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

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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 to produce transformative discoveries that keep the U.S. observing community on the frontiers of astronomical research. Upgraded capabilities and new instrumentation are provided though collaborative partnerships primarily with the Caltech and University of California instrument development teams and through additional collaborations with the University of Notre Dame, the University of Hawaii, Swinburne University of

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Technology, industry, and other organizations. This paper summarizes the status and performance of observatory infrastructure projects, technology upgrades, and new additions to the suite of observatory instrumentation. We also provide a status of instrumentation projects in early and advanced stages of development that will achieve the goals and objectives summarized in the 2023 Keck Observatory strategic plan. Developed in collaboration with the WMKO science community, the Keck strategic plan sets our sites on 2035 and meets goals identified in the Astro2020 Decadal Survey.

Keywords: Precision Radial Velocity, Adaptive Secondary Mirror, Data Archive, Laser Guide Star Adaptive Optics, Optical and Infrared Spectroscopy and Imaging, W. M. Keck Observatory

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, Berkeley, Davis, Irvine, and Santa Cruz (UCLA, UCSB, UCSD, UCB, UCD, UCI, UCSC), Swinburne University of Technology, University of Notre Dame, and the Space Science Laboratory (SSL) in Berkeley are developing new capabilities and upgrading existing facility instruments. With leading contributions from the WMKO Science Steering Committee (SSC) and the Directors at Palomar and Lick Observatories, WMKO Deputy Director and Chief Scientist, John O'Meara, released in 2023 a new strategic plan that has as its horizon 2035[1] and meets goals identified in the Astro2020 Decadal Survey[1]. The broader WMKO astronomical community provided input to the strategic plan by identifying synergies with other facilities and evaluating the potential of new initiatives for enabling scientific discovery.

In this paper, we describe the focal plan instrumentation portion of the strategic plan and present recent developments towards achieving the plan's defined goals. A decommissioning process for pieces of the instrumentation suite is discussed as part of the long-term arc for the observatory in the next decade. A summary of the existing instrumentation suite is provided, followed by descriptions of instrumentation that is recently deployed, about to be deployed, and in early phases of development.

2. SCIENTIFIC STRATEGIC PLAN

With input from the science community and observatory staff, the WMKO Science Steering Committee and observatory leadership completed a comprehensive strategic plan with a vision towards 2035. The W. M. Keck Observatory Strategic Plan[1] identified 2035 to scope the plan for several reasons. By 2035:

- A new lease to operate on Maunakea will have to be successfully negotiated
- Significant changes in staffing are anticipated to occur at all levels at the observatory
- The landscape of astronomical capabilities will radically different both on the ground and in space

This focuses observatory leadership on three core elements that are

- Hawai'i Community Relations that focus on the organizations leadership evolution to become an agent for positive change within the astronomical community while becoming a strong reciprocal partner in Hawai'i.
- Organizational Health that identifies the observatory staff as a core asset with focus on investing in the staff, where and how they work, and creating opportunities for professional growth.
- Science that is driven by the ever-evolving technical landscape including new flagship ground-based facilities in the northern and southern hemispheres along with space-based missions that drive community expectations for how the tsunami of data will be used, processed, and distributed.

This paper focuses on the Science element of the strategic plan as it pertains to the development of future instrumentation and capabilities. For details on the first two core elements, readers are encouraged to review the W. M. Keck Observatory Strategic Plan. Under the core Science element, there are six strategic goals that set the parameters for the portfolio of new technologies and upgraded capabilities for the identified time horizon. Guiding principles for the development of these goals are that WMKO will remain one of the largest OIR until the onset of ELT operations and as a result WMKO should continue to provide state of the art instrumentation with a broad range of capabilities. Even in the era of ELTs, WMKO can be competitive and a leader in delivering high spatial resolution at the bluest wavelengths. To that end, WMKO is investing in technologies that push AO performance to shorter wavelengths and have demonstrated on sky performance that reduces future risks. Maunakea itself remains a preeminent site for astronomy and WMKO is configured to leverage this geographical advantage by developing UV sensitive systems. Yet, Keck recognizes that a transition will come, and to adjust, WMKO needs to support demonstration technologies as risk reduction for both ELT and space-based projects. To that end, WMKO will work to provide facility interfaces for development testbeds that range from seeing limited to high contrast AO capabilities. Again for more detailed descriptions of the six goals and the technologies that drive them see the the W. M. Keck Observatory Strategic Plan. Table 1 summarizes the science strategic goals as identified in the strategic plan.

Table 1. WMKO strategic plan goals.

Strategic Goal	Description
1	Continue to support a broad OIR science portfolio with a diverse set of highly sensitive imaging, spectroscopy, and high spatial resolution capabilities.
2	Enhance the WMKO community's competitive advantages in cadence, time domain, and large sample programs for precision spectroscopy, astrometry, and photometry.
3	Sharpen our view of the universe with near diffraction-limited capabilities at visible wavelengths.
4	Make maximal use of the unique capabilities of the Maunakea observing site including excellent seeing, UV sensitivity, and northern hemisphere access
5	Provide cutting edge science opportunities to the Keck community by hosting technology demonstrations for ELTs and space-based missions.
6	Increase science yield with improved efficiency from instrument upgrades, state of the art seeing management, innovative operations improvements, excellent instrument calibration and characterization, and data reduction pipelines.

As determined by the SSC and WMKO leadership, the top priorities for new facility class instrumentation and upgraded capabilities are grouped into three categories set by the scale of the investments estimated at the time of publication of the strategic plan. Small perturbations to the strategic plan are added. Priorities A, B, & C represent decreasing priorities for the projects listed in each of those categories, but within a category there is no prioritization.

- Large scale initiatives are those with a notional cost of $15 million or greater and are presented in Table 2
- Medium scale initiatives are those with notional cost in the $5 to $15 million dollar range, and are presented in Table 3
- Small scale initiatives are those with a notional cost at $5 million dollars or less and are presented in Table 4

For tables 2-4, we map how the projects enable the set of strategic goals from Table 3. The projects listed in the large, medium, and small categories are at different phases of maturity. Some are in early conceptual phases while others are about to start the construction phase. In the subsections to follow, we discuss the technical scope and schedule status with reference to the WMKO project lifecycle milestones. Here we quickly list the acronyms in the tables below, and for a complete description of the projects, please see the sections to follow on future capabilities. Some of the initiatives in the tables are descriptive without initiatives, indicating that these projects have not been started nor is there a PI associated with them (purple text). The exceptions are the funding initiatives that WMKO is pursuing (italic).

- ASM – Adaptive Secondary Mirror with project called KASM, Keck Adaptive Secondary Mirror
- DEIMOS+ – DEIMOS throughput and detector upgrade.
- GLAO – Ground Layer Adaptive Optics
- FOBOS – Fiber Optic Broadband Optical Spectrograph
- HAKA – Deformable mirror upgrade for KII
- HISPEC – High-resolution Infrared Spectrograph for Exoplanet Characterization

- KPF KII FIU – Fiber Feed to the Keck Planet Finder from the KII telescope
- KWFI – Keck Wide Field Imager
- Liger – Second generation near infrared integral field spectrometer and imager
- LRIS-2 – Second generation Low Resolution Imaging Spectrograph
- MCAO – Multi Conjugate Adaptive Optics
- MOSFIRE – Multi-Object Spectrograph For Infra-Red Exploration; current instrument
- VIPER – Visible AO imager and Polarimeter
- ZShooter – Single object U-K band spectrograph

Table 2. Large Scale Projects

Priority	Name or Description	Strategic Goal Mapping
A	KASM on KI for GLAO and Visible MCAO Liger	1,2,3,4,5,6 1,2,3
B	FOBOS GLAO on KI to support LRIS-2 & MOSFIRE KWFI Visible AO on KI ZShooter*	1,2,4 1,2,4 1,2,4 1,3,4,5 1,3,4,6
C	GLAO on KII KII ASM Visible AO IFS for KI	1,3,4 1,4,5,6 1,3,4

Table 3. Medium Scale Projects

Priority	Name or Description	Strategic Goal Mapping
A	HISPEC *Instrumentation Development Fund* LRIS-2	1,2,3,4,5 1,2,3,4,6 1,2,4
B	Visible AO imager	1,3,4

Table 4. Small Scale Projects.

Priority	Name or Description	Strategic Goal Mapping
A	*AO Development Fund* DEIMOS+ HAKA KPF KII FIU	1,3,4,5,6 1,2,6 1,3,4,5 1,2,4,5
B	High Contrast Technology Development MOSFIRE updated for GLAO	1,5 1,2,4,6

* indicates an modification to the strategic plan

The strategic plan is a guiding document and not all the of the current instrumentation initiatives are listed in the tables above. For example, Caltech is pursuing concepts for an Xshooter like instrument currently dubbed Zshooter to advance time domain science. With Zshooter as an example, we state that the strategic plan and the technologies identified are guidelines and that the strategic plan has some flexibility as long as the technologies proposed meet the goals identified in Table 1.

The strategic plan identifies a very ambitious suite of new instrumentation that would rejuvenate WMKO's capabilities. To fund some aspects of the technology initiatives identified in the strategic plan, Caltech received a gift specifically to support three facility class instruments for WMKO Keck. Early funds from the Caltech fund for Keck Instrumentation (CKI) are committed to HISPEC for construction as well as for preliminary design funding for LRIS2. Feasibility funding was provided to the KASM/GEO project along with ZSHOOTER to start these projects and WMKO provided some matching funding to KASM through WMKO's white paper process as KASM/GEO is the top large initiative in the strategic plan. CKI provides significant support and security for these instrumentation programs but given today's costs for larger scale facility class instruments, public and private partnerships are necessary to cover full construction and commissioning costs.

To fuel the medium scale instrument development fund and the small scale AO development fund identified in Table 3 and Table 4 respectively, WMKO is seeking new or expanded partnerships with institution commitments contributing funds for the development of facility class instrumentation projects identified in Tables 2-4 in exchange for time on the telescope. Institutions interested in new or expanded partnerships are encouraged to discuss opportunities with WMKO's Instrument Program Manager (lead author) and Chief of Advancement, Ed Harris.

3. OBSERVATORY INFRASTRUCTURE UPDATES IMPACTING INSTRUMENTATION

There are two major infrastructure projects that impact instrumentation at the observatory and are setting new requirements for future projects. These are the Unattended Night Operations (UNO) and Data Services Initiative. Many Maunakea observatories have full remote operations and WMKO is working towards achieving this in the coming years. The Data Services Initiative is resetting how data providence is established to better correlate matching data sets that are more easily identifiable by the community that will lead to improved and more readily accessible data products and pipelines. A brief summary of both projects is provided below.

