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# Panoramic SETI: On-sky Results at Palomar Observatory

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## ABSTRACT

We report on the initial on-sky results from the Panoramic Search for Extraterrestrial Intelligence (PANOSSETI) experiment deployed at Palomar Observatory. PANOSSETI is a wide-field optical observatory designed to explore fast optical phenomena across nanosecond-to-second timescales. Building on system verification at Lick Observatory, the Palomar deployment comprises four telescope sites, enabling cross-site coincidence detection and contributing to a broader science program encompassing optical technosignature searches, ultra-high-energy phenomena, and time-domain astrophysics. We summarize the performance of the deployed 0.48-meter f/1.32 Fresnel lens telescopes, which operate in two complementary readout modes: pulse height mode for nanosecond-scale triggered events and continuous imaging mode for variability on millisecond-to-second timescales. The detector characterization presented here focuses on the pulse-height readout mode. We characterize the Hamamatsu silicon photomultiplier (SiPM) detector focal plane through triggering rate curves, sky background as a function of lunar conditions, and false-alarm statistics across single- and multi-telescope coincidence configurations. We derive the two-telescope coincidence rate from measured triggering rate curves and establish the detection thresholds and operational baseline for the survey program. We present on-sky results for one of the technosignature observational fields, showcasing PANOSSETI capabilities in this field.

## 1. INTRODUCTION

### 1.1 Scientific Motivation

Time-domain astronomy has advanced rapidly over the last decade, yet a significant observational gap remains for very fast sub-second optical transient facilities. Wide-field surveys like Rubin/LSST, ZTF, ATLAS, and PanSTARRS are optimized for imaging, not photon-counting at sub-millisecond time scales. The combination of high-time resolution detectors, high duty cycle per field and large instantaneous sky coverage required to continuously monitor the nanosecond-to-second (ns-s) regime remains largely unaddressed.<sup>1–3</sup> The Astro2020 Decadal Survey identifies time-domain and multi-messenger discovery as a key scientific priority for the coming decade, highlighting the need for facilities capable of high duty cycles while retaining nanosecond timing and strong false-alarm control.<sup>4</sup> The Panoramic SETI experiment is designed to address and fill this crucial observational gap.<sup>5–15</sup> PANOSSETI’s science program encompasses three primary cases: (1) searches for optical technosignatures via nanosecond pulses that produce high contrast over the sky background; (2) fast time-domain astrophysics, including optical counterparts to fast radio bursts (FRBs), gamma-ray bursts (GRBs), compact objects, and gravitational-wave events; and (3) atmospheric Cherenkov emission associated with ultra-high-energy (UHE) cosmic ray and gamma-ray air showers. All three cases rely on nanosecond photon counting over a wide field, a capability provided by silicon photomultipliers (SiPMs).

### 1.2 Silicon Photomultipliers

SiPMs are ideal detectors for fast transient optical searches due to their single-photon sensitivity, fast timing response, compact form factor, robustness, low operating voltage, and high photon detection efficiency (PDE).<sup>16</sup>

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Compared to traditional photomultiplier tubes (PMTs), SiPMs offer a similar gain with lower cost per channel and greater compactness, allowing for the construction of large-format tiled focal planes. SiPM performance is limited by three intrinsic noise processes. The dark count rate (DCR) arises from thermally generated electron-hole pairs that produce triggers indistinguishable from single photons. Optical crosstalk between microcells induces multi-pixel triggers that mimic photon detections. Afterpulsing generates secondary pulses following avalanche events. Crosstalk and dark counts set the noise floor and false alarm rate (FAR) in the absence of coincidence rejection. PANOSSETI uses the Hamamatsu S13361-3050AE-08 array, selected for its low optical crosstalk (2–3%) at the nominal operating overvoltage and its spectral response spanning 320–900 nm with peak PDE near 450 nm.<sup>17</sup>

