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W. M. Keck observatory instrumentation status and future direction

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Abstract
Since the start of science operations in 1993, the twin 10-m W. M. Keck Observatory (WMKO) telescopes have continued to maximize their scientific impact and to produce transformative discoveries that keep the observing community on the frontiers of astronomical research. Upgraded capabilities and new instrumentation are provided through collaborative partnerships with Caltech, the University of California, and the University of Hawaii instrument development teams along with industry and other organizations. The observatory adapts and responds to the observers' evolving needs as defined in the observatory's strategic plan periodically refreshed in collaboration with the science community.

For affiliations refer to page 17

This paper is an overview of the instrumentation projects that range from commissioning to early conceptual stages. An emphasis is placed on the detector, detector controllers, and capability needs that are driven by the desired future technology defined in the 2022 strategic plan.

KEYWORDS

Keck observatory, optical and infrared instrumentation, adaptive optics

1 | INTRODUCTION

Located atop Maunakea on the island of Hawaii, the W. M. Keck Observatory (WMKO), with its twin 10-m telescopes, has a history of transformative discoveries, instrumental advances, and education for young scientists since the start of science operations in 1993. Observing time is available primarily to Caltech, University of California (UC), NASA, and University of Hawaii (UH) and some nights are also available through Yale, Notre Dame, Northwestern University, and Swinburne University as well as NOAJ through a time exchange with Subaru. To maintain the scientific leadership of this observing community, WMKO develops and maintains state-of-the-art instrumentation and systems that keep the observer's science at the cutting edge in astronomy. The observers use well-designed, workhorse instruments that, when combined with the 10-m aperture and excellent Maunakea seeing, offer high sensitivity measurements. Nightly operations focus on maximizing efficient data acquisition with a classical "astronomer first" approach that allows for agility and flexibility.

To maximize WMKO's scientific impact, WMKO's community of instrument developers currently at Caltech, The University of California at Los Angeles, Santa Barbara, San Deigo, Irvine, and Santa Cruz (UCLA, UCSB, UCSD, UCI, UCSC), Swinburne, Macquarie, and the Space Science Laboratory (SSL) in Berkeley are developing new capabilities and upgrading existing facility instruments. In early 2023, a revised WMKO science strategic plan was released and set a directive for new technologies to pursue over the next decade (https://www2.keck.hawaii.edu/inst/scistratplan/ssp.html). The strategic plan revision is led by WMKO Deputy Director and Chief Scientist, John O'Meara, with leading contributions from WMKO's Science Steering Committee (SSC) and the Directors at Palomar and Lick Observatories. The broader WMKO astronomical community provided input by identifying synergies with other facilities and evaluating the potential of new initiatives for enabling scientific discovery.

In this review, we present recent developments toward achieving the goals in the WMKO strategic plan are described below. A summary of the existing instrumentation suite and their detector systems is provided, followed by descriptions of instrumentation and detector systems that are recently deployed, about to be deployed, and in early phases of development.

2 | CURRENT INSTRUMENTATION

WMKO's core set of instrumentation described below in Table 1 combined with our classical scheduling and rapid Target of Opportunity (ToO) capabilities via the Keck I deployable tertiary mirror provide flexibility and responsiveness capability to enable science that directly addresses science themes called out in Astro2020 (National Academies of Science 2021) including the rapidly evolving theme of TDA.

Table 1 shows instrument capabilities available to all observers at WMKO in 2022. Due to the availability of the deployable tertiary on Keck I, and the ability to rotate the tertiary mirror on both telescopes, availability of three instruments on both telescopes is possible in each night. On KI, OSIRIS with adaptive optics and HIRES are available at the Nasmyth ports any night with either LRIS or MOSFIRE at the Cassegrain location. On KII, NIRC2/AO is available at a Nasmyth port, NIRES is at a bent Cassegrain port, and on the second Nasmyth port, DEIMOS, NIRSPEC, or KCWI may be in beam. When installed at Cassegrain, ESI is the only instrument available on Keck II that night.

The adaptive optics (AO) benches on KI and KII have several detector system incorporated for operations and calibration to accommodate multiple modes. Table 2 provides a summary of the deployed systems in use with AO at WMKO.

TABLE 1 The current suite of instrumentation at WMKO in 2022.

Name	Tel	Capabilities	Delivery	Detector	Electronics
LRIS	KI	Low Resolution Imaging Spectrometer. Multi-object, 310 to 1000 nm dual-beam spectrometer and imager. Long slit, multi-slit, R = 300 to 5000, imaging 6 × 8 arcminute FOV, polarimetry.	1993	Blue: 2 × 2K × 4K Marconi (E2V) Red: 2 × 2K × 4K LBL	Blue: Leach GenII Red: Archon
HIRES	KI	High Resolution Echelle Spectrometer. Single object, 320 to 1000 nm echelle spectrograph; R = 30,000 to 80,000. 4k × 6k detector.	1993	2k × 4k LL-MIT	Leach Gen II
MOSFIRE	KI	Multi-Object Spectrometer for Infra-Red Exploration. 0.9 to 2.5 μm spectrometer and imager. Multi object up to 46 slits over a 6.1 × 3 arcminute field with R 3300 or a 6.1 × 6.1 arcminute FOV	2012	H2RG	Sidecar Windows
OSIRIS	KI	OH-Suppressing IR Imaging Spectrograph. Near IR integral field spectrograph (0.9 to 2.5 μm), simultaneous diffraction-limited imaging and R 3900 spectroscopy behind the Keck I AO system.	2005	Spec: H2RG Img: H2RG	Sidecar Windows
ESI	KII	Echellette Spectrograph and Imager. Single object, 390 to 1000 nm imager (to 2' × 8' field) and spectrograph (R = 1000 to 32,000).	1999	2k × 4k E2V	Leach Gen I and II
DEIMOS	KII	Deep Extragalactic Imaging and Multi-Object Spectrograph. 400 to 1000 nm imaging (17' × 5' FOV) and R up to 6000, long slit, multi-object spectroscopy.	2002	8–2K × 4K E2V	Leach Gen I and II
KCWI	KII	Keck Cosmic Web Imager. visible band (350–600 nm), seeing-limited integral field spectrograph, moderate to high spectral resolution R = 900–18,000, configurable field of view and image resolution, 40 arcsec FOV.	2017	4k × 4k E2V	Leach Gen II and III
NIRSPEC	KII	Near Infrared Spectrometer. Single object, 0.95 to 5.5 μm spectroscopy (R = 2500 and R = 25,000) with 1k × 1k detector.	1999	Spec: H2RG Img: H2RG	Sidecar Linux
NIRES	KII	Near-Infrared Echellette Spectrometer. Single object, prism cross dispersed near-infrared spectrograph, simultaneous J, H and K band R-2700 spectra in five orders from 0.94 to 2.45 μm.	2017	Spec: H2RG Img: H1	Leach Gen II and III
NIRC2	KII	Near Infrared Camera 2. 1 to 5 μm high resolution imager (0.01 to 0.04 arcsec pixel scale, 10 to 40 arcsec field) and R = 5000 spectrograph.A PyWFS is available for use with NIRC2.	2001	1k × 1k Aladin III InSb	Transputers

3 | COMMISSIONED INSTRUMENTATION AND ANTICIPATED DEPLOYMENTS

There are four instrumentation projects that are in the deployment and commissioning phase at the observatory. These projects are listed in Table 4 and will become available to the US community in the next couple of years. In addition, WMKO recently upgraded the LRIS II red detector system and that project is described below. The detector systems for LRIS, KPF, KCRM, and NIRC2 share common readout electronics hardware by deploying STA Archon controllers as the next-generation controller at WMKO. LRIS is not included in Table 3 and is instead summarized in Table 1.

TABLE 2 AO detector systems at WMKO in 2022.

Capabilities	Delivery	Detector	Electronics
KI AO			
WFS	2006/2023	SciMeasure CCD39 (cur) OCAM2k (planned)	CameraLink + Microgate custom (NGWFC) Microgate custom interface module (IM)
STRAP	2009	Microgate 2 × 2 APD array	Custom Microgate
LBWFS	2016/2017	SciMeasure LittleJoe e2V 47–20	CameraLink + Fiber converter
TRICK	2013	H2RG (eng grade)	ARC (Leech) gen III
ACAM	2006/2023	Photometrics PXL (cur) Andor Mirana (planned)	Photometrics USB3 + fiber
KII AO			
WFS	2007/2023	SciMeasure CCD39 (cur) OCAM2k (planned)	CameraLink + Microgate custom (NGWFC) Microgate custom interface module (IM)
STRAP	2003	Microgate 2 × 2 APD array	Custom Microgate
LBWFS	2016/2017	SciMeasure LittleJoe e2V 47–20	CameraLink + Fiber converter
ACAM	2021	Andor Marana	USB3 + fiber
PyWFS	2019	Leonardo SAPHIRA IR APD array	UH custom Pizzabox

TABLE 3 Future Instrumentation in integration and deployment phases.

