetry(in_telemetry)
                result.setProtonTelemetry(p_telemetry)
                result.setPDaughterTelemetry(dp_telemetry)
                result.setNeutronTelemetry(n_telemetry)
                result.setNDaughterTelemetry(dn_telemetry)
                self.results.append(result)

        print('done!')

    def HaversineSeparation(pos1, pos2):
        """ Normalized the earth radius aka 1 = Re
        """
        pos1 = np.asarray(pos1)
        pos1 = pos1 / np.sqrt(np.dot(pos1, pos1))

        pos2 = np.asarray(pos2)
        pos2 = pos2 / np.sqrt(np.dot(pos2, pos2))

        theta1 = np.arccos(pos1[2])
        theta2 = np.arccos(pos2[2])

        phi1 = np.arctan2(pos1[1], pos1[0])
```

```
        phi2 = np.arctan2(pos2[1], pos2[0])

        lat1 = np.pi/2. - theta1
        lat2 = np.pi/2. - theta2

        lon1 = phi1
        lon2 = phi2

        part1 = np.sin( (lat2 - lat1) / 2. )**2.
        part2 = np.cos(lat1) * np.cos(lat2)
        part3 = np.sin( (lon2 - lon1) / 2. )**2.

        return 2. * np.arcsin( np.sqrt(part1 + part2 * part3) )

    def summerize(self, atol=1e-2):
        p_list  = []
        dp_list = []
        n_list  = []
        dn_list = []
        for r in self.results:
            r.findLastPos()
            p, dp, n, dn = r.getSummary()
            p_list.append(p)
            dp_list.append(dp)
            n_list.append(n)
            dn_list.append(dn)

        p_near  = np.isclose(p_list,  [1.], atol=atol)
        dp_near = np.isclose(dp_list, [1.], atol=atol)
        n_near  = np.isclose(n_list,  [1.], atol=atol)
        dn_near = np.isclose(dn_list, [1.], atol=atol)

        p_dp_both = p_near * dp_near
        n_dn_both = n_near * dn_near

        """
        p_xor_dp = (p_near * ~dp_near) + (~p_near * dp_near)
        n_xor_dn = (n_near * ~dn_near) + (~n_near * dn_near)

        p_neither = ~(p_dp_both + p_xor_dp)
        n_neither = ~(n_dn_both + n_xor_dn)
```

```
        p_both = len(p_dp_both[p_dp_both])
        n_both = len(n_dn_both[n_dn_both])
        p_solo = len(p_xor_dp[p_xor_dp])
        n_solo = len(n_xor_dn[n_xor_dn])
        p_none = len(p_neither[p_neither])
        n_none = len(n_neither[n_neither])
        print('N sims: ' + str(len(self.results)))
        print('Proton both:     ' + str(p_both) + ', ' + str(p_both / len(self.results) * 100.) + '%')
        print('One, not both:  ' + str(p_solo) + ', ' + str(p_solo / len(self.results) * 100.) + '%')
        print('Proton none:     ' + str(p_none) + ', ' + str(p_none / len(self.results) * 100.) + '%')
        print()
        print('Neutron both:    ' + str(n_both) + ', ' + str(n_both / len(self.results) * 100.) + '%')
        print('One, not both:  ' + str(n_solo) + ', ' + str(n_solo / len(self.results) * 100.) + '%')
        print('Neutron none:    ' + str(n_none) + ', ' + str(n_none / len(self.results) * 100.) + '%')

        print()
        print(np.asarray(p_list)[p_xor_dp])
        print()
        print(np.asarray(dp_list)[p_xor_dp])
        print()
        print(np.asarray(n_list)[n_xor_dn])
        print()
        print(np.asarray(dn_list)[n_xor_dn])
        print()

        if (len(np.asarray(self.results)[p_neither])>0 or len(np.asarray(self.results)[n_neither])>0):
            fig0 = plt.figure(figsize=[15,15])
            print()
            print('Neither (proton): ')
            for r in np.asarray(self.results)[p_neither]:
                p = r.getEarthRadii(r.p_telemetry[-1])
                pl = r.getEarthRadii(r.p_last)
                dp = r.getEarthRadii(r.dp_telemetry[-1])
```