Previous to PANOSSETI, the few experiments operating at nanosecond optical timescales and characterizing background event rates were limited to targeted, narrow-field approaches, with SiPMs otherwise deployed at these timescales primarily in Cherenkov imaging arrays such as FACT.<sup>18</sup> Early efforts by Eikenberry & Fazio<sup>19</sup> and Barbieri et al.<sup>20</sup> demonstrated the feasibility of fast optical transient searches while remaining limited by small instantaneous sky coverage. The Ultra-Fast Astronomy (UFA) program mounted single-channel SiPMs of the same  $3 \times 3$  mm format used here on a 0.7 m telescope, with each channel viewing a  $2.27' \times 2.27'$  field, recording a linear response against Gaia *G*-band flux and a  $5\sigma$  sensitivity near 14th magnitude in 200 ms exposures against a  $\sim 200$  kcps sky background. Crosstalk was measured at  $\sim 10\%$ , against the 5–7% specified for those devices, and limits nanosecond detection to 12 photoelectrons, corresponding to a fluence of  $\sim 155$  photons per square meter.<sup>21</sup> These results confirm the discovery potential of the ns-s regime and identify its limiting factor: with a single channel and no coincidence requirement, correlated avalanches are indistinguishable from real pulses, so sensitivity at the shortest timescales is set by crosstalk rather than by sky background. Where UFA read out a single SiPM pixel, PANOSSETI tiles 1024 into each focal plane, with coincidence between separated telescopes rejecting noise no single pixel can distinguish from a real pulse.

## 2. INSTRUMENT AND DEPLOYMENT CONFIGURATION

PANOSSETI’s instrument architecture, focal-plane electronics, and timing systems have been described in detail in prior work.<sup>6,9–11</sup> Telescope modules and systems were previously verified on-sky at Lick Observatory, demonstrating stable detector performance, sub-nanosecond timing, and detection of atmospheric Cherenkov events in multi-module coincidence.<sup>14</sup> Lick operations continued through 2024. The Palomar deployment represents the transition to a permanent multi-site array, enabling cross-site coincidence across baselines and the beginning of sustained survey operations.

### 2.1 Telescope Module Design

Each telescope module integrates a wide-field refractive optical system, a tiled SiPM focal plane, and onboard trigger and timing electronics into a single removable package. The optical system uses a lightweight acrylic Orafol SC214 Fresnel lens with a 0.48m diameter and  $f/1.32$  focal ratio, providing a wide field of view (FoV) of approximately  $10^\circ \times 10^\circ$  per module with a pixel scale of  $0.31^\circ$  per pixel on-sky. The focal plane is built around a motherboard (mobo) hosting four quadrant boards (quabos), each containing 256 SiPM pixels of tiled Hamamatsu S13361-3050AE-08 detectors, forming a tiled  $32 \times 32$  pixel array. Analog SiPM signals are processed by MAROC3A ASICs for amplification, shaping, and discrimination, followed by FPGA logic implementing trigger counting and data formatting. Science data and precision timing are transmitted via dual SFP fiber links, with data acquisition handled by the HASHPIPE circular-buffer framework.

### 2.2 Observing Modes

PANOSSETI operates in two complementary readout modes spanning the full ns-s range. In pulse-height (PH) mode, the system triggers on bright pulses above a configurable photoelectron threshold and assigns each event a sub-nanosecond timestamp, making PH the primary mode for nanosecond-scale flashes including optical technosignatures, astrophysical transients, and atmospheric Cherenkov events. In continuous imaging (CI) mode, the system records high-cadence per-pixel count images, accumulating flux over longer windows to track millisecond-to-second variability. The two modes run independently and simultaneously, providing complementary sensitivity across the timescale range.

