Keck Adaptive Optics Current and Future Roles as an ELT Pathfinder

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ABSTRACT

The segmented nature of the 10-m Keck telescopes combined with facility-class AO systems and science instruments, and a history of science-driven upgrades to these systems, offers a uniquely powerful pathfinder for future AO science facilities on the segmented ELTs. Keck's 2035 Strategic Vision includes visible, high contrast and ground layer AO facilities all of which could support ELT AO pathfinding. Keck's pathfinder strength is not just demonstrating new techniques or technologies but developing them into operational science capabilities. For example, since first Keck AO science in 1999, Keck has successfully implemented three generations of sodium-wavelength lasers and is currently implementing its third generation of real-time controller (this time GPU-based). Current pathfinder-related developments include laser tomography, near-infrared low order wavefront sensing and PSF-reconstruction for high Strehl ratio and high sky coverage on the Keck I AO system. Current AO-based primary mirror phasing techniques under development include the use of Zernike, pyramid and phase diversity techniques. High-contrast AO developments include near-infrared pyramid wavefront sensing, on-sky phase diversity, speckle nulling and predictive wavefront control. Another pathfinder development is the NASA Goddard-led ORCAS satellite to provide a bright artificial point source for AO-correction. A fast, visible science camera has been implemented in support of ORCAS, demonstrating 15 mas FWHM, and, in a further move toward the visible, ALPAO is developing a 2.5 mm spacing, 60x60 actuator deformable mirror for Keck. In addition, three new AO science instruments are planned: Liger as a prototype of TMT's IRIS, HISPEC which is the same as TMT's MODHIS (based on KPIC's science success), and SCALES.

Keywords: Adaptive optics, real-time control, wavefront sensing, phasing, segmented mirrors, ORCAS.

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1. INTRODUCTION

The Keck telescopes were the first large telescopes to be equipped with both natural guide star (NGS) and laser guide star (LGS) adaptive optics (AO) systems.[1,2] These systems have been scientifically productive and have remained scientifically competitive through an ongoing series of AO upgrades and new science instruments. Furthermore, the Keck telescope segmented primary mirror technology has been the successful pathfinder for the James Webb Space Telescope (JWST), the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (ELT).

2. CONTEXT AND MOTIVATION

2.1 Current capabilities and science productivity

The Keck AO systems have proved to be very productive scientifically. The first refereed astronomical science papers using Keck NGS AO, on the Keck II telescope, were published in 2000. A similar AO system was implemented on the Keck I telescope, initially to support the Keck Interferometer[3]. Both systems were subsequently upgraded to perform LGS AO. Through the end of 2022 a total of 1174 refereed science papers have been published using the Keck AO systems, including 452 papers using LGS AO mode. The cumulative publications by year, and broad science categories, is shown in Figure 1.

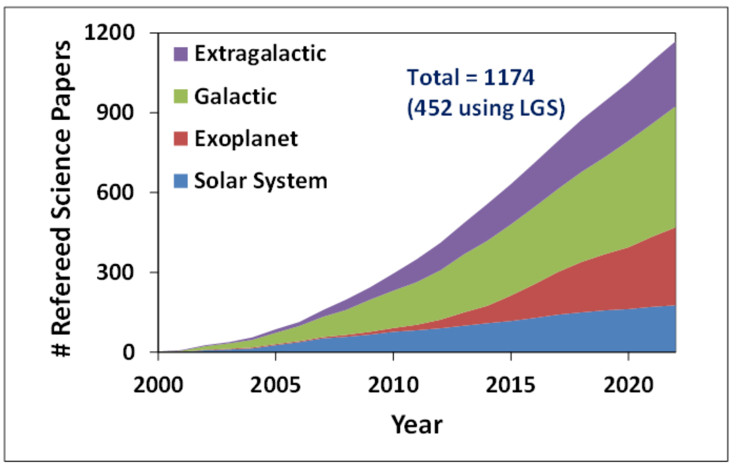

Figure 1. Cumulative number of refereed astronomical science papers by year published using data from the Keck AO systems. These papers are divided into four broad science categories.

Table 1. 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.