Name	Tel	Capabilities	Delivery	Detector	Electronics
KPF	KI	Keck Planet Finder. Fiber-fed, single object, high-resolution (R = 90,000) optical spectrometer covering 445–870 nm and is specifically designed to measure precise radial velocities (RVs) with a precision of 50 cm/s or better.	2022 (deployed at time of publication)	"Green: 4k × 4k STA Red: 4k × 4k STA	Green: Archon Red: Archon
KCRM	KII	Keck Cosmic Reionization Mapper. Red beam upgrade to the KCWI instrument extending the wavelength coverage of KCWI to 1 μm	2023	4k × 4k LBL	Archon
NIRC2 Upgrade	KII	Near Infrared Camera 2. 1 to 5 μm high resolution imager (0.01″ to 0.04″ pixel scale, 10″ to 40″ field) and R = 5,000 spectrograph.A PwFS is available for use with NIRC2.	2023	1k × 1k Aladin III InSb	Archon
KAPA	KI	Keck All-sky Precision Adaptive-optics. Upgrades the KI LGSAO system with a new laser divided into four laser guide stars for more complete atmospheric correction and a new real-time controller and wavefront sensor camera. Improves performance for OSIRIS and dovetails with Liger and VisAO instruments.	2024	See Table 2	See Table 2

3.1 | LRIS red upgrade

In 2020, the LRIS Red detector system performance degraded with increased charge transfer issues. WMKO's support staff worked around the issue using various readout schemes depending on the science schedule that night for the next year. Simultaneously, UCSC and WMKO prioritized an upgrade project that was already underway as a synergistic activity with the KCRM project. The upgrade project would replace the existing LRIS Red detector system with a more sensitive detector and modern controller. The CCD is identical to the KCRM detector, which is a 500-μm thick, fully depleted 4k × 4k CCD made by Lawrence Berkeley Laboratory, the same group that made the previous CCDs in the LRIS red channel as well as the CCDs for the SDSS-BOSS spectrographs and the Dark

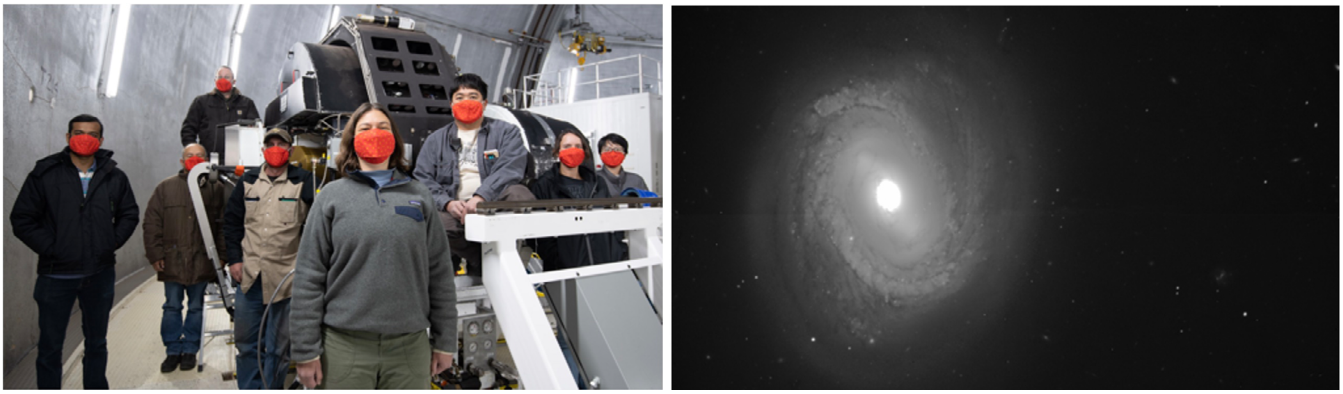

FIGURE 1 LRIS Red summit integration team Sunil Simha, Percy Gomez, Dale Sandford, Nick Souminen, PI Connie Rockosi, Dwight Chan, Arina Rostopchina, and Sherry Yeh. (Right) First light image of M58.

Energy Camera. This new CCD has a faster readout, improved read noise, and a similar QE as the previous red mosaic with binning available in the spatial and spectral direction. The 4k × 4k CCD would eliminate a 30 arcsec chip gap, thus increasing the real estate available for science.

The KCRM CCD controller is an Archon controller by Semiconductor Technology Associates (STA), and although it is the first controller from this vendor deployed at the observatory, it will be identical to KCRM and will have common spare parts with a third instrument. With this deployment, WMKO took a major step in addressing an obsolescence issue with optical CCD controllers at the facility.

LRIS Red IV achieved first light on April 27, 2021 and began science operations on May 7, 2021. Because this project used a previously deployed cryostat that kinematically mated to the existing focus stage, integration was seamless, and performance has been excellent (Figure 1).

3.2 | KPF

KPF (Gibson et al. 2018) is designed to detect and characterize exoplanets via Doppler spectroscopy with a single measurement precision of less than 0.5 m/s. KPF's science case and resulting technical design are centered on key NASA science objectives. KPF will be capable of measuring masses of hundreds of planets discovered by TESS and Kepler/K2, mapping out the dependence of planet density and composition on planetary system architecture and environment. KPF will provide RV confirmation and mass determinations for hundreds of transiting super-Earths identified by TESS and will efficiently identify Uranus mass objects suitable for follow-up study by Roman+CGI. For TESS targets, KPF's precision is comparable to NEID on WIYN, but the 10-m aperture of WMKO will enable surveys of more planets orbiting faint, cool stars. KPF will support JWST with precise masses needed for interpretation of exoplanet transit transmission spectra. It will similarly support Roman by discovering planets for coronagraphic imaging and atmospheric spectroscopy. KPF will measure the mass distribution of Earth-size planets to determine whether they are commonly "rocky" like Earth or are enshrouded in thick envelopes and thus incompatible with life (Figure 2). At the heart of KPF is a stabilized, fiber-fed, high-resolution R = 90,000 echelle spectrometer with *green* (445–600 nm) and *red* (600–870 nm) channels (Figure 3). Light from Keck I enters a Fiber Injection Unit (Lilley et al. 2022a), which includes an atmospheric dispersion corrector (ADC), a wide-field acquisition camera, a tip-tilt image stabilization system, and a calibration system that includes an LFC (Wu et al. 2022). The FIU sends light to the spectrograph and CaHK spectrometer (Baker et al. 2022) via octagonal optical fibers that naturally help "scramble" the light along with the agitator system that suppresses modal noise and a near-far field scrambling system at the input of the vacuum chamber, with all three providing a stable, homogeneous illumination to the spectrometer.

A unique aspect of KPF is the use of a Zerodur optical bench to support the spectrometer because Zerodur is a high-stability, glass-ceramic material with a near-zero response to temperature change (bulk CTE = 4×10-9K-1). With a Zerodur optical bench and Zerodur optics with integral mounts, KPF represents the most stable optical platform of any RV spectrometer. The spectrometer is placed in a vacuum chamber to isolate it from pressure changes, and within a thermal enclosure to ensure that the optics and detectors are insensitive to variations at the mK level, and this helps KPF meet and hopefully exceed a goal of <0.5 m/s for a single measurement.

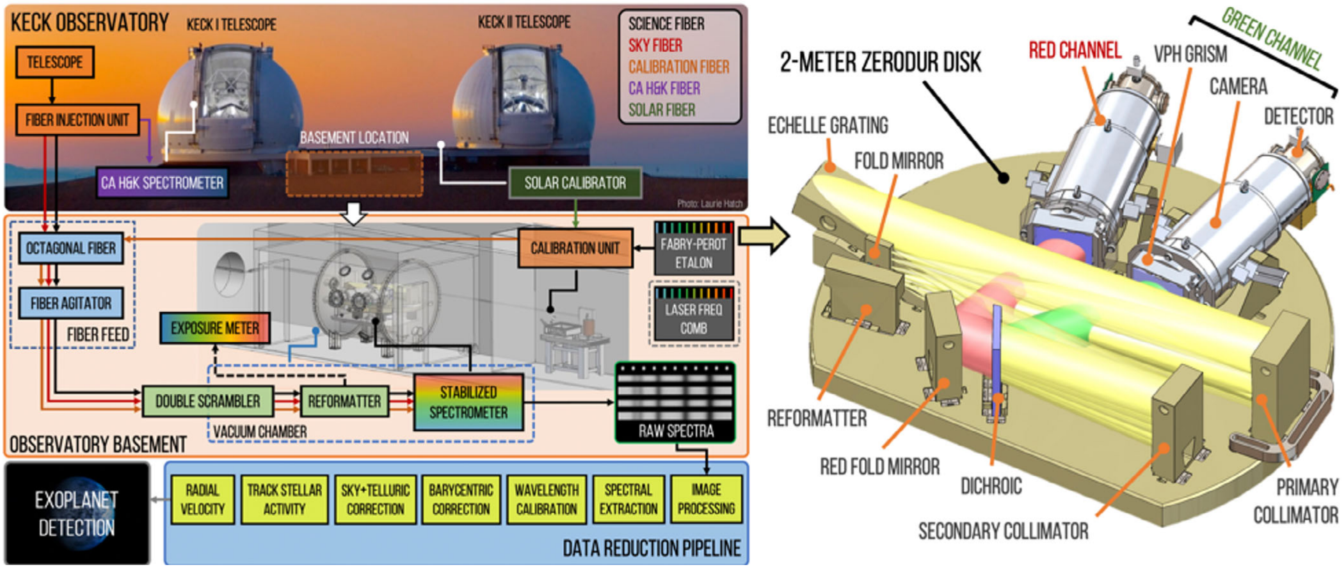

FIGURE 2 KPF is a complete radial velocity measurement system, encompassing a range of subsystems that are optimized for precision and efficiency (left). The instrument has the largest footprint of all instruments at the observatory that extends from the basement to the AO enclosure where the Ca HK spectrometer and Fiber Injection Unit will be installed. The Zerodur optics bench and optics is the heart of the spectrograph designed for maximum stability and will be enclosed in a thermally controlled vacuum chamber.