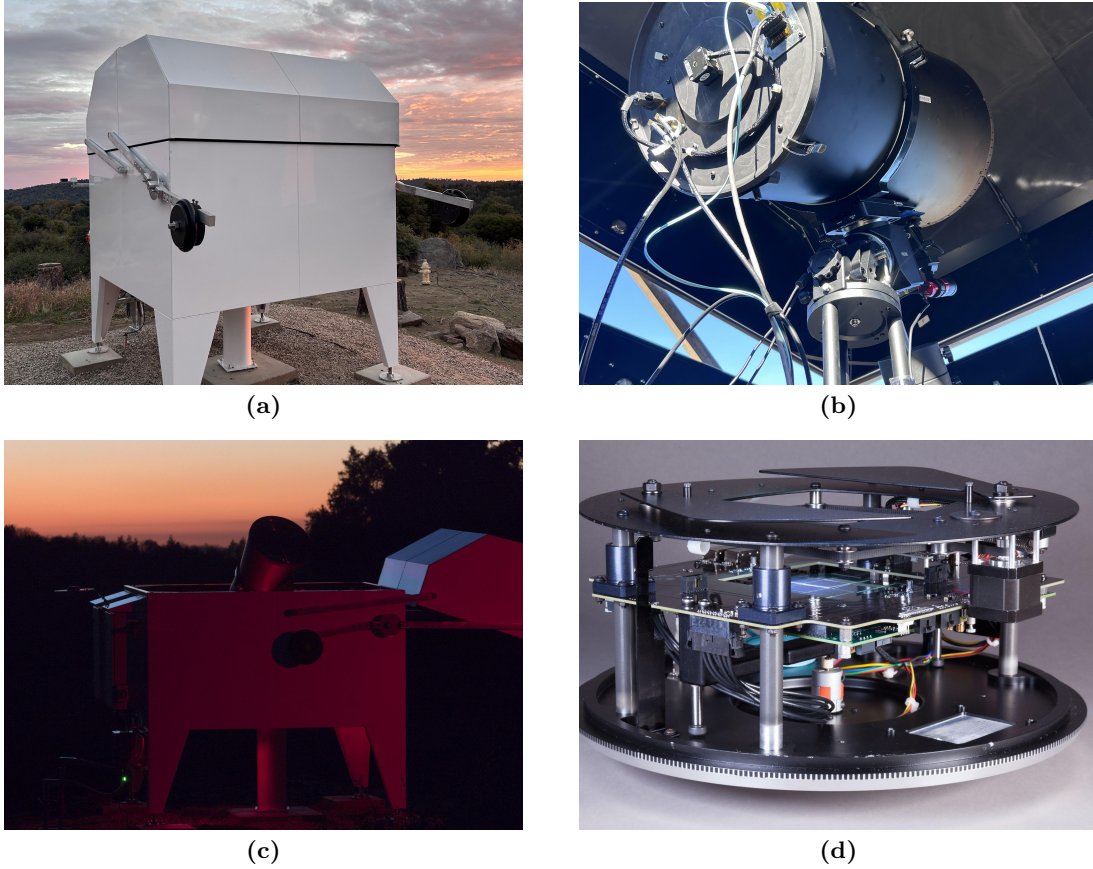


**Figure 1:** PANOSSETI commissioning and deployment at Palomar Observatory. (a) Fornax enclosure at the Winter site, closed during daytime. (b) Telescope module mounted inside the Fern enclosure. (c) Winter enclosure opened for observations. (d) Backend focal plane electronics showing the  $32 \times 32$  Hamamatsu SiPM array.

### 2.3 Timing and Coincidence Architecture

Sub-nanosecond synchronization across telescope sites is provided by a custom global navigation satellite system (GNSS) receiver, which disciplines each module’s clock to a common UTC reference, achieving sub-nanosecond accuracy across all deployed modules. This common time base enables cross-site coincidence filtering with timing windows matched to the propagation timescales that distinguish astrophysical signals from local backgrounds. At sub-nanosecond timescales, the dominant background comes from atmospheric Cherenkov air showers, which illuminate separated telescopes within a narrow window set by the shower geometry and baseline. The baselines between Palomar sites are well-matched to the extent of these showers, making coincidence timing the core mechanism for both false-alarm rejection and Cherenkov event characterization. The expected rate of accidental cross-site coincidences is quantified in Section 4.

### 2.4 Palomar Observatory Site Layout

Four PANOSSETI telescope modules are currently deployed at Palomar Observatory across four independent sites: Gattini, Winter, Heli, and Fern, at an elevation of approximately 1.7 km. Inter-site baselines range from approximately 143 – 597 m, providing multi-baseline sensitivity for Cherenkov shower reconstruction and coincidence event vetting. Each site operates as an independently functioning observatory unit. Three additional sites are planned for deployment in 2026.

### 2.5 Enclosure and Mechanical Infrastructure

PANOSSETI telescope modules are housed in Fornax enclosures that protect the optics and electronics from the elements. Each module is mounted on a custom steel pier, encased in concrete, which interfaces with an iOptron HAE69C equatorial mount. Power is distributed at 120 VAC per site with surge protection, chassis grounding,

and a UPS battery backup. Fiber for the data and timing links enters each enclosure through connectorized cables passing through gland plates in the enclosure walls.

## 2.6 Commissioning Timeline

Full assembly of the telescope modules and integration for the PANOSSETI experiment began in Spring 2025. First light was achieved on December 18, 2025, with all four telescope modules operating simultaneously at the Gattini, Winter, Heli and Fern sites.

