# Adaptive Optics at W. M. Keck Observatory

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## ABSTRACT

The first scientific observations with adaptive optics (AO) at W. M. Keck Observatory (WMKO) began in 1999. Through 2023, over 1200 refereed science papers have been published using data from the WMKO AO systems. The scientific competitiveness of AO at WMKO has been maintained through a continuous series of AO and instrument upgrades and additions. This tradition continues with AO being a centerpiece of WMKO's scientific strategic plan for 2035. We will provide an overview of the current and planned AO projects from the context of this strategic plan. The current projects include implementation of new real-time controllers, the KAPA laser tomography system and the HAKA high-order deformable mirror system, the development of multiple advanced wavefront sensing and control techniques, the ORCAS space-based guide star project, and three new AO science instruments. We will also summarize steps toward the future strategic directions which are centered on ground-layer, visible and high-contrast AO.

Keywords: adaptive optics, real-time control, laser tomography, near-infrared sensing, PSF reconstruction

## 1. INTRODUCTION

Since the first science with the Keck II natural guide star adaptive optics (AO) system in 1999, the W. M. Keck Observatory (WMKO) has been continuing to provide new AO science capabilities to its scientific user community on both 10-m telescopes. We will begin by providing a brief overview of the history of the Keck AO developments over the last quarter century and the scientific productivity of these systems, with over 1200 refereed science papers published using WMKO AO data through 2023. From this context, the focus of the paper will then switch to WMKO's current AO developments and future strategic directions. These future directions are driven by WMKO's scientific strategic plan for 2035 which was published in 2023. AO and AO science instruments play a key central role in this strategic plan with three strategic directions including ground-layer AO for wide-field enhanced seeing, high sky coverage visible AO for high angular resolution over moderate (30 arcsec) fields, and high-contrast AO over narrow fields for exoplanet characterization and technology development.

Current implementation activities fall into the latter two categories. Real-time controller and wavefront sensor camera upgrades on both telescopes provide the basis for high sky coverage visible and high-contrast AO. The KAPA laser tomography upgrade on Keck I will provide improved LGS AO performance and sky coverage. The Liger integral field spectrograph and imager will make maximal use of the KAPA upgrade. The implementation of an ALPAO 2844-actuator deformable mirror and high order Shack-Hartmann wavefront sensor on Keck II (HAKA project) will benefit both visible and high-contrast science. A proposed high-order infrared wavefront sensor ('IWA) will leverage the science that can be achieved with the HAKA deformable mirror and two new high-contrast science instruments: The SCALES 2-5 um integral field spectrograph and the R=100,000 single-mode fiber fed spectrograph HISPEC. A fast, visible imager (ORKID) has been used to demonstrate visible science that will greatly benefit from the HAKA deformable mirror; ORKID is a risk-reduction demonstrator for the ORCAS project to use a guide star beacon on a satellite for visible and very high-contrast science. Multiple advanced wavefront sensing and control techniques are also being tested and implemented, including on-sky focal plane wavefront sensing, primary mirror phasing with Zernike and pyramid wavefront sensors, speckle nulling and predictive wavefront control.

Finally, an overview of the next implementation steps toward WMKO's AO strategic directions will also be provided including the ground-layer AO enhanced seeing system, visible AO system design and high-contrast testbed.

## 2. SCIENCE PRODUCTIVITY AND KECK AO THROUGH 2023

The Keck AO systems have proved to be very productive scientifically. The first refereed astronomical science papers using the Keck II telescope's NGS AO system were published in 2000.[1] A similar AO system was implemented on the Keck I telescope, initially to support the Keck Interferometer.[2] Both systems were subsequently upgraded to perform LGS AO.[3,4] Both systems have undergone a number of upgrades over the years including three generations of lasers (LLNL dye laser on Keck I, LMCT solid state laser on Keck II, TOPTICA-MPBC Raman fiber amplifier lasers[5] on both Keck telescopes), real-time controllers (LLNL, Microgate in 2007[6] and 2024) and wavefront sensor cameras (GTRI, SciMeasure, OCAM2K). A near-infrared tip-tilt sensor[7] was implemented on Keck I and a near-infrared pyramid wavefront sensor[8] on Keck II. An AO operations perspective on the last twenty-five years is provided elsewhere in this conference.[9]

Through the end of 2023, 1269 refereed science papers have been published using the Keck AO systems, including 492 papers using LGS AO mode. The cumulative number of publications by year and science category is shown in **Error! Reference source not found.**. A selection of images from the 95 refereed science papers in 2023 is shown in Figure 2. The top cited papers using Keck AO data are listed in Table 1.

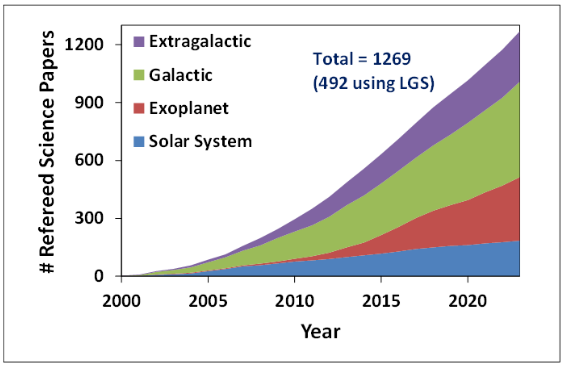


Figure 1: Cumulative number of refereed astronomical science papers published using data from the Keck AO systems. These papers are divided into four broad science categories.

Table 1: Top 10 cited papers using Keck AO.

| Citations (3/22/24) | Year | 1st Author | Journal | Paper | AO |
|---|---|---|---|---|---|
| 1458 | 2012 | Suzuki, N. | ApJ 746, 85 | The Hubble Space Telescope Cluster Supernova Survey. V. Improving the Dark-Energy Constraints above z>1 and Building an Early-Type-Hosted Supernova Sample | LGS |
| 1381 | 2008 | Marois, C. | Science 322, 1348 | Direct Imaging of Multiple Planets Orbiting the Star HR 8799 | NGS |
| 1304 | 2008 | Ghez, A. | ApJ 689, 1044-1062 | Measuring Distance and Properties of the Milky Way's Central Supermassive Black Hole with Stellar Orbits | LGS |
| 917 | 2020 | Wong, K. | MNRAS 498, 1420-1439 | H0LiCOW - XIII. A 2.4 per cent measurement of H0 from lensed quasars: 5.3σ tension between early- and late-Universe probes | LGS |
| 667 | 2008 | Kalas, P. | Science 322, 1345 | Optical Images of an Exosolar Planet 25 Light Years from Earth | NGS |
| 654 | 2008 | van Dokkum, P. | ApJ 677, L5-8 | Confirmation of the Remarkable Compactness of Massive Quiescent Galaxies at z ~ 2.3: Early-Type Galaxies Did not Form in a Simple Monolithic Collapse | LGS |
| 483 | 2012 | Dupuy, T. | ApJS 201, 19 | The Hawaii Infrared Parallax Program. 1. Ultracool Binaries and the L/T Transition | N/LGS |
| 356 | 2009 | Law, D. | ApJ 697, 2057-2082 | The Kiloparsec-Scale Kinematics of High-Redshift Star-Forming Galaxies | LGS |
| 305 | 2019 | Do, T. | Science 365 664 | Relativistic redshift of the star S0-2 orbiting the Galactic center supermassive black hole | LGS |
| 301 | 2016 | Boehle, A. | ApJ 830 17 | An Improved Distance and Mass Estimate for Sgr A* from a Multistar Orbit Analysis | LGS |