FIGURE 3 Left: Keck Planet Finder illuminated from underneath showing subsystems delivered during AIT in November 2022 by Jerry Edelstein. Right: PI Andrew Howard next to the fully populated optics bench and vacuum chamber May 2022.

The KPF development team successfully completed a pre-ship review and is delivering the instrument in July 2020. At the time of this publication, KPF first light was completed in November 2022 and was available for observer use in mid-2023. KPF will offer a completely open-source, open-development DRP package that delivers reduced spectra and RV measurements directly to the observer. KPF is fully funded through a public–private partnership with funding that includes private donations, private foundation support, and NSF grant support. WMKO, NExScI, and the KPF team are currently studying cadence scheduling and operations to optimize KPF science return (Figure 2).

3.3 | KCRM

The Keck Cosmic Reionization mapper (KCRM) is designed to augment the existing KCWI (Matuszewski et al. 2018; Morrissey et al. 2018) instrument and provide seeing-limited visible band, integral field spectroscopy with moderate to high spectral resolution, high efficiency, and excellent sky subtraction at visible wavelengths. The combined KCWI+KCRM distinguishes itself from other instruments with its extraordinary flexibility: simultaneous spectroscopy across the entire visible spectrum with a wide field and configurable spectral resolution as high as R 20,000 in some modes. The KCWI

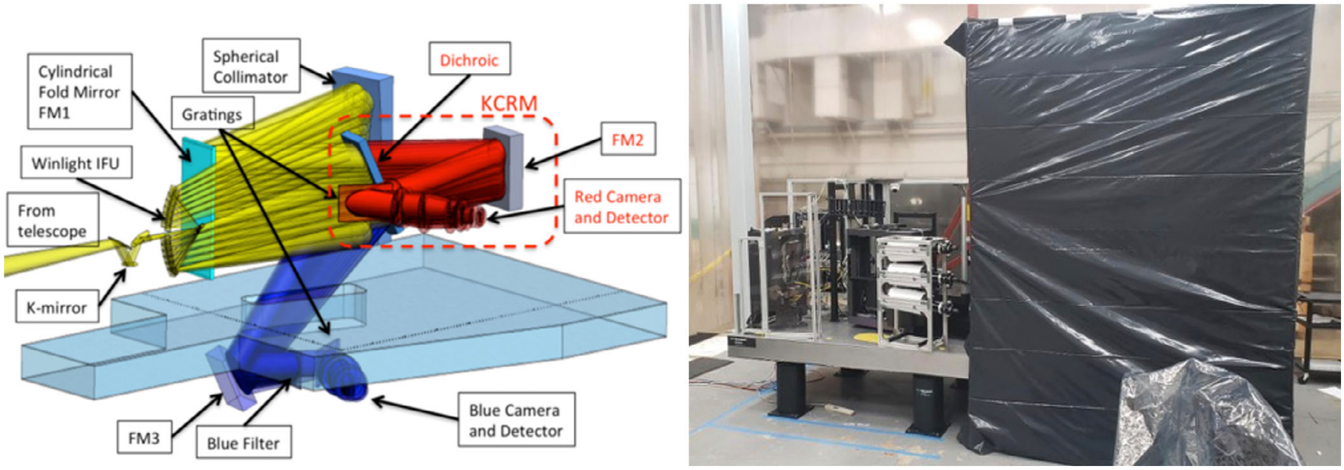

FIGURE 4 Optical layout of KCRM folded into the existing KCWI spectrograph optical design. The dichroic replaces a flat mirror with all elements in red part of the KCRM deliverables. The mechanical articulation stage (not identified) will move the camera and detector assembly to sample wavelength ranges specified by the user. Not shown is an update to the guiding system that will pick off the light at the front of the instrument using an annulus. Right: test bench populated with subsystems and the dark enclosure that can pivot and cover the bench for performance testing in the clean room at Caltech.

opto-mechanical design allowed for a phased deployment of two channels that cover the visible portion of the spectrum from blue (350–560 nm) to red (530–1050 nm). The combination of simultaneous high-efficiency spectral coverage across the optical band, configurable spectral resolution, and superb sky subtraction with available nod-and-shuffle capability makes KCRM a powerful addition to KCWI, opening a window for new discoveries at high redshift.

KCRM is implemented by replacing the current fold mirror in the collimated beam with a blue-reflecting/red-transmitting dichroic beam splitter, followed by a red optimized fold mirror, one of seven VPH low, medium, and high-resolution gratings selectable with the Red Grating Exchanger clocked to the correct angle with the REX rotation stage, focused by the red camera onto a fully depleted 500 μm thick 4 k × 4 k × 15 μm CCD (FDCCD) that provides enhanced QE out to 1080 nm. Like the blue channel, the red CCD assembly includes a deployable nod-and-shuffle mask. The camera and detector assembly are clocked to the correct dispersion angle with the red articulation stage. In addition, we replace the current on-axis red dichroic fed guider behind the de-rotator with an annular guider upstream of the de-rotator. Annular guider images will be de-rotated in software.

The KCRM development team is in a laboratory AIT phase with all major equipment in house except for the red camera assembly due to arrive this summer. The development team expects to deliver the instrument in September 2022 after passing a pre-ship review in August 2022. KCRM first light is planned for the winter of 2022 and will be available to the entire WMKO community that includes NASA starting in the spring of 2023 as part of the 2023A semester (Figure 4).

3.4 | NIRC2 upgrade

The NIRC2 detector controller will be upgraded and released for routine observing in the 2023A observing semester. The NIRC2 detector electronics are transputers that are housed in a 6-foot-tall electronics cabinet inside the AO enclosure. The main motivating factors behind these upgrades are to tackle obsolescence of hardware and software components, boost observing efficiency, enhance the instrument throughput, and add new observing functionality.

The transputer readout electronics will be replaced with an Archon controller with lab development being completed at Caltech. Caltech has demonstrated the capability of reading out both Aladin III and H2RG detectors using the Archon controller from STA. The Caltech development team is using the same controller interface at the dewar wall, which will allow for quick cable switching between systems for daytime testing and night time operations.

Then new controller should increase the duty cycle efficiencies for readouts to recover more on-sky science time, and the deployment will enable new modes. This will be the first time an Archon controller will be used to clock an IR detector at the observatory, and its performance will influence future instrumentation development for IR systems.

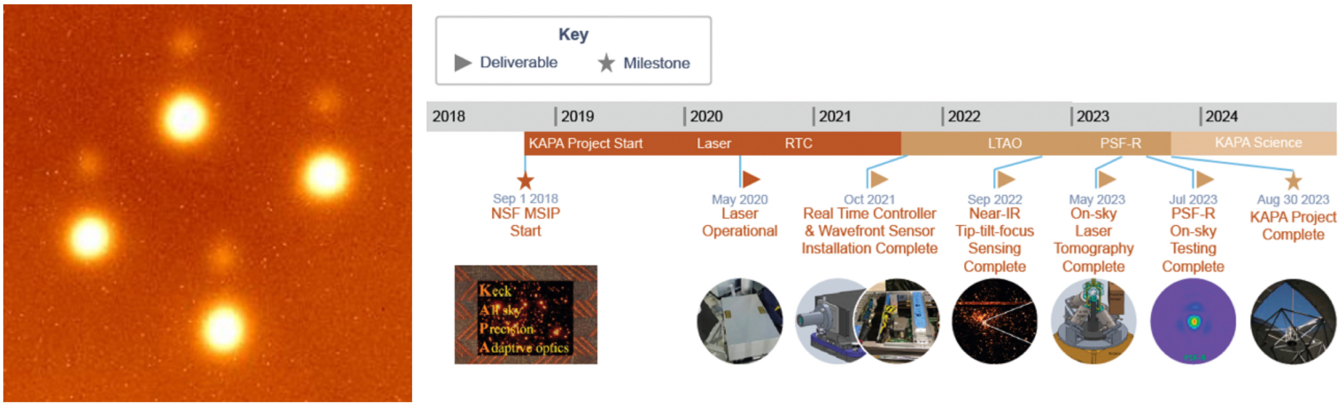

FIGURE 5 Laser Asterism projected on sky in April 2022 (ghosts are from the acquisition camera); Right: KAPA project timeline showing the major deliverables.