## 3. SKY BACKGROUND CHARACTERIZATION

### 3.1 Triggering Rate Curves for Threshold Calibration

The SiPM focal-plane response is characterized through **triggering rate curves**, which map the trigger rate per pixel as a function of the PH discriminator threshold in photoelectrons (pe). Polaris and the Crab Nebula (M1) have served as the primary commissioning targets for threshold determination. Trigger rates are recorded separately for 1-pixel, 2-pixel, and 3-pixel multiplicity requirements. Figure 2 shows a triggering rate curve for the Fern site at Palomar, taken at 1% lunar illumination. The defining feature of each curve is the **knee**, which marks the threshold where the dominant trigger source changes. Below the knee, the rate is governed by SiPM noise processes (dark counts, optical crosstalk, afterpulsing, and sky background) and falls steeply with increasing threshold; above it, the rate flattens onto a plateau set by residual sky background and genuine photon detections, largely independent of threshold. Requiring 2- or 3-pixel multiplicity suppresses the noise floor by up to two orders of magnitude at a threshold of 6 pe and shifts the knee to lower threshold, at the cost of rejecting events confined to a single pixel.

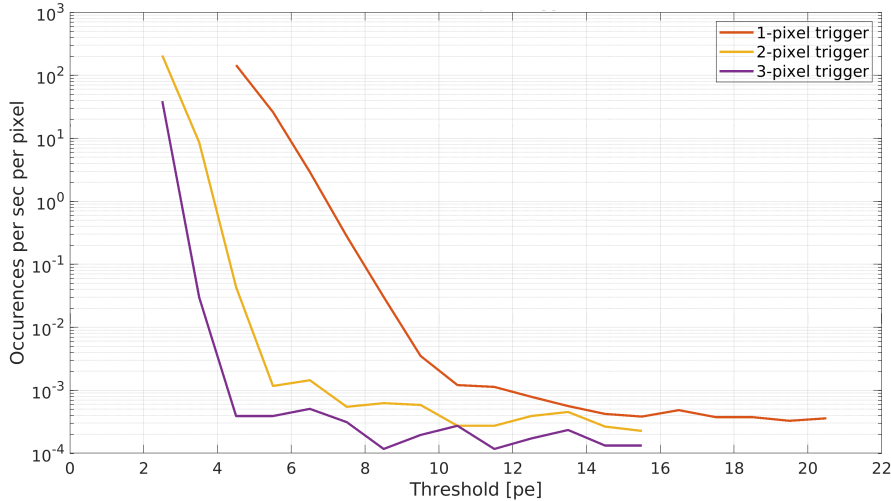


**Figure 2:** Trigger rate measurements for Fern site on January 17-18, 2026, at  $\sim 1\%$  lunar illumination. The trigger rate per pixel (y-axis) is plotted as a function of the PH discriminator threshold in photoelectrons (x-axis) for three multiplicity configurations: 1-pixel (red), 2-pixel (yellow), and 3-pixel (purple). Each curve falls steeply at low threshold, where SiPM noise dominates, before plateauing after the knee, indicating the transition between where the sky-background and genuine-photon floor take over. For the 1-pixel curve the knee occurs near  $\sim 10$ – $11$  pe. These curves are used during commissioning to assess SiPM focal-plane stability and to inform operating-threshold selection for differing science cases.

### 3.2 Targeted Source Response

The on-sky response is explored through targeting of stellar point sources, measured through the detector current as those sources transit the modules FoV. A sequence spanning four magnitudes of brightness is targeted: Capella ( $V=0.08$ ), Elnath ( $V=1.65$ ), Hassaleh ( $V=2.69$ ), Haedus ( $V=3.3$ ), and Tet Aur ( $V=4.0$ ). Figure 3 shows the current vs. time with each star transiting, the SiPM array shows correlated current excursions with peak increases ranging from  $\sim 50$ – $250 \mu\text{A}$  above baseline. The consistent detection of transits across the three sites shown confirms that these focal planes respond predictably to point sources spanning four magnitudes.