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 +PyWFS	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 (2023)	0.5-0.95	10" diameter at 6.7 mas. Up to 750 frames/sec
	+HAKA +PyWFS (2026/27)	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

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 1. The primary differences between the two current AO systems, besides the different science instruments, is that

Keck I has a near-infrared tip-tilt sensor[4] for LGS AO and Keck II has a near-infrared pyramid wavefront sensor (PyWFS)[5] for NGS AO with the NIRC2 (Near InfraRed Camera 2) and KPIC[6] (Keck Planet Imager and Characterizer) science instruments. KPIC provides a single mode fiber feed to NIRSPEC (Near InfraRed Spectrograph).

KAPA[7] (Keck All sky Precision Adaptive optics) is a laser tomography and sky coverage upgrade to the Keck I AO system. HAKA (High order Advanced Keck Adaptive optics) is a high order deformable mirror upgrade to the Keck II AO system. A second, higher order near-infrared PyWFS is planned to be implemented on Keck II to control the HAKA deformable mirror in support of HISPEC and SCALES science instrument observations. Not shown in Table 1 is a number of advanced wavefront control techniques for high contrast science that are being developed with the Keck II AO system.

2.2 US AO Decadal Review

Each decade the U.S. National Academies of Sciences, with the broad participation of the astronomical science community, publishes a consensus report recommending the science and investment priorities for ground and space-based astronomy. The most recent report, Pathways to Discovery in Astronomy and Astrophysics in the 2020s[8], published in 2021, identified three broad key science challenges, along with a science priority area for each, for the next decade: (1) Worlds and Suns in Context with Pathways to Habitable Worlds as the priority area, (2) New Messengers and New Physics with New Windows on the Dynamic Universe, and (3) Cosmic Ecosystems with Unveiling the Drivers of Galaxy Growth as the priority. The top large space and ground-based recommendations were a "large (~6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope" and a coordinated "Extremely Large Telescope Program (ELT)", respectively.

The importance of AO was highlighted in the report with statements such as the number one ground-based priority being "large (20-40 m) telescopes with diffraction-limited adaptive optics", "Key capabilities required on the pathway to habitable worlds include the following: Ground-based extremely large telescopes equipped with high-resolution spectroscopy, high performance adaptive optics, and high contrast imaging" and as a foundation activity "Expand support for early-stage and basic technology development" through APRA and ATI "including the pressing need to develop advanced adaptive optics systems in the optical".

The report also noted the importance of investment in Mid- and Small-Scale Ground Facilities with the statement "The development of adaptive optics (AO) in the 1990s serves as an excellent case in point, and led to ground-breaking advances such as the direct imaging of exoplanets, and the precise definition of the orbits of stars that determined the gravitational forces near the black hole at the center of the Milky Way". Keck AO was used for both these discoveries.

2.3 Keck 2035 Science Strategic Plan

The Keck Observatory, with its science community, has developed its own scientific strategic plan to be achieved by the year 2035[9]**.** The resultant strategic goals are listed in Table 2. A prioritized set of large (>US$15M), medium ($5M-$15M) and small (<$5M) scale projects were identified in support of these strategic goals. These projects and their linkage to the science strategic goals are shown in Table 3. 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 3 does not include some strategic plan activities already funded. These include the NSF MRI funded Keck II real-time controller upgrade, the NSF MSIP funded Keck All sky Precision Adaptive optics (KAPA) project on Keck I and the NSF and Heising-Simons Foundation funded SCALES science instrument.

Table 2. 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

Table 3: 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

2.4 AO implementation of the Keck 2035 science strategic plan

The Keck AO future study group, consisting of AO users and developers, has identified a potential timeline, shown in Table 4, for the implementation of the AO capabilities in Table 3. For reference the current construction completion dates for both US ELTs are in 2035. The AO capabilities and science instruments have been divided into four systems:

high sky coverage with high performance AO on Keck I, high contrast AO on Keck II, and AO for enhanced seeing (i.e. ground layer AO or GLAO) on both telescopes. An adaptive secondary mirror (ASM) is assumed to be the basis for enhanced seeing and if available would also be used for the Keck I high sky coverage visible AO system.

Table 4: Proposed AO implementation timeline for the Keck 2035 science strategic plan. The fiscal year (FY) is shown in the left column. Green background are items with identified funding; yellow are currently unfunded.

