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Innovations and advances in instrumentation at the W. M. Keck Observatory, vol. II

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ABSTRACT

Since the start of science operations in 1993, the twin 10-meter 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

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development teams, as well as 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. This paper summarizes the performance of recently commissioned infrastructure projects, technology upgrades, and new additions to the suite of instrumentation at the observatory. We also provide a status of projects currently in design or development phases, and since we keep our eye on the future, summarize projects in exploratory phases that originate from our strategic plan updated in 2022.

Keywords: Infrared, Optical, Instrumentation, Imager, Spectrograph, Integral Field, Laser Guide Star, 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, work- horse 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), and the Space Science Laboratory (SSL) in Berkeley are developing new capabilities and upgrading existing facility instruments. At the end of 2022, a revised WMKO strategic plan will be released, setting a directive for new technologies to pursue over the next decade. 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 towards achieving the goals in both the current and future strategic plans are described below. A summary of the existing instrumentation suite is provided, followed descriptions of instrumentation that is recently deployed, about to be deployed, and in early phases of development. Last, we mention the impact of the global pandemic has had on both projects and science operations.

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 [1] including the rapidly evolving theme of TDA.

Table 1 shows instrument capabilities available to all observers on 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, simultaneous 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.

3. EXPANDING AND ENHANCING WMKO CAPABILITIES

Over the next decade, WMKO will deploy new flagship instrumentation and adaptive optics capabilities and begin or continue design investments in instrumentation to be delivered in 2028 and beyond. WMKO will develop new software infrastructure and user services to support both existing and future capabilities with direct benefits to the US astronomical community as recommended by Astro2020 [1]. New capabilities not only drive science, but also increase efficiency and impact of our current operations. Advances in our software infrastructure that configures and controls instrumentation improves the amount of on-sky science time, and improvements in AO deliver more science per second on the sky. Advancing data reduction pipelines and archival capabilities reduce the time and effort required to yield science quality data and make data from WMKO more accessible to the US community through Keck Observatory Archive (KOA).

Table 1: The current suite of instrumentation and AO at WMKO in 2022.

Current instrumentation suite as of 2022A semester			
Name	**Tel**	**Capabilities**	**Delivery**
LRIS	KI	Low Resolution Imaging Spectrometer. Multi-object, 310 to 1000 nm dual-beam spectrometer/imager. Long slit, multi-slit, R = 300 to 5,000, imaging 6' x 8' FOV, polarimetry.	1993
HIRES	KI	High Resolution Echelle Spectrometer. Single object, 320 to 1000 nm echelle spectrograph; R = 30,000 to 80,000. 4k x 6k detector.	1993
MOSFIRE	KI	Multi-Object Spectrometer for Infra-Red Exploration. ~0.9 to 2.5 µm spectrometer/imager. Multi object up to 46 slits over a 6.1' x 3' field with R ~3,300 or a 6.14' x 6.14' FOV	2012
OSIRIS	KI	OH-Suppressing IR Imaging Spectrograph. Near IR integral field spectrograph (0.9 µm to 2.5 µm), simultaneous diffraction-limited imaging and R ~ 3,900 spectroscopy behind the Keck I AO system.	2005
KI AO	KI	Adaptive Optics System. Natural guide star and laser guide star modes available for use with OSIRIS. 22 watt solid state 589 nm laser for the LGSAO system.	2001(NGS) 2010(LGS)
ESI	KII	Echellette Spectrograph and Imager. Single object, 390 to 1000 nm imager (to 2' x 8' field) and spectrograph (R = 1,000 to 32,000).	1999
DEIMOS	KII	Deep Extragalactic Imaging and Multi-Object Spectrograph. 400 to 1000 nm imaging (17' x 5' FOV) and R up to 6,000, long slit, multi-object spectroscopy.	2002
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
NIRSPEC	KII	Near Infrared Spectrometer. Single object, 0.95 to 5.5 µm spectroscopy (R = 2,500 and R = 25,000) with 1k x 1k detector.	1999
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
NIRC2	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.	2001
KII AO	KII	Adaptive Optics System. Natural guide star and laser guide star modes available for use with NIRC2 and NIRSPEC (NIRSPAO). 22 watt solid state 589 nm laser for the LGSAO system. NIRSPAO interfaces with AO for 1-5 mm spectroscopy or may be fed light through a fiber from a fiber injection unit called KPIC.	1999(NGS) 2003(LGS)

Astro2020 [1] identifies updates to the US observatories' suite of instrumentation are critical to the future effectiveness of ground-based facilities, and WMKO recognizes that our leadership role in discoveries is maintained by investments in facility class instrumentation. Direct imaging of exoplanets and the gravitational effects near the Milky Way's central black hole are just two examples of technology-enabled discoveries that are achievable through a robust support of technology renewal at WMKO.

To further our technology-enabled discoveries, WMKO executes an instrument lifecycle development program designed to mature and deploy new instrumentation technologies that meet the needs of the evolving science interest of the observing community. WMKO's lifecycle development process is inspired by NASA and NSF program principles and streamlined to emphasize and maintain flexibility to adapt to different project scales. WMKO's instrumentation lifecycle is broadly categorized by Design Formulation and Construction that is consistent with NASA's nomenclature with progressive steps under these categories tied to reviews and key decision points before moving to the next stage of the project (see figure 1). SSC prioritized projects advance to the next phase when recommended by the SSC and endorsed by the observatory Board. Key decision points often follow a review by an external committee that is designed to provide periodic assessments of technical and programmatic health. Reviews serve to inform stakeholders that includes NASA representation at the SSC and NIKUG, and those stakeholders then make recommendations for technology development to the Board and WMKO leadership before committing to the full construction.

Design Formulation starts with the initial concept and brings it to a full Preliminary Design with phases that includes 1) initial concept development, 2) Phase A system design maturation, 3) Proposal Development characterized by the submission to funding agencies, and finally, 4) preliminary design phase with common definitions with federal funding agencies. The trajectory for the early design formulation phases is tied to the calendar year as it is driven by national grant deadlines with more common instrumentation grant opportunities found during the winter months. The community composes and submits white papers for concepts, phase A/system design, proposal development activities, and mini grants in response to a white paper call from WMKO and the SSC in May as part of the annual cycle (https://www2.keck.hawaii.edu/inst/common/Instrument_Development/InstrumentDevelopment.php). The progression assumes a one-year duration for each phase, but the schedule and process are flexible. At the request of the SSC, some projects may spend multiple years in a phase before advancing to the next. Larger projects may require multiple years of design investment before the SSC and Board approve moving forward. The construction category encapsulates both the implementation phase that includes finalizing the instrument designs and building the instrument, and a commissioning phase that includes integration of the instrument at the observatory and nighttime engineering activities before releasing the instrument for general use.

In the sections to follow, we present the instrumentation that has been commissioned, in the final stages of construction and deployment, and new strategic initiatives that tie back to WMKO's strategic plan to be released fall 2022.