3.5 | KAPA

The Keck All-sky Precision Adaptive optics (KAPA) (Wizinowich et al. 2022) project is an upgrade to the Keck I Adaptive Optics (AO) system funded by the NSF Mid-Scale Innovations Program, with additional support from the Gordon and Betty Moore Foundation and Heising-Simons Foundation. KAPA offers three fundamental improvements over the existing AO system: Higher Strehl ratios achieved using four laser guide stars for atmospheric tomography (Lilley et al. 2022b; Surendran et al. 2022) to eliminate the "cone effect"; increased sky coverage using partially AO-corrected near-infrared stars for low order correction; and accurate point spread functions (PSFs) with each science exposure based on PSF reconstruction techniques.

The KAPA project began in late 2018 and is expected to enable science in 2024. To date, the new higher return, high reliability laser system is operational, and a new wavefront sensor camera and real-time controller system are undergoing on-sky testing. The remaining hardware to produce, sense, calibrate, and test a four-laser guide star system are in various stages of integration and test at the observatory. In parallel, the KAPA science team has been developing a set of planning and data reduction tools and identifying science targets in support of the four key science programs to be carried out with the completed system (Figure 5).

4 | FUTURE INSTRUMENTATION

Table 4 lists the instrument projects in different development phases and range from early concept development to early construction. There is a near-term emphasis on developing the next generation of AO-fed instruments: HISPEC, SCALES, and Liger. Along with KPF, HISPEC and SCALES would augment WMKO's exoplanet portfolio, providing the exoplanet observing community with instrumentation capable of high resolution, high contrast, and high spatial resolution over a large range of wavelengths. Liger covers a broad range of science capabilities that includes exoplanets, and it will improve the overall productivity and science return with the Keck I AO system when Liger replaces the existing OSIRIS instrument.

4.1 | HISPEC

HISPEC (High-resolution Infrared Spectrograph for Exoplanet Characterization) is an infrared (0.98 to 2.46 μm) cross-dispersed, R=100,000 diffraction-limited Echellette spectrograph fed by a single mode fiber from the KII AO system (Mawet et al. 2022). HISPEC is fully optimized for (1) exoplanet atmosphere characterization of hundreds of known systems through both transit and direct high-contrast, high-resolution spectroscopy, and (2) exoplanet detection and mass measurements of hundreds of known and new systems through infrared precision radial velocity, complementing KPF. Besides being a timely, cost-effective facility addressing all three major exoplanet detection and characterization techniques (transit spectroscopy, direct spectroscopy, and radial velocity), HISPEC will also conduct studies beyond the exoplanet frontier such as measuring the radial velocity of stars orbiting the Galactic Center with unprecedented precision. HISPEC is in the preliminary design phase and is funded through the preliminary design phase to the start of the construction phase. Project leadership is working to secure construction funds while finalizing the full scope of the instrument in the preliminary design. HISPEC is a collaborative project between Caltech, UCLA, UCSD, and WMKO (Figure 6).

TABLE 4 Future instrumentation in early development phases.

Name	Tel	Capabilities	Delivery	Detector	Electronics
Future Instruments in Late Design and Construction Phases					
HISPEC	KII	High-resolution near-Infrared SPectrograph optimized for forefront Exoplanet atmospheric Characterization. Single object AO Fiber fed high resolution (R>100,000) spectrograph optimized for precision radial velocity (<30 cm/s) and high-contrast high-resolution spectroscopy	2025	Blue: H2RG/H4RG Red: H2RG/H4RG	Archon
SCALES	KII	Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy. Integral field spectrograph and imager, wavelengths 2 to 5 μm, configurable 0.13–4.5 square arcsec FOV and resolutions (R = 50–7000). Imaging 13 arcsec FOV.	2025	Spec: H2RG Img: H2RG	Sidecar Macie
Liger	KI	Second Generation IR integral field spectrograph. Configurable spectral resolutions (R = 4000–10,000) and 0.4–90 square arcseconds FOV, wavelength coverage from the optical through the near infrared (0.84 to 2.4 μm). Imaging arm 20 arcsec FOV.	2027	Spec: H4RG Img: H2RG	Sidecar Linux
DEIMOS Upgrade	KII	Detector mosaic and flexure compensation upgrade for the DEIMOS multi-object spectrograph. Predicted throughput improvement across the entire 400 to 1000 nm observable passband with a factor of two improvement at the shortest and longest wavelengths.	2025	8–2K × 4K E2V	Archon
Future Instruments in Conceptual Phases					
ASM	KI KII	Adaptive Secondary Mirror. Enhances the existing AO system and enables ground-layer adaptive optics. Will lead to throughput and sensitivity improvements for all existing instrumentation. In support of the ASM, existing seeing limited instrumentation would develop WFS packages for GLAO observations.	TBD	Fast readout detectors for WFS	
WFI	KII	Wide Field Imager. Prime focus, 1 degree field of view imager covering 300–1000 nm.	TBD	CCDs and CMOS	Archon
LRIS-2	KI	Second generation Low Resolution Imaging Spectrometer. Maintains LRIS swiss-army knife core capabilities with technological advances that optimize its use with the GLAO system enabled by the ASM.	TBD	Blue optimized TBD Red optimized	Archon
FOBOS	KII	Fiber Optic Broadband Optical Spectrograph. Multi-object fiber fed spectrograph flexible acquisition system that will position 1800 individual fibers or 45 fiber-bundles over a 20 arcmin FOV, full optical band (0.31–1 μm), moderate spectral resolution (R = 3500).	TBD	12 CCDs optimized for 4 wavelength bands	Archon
TBD	KI	Visible AO instrument. Imager or integral field spectrograph paired with an adaptive optics system optimized for shorter wavelengths.500 nm 1 μm. A few arcsec field of view, R of 3500.Corresponding modifications required on the AO bench to extend performance to shorter wavelengths.	TBD	Optical to NIR sensitivity	
TBD	KII	Target of Opportunity Instrument. Single object, high throughput, OIR spectrograph, R 2000–4000 specifically optimized for time domain astronomy	TBD	UV-NIR	
TBD	KII	Second generation NIRSPEC. Single object spectrograph with 1.0 to 5.4 μm wavelength coverage, high resolution R = 30,000.	TBD	1–5 μm	

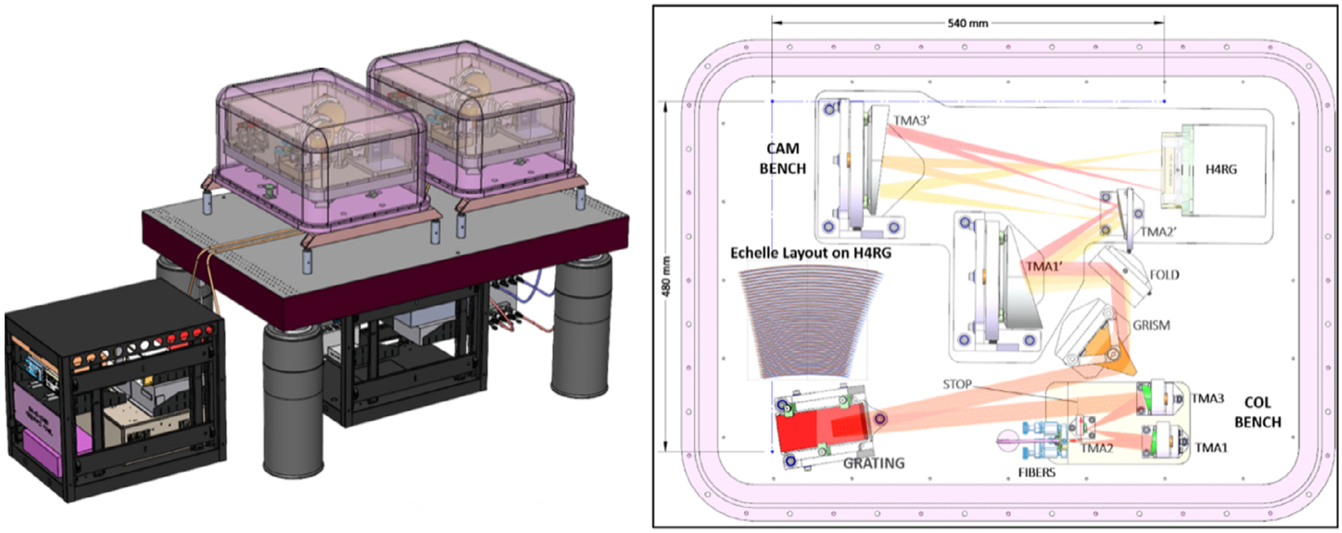

FIGURE 6 Left: HISPEC instrument layout including 6-foot lab bench, electronics racks, and cryostat to be in the basement of Keck II. Right: Top view of the spectrograph opto-mechanical layout inside the cryostat.