4.1 UNO: Unattended Night Operations

Over the last several years the Observatory has been making a series of improvements and upgrades to enable unattended nighttime observing. Under this scheme the summit facility will be unstaffed at night with the telescopes being operated remotely from Keck Headquarters in Waimea.

Most of the improvements have been incremental and primarily involved adding cameras and sensors to facilitate situational awareness that was previously provided by an Observing Assistant or Night Attendant physically walking around the facility. Major efforts include developing new control systems for the shutters and hydrostatic bearing systems. Instrumentation has benefitted from the addition of more remote power cycling to more easily recover from faults. UNO places a small limitation on calibrations as a virtual walk around the telescope requires all lights on just before sunset, and if there is bad weather, there is the potential of a small inefficiency as in the beginning the support staff is instructed to be more cautious to open until confidence in the metrology system is established.

In February 2024, WMKO began operating in the first of three phases under UNO. In Phase I, one telescope is operated entirely remotely while an observing assistant operates the other telescope at the summit with a night attendant present on site for safety. During this phase, when issues are encountered, the remote operator must spend 15 minutes troubleshooting before a 'hands on' solution is initiated. To date, minimal operational impacts have been seen with only one unique problem having resulted in on-site assistance. In phase one, some systems are not yet available or fully commissioned in this phase. Notably before remote operations may be fully supported, an upgrade to the shutter control systems with an autonomous facility protection system that will close the shutters and put the facility in a safe state should communications be lost or other potentially dangerous conditions be detected.

Later this year, WMKO will enter Phase II that starts with the completion of all engineering efforts. Phase II builds on phase I but with all systems operating and somewhat different policies regarding how observing is conducted. Once enough experience with the new tools is achieved and the risks are deemed acceptable Phase III will be started in which the summit facility is unstaffed at night and the system is fully operational.

4.2 DSI: Data Services Initiative

The Data Services Initiative (DSI) represents an end-to-end augmentation of how WMKO approaches astronomical data generated by instruments at the Observatory. It encompasses observation planning, observation execution, real-time ingestion of raw data at the Keck Observatory Archive (KOA), and automated reduction and ingestion into KOA of raw data via data reduction pipelines (DRPs) as discussed in past SPIE proceedings [2-5].

At the top level, DSI has as improvement goals over the data lifecycle at WMKO prior to its inception: 1) Reliable calibrations associated with all science data for the PI of the observing program and for future archival use by the community, 2) Access in near real time (requirement of < 5 minutes) of raw data in an observing program to anyone the PI of the program has granted access to, 3) Quick processing through community-developed or instrument-team developed open-source data reduction pipelines to gauge the scientific viability of the data within 24 hours of observation, and often within minutes, depending on the complexity of the data, and 4) Augmentation of the metadata for raw and DRP-processed data to allow recovery of the data provenance for future archival use. For DRPs, WMKO has engaged the larger community (e.g. the PypeIt team [6]) to develop pipelines matched against a set of Observatory requirements for those instruments already deployed at WMKO and has established a DRP framework as a requirement for future instruments coming to the Observatory. To date, half of the spectrographs and integral field spectrograph instruments at WMO are now delivering DRP-processed data to KOA, with a future goal of complete instrument coverage in the coming years.

At the present time, DSI has focused on real-time ingestion of raw and DRP developed products into KOA (along with the KOA team at IPAC[7] along with pre-observing planning tools, and raw data header metadata modifications. Early development of database driven observing infrastructure has been refocused following community input. In the coming years, plans for DSI include continued integration with new DRPs, a calibration association manager, and further metadata changes.

4. COMMISSIONED INSTRUMENTATION

Since the last WMKO status report, the observatory commissioned two facility class instruments in 2023: the Keck Cosmic Re-ionization Mapper and the Keck Planet Finder which were both open to the community for use in the second semester of 2023. In the next two subsections, the two new facility class instruments and their performance along with minor anticipated upgrades are described.

1.1 KCRM: Keck Cosmic Re-ionization Mapper

The Keck Cosmic Re-ionization Mapper (KCRM)[8] led by Chris Martin and Matt Matuszewski was designed to augment the existing KCWI instrument[9][10] 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, now known as KCWI, 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.

KCRM was implemented by replacing the original fold mirror in the collimated beam with a blue-reflecting/red-transmitting dichroic beam splitter that was made by Asahi and at the time the largest ground based dichroic, 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. To select the desired wavelength range, the camera and detector assembly are clocked to the correct dispersion angle with the red articulation stage. The guiding system was replaced with an annular guider upstream of the field de-rotating K-mirror, and all annular guider images are de-rotated in software.

Although WMKO planned to take KCWI off sky for only six months, schedule slips resulted in KCWI being unavailable for the majority of two semesters starting in the summer of 2022. To install, KCRM the instrument was removed from the telescope and transported to the KI dome where it was installed in a cleanroom before starting KCRM's summit AIT phase. On Sky commissioning was completed in the 2023A semester with performance results provided to the community (with routine operations starting in the 2023B semester and was an instrument in high demand with its return to operations. As part of the commissioning activities, Director Rich Matsuda hosted members of the state and local legislature to participate in first light to share the excitement of delivering new instrumentation and new capabilities to the astronomical community.

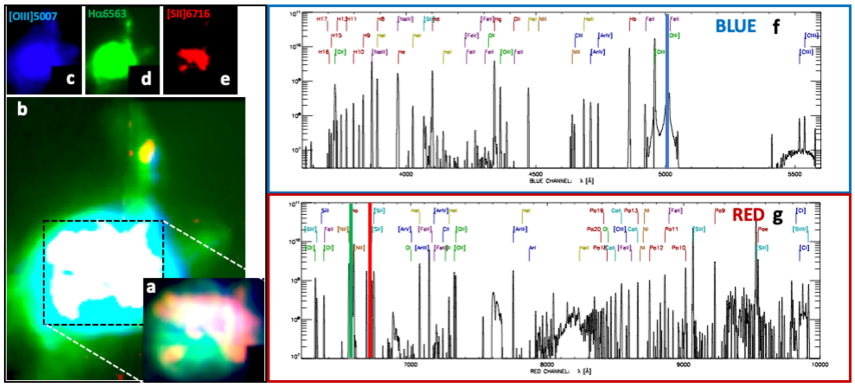

Figure 1 First light Spectroscopy of the Turtle Nebula, NGC 6210, a complex planetary nebula created by a hot, dying star that has blown off its envelope. The spectrum of the nebula shows a wealth of emission lines with both red and blue shifted components.

Figure 2 Photos from Frist Light activities.

5.2 KPF: Keck Planet Finder

The Keck Planet Finder (KPF)[11] 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 ≥ 98,000) echelle spectrometer with 'green' (445–600 nm) and 'red' (600–870 nm) channels. Light from Keck I enters a Fiber Injection Unit [12][13], 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 [14] 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.

KPF completed commissioning in the 2023A semester with an internal calibration stability of 17cm/s. As part of the calibration system, KPF receives light daily from the Solar Calibrator[15] and because several PRV spectrographs employ solar feeds, KPF observations can be directly compared to other instruments to better understand the systematics(Figure 3). Comparisons between NEID and KPF using nearly simultaneous observations of the Sun demonstrate an on-source precession of 27cm/s and a combined error between NEID and KPF of 40cm/s. Early science results from KPF are in progress as the team works to improve the data reduction software[16] for KPF.

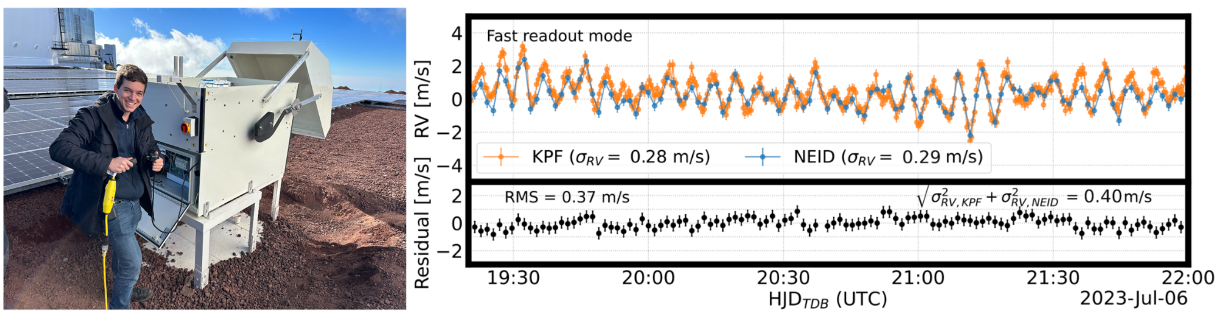

Figure 3 Ryan Rubenzahll plugging in the KPF Solar Calibrator located on the summit facility roof between the two domes (left). P-mode oscillations in the Sun, recorded at ultra-high-cadence with KPF Solar Calibrator and with NEID.

5.3 Mechanical Cooling upgrade for both KCRM and KPF

With the addition of KCRM and KPF, there was an investigation into the total LN2 use at the summit to identify future cost savings initiatives that would impact the budget positively in the long term as well as reduce the burden on summit staff. The rising costs of LN2 for observatories on Maunakea has resulted in an observatory-imposed requirement that all future instruments use mechanical cooling. At an approximate cost of $7.00/L, LN2 consumption at WMKO is a significant operating expense. Currently, WMKO has 10 instrument dewars that are filled daily with LN2 and each requires 180 liters per week when boil off and extras are considered. At this rate, the cost per instrument dewar is about $65k/yr. Retrofitting, KPF with cryocoolers arguably has the highest impact as not only do you recoup the instrument usage costs but also the precooling costs that result each day when we pushed LN2 through multiple meters of warm insulated hose from the KII mechanical room to the instrument in the basement. The cost of filling KPF over the course of a year was calculated to be $184k annually.

In addition to direct cost savings there are other long-term benefits. Retrofitting the systems identified will also positively impact the environment making us greener and more sustainable meeting, a goal of Astro2020[2]. This is because there will be fewer deliveries to the summit, or at the very least, less energy will be used to transport needed deliveries to the summit. Mechanical cooling also reduces the risk to the detectors since they remove the requirement for daily fills that can be interrupted by storms or LN2 supply issues. Typically at WMKO, there are a couple interruptions each year due to winter storms, hurricanes, or supply interruptions from the single source AirGas. Furthermore, CCR's reduce labor, both from daily fills and from recovery efforts associated with unintentional warm-ups. The conservative estimated labor effort to maintain each LN2 Dewar for this analysis is placed at 0.1 FTE. The LN2 daily servicing also limits other activities due to telescope access limitations during service and thus the observatory recovers opportunities for other observatory activities. Figure 4 shows that in three years, WMKO will recover the initial costs on investment for the two instruments.