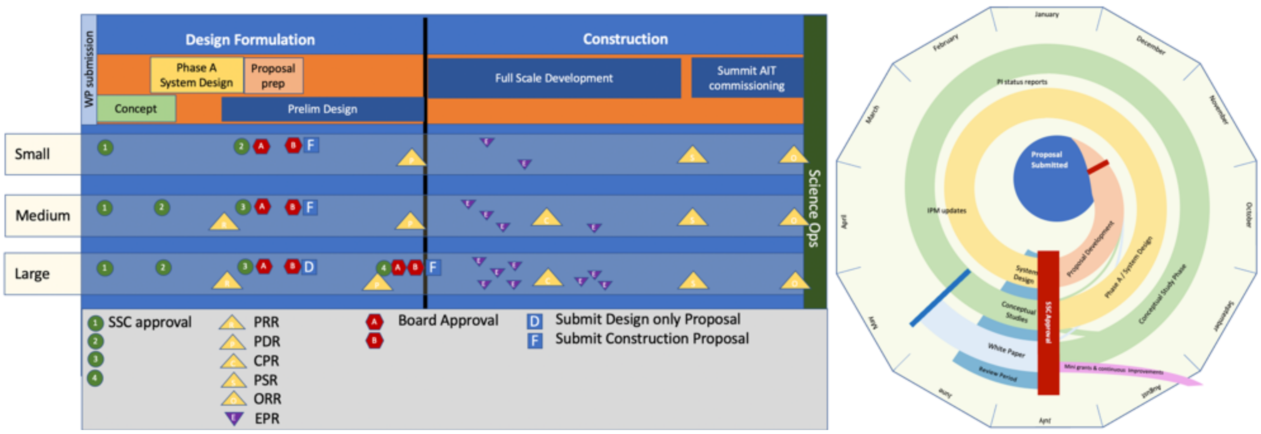

Figure 1: Left: Instrumentation Life Cycle for WMKO projects. SSC and Board approval happen during Design formulation phases. Major project reviews are defined by the yellow triangles. Engineering Peer reviews combined with the Construction Programmatic Review for a two-stage review process during full scale development that is consistent with NASA. Right: Early Design Formulation Phases are funded internally though a flexible early development cycle tied to the calendar year as funding opportunities are driven by annual proposal call from public granting agencies. Proposals are submitted during Design Formulation to secure full project funding following SSC and Board recommendations and are often submitted to NSF opportunities offered in late fall and winter.

4. COMMISSIONED INSTRUMENTATION

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 (see next section). The upgrade project would replace the existing LRIS Red detector system with an more sensitive detector and modernize the controller. The CCD is identical to the KCRM detector that is a 500 um thick, fully-depleted 4k x 4k CCD made by Lawrence Berkeley Laboratory, the same group that made the current CCDs in the LRIS red channel as well as the CCDs for the SDSS-BOSS spectrographs and the Dark Energy Camera. This new CCD has a faster readout, improved readnoise, and a similar QE as the previous red mosaic with binning available in the spatial and spectral direction. The 4k x 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 sparing with a third instrument. With this deployment, WMKO took a major step in addressing an obsolescence issue with optical CCD controllers at the facility.

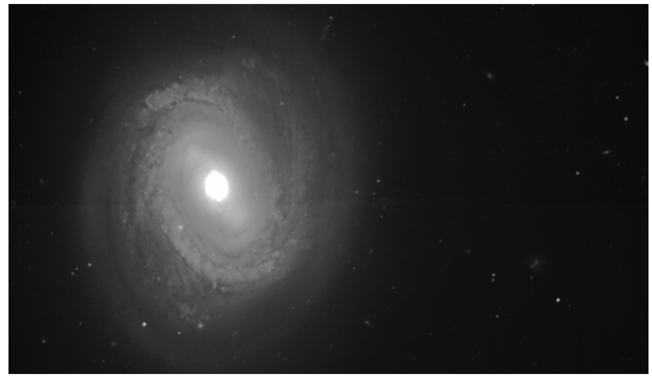

Figure 2: (Left) LRIS Red summit integration team Sunil Simha, Percy Gomez, Dale Sandford, Nick Souminen, PI Connie Rockosi, Dwight Chan, Arina Rostopchina, and Sherry Yeh. (Right) First light image of M58.

LRIS Red IV achieved first light on 27 April 2021 and began science operations on 7 May 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.

5. INSTRUMENTS IN THE CONSTRUCTION PHASE:

There are four instrumentation projects in the construction phase of development that will become available to the US community in the next few years. These instruments are summarized in Table 3 and explained in detail below. These projects have full funding and will soon be fully commissioned and released for community use.

Table 2: Instrumentation and AO capabilities in the final construction phase.

Future Instrumentation the Final Construction Phase			
Name	Tel.	Capabilities	Delivery
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
KCRM	KII	Keck Cosmic Reionization Mapper. Red beam upgrade to the KCWI instrument extending the wavelength coverage of KCWI to 1 μm	2022
LFC	KII	Laser Frequency Comb for the infrared. Picket fence calibration spectrum covering the 900-2400 nam range suitable initially for use with NIRSPEC and eventually for HISPEC	2022
KAPA	KI	Keck All-sky Precision Adaptive-optics. Upgrades the KI LGSAO system with a new laser divided into three laser guide stars for more complete atmospheric correction, upgraded hardware for real-time wavefront corrections, and the camera that measures the atmospheric turbulence. Improves performance for OSIRIS and dovetails with Liger and VisAO instruments.	2024

5.1 The Keck Planet Finder

KPF [2] 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 if they are commonly "rocky" like Earth or are enshrouded in thick envelopes and thus incompatible with life.

At the heart of KPF is a stabilized, fiber-fed, high-resolution ($R \geq 90{,}000$) echelle spectrometer with 'green' (445–600 nm) and 'red' (600–870 nm) channels (Figure 3). Light from Keck I enters a Fiber Injection Unit [3], 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 [4]. The FIU sends light to the spectrograph and CaH&K spectrometer [5] 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.

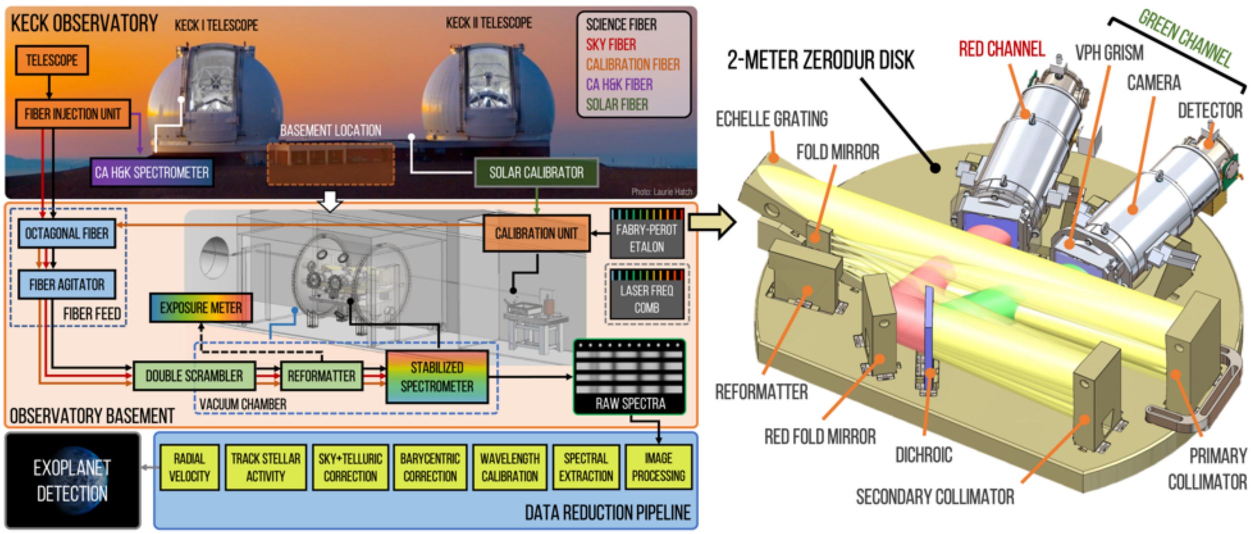

Figure 3 KPF is a complete radial velocity measurement system, encompassing a range of subsystems that are optimized for precision and efficiency (left). The instrument has the largest footprint of all instruments at the observatory that extends from the basement to the AO enclosure where the Ca H&K 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 4 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.