FY	Keck 1: High Sky Coverage				K1&2	Keck 2: High Contrast				Keck 1: Enhanced Seeing				K2: Enh. Seeing	
	AO	AO Instruments			AO	AO	AO Instruments			AO	GLAO Instruments			AO	Instr.
23	KAPA	Liger				HAKA; IR pyramid & RED-WOODS	KPIC	ORKID	SCALES	ASM dev	LRIS2				
24					ORCAS		HISPEC	VIPER		ASM + GLAO					FOBOS
25	Visible AO														
26			Vis Imager	Vis IFU											
27															
28						High-contrast Testbed									
29										GLAO		MOS-FIRE		ASM + GLAO	
30															
31		PRV Feed											PRV Feed		
32															
33															
34															
35															

3. CURRENT KECK AO DEVELOPMENTS

3.1 Keck AO error budget and development projects

Table 5: 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

The largest terms (> 30 nm rms) in the Keck LGS AO error budget are shown in Table 5. This error budget and a similar budget for NGS AO were anchored against nightly AO performance measurements using a bright, on-axis guide star 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 current Keck AO development projects are designed to reduce the largest error terms in Table 5 and to support both the visible and high contrast AO strategic directions in Table 4:

- Sect. 3.2. The real-time controller upgrade on both telescopes will address 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 address the LGS focal anisoplanatism error and the tip-tilt error margin.
- Sect. 3.4 and 3.5. The advanced wavefront control projects, currently on Keck II, will primarily address the high order wavefront error margin including improved mirror segment phasing.
- Sect. 3.6. The Keck II HAKA project to implement a high order deformable mirror will address atmospheric fitting error and uncorrectable static telescope aberrations, while also supporting improved advanced wavefront control.
- Sect. 3.7. The HAKA associated Keck II near-infrared wavefront sensor would support a range of additional science targets to be observed using the HAKA deformable mirror.
- Sect. 3.8. 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 for both telescopes simultaneously.

The current capability of the Keck AO to work at visible science wavelengths has been demonstrated with the ORKID camera (sect. 3.9). The performance measured with this camera will be improved as the Keck II AO development projects are implemented.

All of the projects described in the following sections will provide pathfinders and lessons learned for future ELT AO systems, especially since they are being carried out on segmented mirror telescopes.

3.2 Real-time control

The real-time controllers of both Keck AO systems are being replaced in 2023 by a Microgate led consortium including Swinburne University of Technology and Australia National University.[10] The upgrade includes a module to interface with the wavefront sensors and controlled hardware, 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. The existing Shack-Hartmann wavefront sensor cameras from SciMeasure are also being replaced with OCAM2K cameras to provide lower noise and larger formats.

3.3 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.[7] The KAPA hardware elements are shown schematically in Figure 2. A 20W 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 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. On the Keck I AO bench the major modification is the implementation of four LGS on the Shack-Hartmann wavefront sensor camera.