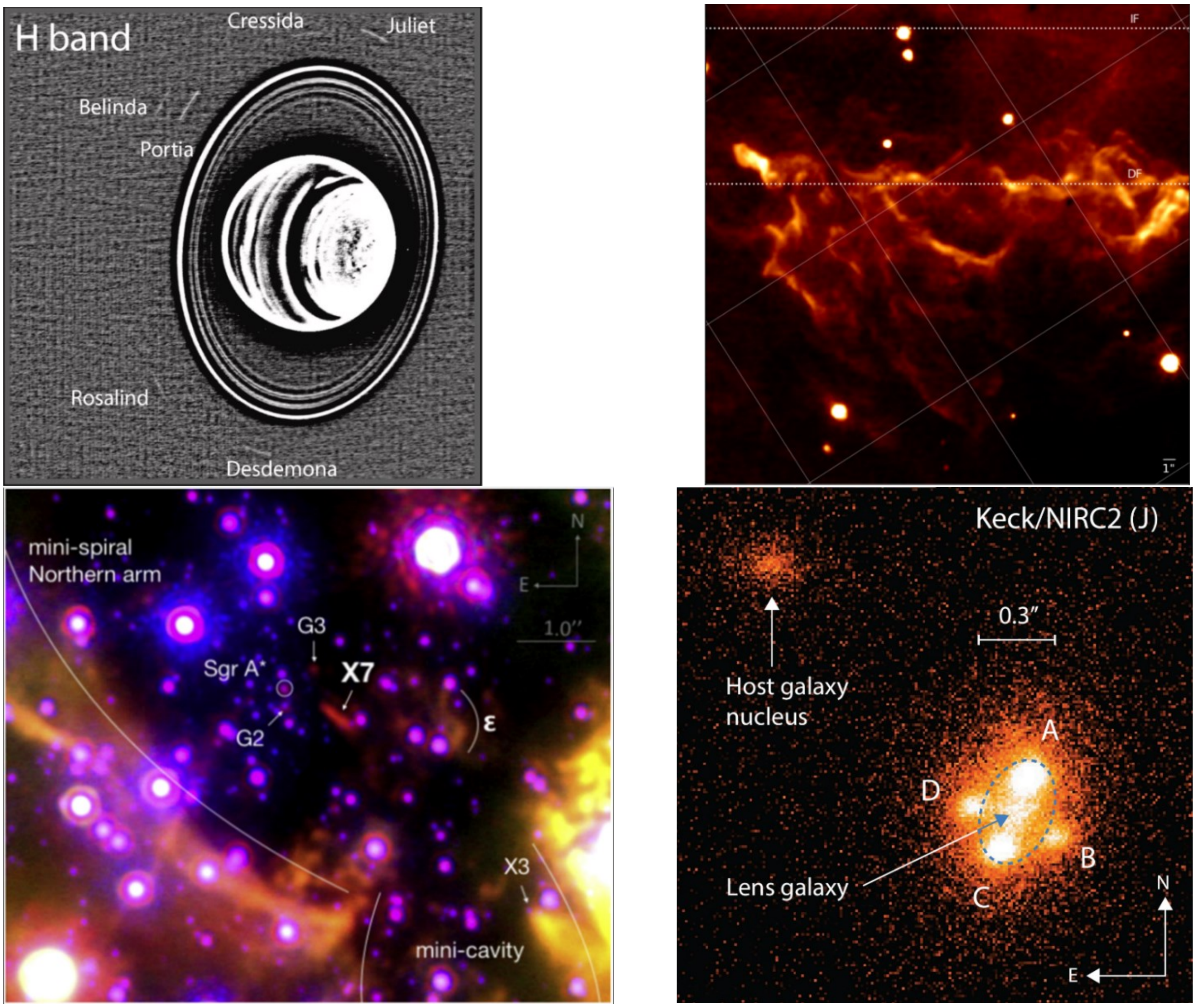


Figure 2: A selection of images obtained with the Keck AO systems published in 2023. Top-left: Photometry of the small Uranian satellites (Paradis et al. 2023).[10] Top-right: Orion bar H2 region (2.12 μm; Habart et al. 2023).[11] Bottom-left: Galactic Center (Ciurlo et al. 2023).[12] Bottom-right: Gravitational lens galaxy (Goobar et al. 2023).[13] Uranus was observed with NGS AO while the other three objects were observed with LGS AO.

## 3. CURRENT AO DEVELOPMENTS ACTIVITIES

Both Keck telescopes are equipped with AO systems capable of acquiring science data using a Shack-Hartmann wavefront sensor and NGS or LGS modes. These systems and their associated science instruments are summarized in

Table 2. The KAPA, HAKA and ‘IWA upgrades will be discussed in subsequent sections. A photo of the Keck I AO system and the OSIRIS instrument is provided in Figure 3.

Three AO-fed science instruments are currently in operational use: KPIC[14,15] (PI: D. Mawet), NIRC2 (PI: K. Matthews), NIRSPEC[16] (PI: I. McLean) and OSIRIS[17] (PI: J. Larkin). Three new science instruments are in development: SCALES[18] (PI: A. Skemer), HISPEC[19] (PI: D. Mawet) and Liger[20] (PI: S. Wright). ORKID[21] (PI: E. Peretz) is currently a demonstrator. A dichroic beamsplitter transmits ≥ 950 nm light to the science instruments and reflects the shorter wavelength light for wavefront sensing (and ORKID). The Keck I dichroic will be switched to transmit ≥ 800 nm light to Liger.

Table 2: Summary of the AO systems and science instruments on both Keck telescopes. The science instrument wavelength ranges and details are provided. Green background systems are in science operation while yellow background indicates systems currently under development. The expected first light dates for new capabilities are included.

| Telescope | AO Sys. | Instrument | λ | Details |
|---|---|---|---|---|
| Keck I | K1AO | OSIRIS | 0.95-2.4 | R=3k; 0.3x1.3" at 20mas to 4.8x6.4"at 100mas |
| | | | | 20x20" at 10 mas |
| | +KAPA (2024) | Liger (2027) | 0.8-2.4 | R=4-10k; 1.9x1.9" at 14mas to 13x7" at 150mas |
| | | | | 20x20" at 10 mas |
| Keck II | K2AO | NIRC2 | 0.95-5 | 10x10" at 10 mas to 40x40" at 40 mas; vortex; SAM |
| | | NIRSPEC | 0.95-5.5 | R=35k slit |
| | | KPIC+NIRSPEC | 2-3.5 | Single mode fiber fed; R=35k |
| | | ORKID | 0.5-0.95 | 10" diameter at 6.7 mas. Up to 750 frames/sec |
| | +HAKA (2026) | all above | 0.5-5 | 64x64 actuator DM to replace 20x20 DM |
| | +'IWA (2027) | SCALES (2025) | 2-5 | R=35-250, 2.15x2.15" at 20mas. R=3-7k, 0.36x0.36" at 20 mas |
| | | | 1-5 | 20x20" at 10 mas |
| | | HISPEC (2026) | 0.95-2.5 | Single mode fiber fed; R=100k |

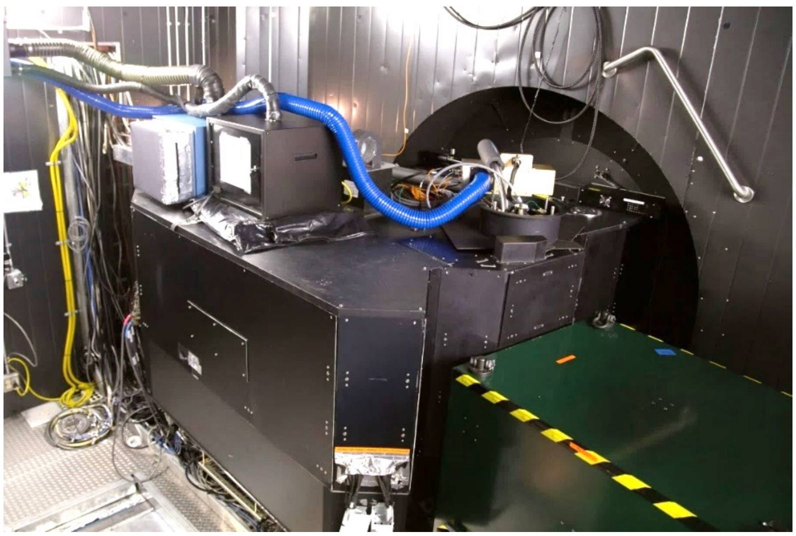

Figure 3: The Keck I AO system (black box) and OSIRIS (green box).