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^{-9}K^{-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 <0.5m/s for a single measurement.

The KPF development team successfully completed a pre-ship review and is delivering the instrument in July 2020. KPF first light is planned for November 2022 and will be available for observer use starting in the 2023A semester. 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.

5.2 The Keck Cosmic Reionization Mapper

The Keck Cosmic Re-ionization mapper (KCRM) is designed to augment the existing KCWI [6,7] 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 opto-mechanical design allowed for a phased deployment of two channels that cover the visible portion of the spectrum from blue (350 to 560nm) to red (530nm to1050 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.

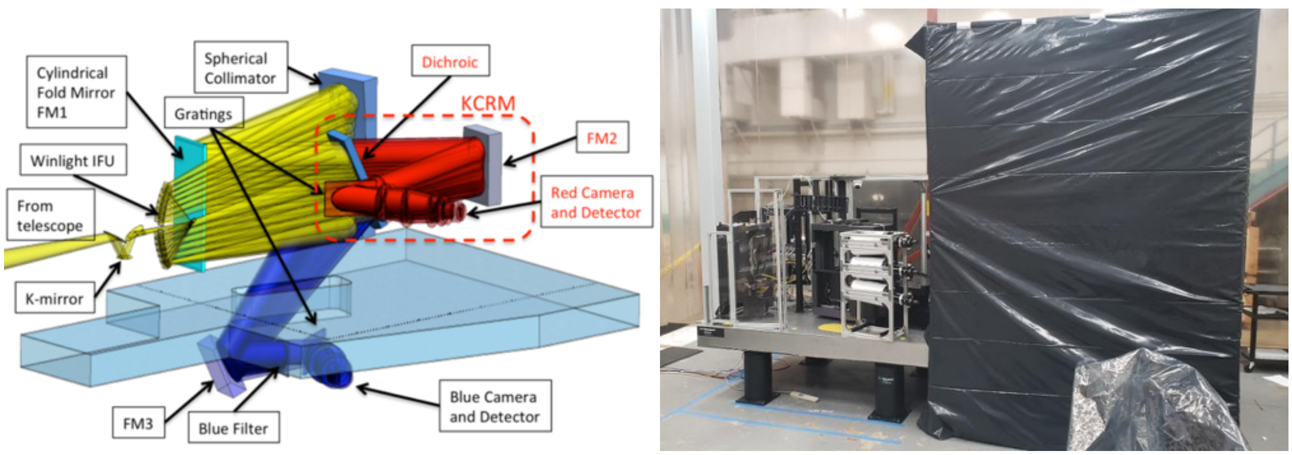

Figure 5 Left: Optical layout of KCRM folded into the existing KCWI spectrograph optical design. The Dichroic replaces a flat mirror with all elements in red part of the KCRM deliverables. The mechanical articulation stage (not identified) will move the camera and detector assembly to sample wavelength 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.

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 4k x 4k x 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 AI&T 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 Spring 2023 as part of the 2023A semester.

5.3 Infrared Laser Frequency Comb

Offering precision radial velocity calibration capabilities in the near-infrared, the IR Laser Frequency Comb (LFC) will enhance the existing NIRSPEC behind AO which to date has demonstrated 50 m/s precession [ref]. Adding an LFC to NIRSPEC would immediately provide a wavelength solution that is anticipated to provide an order of magnitude improvement in RV measurements (less than 3 m/s), and thereby open up new areas of exoplanet research at Keck, especially those orbiting cool stars. The LFC would also characterize the spectral resolution and line shape of NIRSPEC which are critical for obtaining direct exoplanet spectra. NIRSPEC and the LFC will benefit from two deployed systems that includes A near-infrared pyramid wavefront sensor implemented with the Keck II AO system [28] and the recently implemented Keck Planet Imager and Characterizer (KPIC). The PyWFS works in conjunction with NIRC2 as well as NIRSPAO with KPIC which consists of an AO-fed single mode fiber injection unit [29] that couples exoplanet light into NIRSPEC to provide spectral resolutions of ~30,000.

When NIRSPEC is supplanted by the proposed HISPEC (see below), the same LFC with only minor upgrades will provide HISPEC observers sub-m/s precision across the near-infrared. The LFC would immediately transfer over to HISPEC to provide sub-m/s instrumental stability. Only modest upgrades would be needed to expand the LFC's wavelength coverage to cover the 900-2400 nm range of HISPEC. Science goals enabled by the addition of the LFC to NIRSPEC and subsequently to HISPEC include: 1) Validating and characterizing transiting planets which orbit classes of stellar hosts challenging to observe with other instruments. These include late M stars, young active stars, and close binary stars which can only be spatially resolved with an AO system; 2) Using the Doppler technique to map the surface properties of the surface of brown dwarfs (with NIRSPEC) and eventually of exoplanets (with HISPEC) 3) Improving direct exoplanet spectroscopy with the existing KPIC Fiber Injection Unit (FIU) by providing a more accurate wavelength solution; and 4) Investigating the wavelength dependence of stellar activity by combining data from visible light instruments, initially Keck's existing HIRES spectrometer and soon the new Keck Planet Finder (KPF). Noise due to uncorrected stellar activity is one of the major impediments to the detection of low mass planets. The LFC development team is in the final phases of the laboratory AI&T and will deliver the instrument in fall 2022. The LFC first light with NIRSPECAO is planned for early 2023, with science operations beginning in the 2023A observing semester.

5.4 Keck All-Sky Precision Adaptive Optics

The Keck All-sky Precision Adaptive optics (KAPA) [8] 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 [9,10] to eliminate the "cone effect"; increased sky coverage by 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.

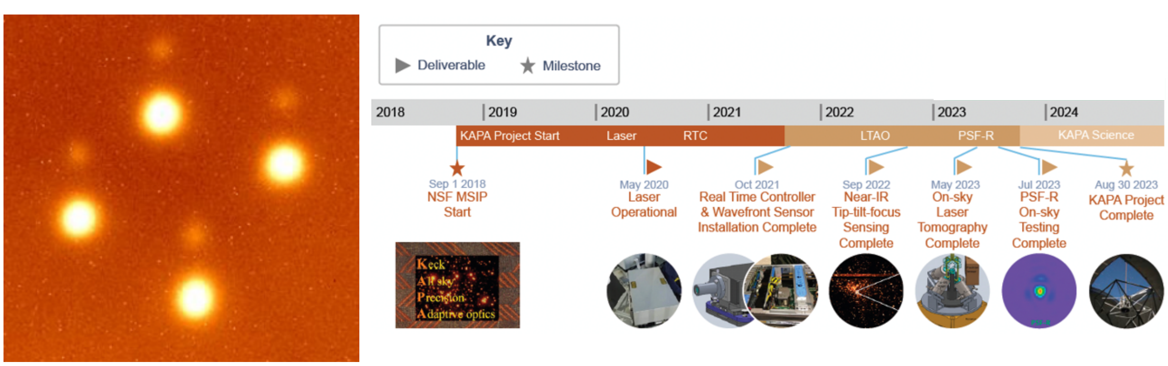

Figure 6: Left: Laser Asterism projected on sky in April 2022 (ghosts are from the acquisition camera); Right: KAPA project timeline showing the major deliverables.