WMKO anticipates that the KPF upgrade will be completed before the end of the calendar year 2024 while KCWI will be completed in the summer of 2025. For KPF, members of the original KPF team are fabricating a test dewar and mock detector package so that they can test and demonstrate temperature control necessary to meet the KPF radial velocity requirements. The KPF team has selected the ARS Cryo ORCA as their mechanical cooling system. For KCWI, the development team is currently assessing vendor options for mechanical coolers.

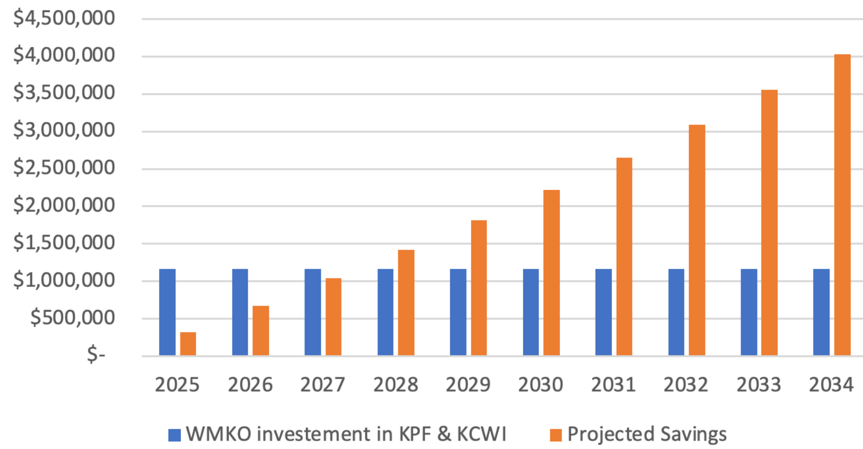

Figure 4 ROI by retrofitting KCWI and KPF LN2 systems with mechanical cooling.

The original system (Figure 5) fed the two 50L dewars from the LN2 plant generator on the first floor and pumped LN2 through tens of meters of hose to the two 50L dewars. Because the generator and lines were relatively unstable at the time of KPF commissioning, a 180L dewar is now used to bypass the generator at the basement location. Two circulation pumps pull LN2 from the 50L dewar to the detector heads before the gas is vented to the outside via long copper pipes. The new system for KPF will interface with the existing cryostats and replace the 180L dewar, the two 50L dewars, two circulation pumps, and hoses that are pictured in Figure 5.

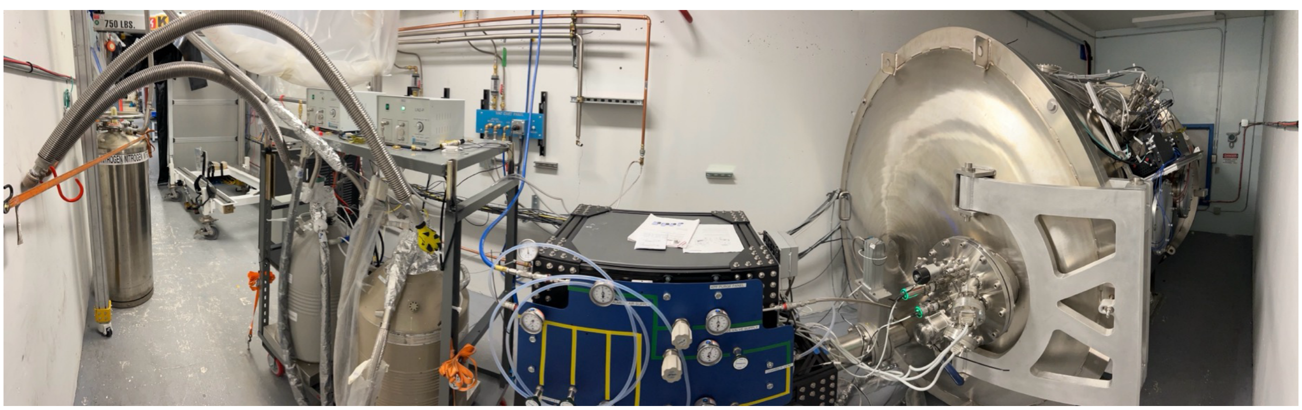

Figure 5 KPF instrument along with the vacuum cart and cryogenic fill system. A 180L shown temporarily secured to the wall that feeds two 50L dewars on a cart. Two pumps circulate LN2 from the 50L dewars to the cold heads on the blue and red detectors.

5. CURRENT INSTRUMENTS AND DECOMMISSIONING

A list of the current instruments and their capabilities, including the two instruments commissioned in the last year, are provided in Table 5. The current instruments are available any night with up to four of the five KI instruments accessible any time during the night and four of six KII instruments accessible any time during the night. This flexibility is coveted by the WMKO observing community to maximize observing science efficiencies as well as support Time Domaine Astronomy (TDA) programs that require a few hours nightly for cadence observations or rapid response to event driven discoveries.

Astro2020[2] identifies updates to the US observatories' suite of instrumentation as 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 were 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 and informed by NASA and NSF program principles and streamlined to emphasize and maintain flexibility to adapt to different project scales. Please see past discussions of the lifecycle process in the previous WMKO SPIE status report.

Table 5. Current WMKO instrumentation.

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
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.	2023
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 with KCRM	KII	Keck Cosmic Web Imager. visible band (350-1,000 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 2023
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)

To support new technologies, it may be necessary to decommission some portion of the current instrument suite, and to assess this possible need, the WMKO SSC convened a working group to consider options for the evolution of the WMKO instruments with a goal of identifying 1-3 instruments on each telescope that could be queued for retirement either permanently or temporarily. In the observatory's 30+ history, three capabilities have been retired: NIRC (first light IR camera for Keck I), the Long Wavelength Spectrometer, and the interferometer system. The decision for these systems was motivated by space considerations and funding. The newly formed committee to review the current instruments is called the Instrument Suite Evolution Working Group (ISE) and is considering a large breadth of information. The decision to decommission an instrument is based on demand, usage, and scientific productivity of each instrument and includes highlighting achievements from the past as well as projections regarding the potential for world-leading science in the future. The ISE was informed of standard maintenance needs and staffing requirements for continued operation of each instrument, and the group was provided a severity-likelihood risk matrices for each instrument. The ISE also considered how space and infrastructure needs for new instruments currently under construction or in development inform retirement options. Most inputs considered by the ISE are listed in Table 6. For instruments, the ISE concluded are less important to continue operations, the ISE will present a scheduled process for decommissioning that includes sufficient opportunity for close-out observations by the WMKO community of observers.

To solicit input from the WMKO science community, the ISE held an open forum discussion at the Keck Science Meeting in September 2023 and sent a survey to the community requesting opinions and forecasting on the current instrument suite. The ISE then followed up with the top ten observers on each instrument to ensure that they provided feedback in the survey. Observatory staff provided information on the operational burden and annual opportunity costs that included the number of hours spent working on the instrument vs the number of nights on sky, equipment and consumables costs, and when relevant opportunity costs if an instrument maintenance activity monopolized the telescope. As an example of the observatory burden assessed, for every day spent observing with DEIMOS and LRIS, there is a person day spent on maintenance and troubleshooting.

Table 6 Inputs Assessed for Decommissioning Instrumentation Reviewed By the ISE

Science	Productivity	Operations
• Survey of community science and strategic interests ○ Top ten PIs requested specifically to provide input • Past science emphasis based on survey results and literature review • Near-term science impact • Expected future demands • Astro2020 recommendations • Alignment with the WMKO strategic plan • Landscape discussions both ground- and space-based	• Annual publication rates • Annual citation rates • Number of nights scheduled • Number of partial nights scheduled • H-indices • Proposal pressures • Nights requested vs scheduled • Partner Institutional preferences	• Time spent troubleshooting at night and during the day • Lost time on sky • Consumables such as LN2 • Observatory opportunity costs

The survey asked responders to provide information on the areas of science they pursue, what career level they were, what instruments they expected to use in the next few years, their assessment of instrument relevancy in the near and long term, as well as their advocacy for and against maintaining certain capabilities. Example survey questions and their results are shown in Figure 6 that includes about 130 responses from the community. The science communities with the largest response rate include exoplanets, stellar astrophysics and galaxy evolution. For near-term (2-5 year) timescales, LRIS, NIRC2, KCWI and HIRES were identified the most anticipated future use instruments. The survey results helped guide the ISE in understanding future needs and capabilities.

Evolution of stars and Galaxies along with exoplanets were prominent identified science pursuits with LRIS, NIRC2, KCWI, and HIRES the most anticipated future use instruments. Although a small sample of WMKO observers responded to the survey, the survey results helped guide the ISE in understanding future needs and capabilities.

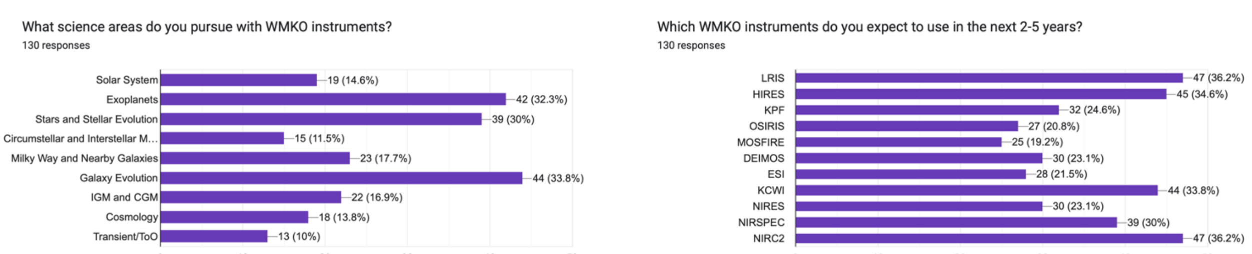

Figure 6 Example survey results on science emphasis and near term expected use.

Publication titles were used to provide a more unbiased assessment of the science that was completed with each instrument with small trends appearing in the last 4 years. Taking LRIS as an example, supernovae and galaxy studies are a prominent part of LRIS science output in its early and late career, while transient science follow up has become more prominent and supported by the number of Target of Opportunity triggers that have used LRIS since interrupts of the classically scheduled observers were allowed (Figure 7).

Publications and citations (Figure 8) to those publications were used to assess the productivity and impact of an instrument. The measured productivity and impact are influenced by proposal pressures and scheduled time on the telescope, and thus, the SLT explored various normalizations to better compare performance. As an example of a variances on recent trends, ESI was a highly requested by the observing community during KCWI's downtime and installation of KCRM. With KCWI available again, we are seeing ESI return to recent on-sky numbers. One of the interesting aspects of exploring publication metrics is that it requires about five years before an instrument's trajectory is well understood and allows a new instrument to be compared to ones with more tenure. As an example, MOSFIRE is on track to becoming one of the observatory's most productive instruments, and this is one motivating reason for MOSFIRE to remain in service for the long term.