### 3.1. ERROR BUDGET

The largest terms (> 30 nm rms) in the Keck LGS AO error budget are shown in Table 3. This error budget and a similar budget for NGS AO were anchored against nightly AO performance measurements using bright, on-axis guide stars at high elevation. A Galactic Center LGS AO error budget was anchored against science observations. A high order (HO) wavefront error margin of 130 nm rms was needed to match the measured Strehl ratio for all three error budgets, A tip-tilt (TT) error margin of 7 mas rms was needed to match the measured FWHM for the LGS AO and Galactic Center LGS AO cases. The sources of these errors have not yet been identified.

The current Keck AO development projects are designed to reduce the largest error terms in Table 3:

- Sect. 3.2. The real-time controller upgrade on both telescopes will reduce the bandwidth error and provide a flexible base on which the subsequent projects can be built.
- Sect. 3.3. The Keck I KAPA project will reduce the LGS focal anisoplanatism error and the tip-tilt error margin.
- Sect. 3.4. The Keck II HAKA project to implement a high order deformable mirror (DM) will reduce atmospheric fitting error and uncorrectable static telescope aberrations, while also supporting improved advanced wavefront control.

- Sect. 3.5**Error! Reference source not found.**. The advanced wavefront control projects, currently on Keck II, will primarily address the high order wavefront error margin including improved mirror segment phasing.

In addition:

- Sect. 3.6. The HAKA-associated Keck II near-infrared wavefront sensor ('IWA) would support a range of additional science targets to be observed using the HAKA DM.
- Sect. 3.7. Longer term, the ORCAS project would minimize the measurement and bandwidth errors and remove all the LGS-dependent error terms by providing a bright NGS-like reference source for both telescopes simultaneously. The current capability of the Keck AO to work at visible science wavelengths has been demonstrated with the ORKID camera. The performance measured with this camera will be improved as the Keck II AO development projects are implemented.

**Table 3: Keck LGS AO error budget (terms contributing < 30 nm rms are hidden in this view). Current Keck AO development efforts have been selected to reduce the largest error terms.**

| Science High-order Errors (LGS Mode) | | | Wavefront Error (rms) | | Parameter | | Science Band H | Science Band K |
|---|---|---|---|---|---|---|---|---|
| Atmospheric Fitting Error | | | 121 | nm | 20 | Subaps | | |
| Bandwidth Error | | | 133 | nm | 24 | Hz (-3db) | | |
| High-order Measurement Error | | | 32 | nm | 20 | W | | |
| High-Order Aliasing Error | | | 40 | nm | 0.3 | Fitting reduction factor | | |
| LGS Focal Anisoplanatism Error | | | 153 | nm | 1 | sci beacon(s) | | |
| Uncorrectable Static Telescope Aberrations | | | 66 | nm | 20 | Acts Across Pupil | | |
| Uncorrectable Dynamic Telescope Aberrations | | | 74 | nm | | Dekens Ph.D | | |
| Dynamic WFS Zero-point Calibration Error | | | 50 | nm | | Allocation | | |
| Residual Na Layer Focus Change | | | 41 | nm | 30 | m/s Na layer vel | | |
| DM Finite Stroke Errors | | | 31 | nm | 4.0 | um P-P stroke | | |
| Uncorrectable AO System Aberrations | | | 30 | nm | | Allocation | | |
| Uncorrectable Instrument Aberrations | | | 60 | nm | | NIRC2 | | |
| HO Wavefront Error Margin | | | 130 | nm | | Allocation | | |
| **Total High Order Wavefront Error** | | | **312** | **nm** | **Strehl Ratio** | | 0.32 | 0.50 |
| **Science Tip/Tilt Errors** | **Angular Error (rms)** | | **Equivalent WFE (rms)** | | **Parameter** | | | |
| Residual Telescope Wind Shake Jitter (one-axis) | 2.6 | mas | 44 | nm | 29 | Hz input disturbance | | |
| TT Error Margin | 7.0 | mas | 116 | nm | | Allocation | | |
| **Total Tip/Tilt Error (one-axis)** | **7.7** | **mas** | **119** | **nm** | **Strehl Ratio** | | 0.87 | 0.89 |
| **Total Effective Wavefront Error** | | | **315** | **nm** | **Strehl Ratio** | | 0.28 | 0.44 |
| | | | | | **FWHM (mas)** | | 48.3 | 52.5 |

## 3.2. REAL-TIME CONTROLLER UPGRADE

New real-time controllers for both Keck AO systems were developed by a Microgate-led consortium including Swinburne University of Technology and Australia National University.[22] These systems have recently been put into science operations use with both AO systems. The upgrade includes a module to interface with the wavefront sensors and deformable mirrors, and a Graphical Processing Unit (GPU) based computational engine to meet the system's control requirements and to provide a flexible software architecture to allow future algorithm development and capabilities. As part of this upgrade the existing Shack-Hartmann wavefront sensor cameras from SciMeasure are being replaced with First Light Imaging OCAM2K cameras to provide lower noise and larger formats. The OCAM2K camera is in use on Keck I and will be installed on Keck II in September 2024. A third (spare) RTC remains at Microgate to support developing the HAKA DM interface and will be subsequently shipped to Keck. Real-time controller commissioning results are shown in Figure 4.

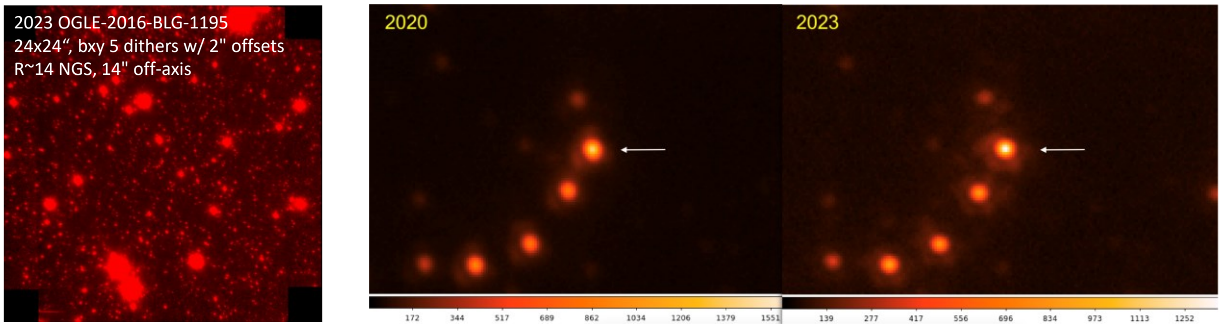


**Figure 4: Keck I LGS AO science observation of OGLE-2016-BLG-1195 to compare the performance of the new real-time controller and OCAM2K wavefront sensor in 2023 to an observation of the same target in 2020 (Vandorou et al. 2024).[23] The 2023 observation was acquired at an elevation of 37° to 33° with ~0.8″ seeing versus 42° to 39° in 2020 with ~0.7″ seeing. The Strehl ratio was improved slightly with the new real-time controller from 0.30±0.06 to 0.32±0.03 while the full-width-half-maximum was reduced significantly from 62.0±5.4 mas to 52.6±1.8 mas. The left image shows the full 24″x24″ field observed in 2023 while the right image shows a small portion of this field.**