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.

6. INSTRUMENTS IN THE DESIGN FORMULATION PHASE

Table 4 lists the instrument projects in different design implementation phases and range from early concept development to ending preliminary design. 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 complete 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 that includes exoplanets, and it will improve the overall productivity and science return with the Keck I AO system when it replaces the existing OSIRIS instrument.

Table 3: Future instrumentation capabilities at different phases of development.

Future Instrumentation in later develement phases			
Name	**Tel**	**Capabilities**	**Delivered**
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
SCALES	KII	Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy. Integral field spectrograph and imager, wavelengths 2–5 µm, configurable 0.13-4.5 square arcsec FOV and ressolutions (R=50--7000). Imaging 13 arcsec FOV.	2025
Liger	KI	Second Generation IR integral field spectrograph. Configurable spectral resolutions (R=4000-10000) and 0.4-90 square arcseconds FOV, wavelength coverage from the optical through the near infrared (0.84-2.4 µm). Imaging arm 20 arcsec FOV.	2027
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
Future Instruments in Conceptual Phases			
ASM	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
WFI	KII	Wide Field Imager. Prime focus, 1 degree field of view imager covering 300-1000 nm.	TBD
LRIS II	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
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
TBD	KI	Visible AO instrument. Imager or integral field spectrograph paired with an adaptive optics system optimized for shorter wavelengths. 500nm-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
TBD	KII	Target of Opportunity Dedicated Astronomy Instrument. Single object, high throughput, OIR spectrograph, R~2000-4000 specifically optimized for time domain astronomy	TBD
TBD	KII	Immersion Grating Near Infrared Spectrograph. Single object spectrograph with simultaneous 1.08-5.4 µm wavelength coverage, high resolution R~30,000. Envisioned as a second generation NIRSPEC.	TBD

6.1 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 [11].

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.

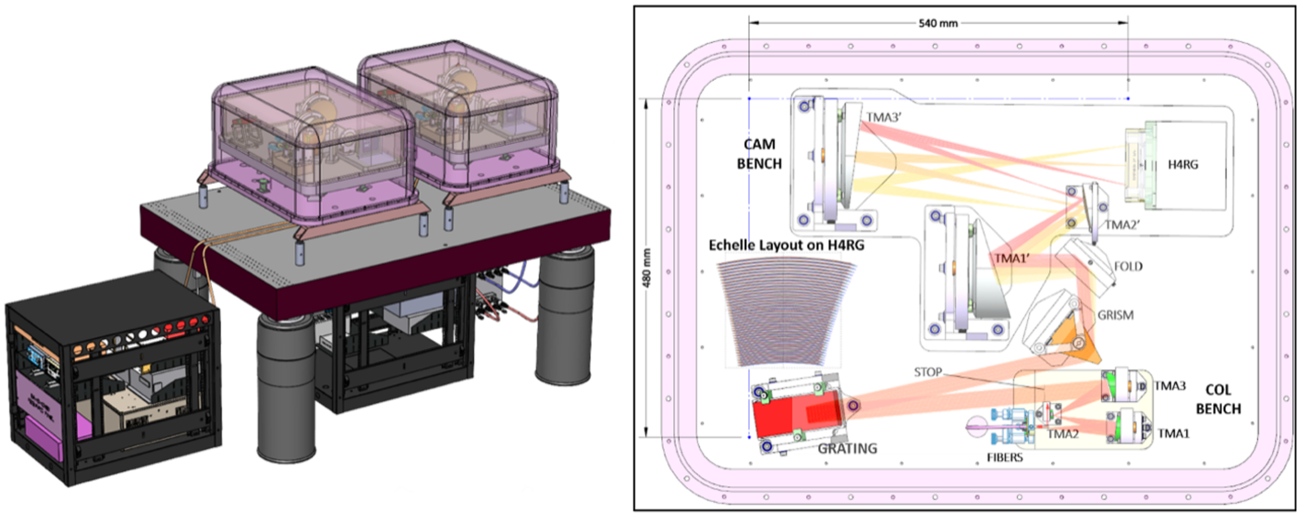

Figure 7 Left: HISPEC instrument layout including 6-foot lab bench, electronics racks, and cryostat to be in the basement of Keck II. Right: Top view of the spectrograph opto-mechanical layout inside the cryostat.

6.2 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 [12]. 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 ($\lesssim$ 1") 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 [13,14,15,17,18]. 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 a FOV of 12 arcsec [18].

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, characterizing, 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.

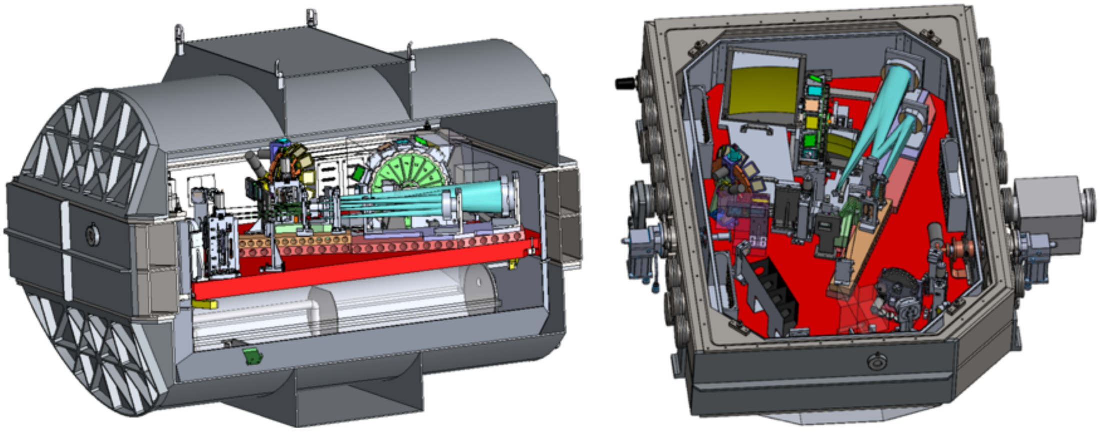

Figure 8 SCALES cryostat and opto-mechanical layout as presented during a preliminary design review. The optical bench is a single layer with two detector systems for both an imager and IFS. SCALES rides on a cart that can roll into the KII AO enclosure.

6.3 LIGER

All three planned Extremely Large Telescopes (ELTs) highlight the scientific need for a general purpose next-generation AO-fed integral field spectrograph and a 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 [19].