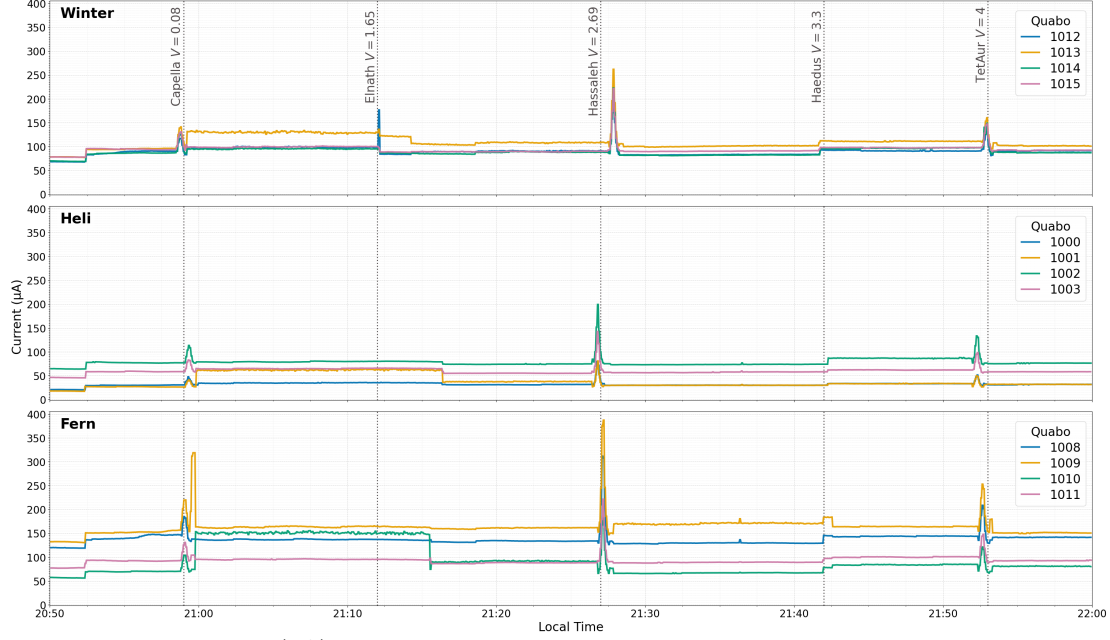


**Figure 3:** The plotted current ( $\mu\text{A}$ ) vs. time represents the SiPM array from the quabo boards. Vertical dashed lines indicate the times at which known sources entered the PANOSSETI’s module FoV; targets included stars spanning magnitudes  $V = 0.08 - 4$  (Capella, Elnath, Hassaleh, Haedus, and Tet Aur) Current excursions are seen with peak increases ranging from  $50 - 250 \mu\text{A}$ . Quabos are from three separate telescope sites (Winter, Fern, and Heli) set to an elevation of  $\sim 70 - 80^\circ$  the night of January 15, 2026 at  $\sim 12\%$  illumination.

### 3.3 Moon-Dependent Background

The sky background during observing is dominated by two Moon parameters: the illuminated fraction of the lunar disk and the angular separation between the Moon and the telescope pointing. Detector current was tracked as a function of Moon–telescope angular separation for quabo 1012 at the Winter site, with a rolling-median window applied to suppress point-to-point scatter. Each observation is colored by the lunar illumination fraction, computed from solar and lunar ecliptic longitude, as shown in Figure 4. Across 19 selected nights spanning October 23, 2025 to June 22, 2026, including pre-commissioning operation of the Winter module prior to first light, detector currents increase by roughly a factor of five under high-illumination conditions ( $\sim 60\text{--}100\%$ ) relative to dark-sky baselines, with this increase further modulated by Moon–telescope angular separation. The trend is qualitatively consistent with the scattered moonlight model of Krisciunas & Schaefer (1991).<sup>22</sup> Characterizing this dependence from Palomar telemetry allows the Moon-driven background to be predicted from observing geometry, and its effect on trigger thresholds and false alarm rates anticipated.

## 4. PULSE HEIGHT MODE: FALSE ALARM RATE AND COINCIDENCE PERFORMANCE

### 4.1 False Alarm Rate Characterization

These SiPM detectors are subject to background pulses: including thermal noise, dark current and detector electronics. The approach to suppress this background, established by Horowitz et. al,<sup>23</sup> requires coincident triggers across two or more independent detectors within a small time window. Real pulsed signals will simultaneously illuminate the detector system while background pulses happen independently in each channel; the rate of accidental coincidence falls off rapidly as the required number of coincident detectors increases. Following the formalism of Wright et al.,<sup>24</sup> for an  $n$ -detector coincidence system with single-detector rate  $r$  and coincidence window  $T$ , the expected rate of accidental coincidences  $R$  is