4.2 | SCALES

The Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy (SCALES) will be a diffraction-limited, thermal infrared (2-5 μm), coronagraphic integral field spectrograph (IFS) with a few arcsecond FOV fed by the KII AO system (Skemer et al. 2022).

As the world's first facility class thermal AO IFS, SCALES will maximize observer's ability to image and spectroscopically characterize exoplanets and will be more sensitive to planets at small angular separations ($\leq$ 1 acrsecond) than any other thermal infrared instrument, including JWST. SCALES accomplishes this by combining the two most powerful methods for imaging exoplanets: (1) Thermal infrared (2–5 μm) imaging, which detects exoplanets at wavelengths where they are bright, and (2) integral field spectroscopy, which distinguishes exoplanets from residual starlight based on the shapes of their spectral energy distributions. SCALES will extend the wavelength range we use to characterize planets, and discover new planets (in particular, cold planets) that are not detectable with near-infrared instruments (Banyal et al. 2022; Kupke et al. 2022; Lach et al. 2022; Li et al. 2022). Despite the competitiveness of the exoplanet imaging field, SCALES's unique parameter space ensures that it will lead a broad range of new science, complementing lower resolution JWST and Roman/CGI spectroscopy of targets from Kepler/K2/TESS, Gaia, RV surveys. IIA is developing an imaging channel with the same wavelength coverage as the spectrograph is designed to image an FOV of 12 arcsec (Banyal et al. 2022).

Thermal infrared imaging and spectroscopy are used for a wide range of solar system, galactic, and extragalactic observations such as monitoring volcanic eruptions on Io, mapping the building blocks in proto-planetary disks through PAH and water ice lines, supernovae morphologies through spatially resolved thermal and PAH lines, and characterizing the dust enshrouded objects at the Galactic Center. SCALES is advancing into the construction phase of development with partial funding to complete long lead purchases and detailed design efforts and has submitted an NSF MRI proposal to complete funding (Figure 7).

4.3 | Liger

All three planned Extremely Large Telescopes (ELTs) highlight the scientific need for a general purpose next-generation AO-fed integral field spectrograph and an NIR IFS is the only technology need deemed a high priority in all three new major facilities. The prioritization of an AO-fed IFS reflects the community's recognition that many of the most pressing scientific questions are not addressed by similar technology at existing facilities due to small FOVs, single spectral resolving powers, and wavelength coverages that are limited to typical NIR band passes. While SCALES addresses a need at the longer thermal bands, the proposed Liger IFS and imager for WMKO addresses this research-driven instrumentation need. Liger takes its name from the hybrid animal offspring of a lion and tiger because the instrument builds on the success of both the Keck/OSIRIS and incorporates the design efforts of the TMT/IRIS instrument (Wright et al. 2022).

Liger will combine a 0.81–2.45 μm imaging camera and IFS that may operate simultaneously (Cosens

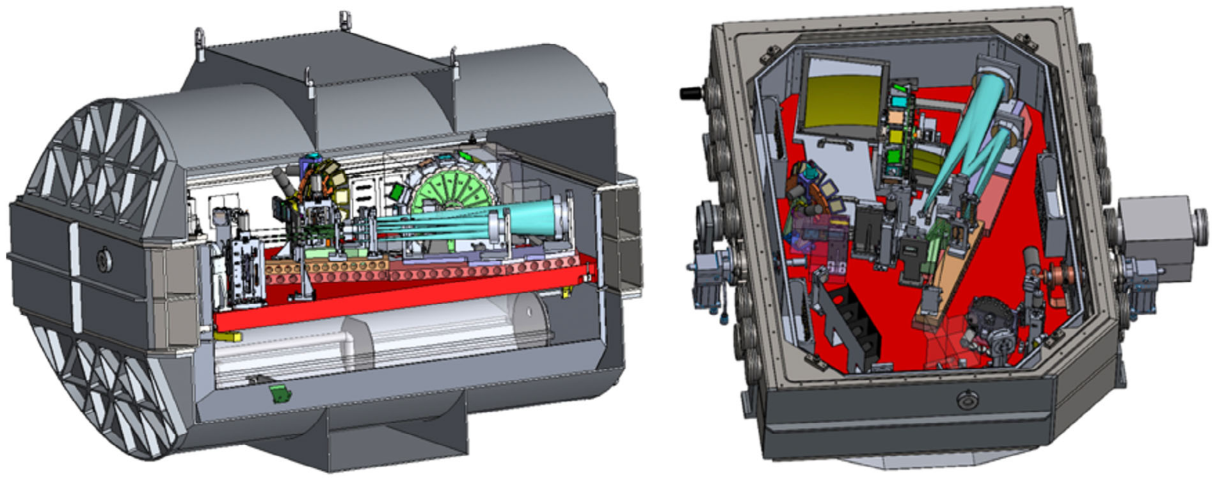

FIGURE 7 SCALES cryostat and opto-mechanical layout as presented during a preliminary design review. The optical bench is a single layer with two detector systems for both an imager and IFS. SCALES rides on a cart that can roll into the KII AO enclosure.

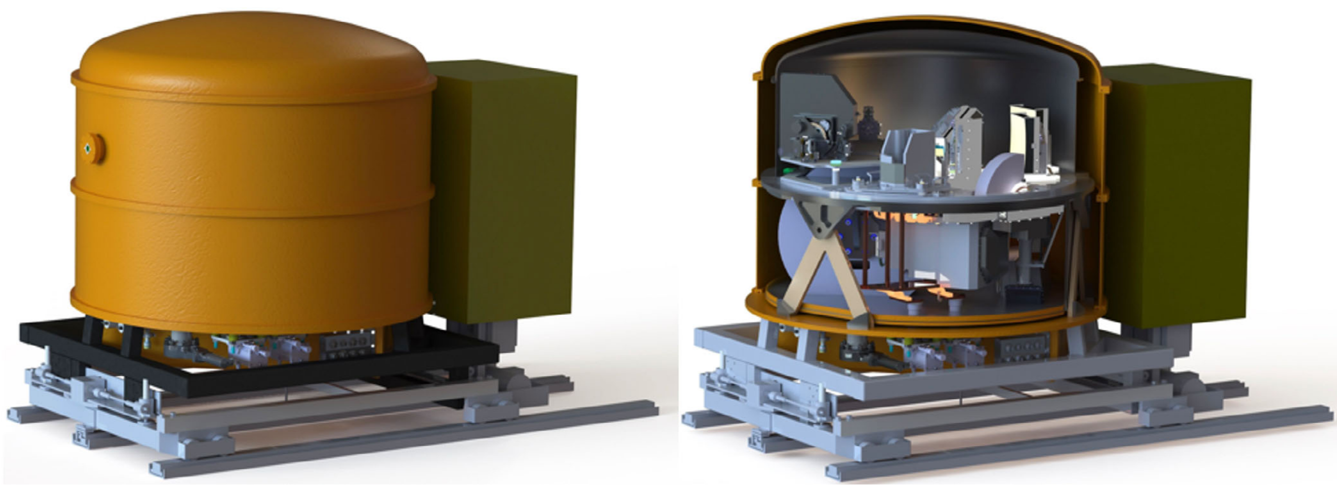

FIGURE 8 Liger cryostat on the transfer cart with entrance window on the cryostat. (Right) Cross section of the cryostat revealing the subsystem layout above and below the primary optics bench.

et al. 2022). Liger has a custom-designed imaging camera (Wiley et al. 2022), and its IFS is a duplicate of the IRIS spectrograph (Wiley et al. 2022). The Liger/IRIS spectrograph is an innovative design with user-selected modes that take advantage of either a slicer or lenslet IFS that results in options for FOV and resolutions that range from 13.2” × 6.8” to 1.9” × 1.9” and either R=4000, 8000, or 10,000. One advantage over other existing AO-fed IFUs is that the wavelength coverage extends into the visible bands at 0.81μm, and when combined with the KAPA upgraded KI AO system, the larger FOVs and optical wavelength coverage enables new science opportunities. The construction of Liger, which is highlighted as a need in Astro2020 (National Academies of Science 2021), will not only provide the WMKO community with technology maximized IFS capabilities, but it will also retire significant risk for the TMT/IRIS instrument as IFS optical design for the opto-mechanical bench is the same. Liger is funded through completion of the full-scale design phase, and the project is in the process of raising full construction funds (Figure 8).