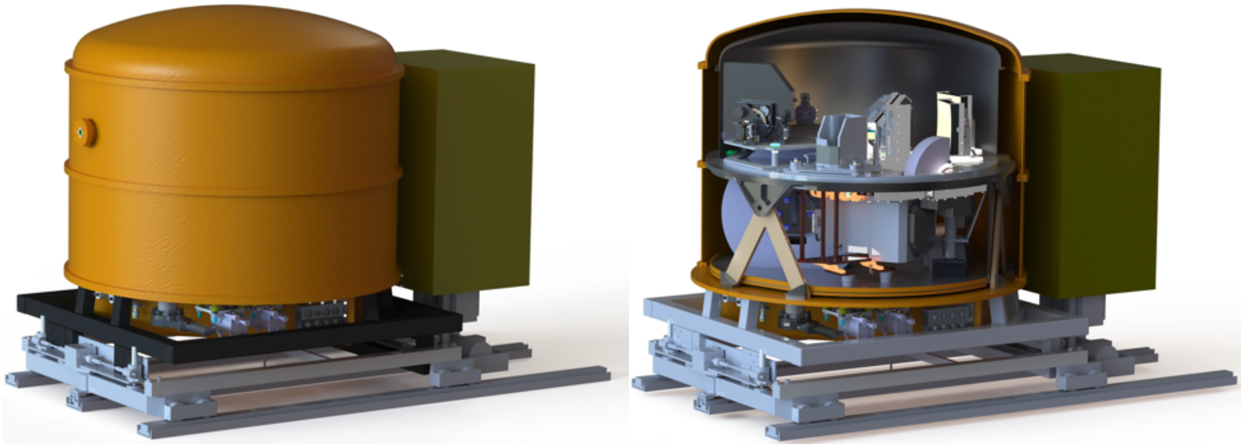

Figure 9: (Left) Liger cryostat on the transfer cart with entrance window on the cryostat. (Right) Cross section of the cryostat revealing the subsystem layout above and below the primary optics bench.

Liger will combine a 0.81-2.45μm imaging camera and IFS that may operate simultaneously. Liger has a custom-designed imaging camera [21], and its IFS is a duplicate of the IRIS spectrograph [22]. 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"x6.8" to 1.9"x1.9" 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 [1], 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 was funded through completion of the preliminary design phase, and the project is in the process of raising full construction funds.

6.4 DEIMOS Upgrade

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. Amongst the most prolific optical multi-object spectrographs is the Deep Imaging Multi-Object Spectrograph (DEIMOS), commissioned in 2002. Overall DEIMOS remains a workhorse 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.

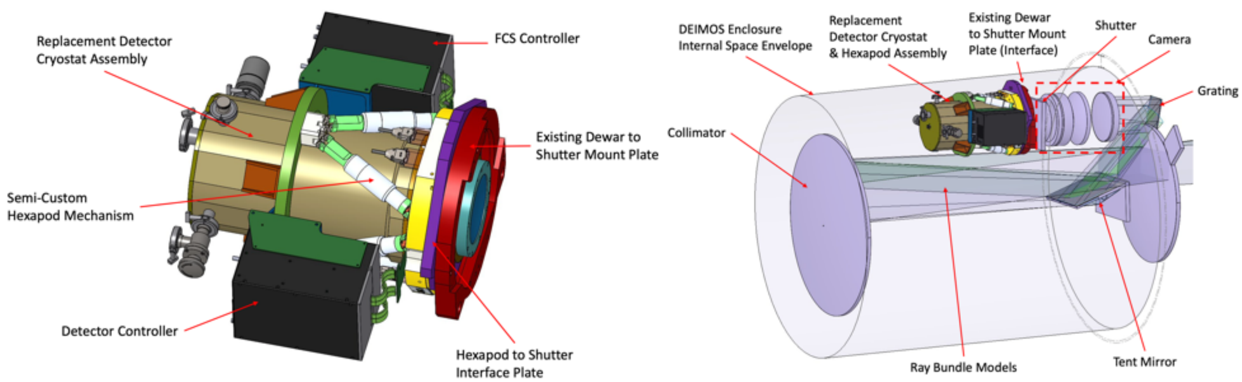

Figure 10: Left: Rendering of the DEIMOS upgrade subcomponents. Right: The shutter mount plate is the interface with the existing spectrograph and the upgrade components are show in context with the DEIMOS optical layout in the instrument barrel.

7. INSTRUMENTS IN THE CONCEPTUAL PHASE:

In the upcoming strategic plan, the WMKO community anticipates that a major emphasis will be placed on developing adaptive secondary mirrors (ASM) for both telescopes and that this enabling technology will drive new innovations for the existing AO benches as well as instruments that that work with AO or with a GLAO system. WMKO anticipates that all traditionally seeing limited instrumentation should now be GLAO compatible. ASMs on 8-10m class telescopes will provide a competitive advantage in the next decade as future space-based missions deploy and new large ground-based facilities achieve first light. Table 4 lists instruments in the conceptual phase. These have been identified by the SSC as of strategic importance to the future. If funding were secured for instruments in the conceptual phase, these instruments would come online in the 5-10 years.

7.1 ASM

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\cite{Hinz2020}. Current generation ASMs are implemented at several telescopes, including the MMT, LBT~\cite{Riccardi2010}, Magellan, and VLT using Lorentz force (commonly called voice-coil) actuators that deform thin glass shells that serve as the secondary mirrors (see \cite{Biasi2010} for an overview). 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 to 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 [22].

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\cite 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.

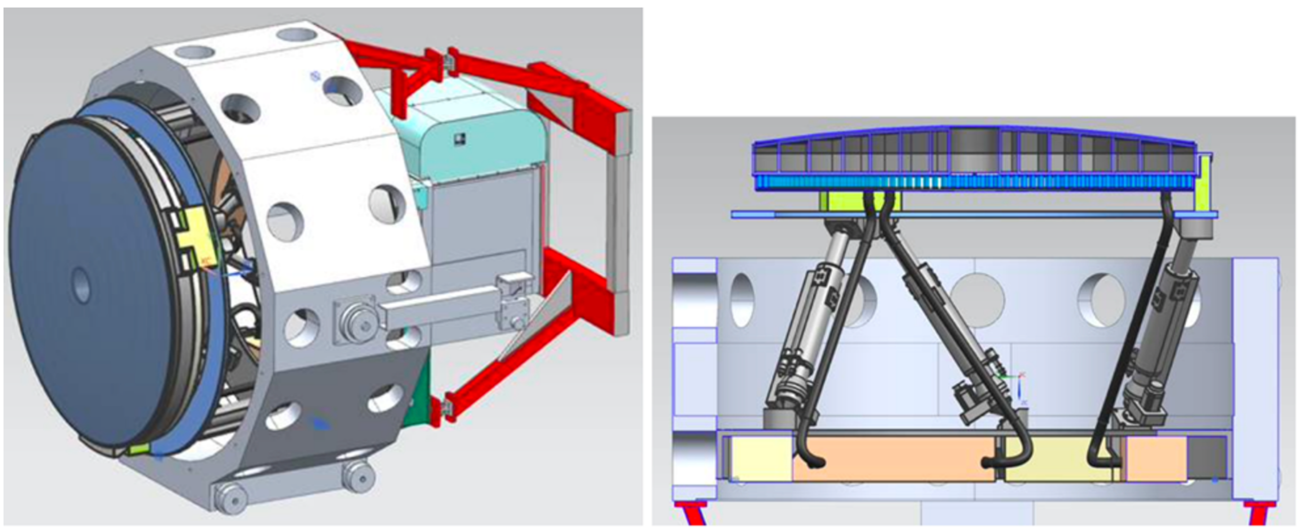

Figure 11: Left: concept for an ASM for Keck housed in an existing Keck top-end hexagonal structure that defines at the secondary socket. Right: cross section showing the ASM mounted on a hexapod for precision static alignment.