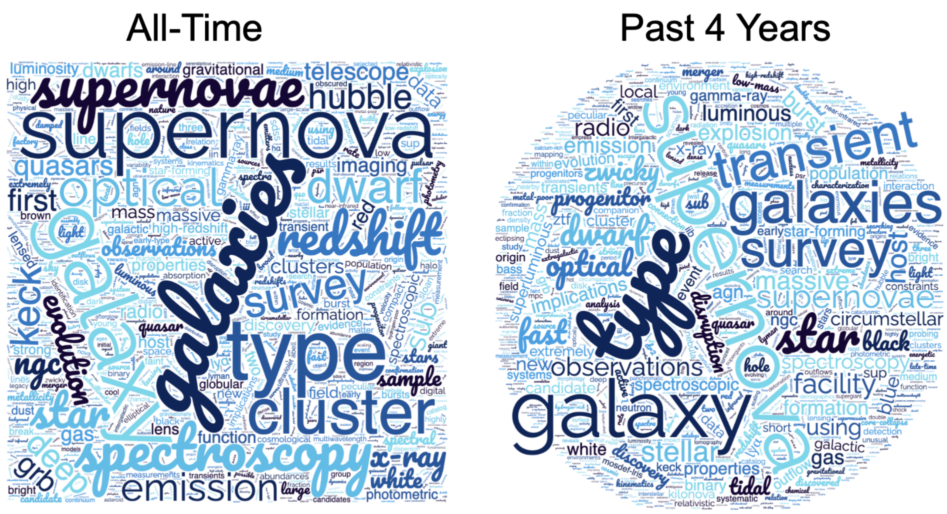

Figure 7 Example word clouds for LRIS that incorporates words from publication titles for all publications over the lifetime of the instrument and only the last 4 years.

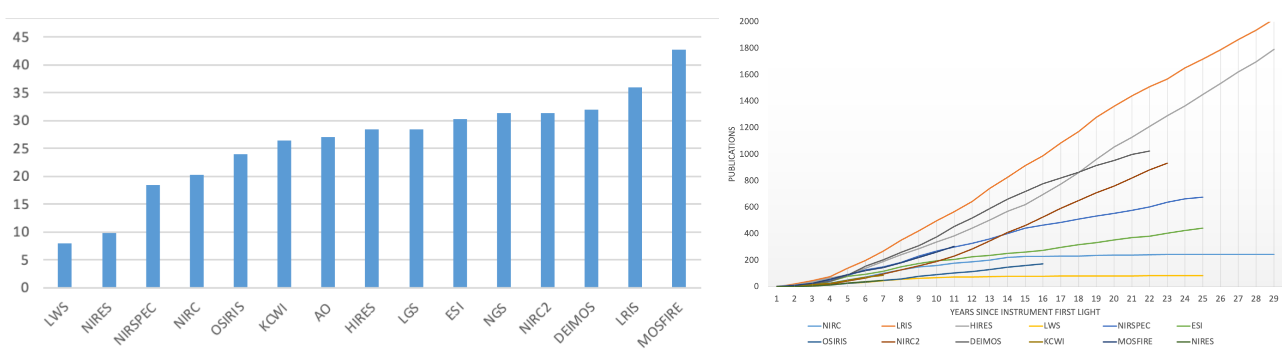

Figure 8 Ratio of the number of citations to publications over the last five years ordered lowest to highest (left); Cummulative number of publications since normalized to first light for the instruments (KPF not yet included).

The ISE provided initial findings and documentation to the WMKO SSC in May 2024, and the SSC will review and provide feedback in July 2024. Following the July feedback, the observatory is expected to move forward with decommissioning decisions. It is anticipated yet not confirmed that once an instrument is identified for decommissioning there will be a two-year process that will involve a one-year "last call" for observations followed by a year where the instrument is off but not yet removed. After two years, the instrument would then be removed from the observatory. Homes for decommissioned instrumentation are being considered.

For some instruments, there is a natural progression for decommissioning with more modern instrumentation with similar capabilities superseding current instrumentation (see Table 7). The timeline for the modern and more capable instruments in some cases is uncertain, while other new initiatives are in progress with anticipated delivery in the next several years. The deliveries of those planned instruments provide an obvious decision points for considering decommissioning the older technology. Modes of operations are part of the calculous for considering decommissioning and as an example NIRSPAO (NIRSPEC fed by KII AO) will not be supported when SCALES is delivered.

Table 7 Obvious Evolutionary paths new technology superseding older technology

Current	Planned	Year
NIRC2	SCALES	2025
AO KPIC fiber feed to NIRSPEC	HISPEC	2026
LRIS	LRIS-2	2028
OSIRIS	Liger	2029
DEIMOS	FOBOS	TBD
ESI+NIRES	Zshooter	TBD

6. INSTRUMENTATION DEVELOPMENT TIMELINES

With the exception of AO projects, facility class instrumentation is developed by mainland partners with WMKO efforts in a support role to provide all the interfaces necessary to connect and operate the instruments within the facility. AO

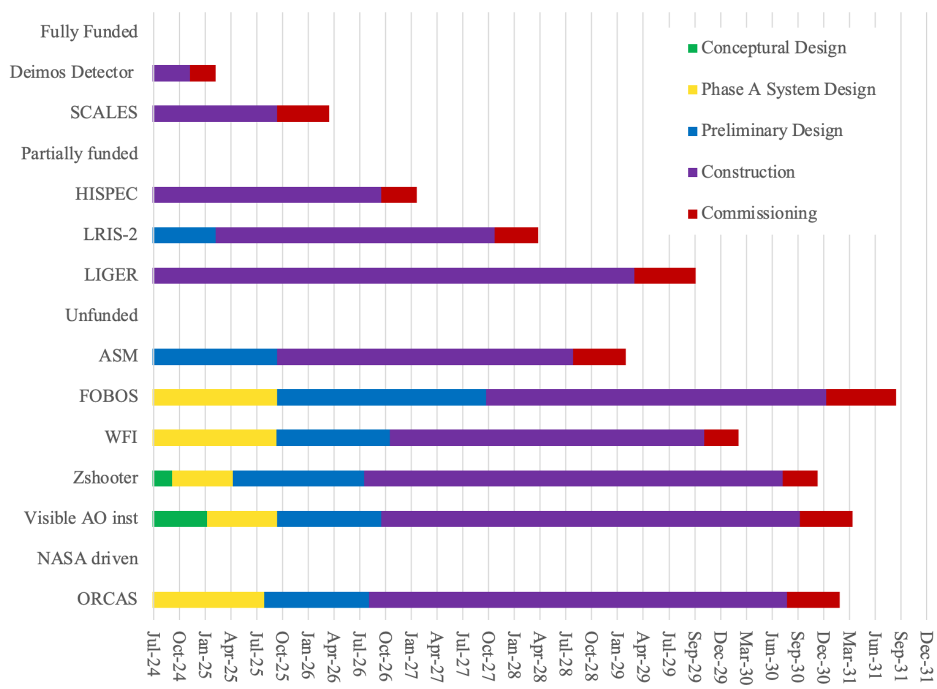

Figure 9 Notational timelines for instrumentation projects and their phases of development focusing on the focal plan instrumentation and WMKO internal AO development efforts.

projects are often led internally at WMKO sometimes in close collaboration with mainland partners. WMKO modifications in support of new instrumentation can be extensive as was the case for KPF which required a basement makeover including the removal of a large quantity of interferometer hardware. It is WMKO's responsibility to prepare the facility in time for the delivery of the instrumentation with notional schedules as shown in Figure 9 that groups projects in to Fully Funded, Partially Funded, and Unfunded. Fully funded instruments have all the needed constructions funds through commissioning. Partially funded is defined as having some portion of the construction costs covered, and the teams are actively working roughly at full speed on construction activities. Unfunded means there is little to no funds available, and the teams are working on these projects under best effort. Schedules for unfunded projects are the most uncertain. In the sections to follow, more details are provided on the instruments under development.

7. INSTRUMENTATION IN THE CONSTRUCTION PHASE

There are six instrumentation projects in the construction phase that we anticipate becoming available to the US community at WMKO over the next several years. These instruments are summarized in the subsections to follow. Four of these projects have full funding while two (Liger and HISPEC) are actively working to secure final construction funds. For Liger and HISPEC, full funding is necessary to maintain the anticipated date for deliver and release of the instrument to the community.

Table 8 Instrumentation in the construction phase of development

Instrumentation in a Construction Phase			
Name	**Tel**	**Capabilities**	**Anticipated**
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.	2024
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
HAKA	KII	High-order All-sky Keck Adaptive optics: Upgrades the deformable mirror to a Xinetics 58x58 actuator count with 2.5mm spacing corresponding to a 20cm spacing a the primary. Upgrades to the Shack Hartmen relay optics and real-time controller are planned in support of the mirror upgrade.	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
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.	2026
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.	2029

7.1 DEIMOS Throughput Upgrade

Although FOBOS was identified as an obvious evolutionary path to DEIMOS in Table 7, it is clear from Figure 9 that the Deep Imaging Multi-Object Spectrograph (DEIMOS) is needed for long term operations for the foreseeable future as near-term retirement of DEIMOS is not recommended by the ISE. DEIMOS is one of the more productive instruments at WMKO (see Figure 10), and unfortunately in recent years the now 20+ old detector system has required a significant amount of effort to maintain science operations. More than one person day is spent troubleshooting for every DEIMOS night on sky, and the majority of the troubleshooting efforts concerns the detector system.

Two years ago, 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 of one lunar cycle. All the detectors in the mosaic are fabricated and currently undergoing performance testing at Teledyne before being shipped to Caltech for integration.

This project is a collaboration between Notre Dame and Caltech with ND developing the cryostat and flexure compensation mechanics system and Caltech working on the detector system for both the science mosaic and flexure compensation system. The Project is led by Dr. Evan Kirby at ND and Mitsuko Roberts at Caltech. The project is expected to complete lab AIT in Fall 2025 and ship the instrument to Keck around the new year. Below we highlight the engineering group responsible for the work at ND.