### 3.3. KAPA: LASER TOMOGRAPHY

The Keck All sky Precision Adaptive optics (KAPA) project will upgrade the Keck I AO system with laser tomography as well as improved low order sensing.[24] The KAPA hardware elements are shown schematically in Figure 5. A 20 W Toptica Raman-fiber amplifier laser was implemented on the telescope's elevation ring to provide higher sodium-wavelength return than the previous Nasmyth-mounted LMCT solid state sum-frequency laser. An asterism generator[25] was implemented just before the launch telescope, behind the Keck telescope secondary mirror, to split the single laser into four LGS on a 7.6″ radius. The laser, asterism generator and laser launch telescope are shown in Figure 6. Figure 7 shows the on-sky images of the four LGS on the AO acquisition camera and wavefront sensor, along with the new wavefront sensor pupil relay optics.

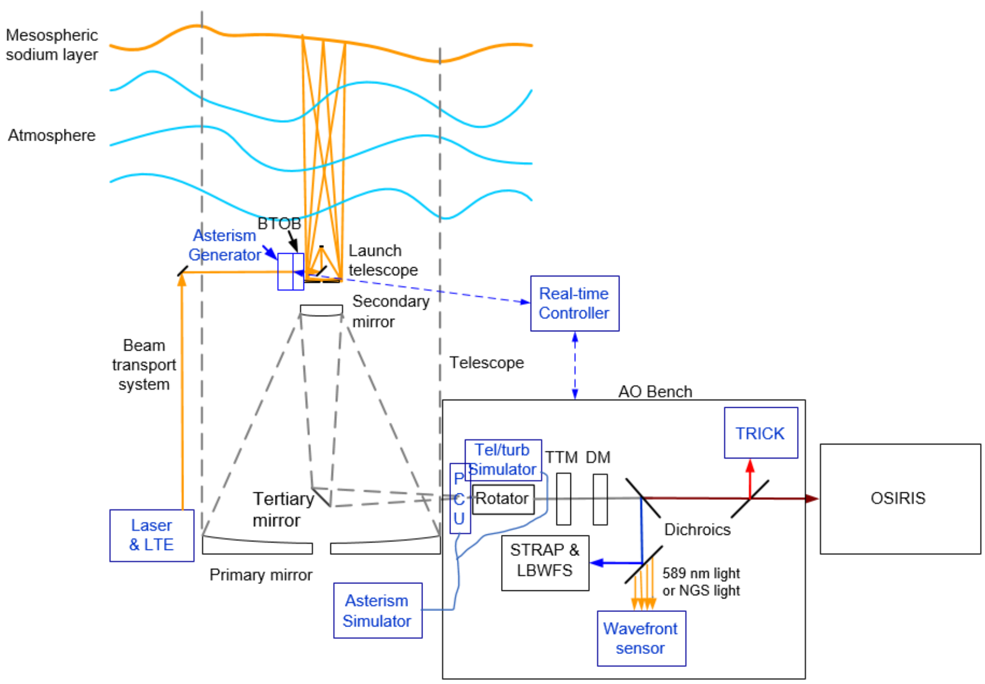


**Figure 5: Schematic of the KAPA upgrade to the Keck I AO system. Blue boxes indicate new or modified systems. (Acronyms: BTOB = Beam Transfer Optics Bench, DM = Deformable Mirror, LTE = Laser Table Enclosure, PCU = Precision Calibration Unit, STRAP = visible tip-tilt sensor, Tel/Turb = Telescope/Turbulence, TRICK = near-infrared tip-tilt sensor, TTM = Tip-Tilt Mirror).**

On the Keck I AO bench, the major modifications are the implementation of four LGS on the Shack-Hartmann wavefront sensor camera and the tools for daytime calibration and tomographic testing (asterism simulator, precision calibration unit and telescope and turbulence generator shown in Figure 8)[26].

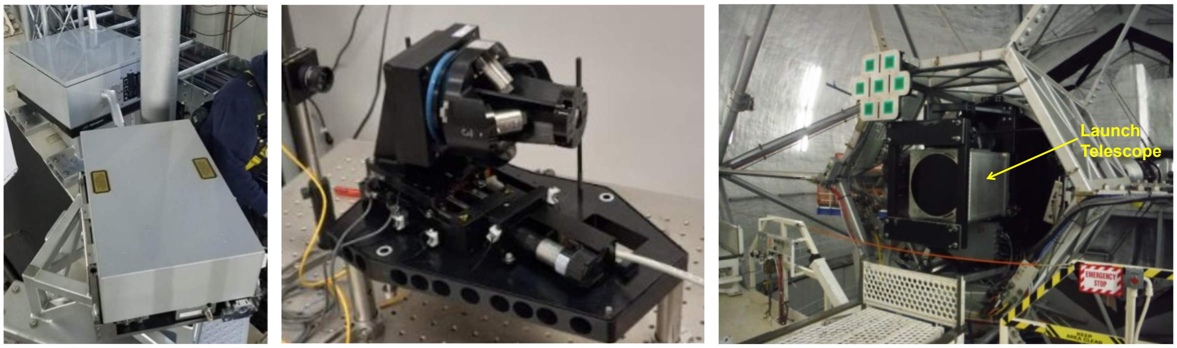


Figure 6: Laser and laser table enclosure on the telescope elevation ring (left), asterism generator (center) mounted next to the laser launch telescope (right).

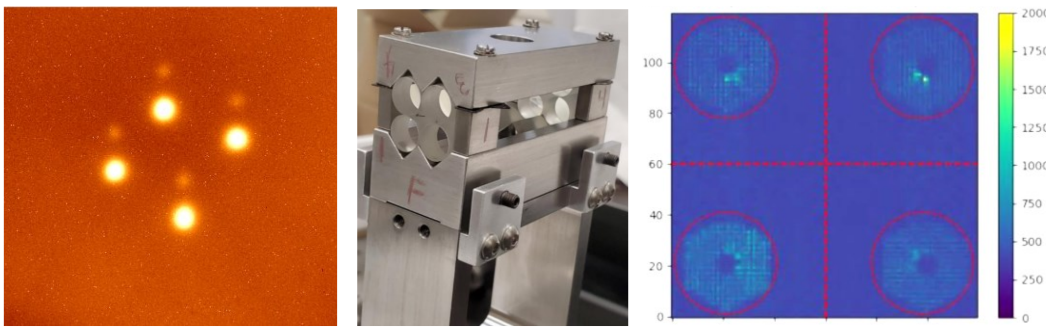


Figure 7: Four LGS on-sky as imaged by the acquisition camera (left) and wavefront sensor camera (right). The relay optics used to produce the four pupil images on the wavefront sensor are shown at center.