$$R = r^n \cdot T^{(n-1)} \cdot \text{QE} \cdot \cos(\alpha) \quad (1)$$

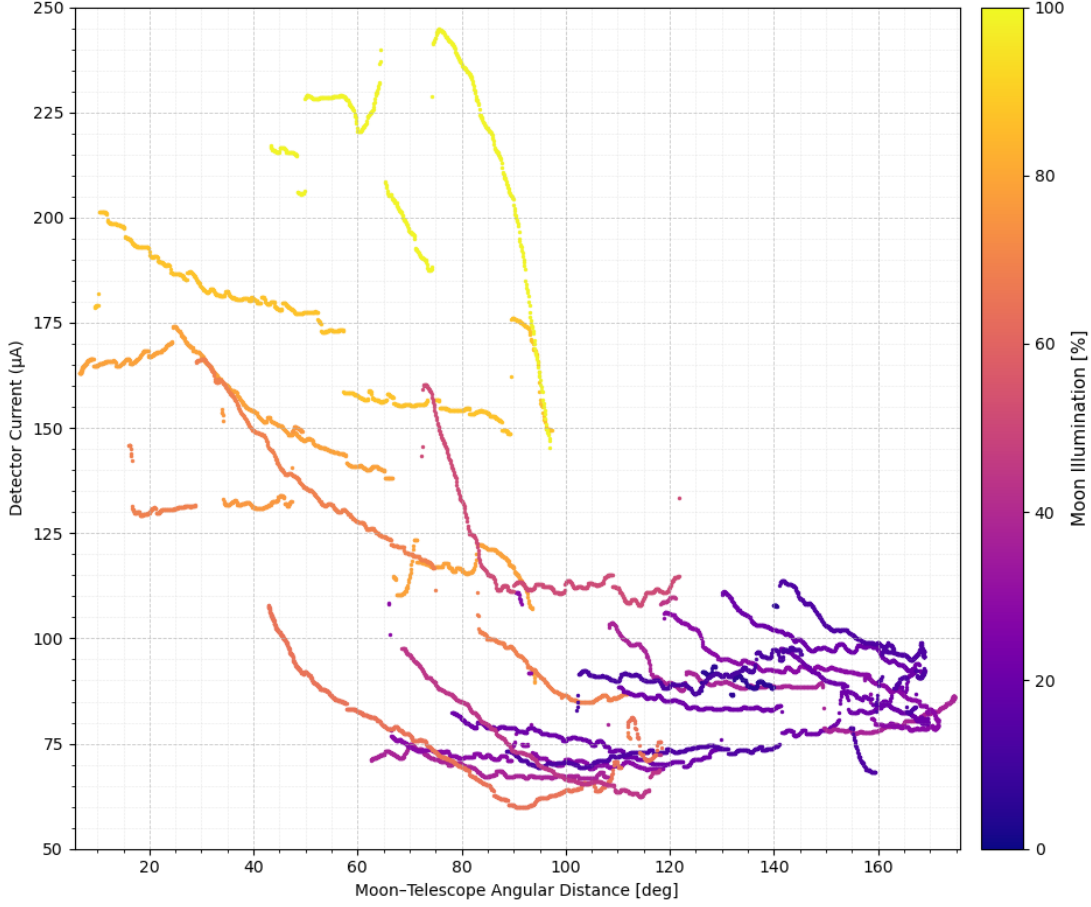


**Figure 4:** Rolling-median-smoothed detector current for a quabo on the SiPM focal plane at the Winter site, plotted against Moon–telescope angular separation and colored by lunar illumination fraction across 19 selected nights from October 23, 2025 to June 22, 2026. Currents increase by roughly a factor of five under high-illumination conditions relative to dark-sky baselines, with elevated currents concentrated at smaller angular separations.

where  $QE$  is the detector quantum efficiency and  $\alpha$  is the airmass-dependent elevation correction. Wright et al. derive this expression for a single telescope whose beam is divided among  $n$  detectors; each PANOSSETI telescope collects light independently, so no splitting factor applies and  $r$  is the full trigger rate of a single module.

We characterize a single-telescope FAR as a function of PH threshold using triggering rate curves measured for each of the four deployed sites. For a given threshold, the per-pixel trigger rate is scaled by the  $32 \times 32$  pixel focal plane to obtain the per-telescope trigger rate. Equation 1 is then applied to compute the multi-telescope coincidence rate across the same threshold range. Figure 5 shows this pipeline applied to the Heli site for 1-pixel trigger and any trigger mode. The left panel shows the single-detector trigger rate, both at the per-pixel level (raw triggering rate curve) and scaled to the full per-telescope rate. The right panel shows the resulting two-telescope coincidence rate, with dashed lines marking the thresholds for one false alarm per year and per five years. The shaded green region indicates the threshold range under consideration for nominal PANOSSETI operations. An operating threshold of 10 pe yields an expected false alarm rate of one event per year for two telescopes in a 10 ns coincidence window. Measured cross-site coincidence rates from paired PH-mode observations will be presented in future work.