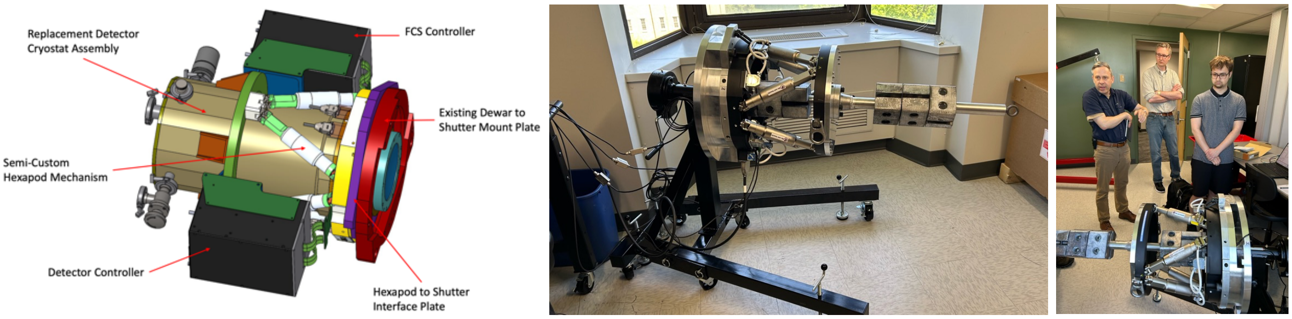

Figure 10 Left: Rendering of the DEIMOS upgrade subcomponents (left). The delivered hexapod system with counterweights to simulate the cryostat and detector hardware (middle). The hexapod system is undergoing lab AIT with ND undergrad Alexander Sterling leading the control development and testing with Dave Cavalieri and Josh Holewczynski providing engineering oversight.

7.2 KAPA: Keck All-sky Precision Adaptive optics

The Keck All-sky Precision Adaptive optics (KAPA) [17] 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. Led by Peter Wizinowich, Antonin Bouchez, and Eduardo Marin with Jessica Lu as the project scientist, KAPA offers three fundamental improvements over the existing AO system: Higher Strehl ratios achieved using four laser guide stars for atmospheric tomography [18][19] 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.

The KAPA project began in late 2018 and is expected to enable science in 2025. To date, the new higher return, high reliability laser system is operational, and a new wavefront sensor camera and real-time controller system is released for operational use with support from the development team. The remaining hardware to produce, sense, calibrate, and test a four-laser guide star system are in various stages of integration 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.

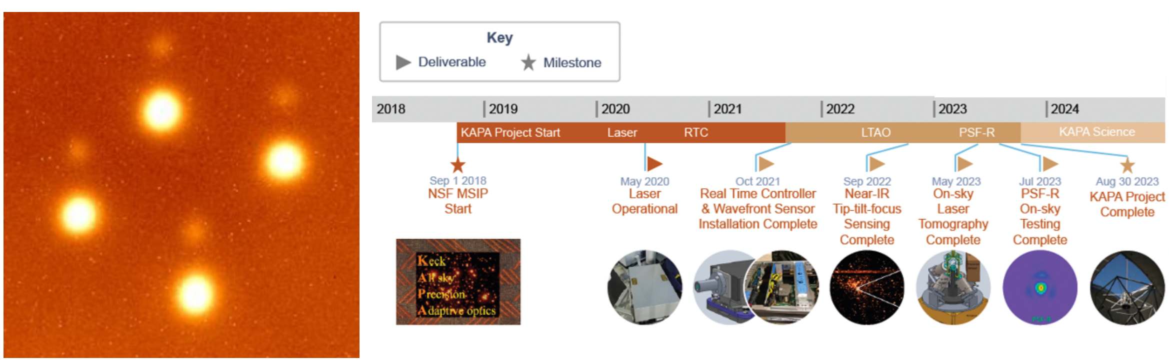

Figure 11: Left: Laser Asterism projected on sky in April 2022 (ghosts are from the acquisition camera); Right: KAPA project timeline showing the major deliverables.

7.3 HAKA: High-order All-sky Keck Adaptive optics

The High-order All-sky Keck Adaptive optics (HAKA) project builds on the scientifically productive Keck KII AO system supporting both natural and laser guide start facilities. Led by Peter Wizinowich, Antonin Bouchez, and Eduardo Marin with Rebecca Jensen-Clem as the project scientist, the purpose of the project is to provide higher Strehl and higher contrasts over a large fraction of the sky with the most significant component of the upgrade being a new higher order deformable mirror that should reduce the atmospheric and segment residual fitting errors. The high contrast will be achieved through use of a higher order DM for speckle nulling and will benefit both the SCALES and HISPEC projects that are picking out objects very close to their host stars. The project includes replacing the current DM with one having a 2.5 mm actuator spacing (current DM has 7mm), modifications to the Shack-Harmann, and modifications to the real-time control software to provide the additional control of more actuators.

The project has purchased the longest lead item that is the ALPAO DM that will provide a 58x58 actuator count that corresponds to a 20cm spacing on the primary mirror [19]. The WMKO AO development team is gearing up to develop the system upon receipt of the ALPAO DM. A new DM mount is under design, and the team has worked to identify the cable routing and electronics rack space needed to support all the actuators. In concert with both SCALES and HISPEC, modifications to the AO bench and AO room along with a phased approach for installing and decommissioning electronics is planned in the upcoming year. As part of the development process, the team is working on a lab test bed so that the system may be put through its paces ahead of going on sky.

7.4 SCALES: Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy

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 [21]. 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. Led by PIs Steph Sallum at UCI and Andy Skemmer at UCSC, 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. 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. In addition, SCALES may be able to extend the hours of normal operations by taking significant advantage of twilight time that is available often at the end of the night [21] IIA is developing an imaging channel with the same wavelength coverage as the spectrograph and is designed to image a FOV of 12 arcsec. 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.

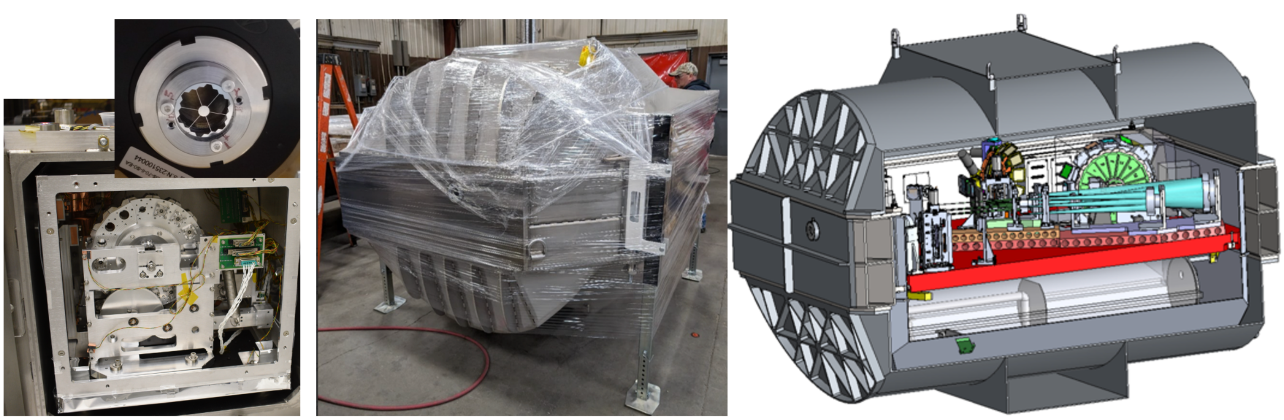

Figure 12 SCALES pupil wheel in the cold testing box with an enlarged view of the rotating pupil mask (left) along with the cryostat at the vendor shop (middle, and CAD of the cryostat and the opto-mechanical model of the bench.

The project is a collaboration between UCSC, UCI, UCLA, India Institute for Astronomy, and Durham Precision Optics. Durham is responsible for completing the slicer optics that achieve the medium resolution mode of the IFS, and the delivery of the slicer mechanism is on the schedule's critical path. IIA has work extensively on the imaging channel of the instrument and has taken on more design activities having demonstrated a depth of in-house knowledge on complex mechanical systems and delivering well design mechanisms with supporting documentation that has been well received by the instrument partnership. The team received the cryostat (Figure 12), optics, various stages, and detectors with more subsystems on their way. The project team has taken major steps on many of the subsystems [23-35], with the team having started lab AIT on all campuses with cold testing optics and mechanisms as well as establishing software control. At WMKO, the infrastructure modifications are near design completion and parts will soon be ordered.

Internally at WMKO, the infrastructure in support of the systems will be installed around the work being completed for the pier repair project due to resource needs with the expectation that most modifications are completed at WMKO by March 2025.The instrument team is anticipating a preship review in the summer of 2025 with deliver in the fall. Routine operations is expected to begin in the 2026A semester.

7.5 HISPEC: High-resolution Infrared Spectrograph for Exoplanet Characterization

The High-resolution Infrared Spectrograph for Exoplanet Characterization (HISPEC) 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 [34]. 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 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 completed the preliminary design phase and has entered the final design and construction phase. Led by PI Dimitri Mawet at Caltech and Project Scientistic Quinn Konopacky at UCSD, HISPEC is a collaborative project between, Caltech, UCLA, UCSD, and WMKO.

The project just completed a design review of the Front End Instrument (FEI) [35] that is the fiber injection system on the back stream of the KII AO bench. The team is securing two detectors from Goddard that will be the sensors for the blue and red arms of the spectrograph that are housed in two separate cryostats in the basement of the WMKO summit facility (see Figure 13). A significant amount of the design is complete [36-43]. At the observatory, the FEI and the modifications in support of that system are part of the larger phased plan of integration that includes HAKA and SCALES. The project is planning to complete summit integration in the 2026B semester with operations starting in the 2027A semester.

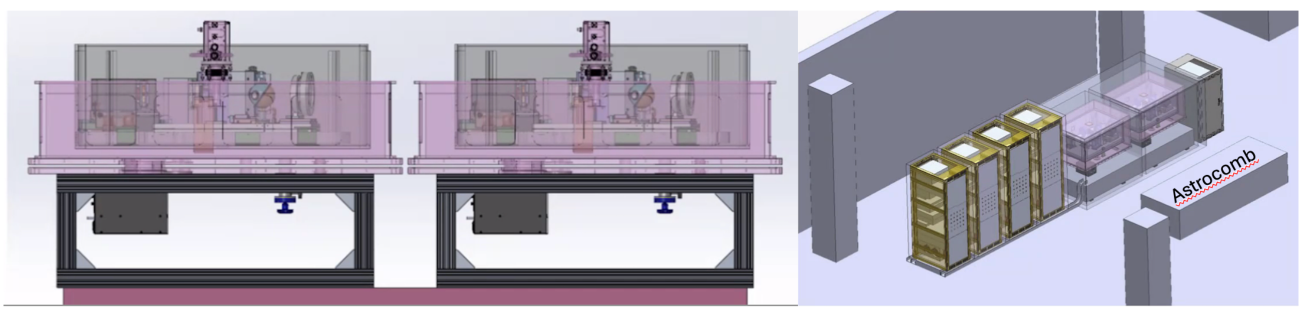

Figure 13 CAD rendering of the HISPEC duel channel spectrographs in their separate cryostats installed on a vibrationally isolated optics bench (left). CAD rendering of the WMKO basement facility showing the five electronics cabinets and two spectrographs inside a thermal enclosure located next to the optics bench for the already installed and operational IR astrocomb that will serve as HISPEC's primary calibration system.