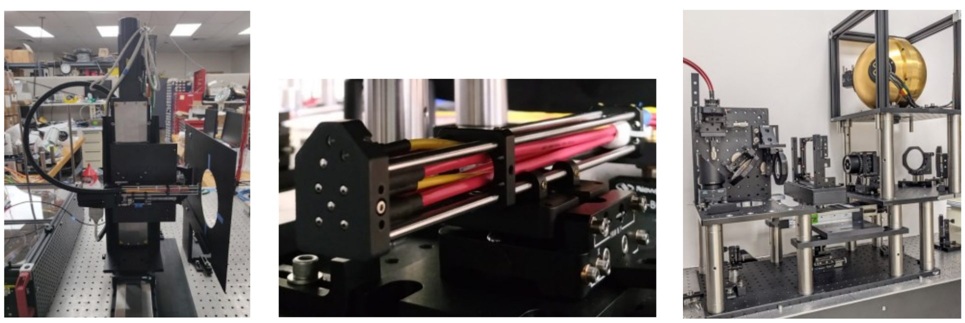

Figure 8: Precision calibration unit (PCU, left) that moves the fibers or a fold mirror to the telescope simulator into the beam. The fiber assembly (center) with four LGS multi-mode fibers on a 7.6” radius and two NGS single-mode fibers mounted to the PCU. The telescope simulator (right) with a Keck pupil mask, LGS fibers at 100 km equivalent distance and a NGS fiber at infinity, along with a mount for a turbulence phase screen that can move to simulate wind and altitude changes.

As of May 2024, all KAPA hardware is installed. One of the sets of four pupil relay optics is being used to support NGS and single LGS AO science operations, although some remaining calibration work is needed to fully address non-common path aberrations over a range of seeing conditions.

As of June 2024, development efforts will be focused on the daytime calibration and testing phase.[25] This phase includes implementing: (1) calibrations for the four LGS wavefront sensors, (2) laser tomography on the real-time controller as shown in Figure 9, (3) soft-real-time control laser tomography tools such as the reconstructor generator, (4) performance testing with turbulence from the tip-tilt mirror, deformable mirror and a moving phase screen at altitude, and (5) evaluating error budget terms that can be measured in daytime. We will also be testing low order wavefront control algorithms, including phase retrieval on the near-infrared tip-tilt sensor (TRICK) to measure focus.[27,28]

The KAPA science team has been developing tools to support their observation planning and data reduction. The resultant exposure time calculator (https://oirlab.ucsd.edu/osiris/etc/), Strehl ratio calculator (http://altair.dyn.berkeley.edu:8501/), spectrometer and imager data reduction pipeline (https://github.com/Keck-DataReductionPipelines/OsirisDRP), and distortion solution[29] are all publicly available. Work has also progressed toward on-axis[30] and off-axis[31-34] point spread function reconstruction.

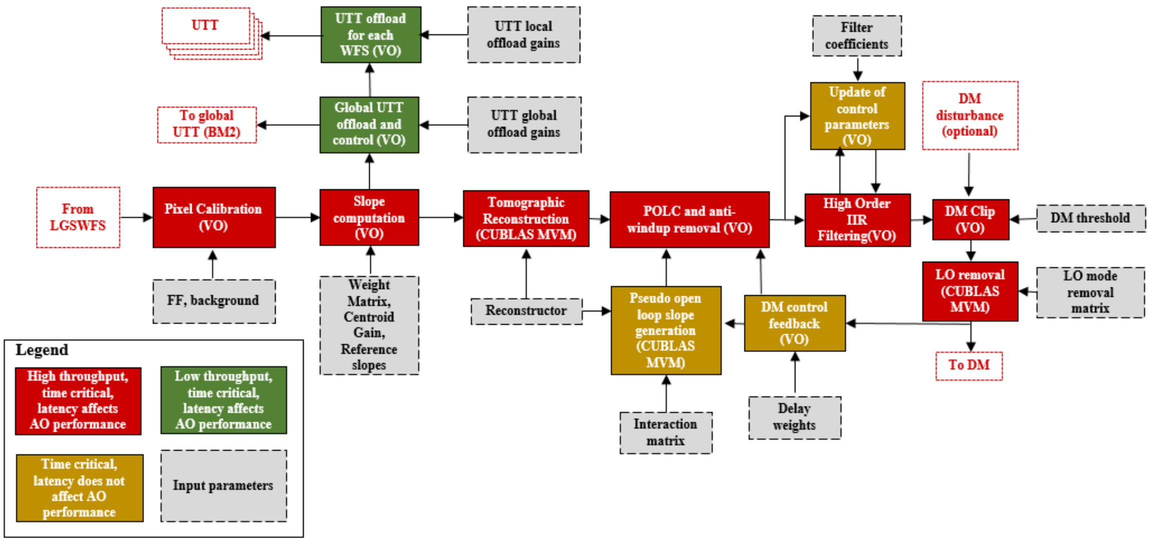


Figure 9: KAPA laser tomography real-time control sequence.

### 3.4. HAKA: HIGH ORDER DEFORMABLE MIRROR

The HAKA project will replace the existing 349-actuator Xinetics deformable mirror on the Keck II AO bench with a 2844-actuator ALPAO deformable mirror and upgrade the existing Shack-Hartmann wavefront sensor from 20x20 subapertures to 60x60. The ALPAO deformable mirror and its position on the AO bench is shown in Figure 10.

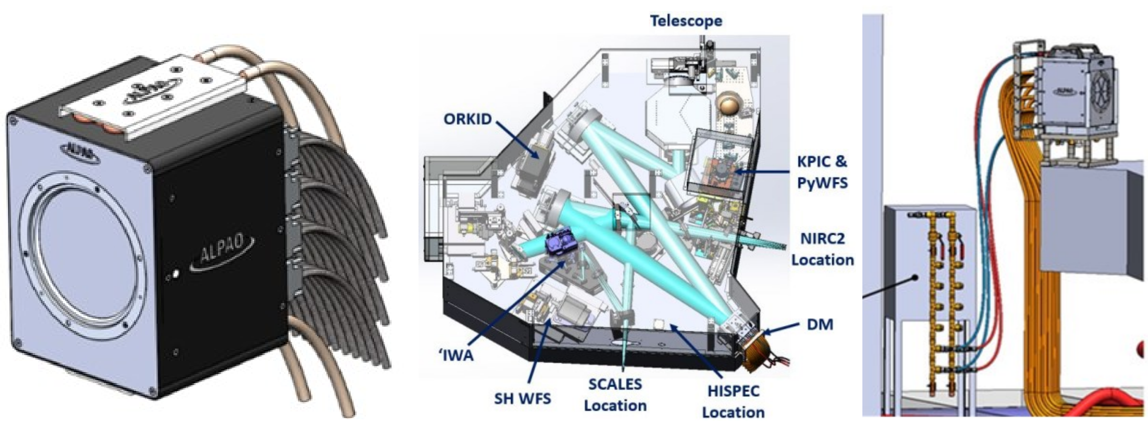


Figure 10: The ALPAO deformable mirror (left) will be located at the DM location on the Keck II AO bench (center), using the cable and glycol routing management shown at right. The Shack-Hartmann wavefront sensor (SH WFS) will also be modified. The location of the science instruments (HISPEC, KPIC, NIRC2, ORKID, SCALES) and the proposed location of the Infrared Wavefront sensor for Ao ('IWA) are also shown.

ALPAO is in the fabrication phase for this deformable mirror with expected delivery to Keck by December 2024. Once implemented, atmospheric fitting error, the largest error term in the NGS AO error budget, should be reduced by a factor of ~ $3^{5/6} = 2.5$ when using with bright guide stars. The predicted Strehl ratio improvement is shown in Figure 11. The higher-order deformable mirror will also reduce the uncorrectable static aberrations and enable improved speckle nulling.

The HAKA project completed a preliminary design review in April 2024. Opto-mechanical components[35] were reviewed at the detailed design level allowing orders for the long lead optics to be placed in May 2024. A lab has been set up where closed loop testing of the DM can be performed using the spare RTC and wavefront sensor camera.