```
                dpl = r.getEarthRadii(r.dp_last)
                print('\t' + r.filename + ': ')
                print('\t\t' + str(p)  + ' => ' + str(pl))
                print('\t\t' + str(dp) + ' => ' + str(dpl))
                pos_p = []
                pos_dp = []
                for t in zip(r.p_telemetry, r.dp_telemetry):
                    pos_p.append(r.getEarthRadii(t[0]))
                    pos_dp.append(r.getEarthRadii(t[1]))
                plt.plot(pos_p)
                plt.plot(pos_dp)
            print()
            print('Neither (neutron): ')
            for r in np.asarray(self.results)[n_neither]:
                n = r.getEarthRadii(r.n_telemetry[-1])
                nl = r.getEarthRadii(r.n_last)
                dn = r.getEarthRadii(r.dn_telemetry[-1])
                dnl = r.getEarthRadii(r.dn_last)
                print('\t' + r.filename + ': ')
                print('\t\t' + str(n)  + ' => ' + str(nl))
                print('\t\t' + str(dn) + ' => ' + str(dnl))
                pos_n = []
                pos_dn = []
                for t in zip(r.n_telemetry, r.dn_telemetry):
                    pos_n.append(r.getEarthRadii(t[0]))
                    pos_dn.append(r.getEarthRadii(t[1]))
                plt.plot(pos_n)
                plt.plot(pos_dn)
            plt.xlim(.9,1.1)
        """

        #fig1 = plt.figure(figsize=[15,15])
        #bins = np.linspace(0., 1 + 100 * atol, 100)
        #plt.hist(p_list,  bins=bins, density=True, log=True, color=mpl.colors.to_rgba('b
            ↪ ',.3), label='Proton')
        #plt.hist(dp_list, bins=bins, density=True, log=True, color=mpl.colors.to_rgba('m
            ↪ ',.3), label='Z-1 Daughter')
        #plt.hist(n_list,  bins=bins, density=True, log=True, color=mpl.colors.to_rgba('r
            ↪ ',.3), label='Neutron')
        #plt.hist(dn_list, bins=bins, density=True, log=True, color=mpl.colors.to_rgba('y
            ↪ ',.3), label='Z Daughter')
```

```
        #plt.legend()
        #plt.show()

        p_dp_dist = []
        for pair in np.asarray(self.results)[p_dp_both]:
            _p  = pair.p_last  - coordinates.Cartesian.earth
            _dp = pair.dp_last - coordinates.Cartesian.earth
            p_dp_dist.append(Results.HaversineSeparation(_p, _dp))

        n_dn_dist = []
        for pair in np.asarray(self.results)[n_dn_both]:
            _n  = pair.n_last  - coordinates.Cartesian.earth
            _dn = pair.dn_last - coordinates.Cartesian.earth
            n_dn_dist.append(Results.HaversineSeparation(_n, _dn))

        #!!!!!! KILOMETERS !!!!!
        p_dp_dist = np.asarray(p_dp_dist) * units.SI.radius_earth / 1000.
        n_dn_dist = np.asarray(n_dn_dist) * units.SI.radius_earth / 1000.

        fig2 = plt.figure(figsize=[20,15])
        plt.rc('font', size=24)
        dist = np.concatenate([p_dp_dist, n_dn_dist])
        """
        n_under1 = len(dist[dist<1.])
        n_under10 = len(dist[dist<10.])
        n_under50 = len(dist[dist<50.])
        print()
        print('Of those who have a pair,')
        print('\tFraction under 1 m:  ' + str(n_under1/len(dist)*100.)  + "%")
        print('\tFraction under 10 m: ' + str(n_under10/len(dist)*100.) + "%")
        print('\tFraction under 50 m: ' + str(n_under50/len(dist)*100.) + "%")

        non_zero = dist[dist > 0.]
        lo_x = np.log10(min(non_zero) / 100.)
        np.place(dist, dist==0., lo_x)
        hi_x = np.log10(max(dist) * 10.)
        """
        lo_x = -3
        hi_x = 4.5
        bins = np.logspace(lo_x, hi_x, 100)
```