7.6 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 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 [44].

Liger, led by PI Shelley Wright at UCSD in collaboration with other UC campuses and WMKO, 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 where performance at WMKO can be realized, 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 [2], will not only provide the WMKO community with technology maximized IFS capabilities, but it will also retire significant risk for the IRIS/TMT instrument as IFS optical design for the opto-mechanical bench is the same.

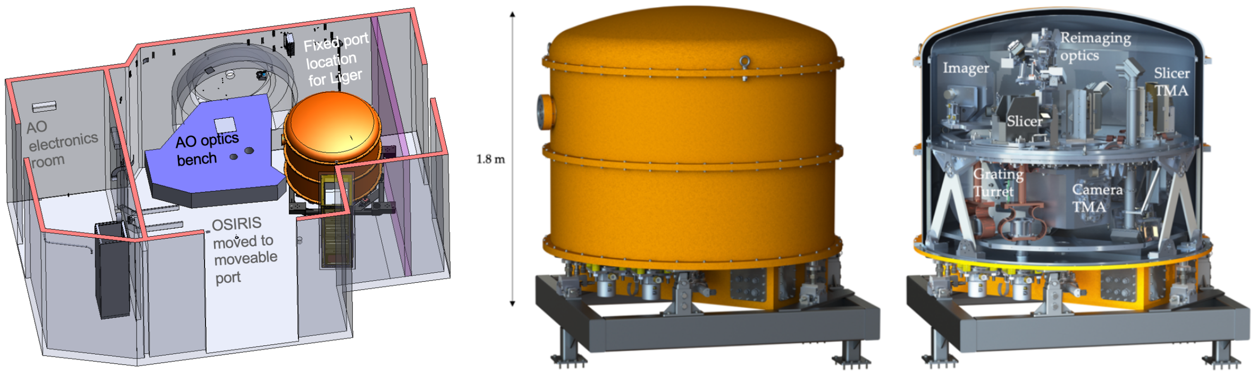

Figure 14 Liger placed in the model of the KI AO enclosure at the fixed port location (left). The Liger instrument on the kinematic interface showing the full size of the croystat and a cross-section to show the two-level design for all the mechanisms.

Liger is currently funded to complete the opto-mechanical components to the front-end instrument that is identical and common to both Liger/Keck and IRS/TMT. The team is fully funded for this first phase of construction and the leads are actively seeking funding for the full construction costs. As part of the current activities, the Liger team has secured the detectors from Teledyne and the team is working on final designs and fabrication of some subsystems [45-47]. At Keck, the Liger instrument is now planned for the direct port, the current port that OSIRIS occupies, because at this port, Liger will be able to take scientific advantage of the IR TT sensor. In the current plan, OSIRIS will be moved temporarily to the moveable folded AO port to establish a baseline with Liger (see Figure 14). Once the science cases are transferred to Liger, OSIRIS would be retired, and thus, freeing a location for additional instrumentation.

8. INSTRUMENTS IN DESIGN PHASES

In Table 9, we list the projects that are in early design phases. For the first two projects in Table 9, they are in preliminary design phases having completed and passed conceptual design reviews. Their schedules are defined and thus dates shown in Table 9 assume that the project has funding when it is needed. The remaining projects are in early feasibility and conceptual phases with timelines unknown. Adaptive secondary mirrors (ASM) for both telescopes are considered an enabling technology that will drive new innovations for the existing AO benches as well as instruments that work with AO or with GLAO systems [1]. WMKO anticipates that all traditionally seeing limited instrumentation should work to be GLAO compatible like LRIS-2, and most projects listed in Table 9 are developing concepts anticipating either AO or GLAO capabilities with an ASM in the system.

Table 9 Future capabilities in early design phases

Future Instrumentation in Design Phases			
Name	**Tel**	**Capabilities**	**Anticipated**
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.	2029
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.	2029
WFI	KII	Wide Field Imager. Prime focus, 1 degree field of view imager covering 300-1000 nm.	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
Zshooter	KII	Target of Opportunity Dedicated Astronomy Instrument. Single object, high throughput, OIR spectrograph, R~10,000 specifically optimized for time domain astronomy	TBD
VIPER	TBD	Visible AO instrument. Imager and polarimeter	TBD
ORCAS	TBD	Hybrid space and ground based facility that will provide unprecedented angular resolution	TBD
TBD	TBD	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	TBD	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

8.1 KASM: Keck Adaptive Secondary Mirror

The Keck Adaptive Secondary Mirror (KASM) [48], led by Phil Hinz at UCSC in collaboration with UCB and Caltech, completed a conceptual design review in April and is now in a preliminary design phase. To maintain a leadership role and compete with new facilities that will be realized in the coming decade, WMKO recognized the need to develop an ASM identified as a key initiative in the WMKO strategic plan [1]. An ASM is an extremely impactful way to increase the overall science return for the facility and is identified as a key capability for WMKO to increase efficiency by improving seeing for a suite of instruments with a first deployment on the KI telescope. Multiple science drivers justify the need for the deployment of an ASM at WMKO and those justifications start with ground-layer adaptive optics and extends to visible wavelength AO applications such as MCAO [49]. A GLAO telescope facility system has multiple components including a laser constellation and WFS package, and the community has invested in KASM as it is recognized that the ASM drives the overall timeline of any new system.

The KASM project is currently assessing actuator technologies (see Figure 15) from two vendors in support of the Keck Adaptive Secondary Mirror, KASM, system. A down select team has been convened to deliver a recommendation for actuator technology and the number of actuators for the KASM preliminary design using an objective and transparent process [48]. The KASM team as well as the down select team is currently tying science requirements and drivers to define the needs for the ASM that will feed into the vendor selection. Key inputs to the down select discussions are the actuator density, stroke, and hysteresis, power and thus cooling requirements at the secondary socket, and overall mass of the system. Both vendors designs appear to meet performance specifications; but struggle with weight constraints. The down select decision is expected this year before the KASM team seeks funding for construction.

KASM will provide the ability to improve image quality for any instrument with an appropriate wavefront sensor and beacon. This will include but is not limited to: improving the image quality and stability of the Keck Planet Finder (KPF), a smaller wavefront error for instruments fed by the current AO bench, a deformable mirror for a future ground layer AO system and a core piece for a multi conjugate adaptive optics system for visible light instruments. KASM will be a key piece for each of these capabilities. For KPF, a deformable secondary mirror could remove most of the telescope inputs into the velocity error budget and lead to a smaller input fiber which would further improve the velocity precision by ~10 cm/s. For AO instruments, KASM would improve the Strehl at all wavelengths, which could as much as double the Strehl at the bluest wavelengths for instruments like OSIRIS and LIGER.

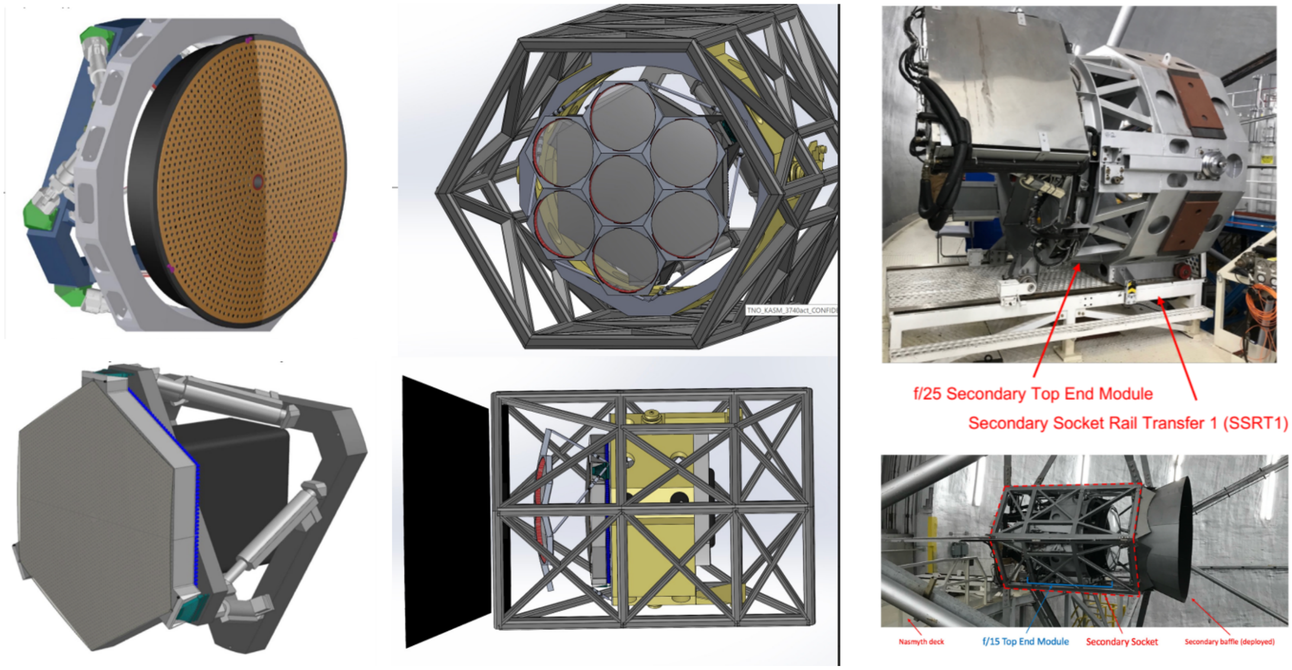

Figure 15 Images presented at the KASM Conceptual Design Review: Secondary Mirrors on hexapods from two vendors (left). CAD rendering of the Hindle Sphere array that would be used for calibrations (middle top). CAD rendering of the system in the secondary socket with the secondary baffles deployed (middle bottom). Photo of the F25 Secondary module that would be reused along with a photo of the current F15 secondary module in the secondary socket with the baffles deployed.

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 ~100 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. Dovetailing with the KASM project is the LRIS-2 instrument described below that will be GLAO compatible, and other seeing limited instruments like KPF and MOSFIRE will also be able to take advantage of improved seeing with small modifications. Finally, the in-development visible light adaptive optics system for Keck I has the potential to provide 50 milli-arcsecond 50 percentile ensquared energies for imaging and spectroscopy over 20 arcsecond fields of view. Such a system would use KASM has one of the three conjugate deformable mirrors.