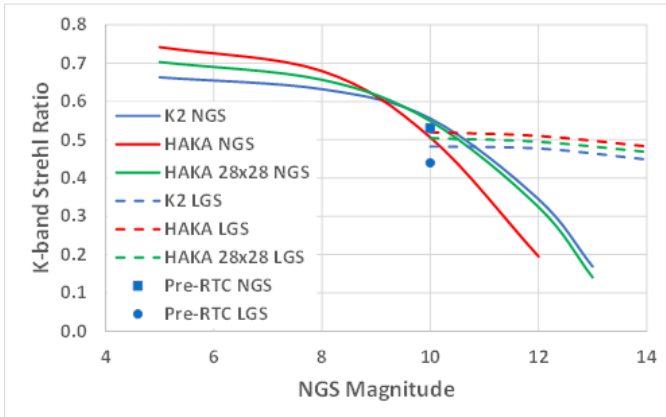


**Figure 11: Predicted median image quality versus guide star magnitude with HAKA, the current K2 AO system, and pre-RTC upgrade on-sky performance. The HAKA SH WFS will have a 56x56 subapertures sampling mode (red curves) and a lower order 28x28 subaperture mode (green curves). HAKA provides a significant performance improvement for bright NGS, without reducing NGS AO sky coverage (using the low order mode). HAKA provides a modest improvement for LGS AO.**

### 3.5. ADVANCED WAVEFRONT SENSING AND CONTROL

Several advanced wavefront sensing and control algorithms are being tested with the Keck II AO system with the goal of implementing operational science tools.[36] These are discussed in the sequence of operational readiness:

- The Fast and Furious sequential focal plane wavefront sensing algorithm[37] has been demonstrated to improve the Strehl ratio at the 10% level by correcting for non-common-path aberrations and perhaps some segment co-phasing errors. An operational tool (Figure 12) is being implemented with the NIRC2 imager.[38]
- A vector Zernike Wavefront Sensor (ZWFS) was installed as part of the KPIC Phase II upgrade in June 2022. Closed-loop control of the primary mirror segment pistons using this ZWFS has been demonstrated to improve the Strehl ratio on NIRC2 by up to 10%, as shown in Figure 13.[39,40]
- Contrast improvements have been demonstrated, as shown in Figure 14, by appropriately combining a predictive term with the normal leaky integrator term.[41,42] The predictive term is given by a predictive filter and a history vector containing pseudo-open loop DM commands calculated using the residual wavefront and previous DM commands.
- Multiple speckle nulling methods in the focal plane have been tested (see Figure 15).[43] The DM is used to introduce a known perturbation in the focal plane, and an opposing electric field is generated from this measurement and applied using the DM. On sky, speckle nulling has been demonstrated in the lab with NIRC2 to achieve a contrast improvement of ~2X in a 4-8 lambda/D region.

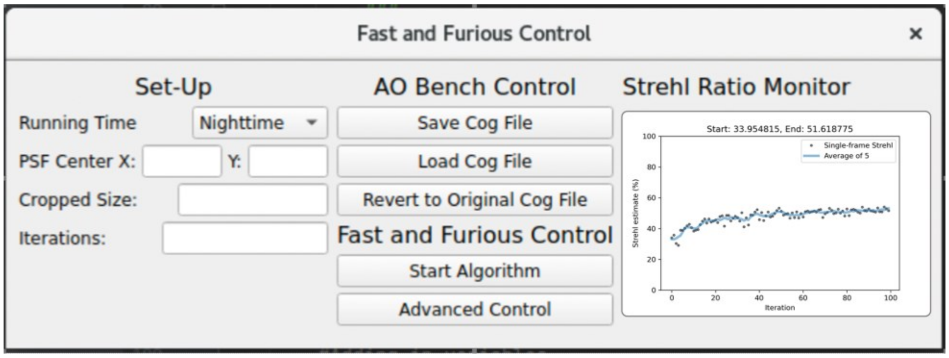


Figure 12: Fast and Furious control GUI showing the Strehl ratio improvement (right plot) as measured by focal plane images.

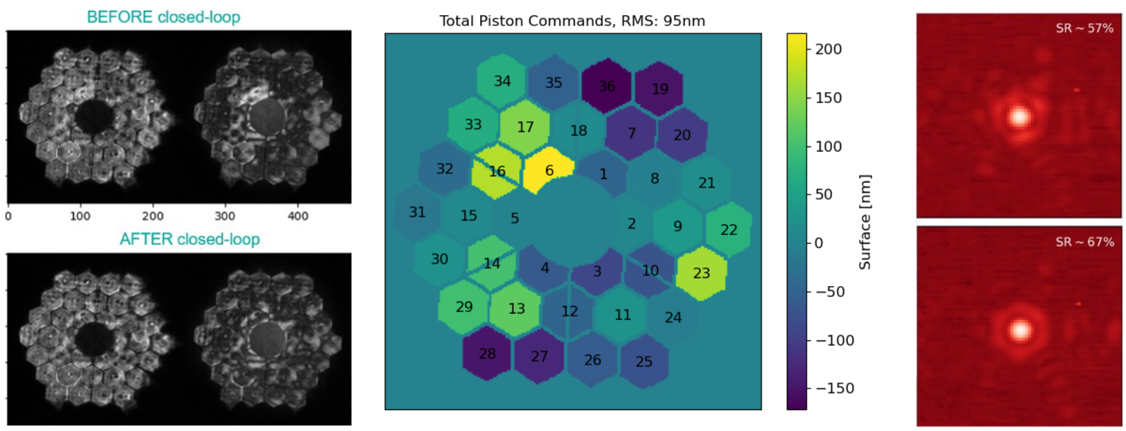


Figure 13: Vector Zernike wavefront sensor images of the Keck telescope pupil before (top-left) and after (bottom-left) closing the correction loop to the telescope primary mirror control system. The corrections applied to the primary mirror segments (center). The AO-corrected images on NIRC2 before (top-right) and after (bottom-right) sending primary mirror corrections. In this case the K-band Strehl ratio was improved from 57% to 67%, corresponding to a 140 nm rms reduction in wavefront error.

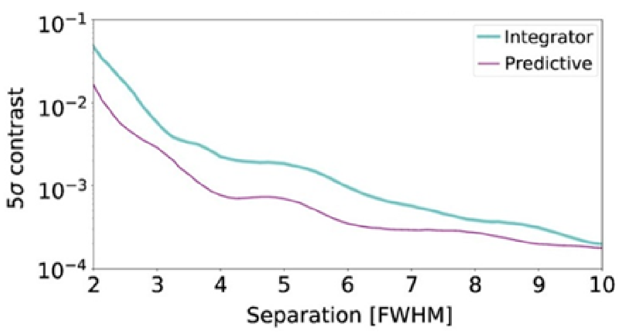


Figure 14: Demonstrated contrast improvement (ADI median subtracted contrast curve for HIP 117578) versus separation using predictive wavefront control.