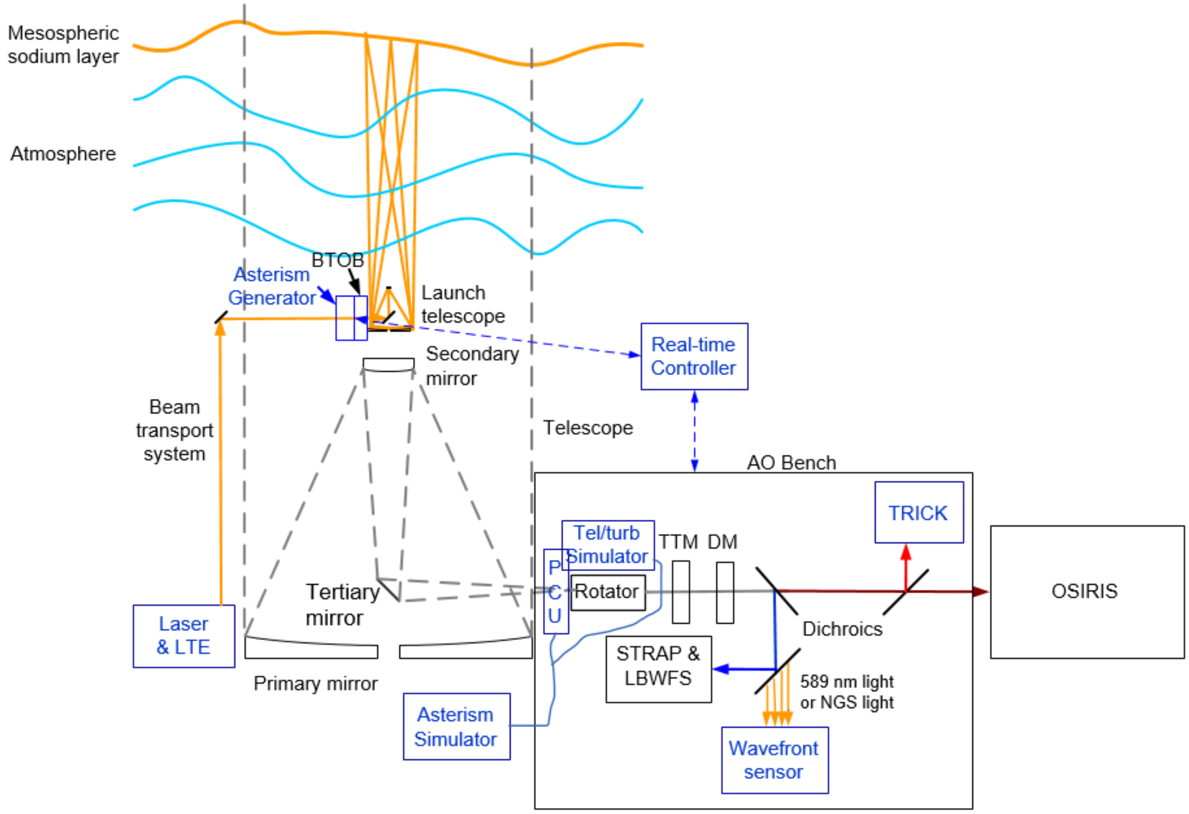

Figure 2: Schematic of the KAPA upgrade to the Keck I AO system. Blue boxes indicate new or modified systems. (Acronyms: BTOB = Beam Transfer Optics Bench, DM = Deformable Mirror, LTE = Laser Table Enclosure, PCU = Precision Calibration Unit, STRAP = visible tip-tilt sensor, Tel/Turb = Telescope/Turbulence, TRICK= near-infrared tip-tilt sensor, TTM = Tip-Tilt Mirror)

3.4 Advanced wavefront control - Primary mirror segment phasing

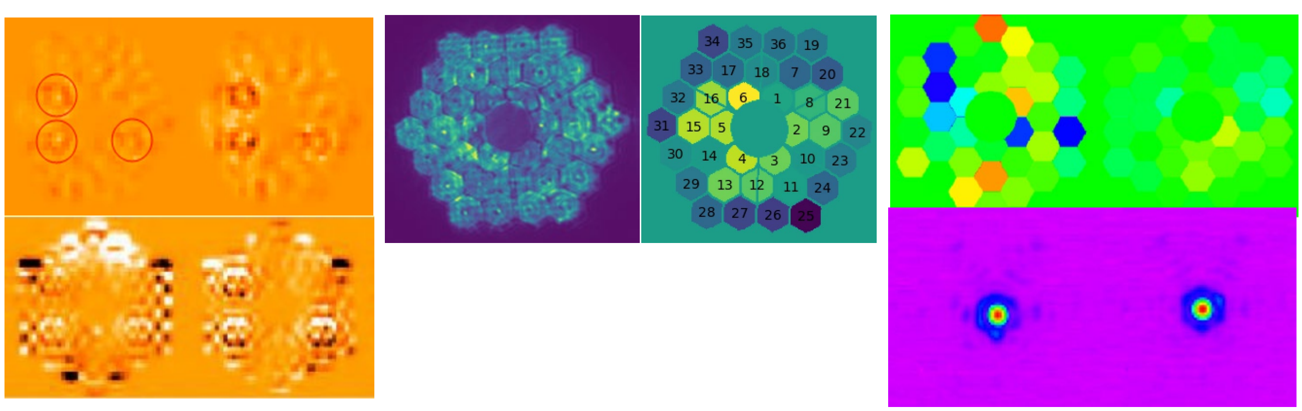

Figure 3. Three wavefront sensing approaches to determining primary mirror segment phasing: pyramid (left), Zernike (center) and phase diversity (right).