7.2 LRIS-2

LRIS is one of the most in-demand, productive, and impactful instruments at WMKO because of its versatility providing sensitive imaging, single-target, and multi-object spectroscopy over the entire ground-based optical window (3100-10,000Å). LRIS's UV optimized optics and detector combined with the 10m aperture, and a superb site make 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' × 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 150mm collimated beam. A dichroic beamsplitter reflects the beam into the blue channel for wavelengths 3100-5600 Å and passes wavelengths 5500−10300 Å 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×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.

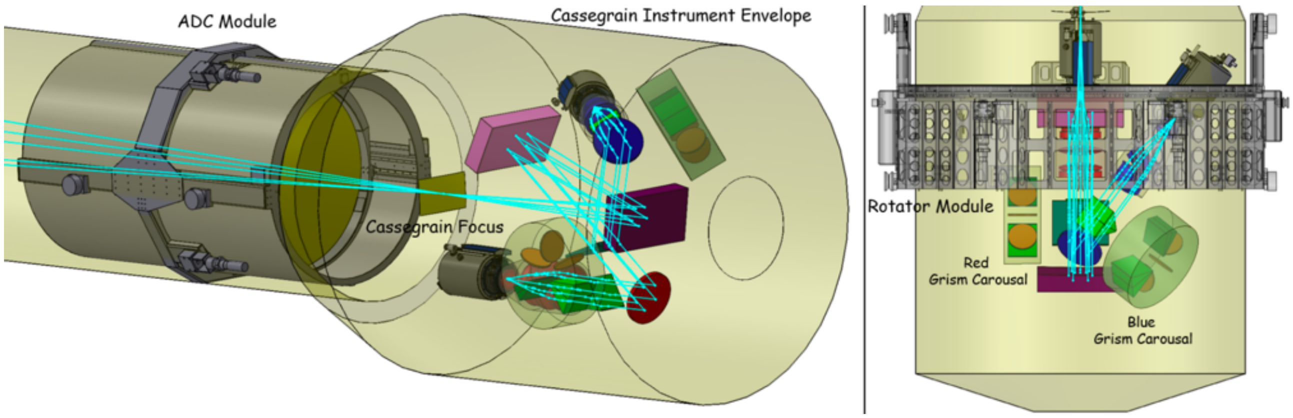

Figure 12: Conceptual optical layout for LRIS-2 with the volume of the KI Cassegrain socket defining the instrument envelope. Also depicted is the existing ADC module that LRIS II will reuse. Top-down view of the instrument with a facility rotator module.

7.3 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) [23].

The FOBOS forward module consists of the atmospheric dispersion corrector, 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 [24]. The StarBug actuators are semiautonomous robots that can move the fibers into almost any configuration by using a pair of piezo ceramic tubes which allow the actuators to walk across 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 targets of opportunity (ToO) with non-negligible localization errors.

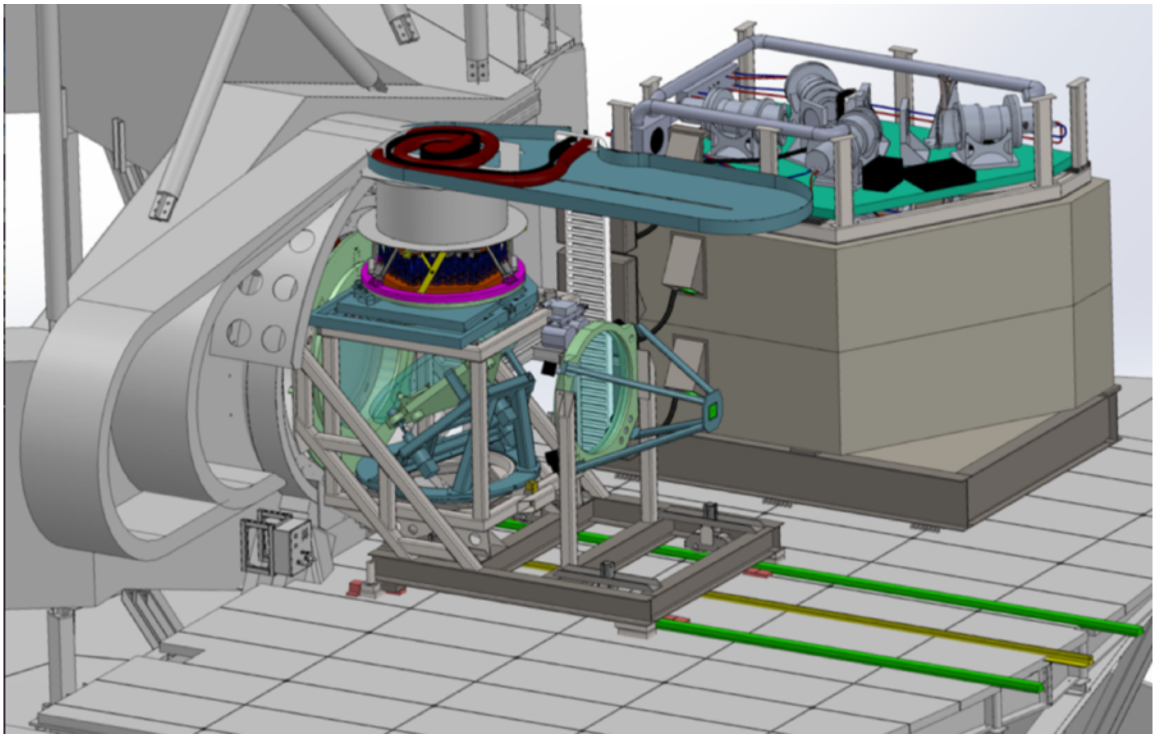

Figure 13: FOBOS conceptual layout on the KII Nasmyth Deck. The forward module that houses the ADC, guiding system, calibration system, and Starbugs fiber positioners. The layered bank of spectrographs has four optical channels and is will be a permanent installation on the Nasmyth deck.

7.4 AO at Optical Wavelengths

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 summer 2022 for exploring 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.

7.5 WFI

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 300nm for the foreseeable future including ELTs. The imaging system is 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.