4.4 | DEIMOS

In addition to adding new capabilities, WMKO continuously assesses risk and opportunity in our existing instrumentation suite. In the near-term future, we have identified one essential upgrade, DEIMOS. Among the most prolific optical multi-object spectrographs is the Deep Imaging Multi-Object Spectrograph (DEIMOS), commissioned in 2002. Overall, DEIMOS remains a workhorse

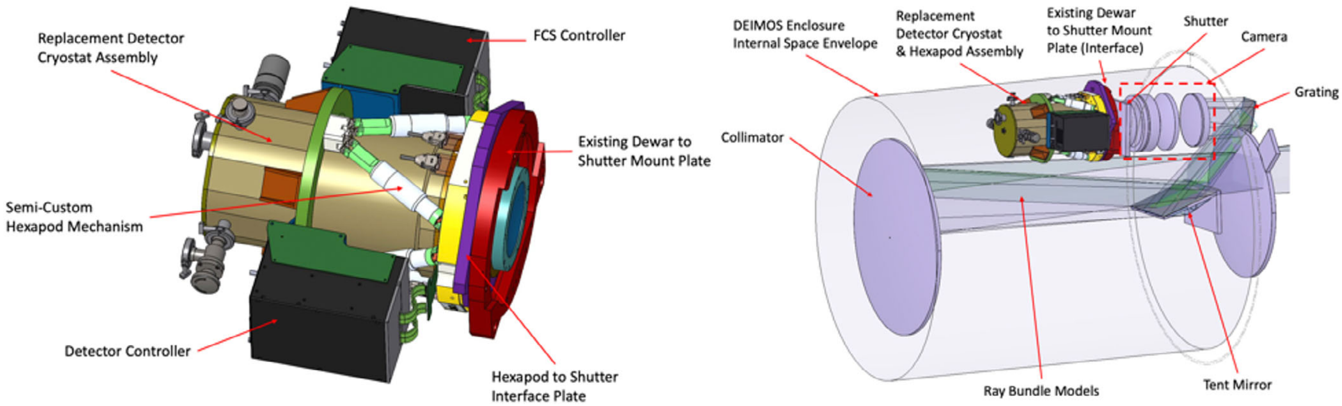

FIGURE 9 Left: Rendering of the DEIMOS upgrade subcomponents. Right: The shutter mount plate is the interface with the existing spectrograph and the upgrade components are show in context with the DEIMOS optical layout in the instrument barrel.

spectrograph for KII. WMKO began an upgrade mission to address detector performance issues that are natural and anticipated after 20 years of continuous operation. The primary purpose of the DEIMOS upgrade mission includes replacing the current detector mosaic with modern E2V detectors from Teledyne that improve upon the existing quantum efficiency over all wavelengths and doubling the instrument Q.E. at both the shortest and longest wavelengths relative to the current detectors. The upgrade will modernize the detector controller and improve stability by replacing the flexure compensation hardware with a hexapod system. The DEIMOS upgrade mission is a three-year project that we anticipate requiring minimal down time, one lunar cycle. The detectors are being purchased and a full construction funding proposal has been submitted to the NSF. The observatory is committed to DEIMOS's long-term success and instrument health, and thus, will strive to complete the project in 2025 (Figure 9).

4.5 | ASM/GLAO

Because WMKO's community recognizes the all-around enhanced sensitivity provided by an ASM for both diffraction-limited AO instrumentation and seeing-limited instruments that employ ground-layer adaptive optics (GLAO) capabilities, WMKO has invested in conceptual design efforts that fold in modern technology advances (Hinz et al. 2022). Current generation ASMs are implemented at several telescopes, including the MMT, LBT, Magellan, and VLT using Lorentz force (commonly called voice coil) actuators that deform thin glass shells that serve as the secondary mirrors. These designs are successful, but the low power efficiency of the actuators drives designs that require active cooling, co-located, high speed position control, and thin (and consequently fragile) reflective facesheets.

The WMKO community is working with the Netherlands Organization for Applied Research (Toegepast Natuurwetenschappelijk Onderzoek or TNO) who have developed a technology with efficiencies approximately 80 times that of similarly sized voice coil actuators. The advanced technology results in very high structural resonant frequencies, compared with voice coil designs, allowing a simple control approach. Further, the power required to correct turbulent wavefronts can be dramatically lower, allowing for simpler, passive cooling approaches to the system. Finally, the additional efficiency can be traded against the facesheet thickness to provide a sturdier deformable facesheet and that reduces fabrication and maintenance risk and complexity, deemed critical for a deployment at WMKO. A small ASM is being tested on Maunakea on the UH 88 in telescope as a demonstration of the new ASM technology (Hinz et al. 2022).

A GLAO system can significantly improve the image width across a field of view that is limited by the total height of the ground-layer disturbance. In the case of Maunakea, it appears that the ground-layer is dominated by a very thin surface layer with most of the optical turbulence within the first 30 meters, suggesting large fields-of-view with improved seeing are possible, and our community of observers have demonstrated significant improvements on small telescopes over large FOVs. WMKO anticipates upgrading MOSFIRE's detector system to provide a better match to the spatial sampling. When paired with an ASM, MOSFIRE and LRIS II will be a powerful combination providing GLAO corrected 6–8' FOVs from the UV to K band (Figure 10).

4.6 | LRIS-2

LRIS is one of the most in-demand, productive, and impactful instruments at WMKO because of its

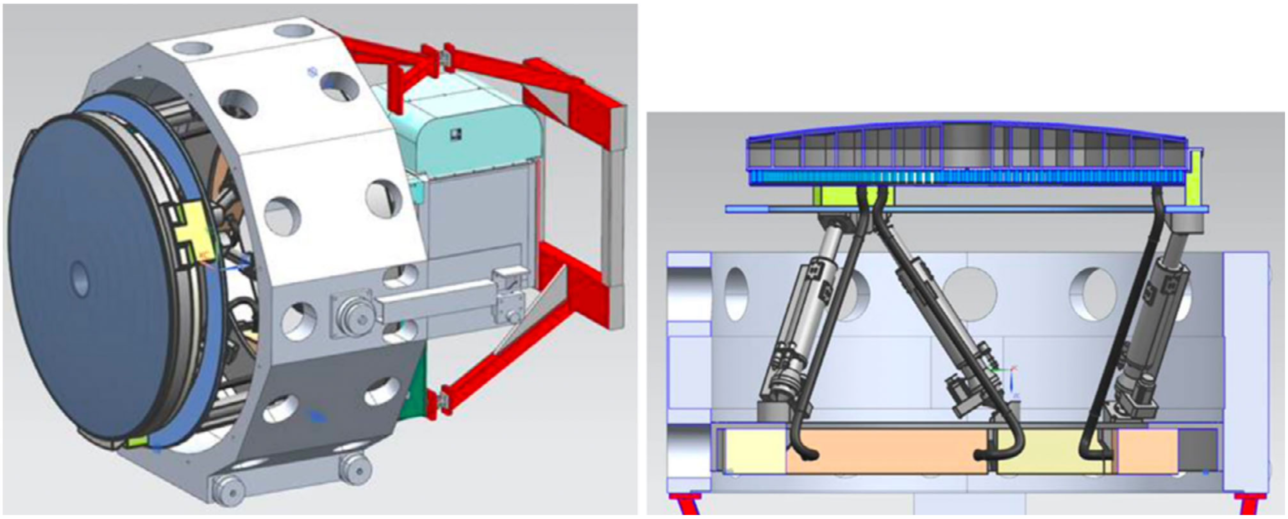

FIGURE 10 Left: concept for an ASM for Keck housed in an existing Keck top-end hexagonal structure that defines at the secondary socket. Right: cross section showing the ASM mounted on a hexapod for precision static alignment.

versatility providing sensitive imaging, single-target, and multi-object spectroscopy over the entire ground-based optical window (0.3-1 μm). LRIS's UV optimized optics and detector combined with the 10m aperture and a superb site makes it the most sensitive UV spectrograph on the planet. WMKO's SSC recognized a need for a second-generation multi-object UV sensitive spectrograph that maintains and expands upon the Swiss-Army knife like capabilities of LRIS, now nearly 30 years old, and over the past two years have invested in early conceptual design efforts.

The baseline LRIS-2 concept is an on-axis imaging spectrometer with a field of view of 10' $\times$ 8', located behind the existing KI Cassegrain ADC. Incoming light from the KI focuses on the f/15 focal surface, where focal plane aperture masks (i.e., slitmasks) are deployed for spectroscopy, and a simple rectangular field stop for direct imaging. After the telescope focus, the on-axis f/15 beam is collimated by a novel 2-mirror system to produce a 150-mm collimated beam. A dichroic beamsplitter reflects the beam into the blue channel for wavelengths 0.31–0.56 μm and passes wavelengths 0.56–1 μm into a red spectrograph channel much like the existing LRIS. At the separate blue and red pupils, selectable dispersers (VPH grisms or Fused-Silica Etched gratings) are used in transmission (the prisms allow the camera axes to be "straight through", so that removing the disperser from the beam puts the system into direct imaging mode), after which refractive cameras (f/2) focus the spectra or images onto a 4k $\times$ 4k detector arrays with 0.153"/pix spatial resolution on the blue and red channels. LRIS-2 will be equipped with a flexure compensating systems and use a cass facility wavefront sensor package that will enable LRIS-2 to take advantage of other future WMKO capabilities such as a GLAO system enabled by an ASM on KI (Figure 11).

4.7 | FOBOS

WMKO's last strategic plan that was developed with input from the US community identified the need of expanding optical MOS capabilities beyond that of the current DEIMOS spectrograph. To that end, instrument scientists have developed the Fiber Optics Broadband Optical Spectrograph (FOBOS) that will be the premier instrument for deep, high-target-density spectroscopy in the era of deep imaging surveys, like the Vera C. Rubin Observatory Legacy Survey of Space and Time, Euclid, and Roman. Its flexible acquisition system will position 1806 individual fibers or 42 fiber-bundles over Keck's full 20' field of view and provide spectroscopy covering the full optical band (0.31–1 μm) at moderate spectral resolution (R = 3500) (Bundy et al. 2022).