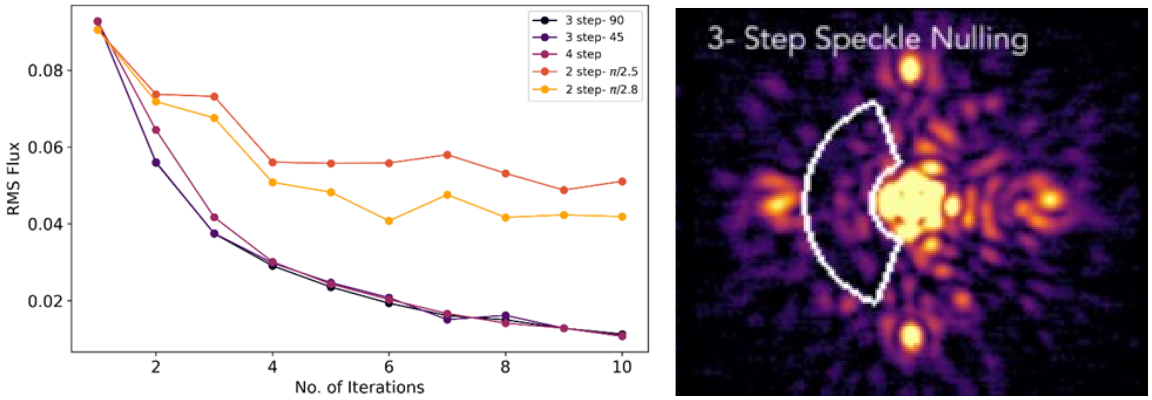


Figure 15: Simulated results from 4, 3 and 2-step speckle nulling algorithms.

## 3.6. ‘IWA: INFRARED WAVEFRONT SENSOR

A proposal has been submitted to implement a near-Infrared Wavefront sensor AO (‘IWA) system to optimize the Keck II AO system’s performance for high-contrast science with the HAKA DM, including exoplanet direct imaging and spectroscopy. This combined system would significantly enhance the performance and sky coverage delivered by the Keck II AO system to three science instruments (HISPEC, SCALES and ORKID). ‘IWA would provide a high-order pyramid wavefront sensor for NGS AO, a low-order mode to increase sky coverage with both NGS and LGS AO, and a Zernike wavefront sensor for periodic primary mirror segment phasing (see Figure 16).

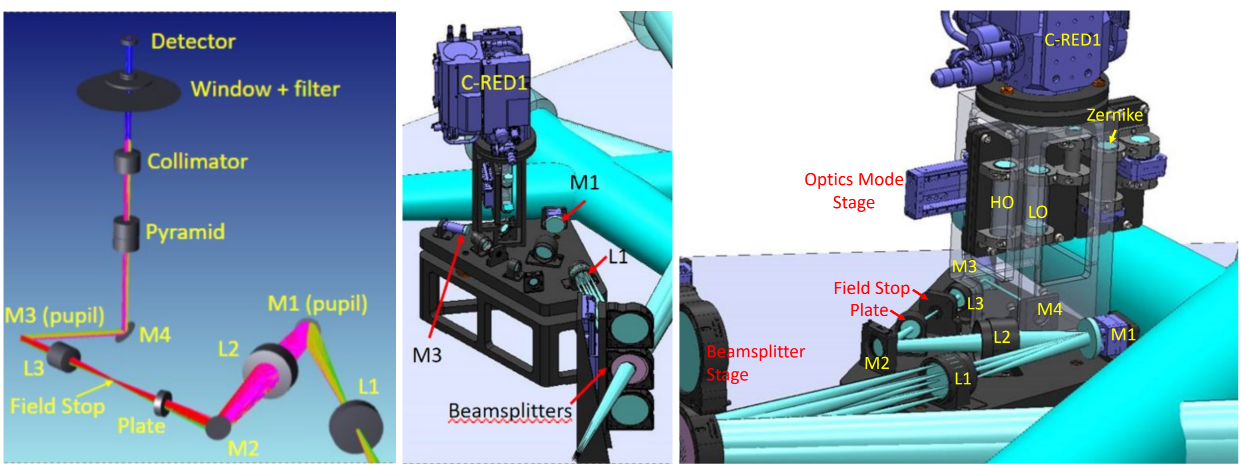


Figure 16: Three views of the proposed ‘IWA sensor.[35] A dichroic beamsplitter in the path to HISPEC and SCALES reflects light to a field lens that reimages the pupil onto the field steering mirror, M1. The optics mode translation stage can support five modes (high order, low order and Zernike are labelled). The M3 stage is at a pupil and provides modulation for the pyramid wavefront sensor.

## 3.7. ORCAS

ORCAS (ORbital Configurable Artificial Star) is a NASA Goddard led project to use a laser source on a satellite orbiting the earth as a guide star (https://asd.gsfc.nasa.gov/orcas/).[44] The laser would appear as a point source moving very slowly with respect to a science target near the apogee (~200,000 km) of its highly eccentric orbit, as shown in Figure 17. ORCAS would provide a very bright NGS for AO correction allowing for visible wavelength and/or high contrast science observations.

Three risk reduction activities have been performed with Keck AO to demonstrate the feasibility of using an ORCAS guide star. The first was to implement a fast visible camera with the Keck II AO system (ORKID camera) and demonstrate near-diffraction-limited performance at visible wavelengths as shown in Figure 18.[45,46] The second was to lock the AO loop on an asteroid at appulse while using the NIRC2 science camera to observe a background galaxy (Figure 19). The third was to lock the AO loops, using the near-infrared pyramid wavefront sensor, on the laser source of the geo-stationary Laser Communication Relay Demonstrator (LCRD; Figure 20) which also demonstrated the ability to coordinate space-ground observations since the LCRD needed to open loop point at the Keck telescope.

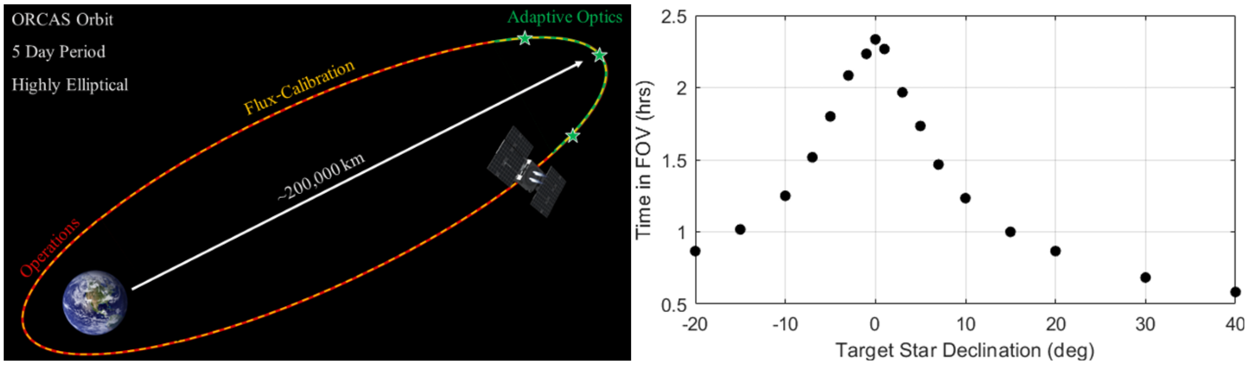


**Figure 17: ORCAS will be in a highly elliptical orbit (left) with AO observations occurring when the satellite is near its apogee and moving slowly with respect to the sky. ORCAS can be within 7.5″ of a science target for more than 2 hours as shown in the plot at right.**