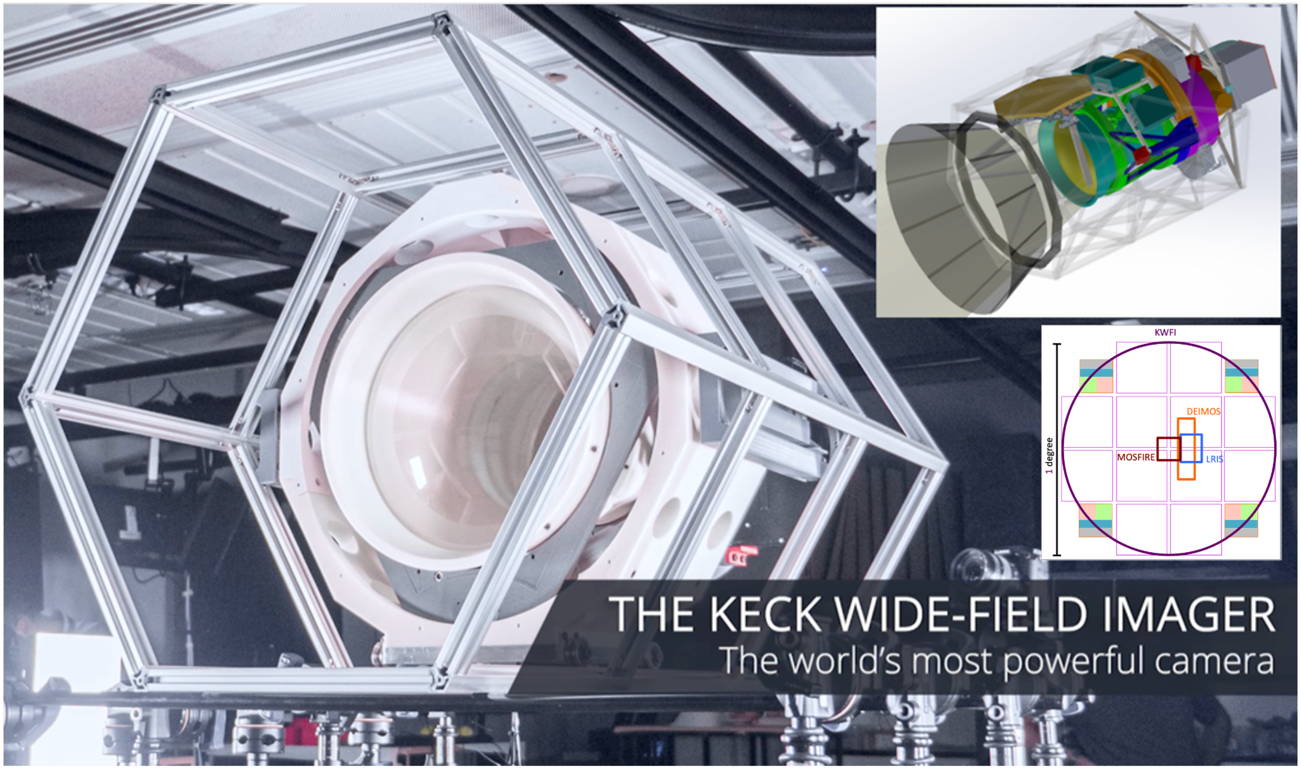

Figure 14: An accurate, working 1/4-scale 3D printed model (built by Swinburne University Factory of the Future) of the Wide Field Imager (WFI) for the Keck telescope demonstrating that the design fits in the telescope secondary socket cage. The WFI instrument design includes an internal structure that 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 x 6K CCDs and corner CMOS chips in relation to existing WMKO instrumentation FOVs with imaging capability. Image credit: Carl Knox, Swinburne University.

7.7 Second generation NIRSPEC

NIRESPEC is a workhorse 1-5μm 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.

8. COVID IMPACTS ON PROJECT DEVELOPMENT

At the start of COVID, WMKO instrument project managers were immediately asked to track COVID related costs, and the PMs worked to differentiate the COVID impacts from natural project delays expected to occur within the natural instrument development cycle. COVID impacts fell into four categories that we categorize as lab and facility restrictions, remote work inefficiencies, vendor and supply chain delays, and staffing retention. Project leads worked to maintain both technical progress and scope at the expense of schedule. Often this led to increase costs.

All partner campuses at the start and height of the pandemic put in place protocols to keep staff and families safe. These protocols were great measures that maintained safety for individuals and helped projects maintain some semblance of momentum. However, project work was inhibited for several reasons. Tasks requiring multiple staff required extraordinary planning and safety measures. On-site problem and brainstorming solutions were restricted to one or two individuals, and thus, what could have been resolved in a few hours in a group setting would take days. Safe-at-work procedures and policies restricted lab capacities, incurred more PPE costs, and required more management overhead. On campus labs and shops shut down resulting in stalled activities and fabrication delays. Restrictions on inter campus visits prohibited staff ability to work in real time on interfaces and sub-system deliveries.

Although video conferencing primarily through Zoom helped keep projects communicating, video conferencing required additional management loads to keep staff connected; site visits with vendors were less effective, major reviews could not evaluate the facility or the subsystems in person, and there was a general loss of team continuity. In addition, no one was prepared to work from home, and thus, delays and costs were incurred as staff set up home offices and garage lab spaces. Internet connections at home were not ready to support a significant increase in required bandwidth. Remote access to work computers were often slow throttling development on major software packages like Solidworks and Zemax. Garage lab spaces were never fully equipped and yet staff proved resilient; a detector controller under development in an EE lab space was being remotely controlled by a software developer from their home miles away. Last, staff had additional family responsibilities. Staff became part-time schoolteachers and cared for elderly parents. On the positive side, family members got to see first-hand the engineering the project staff completed, and in some cases, were drafted to assist.