The FOBOS forward module consists of the ADC, a Starbugs positioning system, transport cart, and cable support system. Atmospheric dispersion correction is accomplished with a compensating lateral ADC or CLADC. The last optical element of the CLADC acts as the focal surface and the drive surface for the StarBug fiber positioning system that makes FOBOS unique relative to existing spectrographs because they allow for high field density sampling that is not achievable using standard patrol field fiber positioners (Adams et al. 2022). The StarBug actuators are semiautonomous robots that can move the fibers into almost any configuration using a pair of piezo ceramic tubes, which allow the actuators to walk across

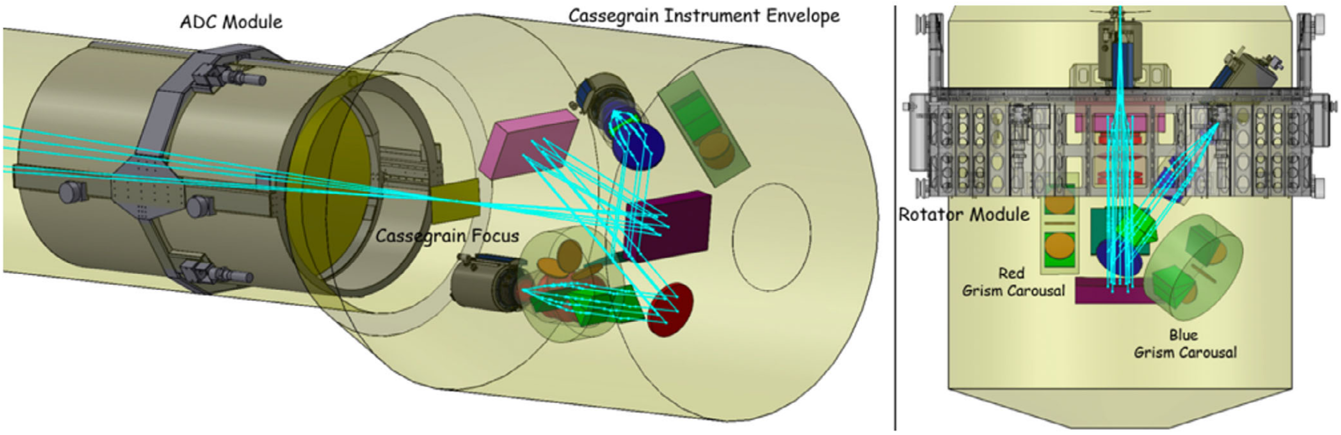

FIGURE 11 Conceptual optical layout for LRIS-2 with the volume of the KI Cassegrain socket defining the instrument envelope. Also depicted is the existing ADC module that LRIS II will reuse. Top-down view of the instrument with a facility rotator module.

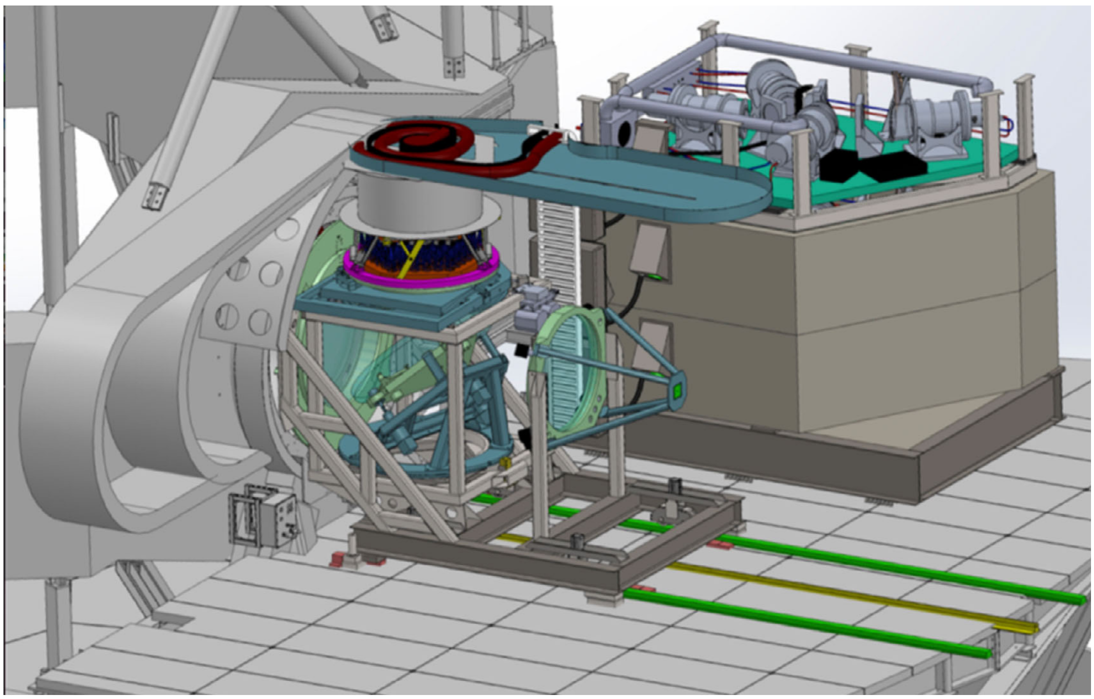

FIGURE 12 FOBOS conceptual layout on the KII Nasmyth Deck. The forward module that houses the ADC, guiding system, calibration system, and Starbugs fiber positioners. The layered bank of spectrographs has four optical channels and will be a permanent installation on the Nasmyth deck.

the focal plane. The design team has envisioned three distinct modes and packaging: Single-fiber multi-object spectroscopy that would allow for approximately 1625 individual objects to be targeted using single fibers each with an on-sky aperture of 0.8”; bundles of 37 fibers for integral field multi-object spectroscopy that would allow for approximately 42 targets to be observed with spatially resolved, integral field spectroscopy over a 5.6” FOV; last, a single 37-fiber IFU will be always available for rapid follow up of ToO with non-negligible localization errors (Figure 12).

4.8 | Wide field imager

Wide field imagers (WFI) have played an essential role for a broad range of science on multiple telescopes, yet a complete concept for an optical imaging system has not been considered despite that a wide-field prime focus camera was part of the original Keck telescope design. The WMKO community recognizes and supports a WFI because combined with the Keck telescope, no other wide-field imager will have the UV sensitivity down to 300 nm for the foreseeable future including ELTs. The imaging system is

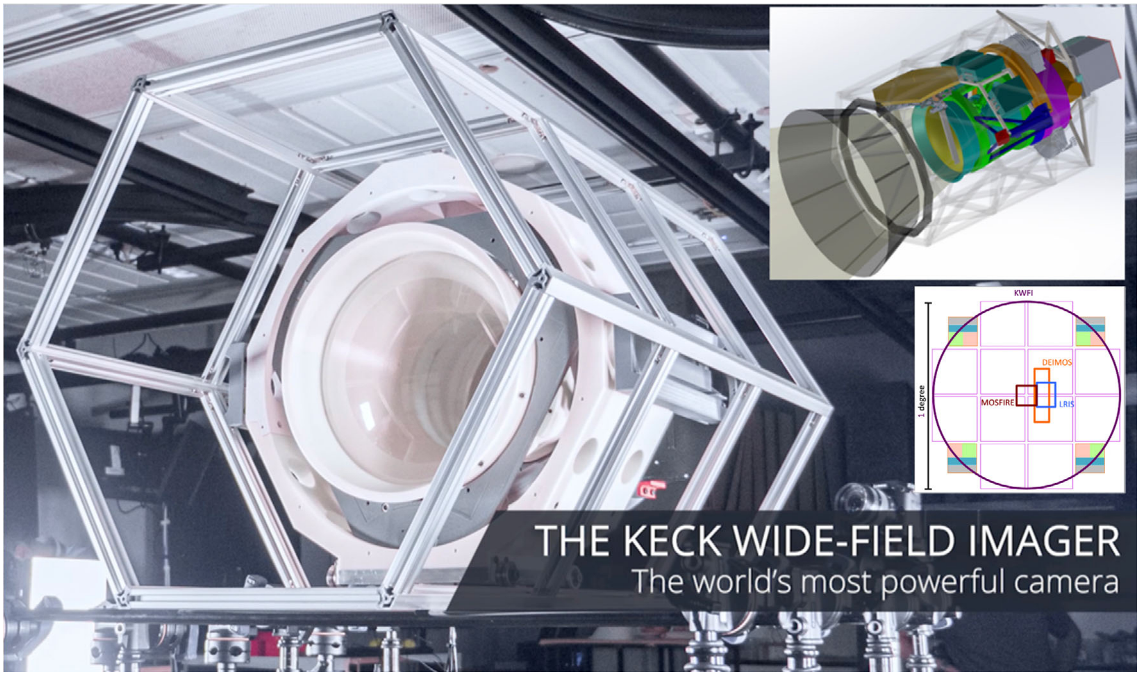

FIGURE 13 An accurate, working 1/4-scale 3D printed model (built by Swinburne University Factory of the Future) of the Wide Field Imager (WFI) for the Keck telescope demonstrating that the design fits in the telescope secondary socket cage. The WFI instrument design includes an internal structure that rolls into the socket that contains the camera barrel housing the optics, a hexapod, rotator, filter exchanger, shutter, electronics, detector, and cryostat system, among other components, established within the volume of the secondary socket. At the top right (inset) is the conceptual design that includes all subsystems and shows a deployable secondary mirror, the laser launch package, and the telescope baffling. The lower right inset shows one of the WFI detector mosaic configurations for achieving a 1-degree FOV using 6K × 6K CCDs and corner CMOS chips in relation to existing WMKO instrumentation FOVs with imaging capability. Image credit: Carl Knox, Swinburne University.