In addition to assessing the actuator technology, the project has completed initial designs for the hexapod support structure that would provide focus, tip/tilt, and centration (an advantage over the existing secondary system), completed risk reduction efforts to slump a face sheet with a prototype deployed at the IRTF, prototyped electronics for controlling the actuators, developed designs for calibration system [50] both in the lab and at the summit using a Hindle Sphere array (see Figure 15) .

8.2 LRIS-2: Second Generation Low Resolution Imaging Spectrograph

LRIS is one of the most in-demand, productive, and impactful instruments at WMKO as demonstrated in Figure 16 that shows that it has produced the most publications over the lifetime of the observatory. LRIS's production is due to its versatility in providing sensitive imaging, single-target, and multi-object spectroscopy over the entire ground-based optical window (3100-10,000Å) as well as polarimetry. 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 three years WMKO has invested in early design efforts that culminated in a conceptual design review in the fall of 2023.

The baseline LRIS-2 concept is an on-axis imaging spectrometer with a spectroscopic field of view of 10’ × 5’, located behind the existing KI Cassegrain ADC [51]. Incoming light from the KI focuses on the f/15 focal surface, where focal plane aperture masks (i.e., mechanical slitmasks) are deployed for spectroscopy [52], 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) [53] focus the spectra or images onto a 4k×4k detector arrays with 0.153”/pix spatial resolution on the blue and red channels (see Figure 16). LRIS-2 will be equipped with a flexure compensating systems and use a Cassegrain 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.

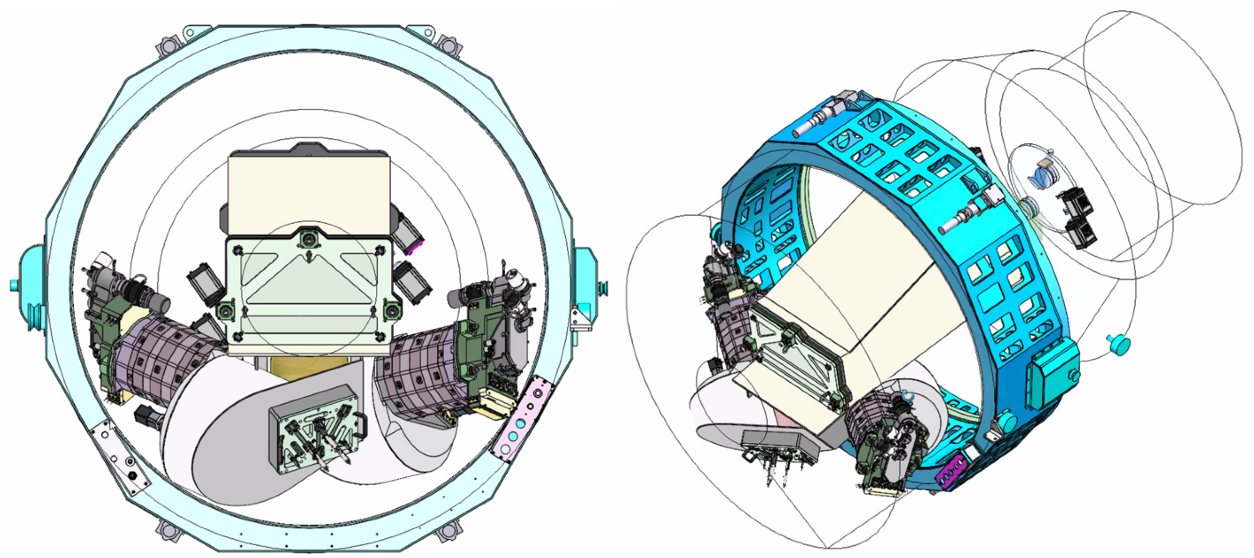

Figure 16 LRIS-2 initial opto-mechanical design showing the two arms of the spectrograph folded inside the rotator (blue ring).

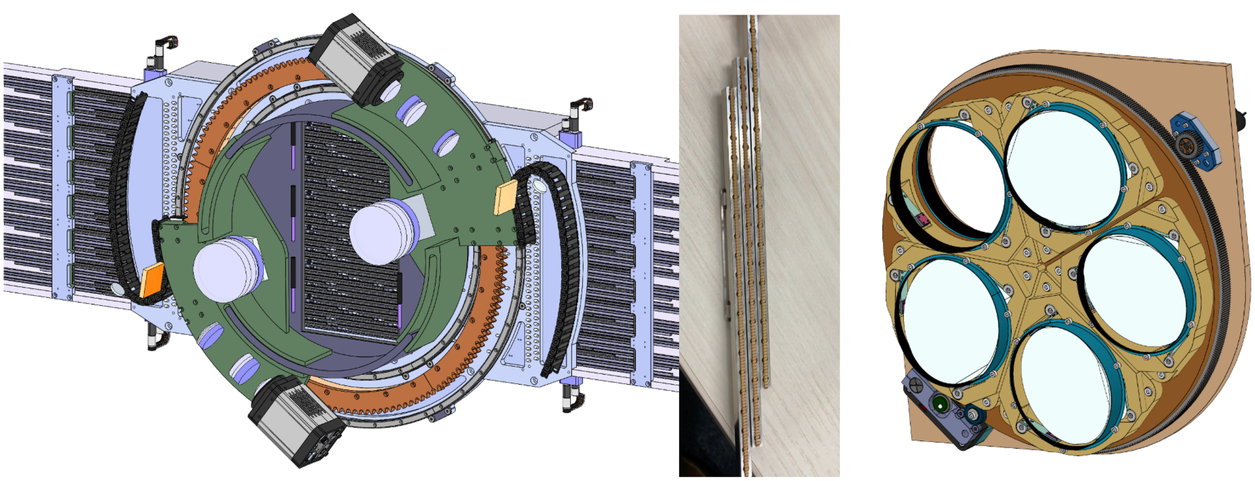

Figure 17 Mechanical configurable slitmask design with the guiding and wavefront sensor optical layouts (left); three bar prototype of the mechanical configurable slitmask (middle) and the grating wheel (right).

The LRIS-2 project has started reaching out to detector vendors to secure detectors for both channels while working towards a preliminary design review in early 2025. Detailed designs for a mechanical configurable slitmask, guiding and wavefront sensor system, detector system, camera optics, and flexure compensation system are well underway. Component prototyping and initial lab testing is also underway for some systems such as the flexure compensation system (e.g. Figure 17). Part of the baseline plan is to re-use the optics and possibly the opto-mechanical assembly for the current LRIS polarimeter module with the addition of a deployment stage to enable use anytime during the night (currently the polarimeter module must be manually installed and when installed limits science to single object spectroscopy for an entire night). Last, the team is working on the packaging and prototyping the control boards for the mechanical slitmask unit that must ride with the instrument.

8.3 KWFI: Keck Wide Field Imager

Wide field imagers have played an essential role for a broad range of science on multiple telescopes yet a complete concept for an optical imaging system for Keck has not been considered despite that a wide-field prime focus camera was part of its original telescope design. The WMKO community recognizes and supports a Wide-Field Imager (WFI) because combined with the Keck telescope, no other wide-field imager will have the UV sensitivity down to 300nm and target of opportunity capability for the foreseeable future including ELTs. In the current design[54], the imaging system is baselined as a 1-degree field of view[55], with a filter exchanger that holds up to eight filters. pulled from a set of 5 broadband and ~20 narrowband 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, led by Jeff Cooke at Swinburne in collaboration with AAO-Macquarie, ANU, and UCSC has completed a conceptual design study and proposal readiness review and has advanced to seeking funding for preliminary design efforts.

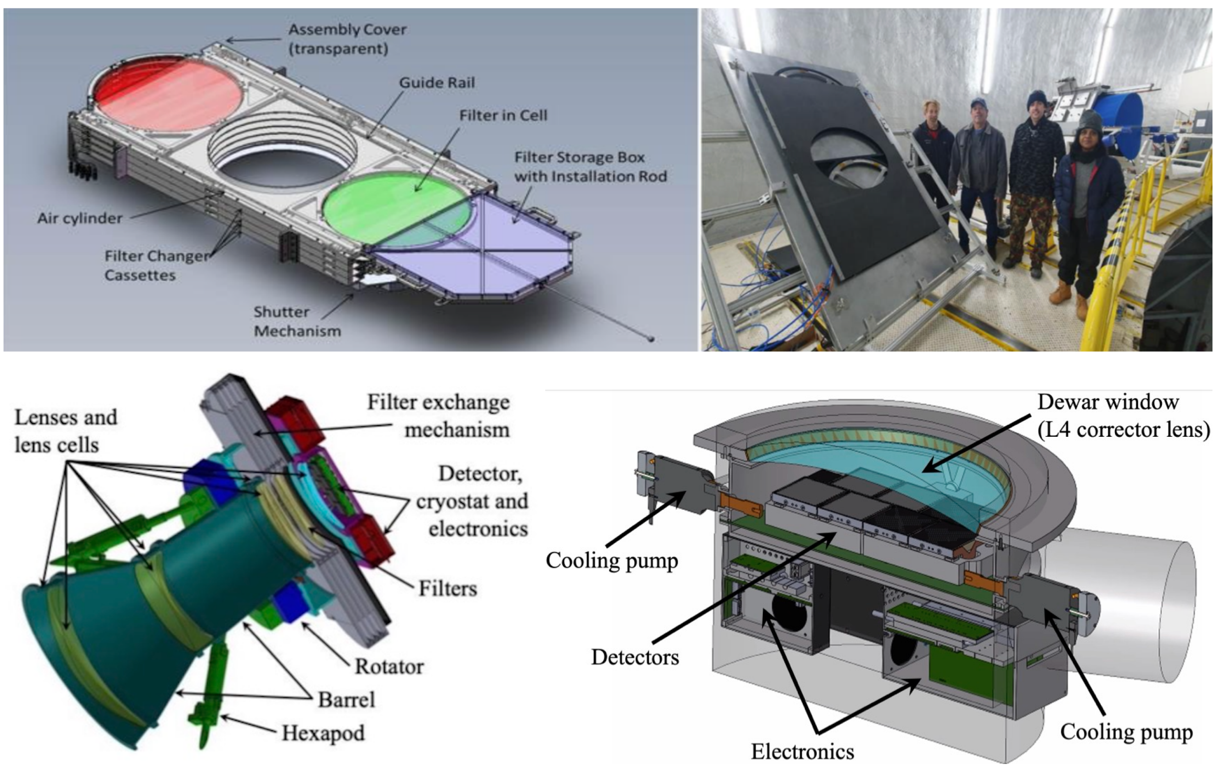

Figure 18 KWFI filter mechanism design and the prototype deployed at the summit with the engineering team standing next to it with designs for the camera system showing the full camera design and a cross section of the cryostat and detector system.