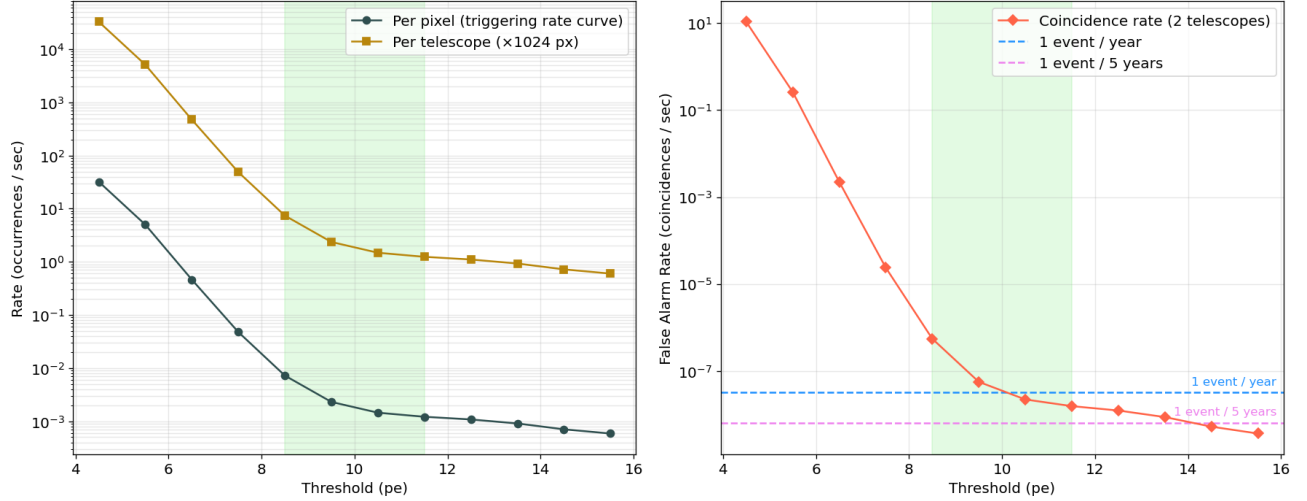


**Figure 5:** FAR characterization for the Heli detector (1-pixel trigger, any-trigger mode). *Left:* Single-detector trigger rate as a function of PH threshold, shown at the per-pixel level (raw triggering rate curve) and scaled to the full  $32 \times 32$  pixel focal plane to give the per-telescope rate. *Right:* Two-telescope accidental coincidence rate computed from Equation 1 with a 10 ns coincidence window. Dashed lines mark the thresholds corresponding to one false alarm per year and one per five years. The shaded green region is being considered as the threshold setting for nominal operation; where a threshold of 10 pe yields approximately 1 false alarm event per year.

## 5. ON-SKY COMMISSIONING AND SCIENCE RESULTS

### 5.1 Pointing, Alignment, and Tracking Validation

On-sky pointing was validated through observations of bright stars, including Polaris and Capella, by confirming each target on the focal plane.\* These observations served as end-to-end tests of the mount model and applied pointing offsets, verifying that the mechanical axes of the module were stable on-sky.

### 5.2 First Deep SETI Field Observations

Target fields for deep optical technosignature searches were selected using a direction-dependent Figure of Merit (FoM),  $F_{deep}$ , that ranks all-sky pointings by combining line-of-sight stellar density with interstellar extinction (Johnson et al., in prep). This framework identifies sightlines that maximize the number of observable stars while minimizing dust attenuation of incident optical pulses. The two highest-ranked fields accessible from Palomar are the Aquila Deep Field, centered at galactic coordinates  $\ell = 54.8^\circ$ ,  $b = -9.4^\circ$ , and the Gemini Deep Field, centered at  $\ell = 210.1^\circ$ ,  $b = 16.9^\circ$ . These fields anchor the first deep-survey observations of the commissioned array and will form a major component of the PANOSSETI survey campaign.

Figure 6 shows the first PANOSSETI observation of the Aquila Deep Field, obtained on June 18, 2026 at a pointing center of RA  $20^{\text{h}}07^{\text{m}}0^{\text{s}}$ , Dec  $+14^\circ35'0''$ . Panel a shows the median-combined  $32 \times 32$  pixel mosaic constructed from the four time-aligned QUABO detectors, while panel b shows the corresponding Stellarium FoV at the same pointing. The agreement between the detected source field and the simulated star field confirms astrometric registration of the focal plane on a genuine science target and demonstrates the array's readiness for sustained deep-field monitoring.

Observations of these deep fields will accumulate continuously over the coming survey season, building the long-baseline temporal coverage required for a transient search. In the absence of a confirmed detection, the survey yield will be interpreted through a model-universe framework that converts the observed null result into an upper limit on the prevalence of optical technosignatures across the monitored stellar population (in prep).