baselined as a 1-degree FOV, with a filter exchanger that hold up to eight filters. At the front is a deployable secondary mirror that will allow WFI to be accessible anytime during the night like the other instruments at the optical ports. WFI has completed a conceptual design study and review and has advanced to seeking funding for preliminary design efforts (Figure 13).

4.9 | Visible wavelength AO instrumentation

In an era of JWST that will dominate IR diffraction-limited observations, the WMKO AO community recognizes that upgrades to the AO bench and new AO instruments capable of operating at wavelengths as short as 500 nm can provide high-contrast imaging that complement JWST observations. The community is exploring the technological parameter space and developing the science cases. NASA's ORCAS mission concept [25] has outlined several science cases supported by optically optimized AO systems and establishes a ground-based synergy that can benefit both WMKO and NASA scientists. As part of this exploration, WMKO in partnership with NASA GSFC will be deploying an imaging camera pathfinder, named the ORCAS-Keck Instrument Development [26], at optical wavelengths in the summer of 2022 to explore the performance of the WMKO AO system down to 650nm. This path will be further paved by an upgrade to the deformable mirror that will be replaced with a new system with an actuator density suitable for short wavelength optical corrections. Over the next five years, WMKO and the community anticipate the development and initial execution of a plan to develop one or more facility class instruments that will supersede the deployed prototype.

4.10 | NIRSPEC second generation

NIRESPEC is a workhorse 1–5 μm high-resolution spectrograph. As stated earlier, it will take advantage of the LFC when it is deployed, but HISPEC is envisioned as the instrument of choice for exoplanet spectroscopy in AO. NIRSPEC is not GLAO compatible nor is it stable. For a couple of years, a team has investigated options for replacing NIRSPEC. The science community would like to preserve solar system science drivers as this instrument has served the NASA solar system observing community.

WMKO would also like to take advantage of emersion grating technology as demonstrated in ISHELL and IGRINS. This year the conceptual design team will continue to review designs for a NIRSPEC replacement that will improve stability, maintain NIRSPEC core science capabilities, and incorporate GLAO technology.

5 | DESIRED FUTURE DETECTOR SYSTEM IMPROVEMENTS, OBSERVATORY TRENDS

In this section, we collected concerns and thoughts from the W. M. Keck community of instrument developers that drive CCD selection. Areas for improvement are presented for future instrumentation or upgrades being considered for the observatory. Although improvements in performance is discussed below, costs for detectors is a driving consideration as the cost for a detector system is a large fraction of the total cost of the instrument and that cost can drive opto-mechanical design choices.

5.1 | Precision radial velocity

To achieve cm/s velocity precision, the KPF team is developing a sophisticated data reduction pipeline that folds in detector characteristics that can mimic radial velocities. How the different detector characteristics impact the ultimate RV measurement floor is a difficult question to answer and platforms like KPF will be used to gain a deeper understanding. Read noise and dark current are random sources of noise, so CCDs are selected with characteristics that exhibit low noise in these two areas. Charge transfer inefficiencies are systematic and can be at the level of 10 cm/s in both the stellar and calibration data. Imperfect charge shuffling can bias the RVs as a function of SNR.

Fringing is a systematic variable that will modulate the stellar spectra, causing apparent RV shifts. Fringing effects can introduce 10s of cm/s error or more in redder (M-dwarf) targets, but is less of an issue for FGK spectral types that have more emission at the bluest wavelengths. The CCDs have been carefully selected to minimize fringing, and KPF has been designed to work at optical passbands where fringing is less of an effect.

Thermal shock during readout can cause a deformation in the CCD flatness, and this warping may result in an RV shift. This has been measured in other PRV instruments, but it is difficult to characterize as the amplitude predicted may be at level of a few cm/s level.

The brighter-fatter effect results in a wider pixel response functions as flux increases, but it is not well understood how much this could impact RVs. KPF will be an instrument where this effect can be probed

To improve the precision of RV measurements and push precision to the cm/s level, improvements to AR coatings can be made to minimize fringing effects, better charge transfer efficiencies will lower CTI induced RV systematics, and improved methods for maintaining temperature across the full area of the CCD will stabilize the detector systems. The latter could come in the form of reducing power required to drive the readouts or perhaps constant clocking to achieve a steady temperature state.

5.2 | Detector systems

Within the WMKO community, STA's Archon detector controllers have become a standard controller for all optical systems. Four Archon controllers are deployed between KPF, KCRM, and the LRIS detector upgrade with a fifth as a common spare. The development of the software hardware external to the Archons is unique at each partner institution, but there is common spare parts between the three projects, and this helps with long-term support.

Caltech engineers have developed an Archon system for IR detectors and have demonstrated successful control of both an H2RG and an Aladdin array. The Aladdin control system is soon to be deployed with the NIRC2 instrument at the observatory and put into routine use in the spring of 2023. With NIRC2, the Archon will eliminate an obsolescence issue as the current Aladdin detector is controlled with an electronics cabinet full of transputers. Not only will this reduce the total power consumption and heat load in the KII AO room, the upgrade to an Archon will improve duty cycle efficiencies and enable new readout modes. The effort with NIRC2 as well as the lab work at Caltech sets a path forward for establishing the Archons as a house controller for all common optical and IR systems.

5.3 | High-level detector characteristic trades

While many CCD characteristics are optimized for the science application, our community of instrument developers are making a key trade when it comes to throughput at long wavelengths, fringing, and cosmic ray detection. These trades are being made because CCDs cannot eliminate fringing and cosmic rays and gain high throughput at the longest optical wavelengths. KPF avoided cosmic rays by selecting thinner CCDs that have good throughput up to 800 nm, while KCRM and LRIS desired the highest throughput at 1 micron at the expense of cosmic rays. KPF avoids both fringing and cosmic rays so that those sources of noise do not impact RV measurements. LRIS and KCRM are able to observe up to 1 micron without fringing, but cosmic rays limit exposure times. In KCRM's case, it will be difficult to discern cosmic rays from emission lines at the highest resolution. Observing techniques will be employed and DRPs will have to be discerning to minimize the impact of cosmic rays at the longest wavelengths.

A few technologies are of interest to the community but are not yet perceived as ready for deployment with facility class instruments. Microwave kinetic inductance detectors, germanium detectors, and skipper CCD technologies are all seen as future possible systems that can be folded into new instrumentation or as upgrades with existing instruments, and the observatory is tracking progress of these technologies.

6 | SUMMARY

W. M. Keck Observatory has a strategic plan that defines a suite of new instrumentation that will support future science pursuits identified by our larger community of observers. The new facility class instrumentation ranges from optical seeing limited imagers to adaptive optics fed infrared integral field spectrographs. The detector systems of deployed instrumentation in use at the observatory is aging and has some obsolescent issues, and identified paths forward to eliminating these issues are underway. Recent work within our community of instrument developers have identified controller hardware that has become the defacto standard for instrumentation due to common use across institutions, and future detector system technologies are of interest to the community in order to reduce the noise floors.

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The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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Marc Kassis is the instrument program manager at the W. M. Keck Observatory working in collaboration with our mainland instrument developers and science community to identify and bring to life new technologies that keep the observatory at the forefront of astronomy. For over a decade, he was a WMKO staff astronomer working with visiting astronomers at night and maintaining and upgrading the instrument suite. He became interested in astronomy while participating in a Research Experience for Undergraduate astronomy program which was sponsored by the National Science Foundation and hosted at the Cerro Tololo Inter-American Observatory in La Serena, Chile. He was raised in Idaho and graduated from Twin Falls High School before enrolling at Willamette University in Salem, Oregon. In between his sophomore and junior years at Willamette, he decided to take a year off to explore what physics had to offer by interning at the Brookhaven National Laboratory and at Cerro Tololo. Eventually, he graduated from Willamette after studying physics and mathematics, and then earned a Ph.D. in Astronomy in 2003 from Boston University where he studied for six years and built an mid-infrared spectrometer and imaging instrument for the NASA Infrared Telescope Facility on Maunakea.

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