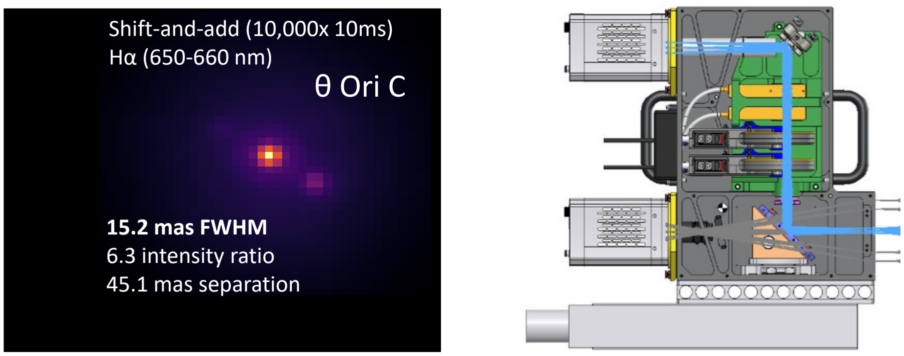


**Figure 18: Demonstration of near-diffraction limited imaging at Hα (λ/D = 13 mas) on the ORKID camera with the Keck II NGS AO loop closed using the visible Shack-Hartmann wavefront sensor on θ Ori. The 10,000 frames acquired were shifted-and-added without any frame selection. The binary is clearly separated. The CAD drawing at right shows the ORKID camera (top) and the previously existing AO acquisition camera (bottom). The light to ORKID reflects off a dichroic and passes through two filter wheels and two Risley prisms used to correct for atmospheric dispersion.**

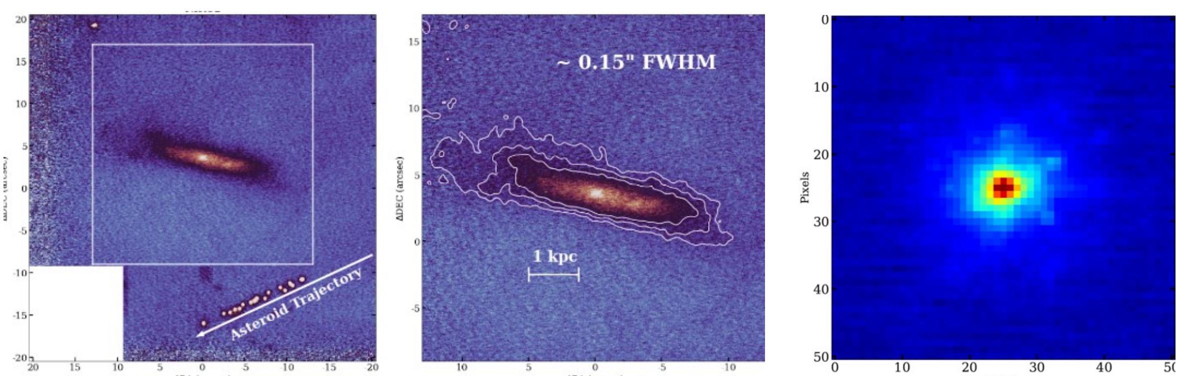


**Figure 19: Demonstration of shift-and-add NIRC2 Kp observations of a galaxy (left, showing asteroid trajectory, and center) and star (right) while the AO loop was locked on an asteroid. The galaxy observation totaled 2550 sec of shifted-and-added 45 sec exposures with a resultant full-width-half-maximum(FWHM) of 140 mas perpendicular to the asteroid motion. A total integration of 3147 sec was used for the star, consisting of 2 sec exposures, resulting in a 80 mas FWHM.**

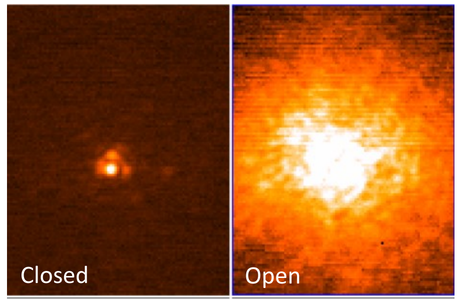


Figure 20: Closed and open loop NIRC2 images of the LCRD laser source. The NGS AO loop was closed using the near-infrared pyramid wavefront sensor since the laser source is at 1550 nm.

## 4. ADAPTIVE OPTICS ROLE IN THE KECK 2035 STRATEGIC PLAN

In 2023 the Keck Observatory, with its science community, published a scientific strategic plan to be achieved by the year 2035 (https://www.keckobservatory.org/wmko-strategic-plan/). The resultant strategic goals are listed in Table 4. A prioritized set of large (>US$15M), medium ($5M-$15M) and small (<$5M) scale instrumentation projects were identified in support of these strategic goals. These projects and their linkage to the science strategic goals are shown in Table 5. Science goals 1, 3 and 5 require high performance AO. Goals 2, 4 and 6 would be enhanced with ground layer AO. All but three projects (KWFI, KPF K2 FIU and DEIMOS+) require or would benefit from AO. Table 5 does not include some strategic plan activities already funded at the time of the strategic planning exercise (e.g. the Keck II real-time controller upgrade, the KAPA project on Keck I and the SCALES science instrument).

Table 4. Keck 2035 scientific strategic 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 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 |

Modest efforts are currently underway on these next-generation strategic AO systems. The first step has been the development of the conceptual design for a Keck I adaptive secondary mirror[47] (ASM). This included design studies by AdOptica and TNO of an ASM with between 2000 and 4000 actuators (23 to 17 cm actuator spacing projected on the primary mirror). The ASM, when combined with a new laser projection system and ground-layer wavefront sensors at the Cassegrain focus, would provide significant sensitivity improvements for visible and infrared multi-object spectrographs on Keck I.

A feasibility study for the visible multi-conjugate AO (VisMCAO) system is currently underway[48]. The VisMCAO system will use 3 DMs (one may be the ASM), 6-8 sodium LGS, and 3 NGS sensed in the near-infrared to correct a 30 arcsec diameter scientific field of view. With an average wavefront error of ≤ 120 nm RMS across this field of view, the VisMCAO system would deliver diffraction-limited images across the visible to a dedicated imager and integral field spectrograph.

Finally, initial design work has begun on a high-contrast technology development testbed that could be used either in the laboratory or fed by one of the existing Keck AO systems. This testbed would be used to test new wavefront sensors, coronagraphs, control algorithms, and observing strategies without impacting operational systems. Successful developments would then be transferred to the operational systems, particularly the HAKA system on Keck II.

**Table 5: Prioritized large (top), medium (center) and small (bottom) projects in support of the Keck 2035 science strategic plan and their mapping to the strategic goals.**

| Priority | Name | Strategic Goal Mapping |
|---|---|---|
| A | Keck 1 ASM for GLAO & Visible MCAO | 1,2,3,4,5,6 |
| | Liger | 1,2,3 |
| B | FOBOS | 1,2,4 |
| | GLAO on K1 for LRIS & MOSFIRE | 1,2,4 |
| | KWFI | 1,2,4 |
| | Visible AO on K1 | 1,3,4,5 |
| C | GLAO on K2 | 1,3,4 |
| | K2 ASM | 1,4,5,6 |
| | Visible AO IFU for K1 | 1,3,4 |

| Priority | Name | Strategic Goal Mapping |
|---|---|---|
| A | HISPEC | 1,2,3,4,5 |
| | Instrumentation Development Fund | 1,2,3,4,6 |
| | LRIS2 | 1,2,4 |
| B | Visible AO imager | 1,3,4 |

| Priority | Name | Strategic Goal Mapping |
|---|---|---|
| A | AO Development Fund | 1,3,4,5,6 |
| | DEIMOS+ | 1,2,6 |
| | HAKA | 1,3,4,5 |
| | KPF K2 FIU | 1,2,4,5 |
| B | High Contrast Technology Development | 1,5 |
| | MOSFIRE + GLAO | 1,2,4,6 |

## 5. CONCLUSION

Adaptive optics has played a scientifically impactful role at WMKO over the last quarter century and has remained scientifically competitive through ongoing upgrades and the addition of new science capabilities. The Keck 2035 scientific strategic plan identifies the continued importance and priority of AO to WMKO's scientific future.


## 6. ACKNOWLEDGEMENTS

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