```
        n1, b, p = plt.hist(p_dp_dist, bins=bins, density=False, log=True, color=mpl.colors.
            ↪ to_rgba('b',.3), label='p-channel')
        n2, b, p = plt.hist(n_dn_dist, bins=bins, density=False, log=True, color=mpl.colors.
            ↪ to_rgba('r',.3), label='n-channel')
        n = np.concatenate((n1[n1>0], n2[n2>0]))
        lo = np.min(n) / 2.
        hi = np.max(n) * 2.
        plt.plot([1e0,1e0],[lo, hi],'k:')
        _d = np.pi * units.SI.radius_earth / 1000.
        plt.plot([_d, _d],[lo, hi],'k:')
        plt.xlabel('Nucleon-Fragment Great Circle Separation Distance [kilometers]')
        plt.ylabel('Counts')
        plt.xscale('log')
        plt.xlim(bins[0], bins[-1])
        plt.ylim(lo, hi)
        plt.legend()
        plt.tight_layout()
        plt.show()

        """
        mean = np.mean(p_dp_dist)
        maxx = np.max(p_dp_dist)
        minn = np.min(p_dp_dist)
        print('Proton pair mean, max, min: ')
        print('\t' + str(mean))
        print('\t' + str(maxx))
        print('\t' + str(minn))
        print()

        mean = np.mean(n_dn_dist)
        maxx = np.max(n_dn_dist)
        minn = np.min(n_dn_dist)
        print('Neutron pair mean, max, min: ')
        print('\t' + str(mean))
        print('\t' + str(maxx))
        print('\t' + str(minn))
        """
```

Listing G.12: Units (units.py)

```python
#!/usr/bin/env python3

"""Wrapper for physical constants and conversions
"""

__project__     = 'GZ Paper'
__version__     = 'v1.0'
__objective__   = 'Phenominology'
__institution__ = 'University of California, Irvine'
__department__  = 'Physics and Astronomy'
__author__      = 'Eric Albin'
__email__       = 'Eric.K.Albin@gmail.com'
__updated__     = '13 May 2019'


class SI:
    lightspeed   = 299_792_458.   # speed of light [meters / second]
    planck       = 6.62607004e-34 # Planck's constant [meters^2 kilogram / second]
    boltzmann    = 1.38064852e-23 # Boltzmann's constant [meter^2 kilogram / second^2 Kelvin ]
    charge       = 1.60217662e-19 # Fundamental unit of charge [coulombs]

    radius_earth =   6_378_100.   # radius of Earth [meters]
    radius_sun   = 695_508_000.   # radius of the Sun [meters]


class Change:
    AU_to_meter    = 149_597_870_700.  # [meters / astronomical unit]
    meter_to_AU    = 1. / AU_to_meter

    amu_to_eV      = 9_314_940_954.  # [eV/c**2] mass of 1 atomic mass unit [amu]
    eV_to_amu      = 1. / amu_to_eV

    tesla_to_gauss = 10_000.  # magnetic field [Gauss] in 1 [Tesla]
    gauss_to_tesla = 1. / tesla_to_gauss

    barn_to_cm2    = 1e-24  # area [barn] in cm**2
    cm2_to_barn    = 1. / barn_to_cm2

    eV_to_joules   = SI.charge # [joules]
```

```
    joules_to_eV   = 1. / eV_to_joules


class Nuclide:

    def neutron_number(proton_number):
        """ Returns average number of neutrons for a given proton_number
        """
        A = Nuclide.mass_number(proton_number)
        if (A == None):
            return None
        return A - proton_number


    def mass_number(proton_number):
        """ Returns an integer-rounded average mass_number for a given proton_number
        """
        if proton_number == 1:
            return 1 # Hydrogen
        elif proton_number == 2:
            return 4 # Helium
        elif proton_number == 3:
            return 7 # Lithium
        elif proton_number == 4:
            return 9 # Beryllium
        elif proton_number == 5:
            return 11 # Boron
        elif proton_number == 6:
            return 12 # Carbon
        elif proton_number == 7:
            return 14 # Nitrogen
        elif proton_number == 8:
            return 16 # Oxygen
        elif proton_number == 9:
            return 19 # Fluorine
        elif proton_number == 10:
            return 20 # Neon
        elif proton_number == 11:
            return 23 # Sodium
        elif proton_number == 12:
            return 24 # Magnesium
```