The Keck primary mirror are phased roughly bi-monthly using an optical phasing camera system. Residual segment phasing errors at the 100 nm rms wavefront level degrade the AO-corrected image quality. We are therefore working to test and implement a means to measure these phasing errors with the AO system and send corrections to the primary mirror active control system. The three techniques shown in Figure 3 have been demonstrated on-sky. Two of these use existing wavefront sensors, the near-infrared PyWFS[11] and Zernike WFS[12], on the Keck II AO bench potentially allowing them to be used in parallel with AO-corrected science observations. The third technique uses on-sky phase diversity measurements of the AO-corrected images on the science (NIRC2) camera.[13]

3.5 Advanced wavefront control - High contrast tools transitioning to operations

An effort is underway to transition demonstrated advanced wavefront control tools to operations.[14] These tools will include a focal plane wavefront sensing algorithm (Fast and Furious), Zernike wavefront sensor for fine phasing of the Keck primary mirror segments, speckle nulling on NIRC2, and predictive wavefront control. Each of these projects have been demonstrated successfully on sky, with performances that motivate development into operational tools. This process builds on each project to make them more robust to errors, accessible to a variety of observing conditions, and easy to operate for observers. Releasing these tools will give observers access to high contrast observational modes without needing detailed knowledge about AO processes.

3.6 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. ALPAO is in the final design 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 ~ $3^{5/6} = 2.5$. The higher order deformable mirror should also allow for improved speckle nulling.

3.7 Near-infrared wavefront sensing

The Keck II AO system is equipped with a modulated near-infrared pyramid wavefront sensor based around a Saphira detector with 40 pixels across the pupil.[5] A new near-infrared wavefront sensor is being designed to support SCALES and HISPEC science using the ALPAO 60x60 actuator deformable mirror. Three modes are envisioned; a high order pyramid wavefront mode (~70 pixels) for NGS AO, a Zernike wavefront sensor for segment phasing, and a mode for sensing low order modes using a NGS (i.e. a truth sensor) in support of LGS AO science.

3.8 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/). 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. ORCAS would provide a very bright NGS for AO correction allowing for visible wavelength and/or high contrast science observations.

3.9 ORCAS - ORKID visible AO demonstrator

One of Keck's strategic goals is to provide high sky coverage, AO correction at visible wavelengths.[15]

ORcas Keck Instrument Development (ORKID) has been implemented as a fast, visible imager demonstration with the Keck II AO system. Figure 4 shows the ORKID camera and its location on the AO bench. The system is designed for Nyquist-sampled pixels at 650 nm.

ORKID was implemented to demonstrate near-diffraction limited angular resolution in the visible when a sufficiently bright NGS is available. It has done that as shown in Figure 5. This image of 5.1 magnitude θ Ori C has a full-width-at-half-maximum of 15.2 mas, nearly achieving the Keck telescope diffraction-limited angular resolution of 13.1 mas at 655 nm.