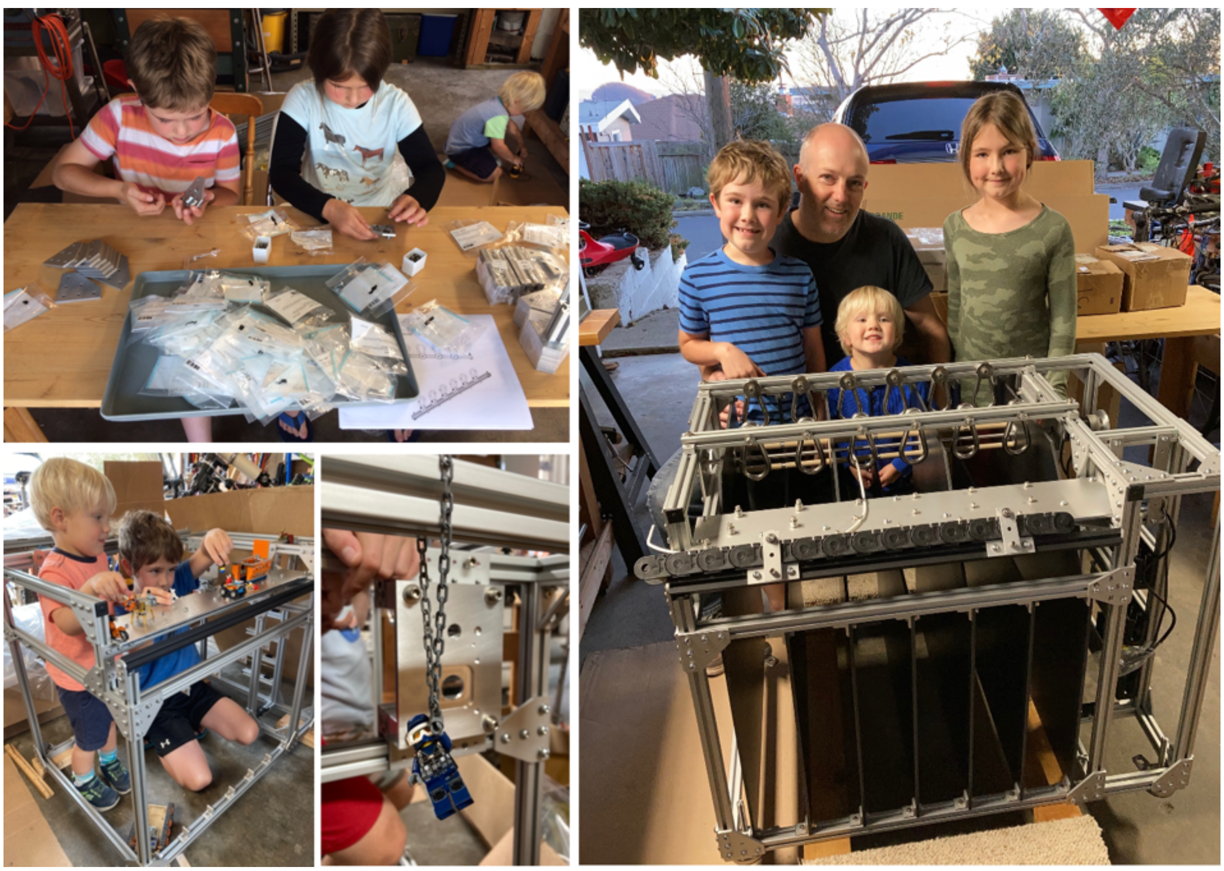

Figure 15: The Gibson family of engineers assembled and delivered the Agitator subsystem. Long breaks were included in the assembly process with the agitator housing serving and the project manager found some Lego workers just hangin' around.

Vendor and supply chain delays required creative solutions and in some cases schedule delays were unavoidable. Projects work moved to alternative DoD vendors when initial vendors closed, but some vendors could not be changed. Vendors became more selective due to their own staffing issues, and in some cases did not take or rejected custom fabrication work.

Force Majeures were triggered to release vendor schedule obligations and supplier deliveries were slower or staggered causing delays and a loss in efficiency

WMKO and partner institutions were not immune from the Great Resignation or Great Re-Evaluation. Staff vacancies halted instrument development activities. A slower turn around in replacing individuals made it difficult to plan and maintain schedule. New hires were sometime unintendedly siloed on projects and isolated from other staff members. While vacancies remained, project management drafted individuals to assist from other departments. All of these contributed to staff stress as institutions tried to accomplish the high priority tasks while unavoidably continuing to slip schedule. Acknowledging this stress and unusual working conditions was key for retention and on-boarding new team members.

9. REMOTE OBSERVING ADVANCES RESULTING FROM COVID

Prior to the onset of the COVID pandemic, approximately 45% of NASA PIs observed remotely using remote operations facilities across the mainland United States (including facilities in Pasadena, New Haven, and Maryland), on O`ahu, and internationally. In response to COVID travel restrictions and social distancing protocols at WMKO, a new mode of remote observing was quickly developed (nicknamed "pajama mode"), allowing observers to conduct observations from any location with an internet connection. This mode of observation effectively constituted all observations for many months and remains very popular (>50% of observations today) as travel and COVID restrictions lift. The NASA IRTF Keck Users Group (NIKUG) highlighted the advantages of this remote observation mode on multiple cases and has encouraged WMKO to retain it indefinitely. WMKO continues to update and enhance this remote capability and anticipates it to be a permanent addition to our observing options [27]. Additional side benefits of "pajama mode" observing include reduced environmental impact, and the ability for larger observing teams and/or students to participate in Keck observing at any one time.

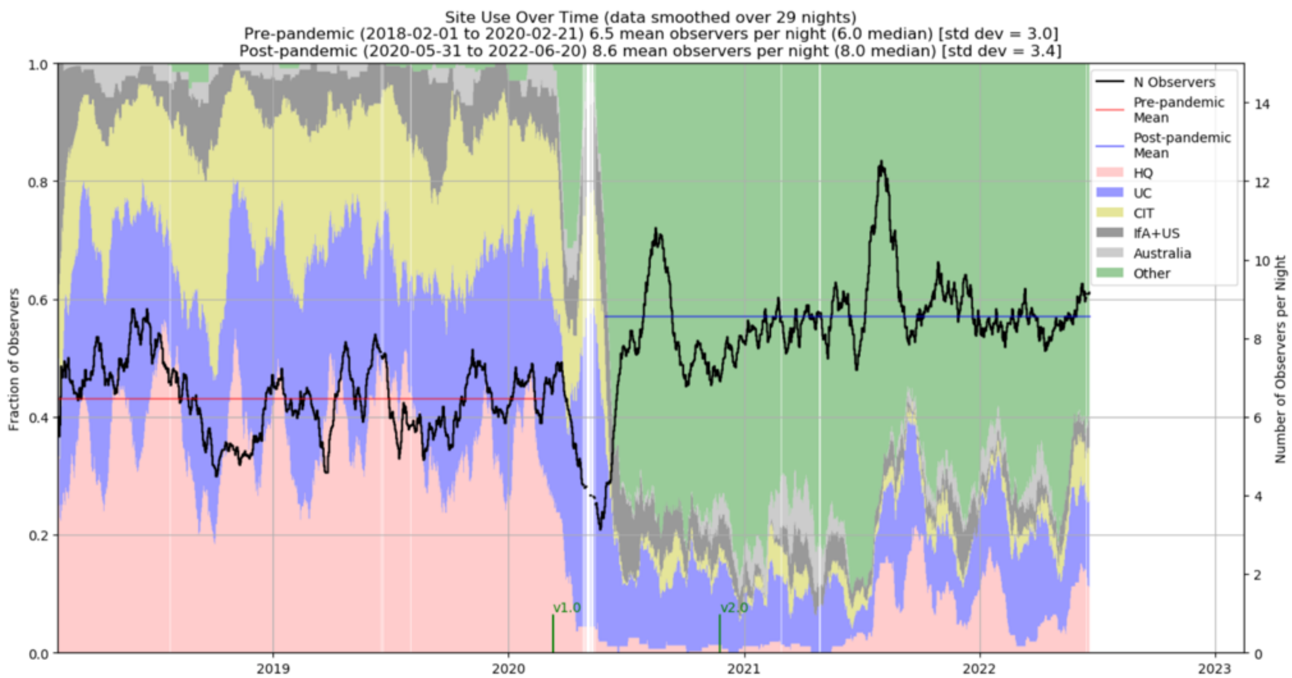

Figure 16: The distribution of observer location pre and post pandemic. The onset of COVID travel and social distancing protocols created the demand for at home observing capabilities.

The use of remote/home observing via "pajama mode" supports a recommendation of Astro2020 [1] that "the astronomy community should increase the use of remote observing, hybrid conferences, and remote conferences, to decrease travel impact on carbon emissions and climate change."

To make observing from home a routine and efficient process, WMKO has updated hardware and software to accommodate our broad observer connection needs. New videoconferencing hardware for Keck was deployed with Zoom replacing obsolete platforms. This push to implement these changes in response to COVID vastly reduced needed effort for WMKO staff and observers required to run remote observing relative to the mid- to late- 2020, and this update applied not only to the at home use, but also to the traditional remote sites at specific host institutions.

Figure 16 shows the dramatic increase in at-home observing categorized as "other" which was not a supported mode pre-pandemic. At-home observing has created several opportunities for our NASA community with the top one being that more observers may connect with roughly one additional observer per telescope in attendance per night. The new mode provides observing opportunities to those who might not otherwise have them and PIs are using the capability of including student classes during the night who may not be able to experience observing with WMKO.

10. ACKNOWLEDGEMENTS

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The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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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