## 6. SUMMARY AND FUTURE WORK

This report has presented the on-sky commissioning and first science operations of the PANOSSETI experiment at Palomar Observatory. Over the 2025 commissioning campaign, four telescope modules were brought to

\*Magnitude of calibration stars ranges from  $V = 0 - 2$ .

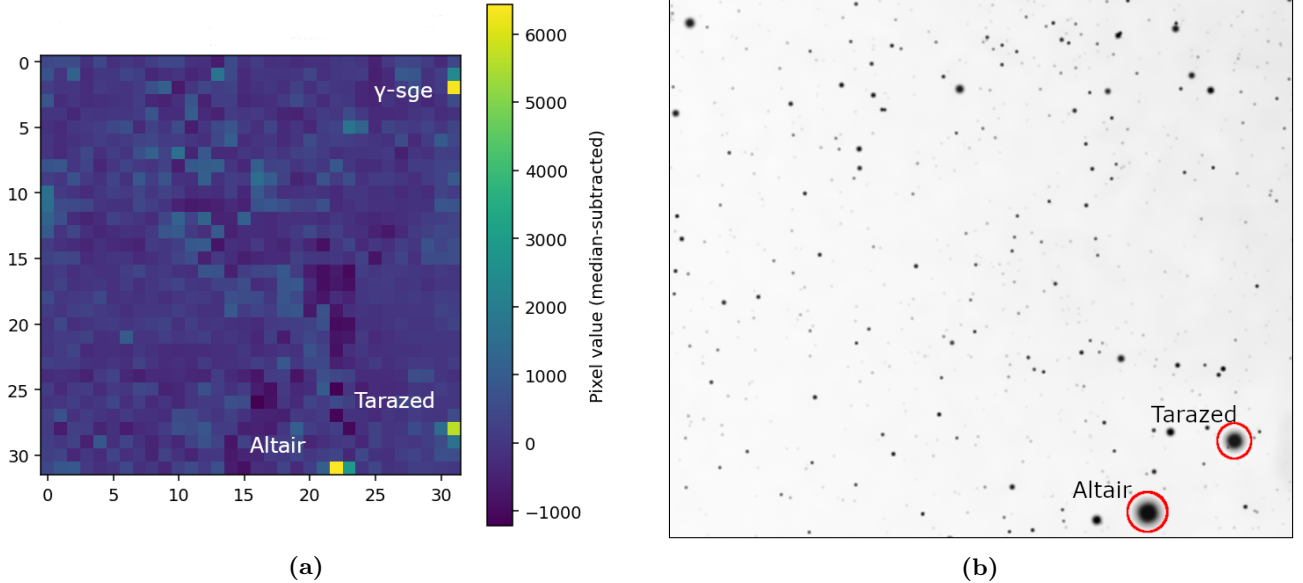


**Figure 6:** PANOSSETI observation of the Aquila field on June 18, 2026. (a) Median-combined  $32 \times 32$  pixel mosaic from the four time-aligned QUABO detectors. (b) Stellarium field of view at the same pointing center (RA  $20^{\text{h}}07^{\text{m}}0^{\text{s}}$ , Dec  $+14^{\circ}35'0''$ ).

operational status at the Gattini, Winter, Fern, and Heli sites, separated by baselines of a few hundred meters to support Cherenkov-shower rejection and coincidence-based false-alarm mitigation. Pointing alignment and full-night tracking stability were validated against bright-star observations. Detector characterization across the deployed focal planes, including SiPM gain, dark count rate, and correlated-noise behavior, was completed through repeated triggering rate curve measurements, which confirmed predictable detector performance and motivated refinement of the nominal PH trigger threshold.

A FAR model was established for Palomar conditions, linking the single-pixel triggering rate to the multi-telescope coincidence rate, while a parallel sky-background model characterized detector current as a function of Moon illumination and Moon-telescope separation. With these calibrations in place, survey operations are now underway, and the deep optical SETI field campaign, anchored by the Aquila and Gemini deep fields, is commencing in Spring and Summer 2026.

The PANOSSETI program aims to deploy three additional sites at Palomar in 2026, bringing the array to seven telescopes. Near-term development priorities include an automated scheduling and quality-monitoring pipeline for sustained high-duty-cycle operation, and an extension of the background characterization pipeline that links measured sky conditions directly to SiPM trigger thresholds and false alarm rates, closing the loop between observed background and operational threshold selection. A comprehensive multi-year instrument paper detailing the full deployed array and survey performance is anticipated for SPIE 2028.

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