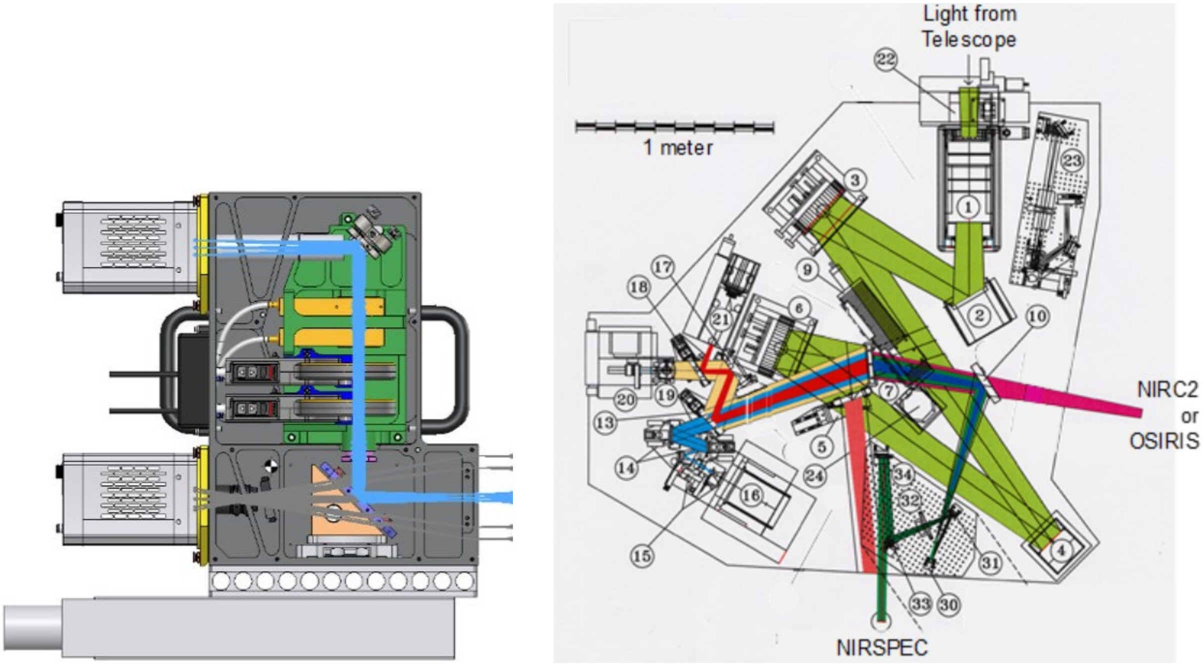

Figure 4. The ORKID opto-mechanics (shown at left) consist of a field lens at right, a dichroic beamsplitter that transmits light to an acquisition camera and reflects light (blue shading) toward the ORKID Andor CMOS camera through two filter wheels, two Risley prisms acting as an atmospheric dispersion corrector, and off a fold mirror. ORKID is mounted at the location of item 21 in the AO bench schematic (right). Light from the telescope passes through an image derotator (item 1), off a fast tip-tilt mirror (2), an off-axis parabola (OAP, 3), the deformable mirror (4) and a second OAP (6) before being reflected by an IR transmissive dichroic (7), a beamsplitter (13) and two flat mirrors (17 and 18) toward ORKID.

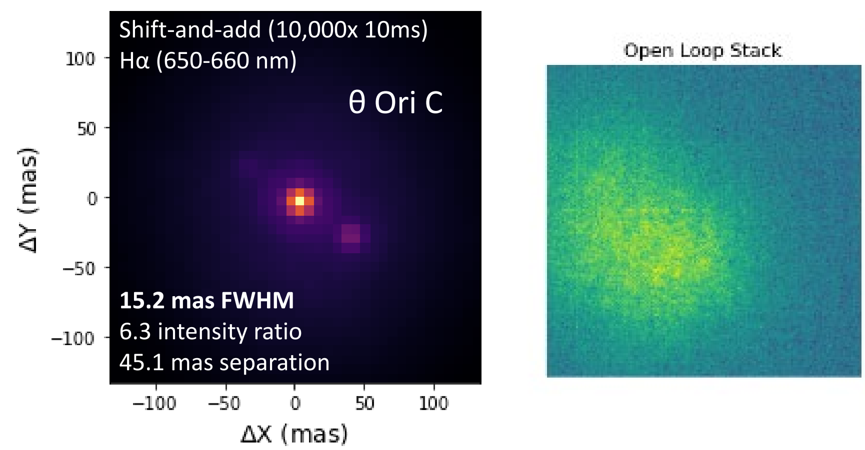

Figure 5. ORKID image of θ Ori C consisting of 10,000 consecutive exposures combined with a simple shift-and-add. For reference an open loop stacked image of another binary is shown at right illustrating the significant benefit of closing the AO loops.

4. CONCLUSION

The Keck telescopes and AO systems offer a uniquely powerful pathfinder for future AO science facilities on the segmented ELTs. Implementation of the Keck 2035 strategic plan will offer many additional opportunities for developing and demonstrating AO technologies, techniques and science.

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