```
        elif proton_number == 13:
            return 27 # Alumininum
        elif proton_number == 14:
            return 28 # Silicon
        elif proton_number == 15:
            return 31 # Phosphorus
        elif proton_number == 16:
            return 32 # Sulfur
        elif proton_number == 17:
            return 35 # Chlorine
        elif proton_number == 18:
            return 40 # Argon
        elif proton_number == 19:
            return 39 # Potassium
        elif proton_number == 20:
            return 40 # Calcium
        elif proton_number == 21:
            return 45 # Scandium
        elif proton_number == 22:
            return 48 # Titanium
        elif proton_number == 23:
            return 51 # Vanadium
        elif proton_number == 24:
            return 52 # Chromium
        elif proton_number == 25:
            return 55 # Manganese
        elif proton_number == 26:
            return 56 # Iron
        elif proton_number == 27:
            return 59 # Cobalt
        elif proton_number == 28:
            return 59 # Nickel
        elif proton_number == 29:
            return 64 # Copper
        elif proton_number == 30:
            return 65 # Zinc
        elif proton_number == 31:
            return 70 # Gallium
        elif proton_number == 32:
            return 73 # Germanium
        elif proton_number == 33:
```

```
            return 75 # Arsenic
        elif proton_number == 34:
            return 79 # Selenium
        elif proton_number == 35:
            return 80 # Bromine
        elif proton_number == 36:
            return 84 # Krypton
        elif proton_number == 37:
            return 85 # Rubidium
        elif proton_number == 38:
            return 88 # Strontium
        elif proton_number == 39:
            return 89 # Yttrium
        elif proton_number == 40:
            return 91 # Zirconium
        elif proton_number == 41:
            return 93 # Niobium
        elif proton_number == 42:
            return 96 # Molbdenum
        elif proton_number == 43:
            return 98 # Technium
        elif proton_number == 44:
            return 101 # Ruthenium
        elif proton_number == 45:
            return 103 # Rhodinium
        elif proton_number == 46:
            return 106 # Palladium
        elif proton_number == 47:
            return 108 # Silver
        elif proton_number == 48:
            return 112 # Cadmium
        elif proton_number == 49:
            return 115 # Indium
        elif proton_number == 50:
            return 119 # Tin
        elif proton_number == 51:
            return 122 # Antimony
        elif proton_number == 52:
            return 128 # Tellurium
        elif proton_number == 53:
            return 127 # Iodine
```

```
        elif proton_number == 54:
            return 131 # Xenon
        elif proton_number == 55:
            return 133 # Caesium
        elif proton_number == 56:
            return 137 # Barium
        elif proton_number == 57:
            return 139 # Lanthanum
        elif proton_number == 58:
            return 140 # Cerium
        elif proton_number == 59:
            return 141 # Praseodymium
        elif proton_number == 60:
            return 144 # Neodymium
        elif proton_number == 61:
            return 145 # Promethium
        elif proton_number == 62:
            return 150 # Samarium
        elif proton_number == 63:
            return 152 # Europium
        elif proton_number == 64:
            return 157 # Gadolinium
        elif proton_number == 65:
            return 159 # Terbium
        elif proton_number == 66:
            return 163 # Dysprosium
        elif proton_number == 67:
            return 165 # Holmium
        elif proton_number == 68:
            return 167 # Erbium
        elif proton_number == 69:
            return 169 # Thulium
        elif proton_number == 70:
            return 173 # Ytterbium
        elif proton_number == 71:
            return 175 # Lutetium
        elif proton_number == 72:
            return 178 # Hafnium
        elif proton_number == 73:
            return 181 # Tantalum
        elif proton_number == 74:
```

```
            return 184 # Tungsten
        elif proton_number == 75:
            return 186 # Rhenium
        elif proton_number == 76:
            return 190 # Osmium
        elif proton_number == 77:
            return 192 # Iridium
        elif proton_number == 78:
            return 195 # Platinum
        elif proton_number == 79:
            return 197 # Gold
        elif proton_number == 80:
            return 201 # Mercury
        elif proton_number == 81:
            return 204 # Thallium
        elif proton_number == 82:
            return 207 # Lead
        elif proton_number == 83:
            return 209 # Bismuth
        elif proton_number == 84:
            return 209 # Polonium
        elif proton_number == 85:
            return 210 # Astatine
        elif proton_number == 86:
            return 222 # Radon
        elif proton_number == 87:
            return 223 # Francium
        elif proton_number == 88:
            return 226 # Radium
        elif proton_number == 89:
            return 227 # Actinium
        elif proton_number == 90:
            return 232 # Thorium
        elif proton_number == 91:
            return 231 # Protactinium
        elif proton_number == 92:
            return 238 # Uranium
        else:
            return None
```