Recent efforts have retired risk on the design in the past couple of years. The first is a full-scale demonstration of the filter exchange mechanism that was tested at the WMKO summit facility in different orientations (see Figure 18). The second is assessing the mass limit of the telescope by completing a mass loading engineering test. The third was demonstrating feasibility through design of a deployable secondary mirror (M2) that would position M2 in front of the WFI when using other instruments at the observatory and fold the M2 out of the beam when using WFI [56]. The deployable M2 was a recent requirement levied by the WMKO SSC so that the WMKO instrument suite could maintain on-sky flexibility and efficiency for observing. In addition, the expected fast image processing for WFI will enable rapid source identification in the wide-field images and minutes-later spectroscopy with any available Keck instrument when retracting the M2.

8.4 FOBOS: Fiber Optic Broadband Optical Spectrograph

WMKO's previous and current strategic plan identify 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), led by Kevin Bundy at UCSC, 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).

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. 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. When completed, FOBOS will occupy the same location as DEIMOS (see Figure 19).

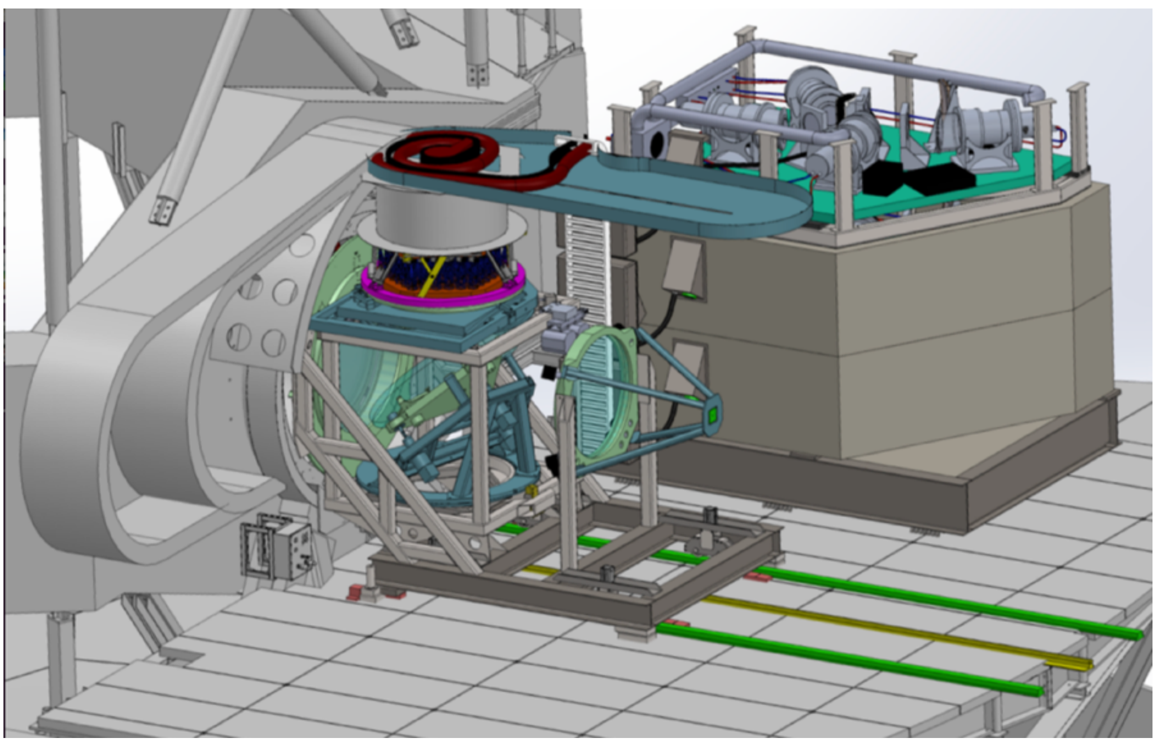

Figure 19: FOBOS conceptual layout on the KII Nasmyth Deck. The forward module that houses the ADC, guiding system, calibration system, and Starbugs fiber positioners. The layered bank of spectrographs has four optical channels and will be a permanent installation on the KII Nasmyth deck where DEIMOS is stowed.

8.5 VIPER

The VIPER concept, led by Max Millar-Blanchaer at UCSB, is a dual-channel imager architecture that can support both differential polarimetry and simultaneous dual-band imaging. It is the only concept to date proposed in support of AO observations at short visible wavelengths and both an imager and an IFS are called out in the WMKO Strategic plan when it comes to pushing into the blue with AO. The two channels will either feed two separate detectors, or fold back to image both channels on the same detector. The polarimetry mode is a triple-differential mode, enabled by an upstream waveplate (to be installed in the Precision Calibration Unit in front of the AO de-rotator), a fast ~kHz switching polarimetric modulator and a polarizing beamsplitter. The beamsplitter can also be used to enable dual-band imaging via two separate filter wheels. With an accessible focal plane, and pupil planes before and after it, VIPER can enable diffraction suppression and focal plane masking for high-contrast imaging. Small inner working angle science will be further enabled by non-redundant masks. In these ways the VIPER will address several Keck community needs, such as wavelength coverage into the blue, extreme spatial resolutions, and high-contrasts, while at the same time providing a potential platform for high-contrast testbed development. VIPER's instrument architecture would also satisfy the needs of the ORCAS team.

8.6 Zshooter

To follow up on discoveries from large survey facilities like Rubin and LIGO triggered multi-messenger events for example, WMKO recognizes the need for high efficiency spectroscopic capabilities at all OIR wavelengths with instruments that are available anytime. The ZShooter concept, led by Shri Kulkarni (PI), Mansi Kasliwal, and Richard Dekany at Caltech, is envisioned as a medium resolution (R ~10,000) slicer spectrograph with a full simultaneous wavelength coverage between the U and K bands. Although the instrument location at WMKO is still in flux, a key requirement is to install ZShooter so that it may be selected for target of opportunity observing, with low latency, on any observing night.

ZShooter is being designed to take full advantage of several emerging technologies. Nearly noiseless optical detectors in the form of p-channel skipper CCDs are intended to be used for all channels operating below 1 micron. Large format HgCdTe Avalanche Photodiode Arrays are identified as sensors that may be used for the NIR wavelengths. With nearly noiseless detectors there is no penalty for binning in software to achieve lower resolutions. Currently designed with nine fixed spectral channels, ZShooter can take additional advantage of new techniques developed at JPL for depositing tapered anti-reflection coatings on silicon which provides >99% QE at all wavelengths because the local coating thickness is optimized for the incident wavelength across the detector. Lastly, the team plans to incorporate Volume Binary Gratings to deliver exceptionally high efficiency. ZShooter is currently in a feasibility study phase and if approved to move forward will start conceptual design efforts in earnest during the 2025 calendar year.

8.7 GEO: Ground Layer Adaptive Optics

The Ground-layer Enhanced Observations project is a partnership of Caltech, UC and WMKO staff (Richard Dekany, interim PI) developing a Ground Layer Adaptive Optics (GLAO) capability to provide multifunctional adaptive optics image quality improvement for the KI telescope. GEO consists of four major subsystems, KASM – the Keck Adaptive Secondary Mirror, LAVA - the Laser Atmospheric Volumetric Array, which serves as the laser guide star (LGS) projection facility, CRAGS – Cassegrain Reconfigurable Array of Guide Stars, the LGS wavefront sensor (WFS) array, and FISSURE – FIelded Software for Supervision and REal-time Control, the real-time compute and control subsystem responsible for calculating the optimal ground-layer turbulence correction signal and providing executive supervision. GEO is intended to provide seeing enhancement over wide field of view (up to 12' diameter) for both LRIS-2 and MOSFIRE at the K1 Cass focus, while providing subsystems common to future additional AO functionalities. Featuring a continuously variable LGS asterism diameter (to as little as 3' diameter), GEO would enable optimization of correction taking into account variations in Cn2(h,t), science field of view, and availability of suitable guide stars (NGS) required for appropriate measurement of tip/tilt/focus wavefront modes via respective on-instrument wavefront sensors.

GEO is recognized as a high priority in the WMKO strategic plan and is pending start of a formal conceptual design phase within which Caltech, UC, and WMKO team members will work together to further model GLAO performance and flow-down top-level science requirements into technological performance and operational requirements for the system.

8.9 ORCAS: Orbital Configurable Artificial Star

The Orbital Configurable Artificial Star (ORCAS) mission is a pioneering hybrid space and ground facility that will enable new science by providing unprecedented angular resolution, exquisite sensitivity and a unique flux calibrator [57][58]. By enabling adaptive optics and flux calibration observations, ORCAS will deliver highly detailed images, unlocking for example the ability to detect a population of supermassive black hole binaries for the first time, as well as constraining the number densities of the faintest star forming clumps and understanding dark energy by measuring the distances of 10-billion-year-old supernovae.

In collaboration with the W. M. Keck observatory the ORCAS NASA mission lead by Eliad Peretz at NASA/Goddard is working to meet the science objectives defined in the ORCAS AS3 Report by delivering a combination of space and ground hardware which will enable high performance Adaptive Optics (AO) at visible and NIR wavelengths on the Keck 10m telescopes. The space-based portion of the project intends to deploy low-risk flight hardware, which includes a commercial ESPA-Grande class satellite bus with solar electric propulsion (SEP) carrying a modified commercial laser module as an AO beacon and a photometric calibrator. The spacecraft would be positioned in a 5-day Highly Elliptical Orbit (HEO), enabling 3 AO observation opportunities per orbit, such that the spacecraft remains within the isoplanatic patch (region of good AO performance) for periods of up to a few hours (target declination and wavelength dependent).

For the ground, WMKO instrument teams (e.g. Viper) are working to develop the instruments and define modifications to the AO system that would be part of the full project and the teams to date have been collaborating on risk reduction efforts that have resulted in unique performance milestones that demonstrate feasibility and functionality [59]. The project is gearing up to solidify mission support funding in the next few years while also further refining the ground-based hardware. For a complete description of the mission and documentation please see https://asd.gsfc.nasa.gov/orcas/

9. SUMMARY OF INSTRUMENTATION PROGRESS AT WMKO

WMKO has a healthy instrument development program that is supported and executed by a community of instrument developers currently at Caltech, the University of California at Los Angeles, Santa Barbara, San Deigo, Berkeley, Davis, Irvine, and Santa Cruz (UCLA, UCSB, UCSD, UCB, UCD, UCI, UCSC), Swinburne University of Technology, University of Notre Dame, and the Space Science Laboratory (SSL) in Berkeley. The community is developing instrumentation that was identified in the updated WMKO strategic plan [1] with a very considered analysis of current technologies that may be decommissioned in the future. Prioritized instrument projects fulfill key aspects of the strategic plan that will keep WMKO as both a leader that provides complimentary capabilities for new facilities both space- and ground based.

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