Enabling high resolution visible AO at the W.M. Keck Observatory

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ABSTRACT

The W. M. Keck Observatory has generated an observatory wide strategic plan for 2035. This plan has identified visible Adaptive Optics (AO) as an attractive science path for the observatory. Given the 10-meter aperture of the Keck telescopes, a visible AO system can achieve extremely high spatial resolutions. These high resolutions will be comparable to that of Extremely Large Telescopes (ELTs) in the infrared, which can lead to synergistic observations between the observatories. To demonstrate the feasibility of visible AO we have recently installed a visible camera (ORKID) that works behind AO as part of the ORbiting Configurable Artificial Stars (ORCAS) mission. ORCAS is a first-of-its-kind hybrid space and ground observatory, using a satellite-based laser as the AO beacon for wavefront sensing. As a risk reduction for ORCAS we have demonstrated the opportunistic use of a passing asteroid (known as an appulse) as a source for AO wavefront sensing on UGC 4729, an object where there is no viable nature guide star for AO observations. To demonstrate the angular resolution of the Keck telescopes at visible wavelengths we have used the ORKID camera to image a number of targets including the close binary Theta Orionis C. The binary is detected at a separation of 44.4 mas, with a FWHM of 15.1 mas at 650nm. This is the sharpest point spread function (PSF) ever measured at Keck demonstrating the potential offered by visible AO. These two demonstrations show the potential for high resolution visible AO science. We present the rational for pushing to the visible, results from ORKID, results of our appulse demonstration, and our AO development plans that will enable high resolution visible AO at the W.M. Keck Observatory.

Keywords: Adaptive Optics, Visible AO, Hybrid observatory, ORCAS

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1. INTRODUCTION

The W.M Keck Observatory (WMKO) Adaptive Optics (AO) systems[1,2] have been highly productive over the years offering diffraction limited performance in the near infrared. Constant innovation and upgrades to the systems have allowed them to remain highly competitive with other AO systems at similar sized observatories. When looking at the era of new space telescopes and much larger ground facilities it remains to be seen what roles Keck and other 8-10 meter telescopes will play in high-resolution astronomy.

2. HIGH RESOLUTION LANDSCAPE

2.1 Context

Each decade the U.S. National Academies of science publishes a comprehensive report with recommendations for science and technological investments in astronomy. In the most recent report "Pathways to Discovery in Astronomy and Astrophysics in the 2020s"[3], the primary ground priority outlined is U.S. investment in Extremely Large Telescopes (ELTs), with diffraction limited AO. In response the Keck Observatory has developed its own strategic plan for 2035[4], outlining how the Keck Observatory can remain competitive in the ELT era. One key outcome is setting up the Keck Observatory for high resolution AO in the visible. More details on the decadal report and WMKO response can be found in Wizinowich et al (2023)[5].

2.2 Landscape

With an effective 10-meter aperture the Keck AO systems are capable of resolutions of 46 mas at 2.2 um wavelength. This has led to synergistic observations with the 2.4-meter Hubble Space Telescope (HST) that offers a similar resolution of 43 mas at 0.5 um. While there are numerous advantages to having a telescope in space the high development and launch cost have prevented a large aperture telescope from being placed in space. The recently launched James Web Space Telescope (JWST) while significantly larger than HST at 6.5 meters is optimized for the IR and has an angular resolution of 71 mas at 2.2um which is larger than what can be achieved from 8-10 meter ground-based telescopes. While the resolution of JWST in theoretically 16 mas at 0.5 microns the telescope was designed to be used in the infrared and has no visible instrumentation. With the lifetime of HST nearing an end this means that no high-resolution optical facility will remain available to the community. In the next 15 years Extremely Large Telescopes (ELTs) will be coming online from both Europe and the US. The European ELT will be the largest with an aperture of 39-meters, while the U.S. led Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT) will have apertures of 30 and 25.4 meters, respectively. All three telescope will offer NIR diffraction limited AO systems at first light, but none have plans for visible AO systems in their first light instruments. Table 1 shows the landscape of resolutions at 0.5 and 2.2 microns:

Table 1: Diffraction-limited angular resolution of existing and planned telescopes

Telescope	Diameter(m)	Resolution at 0.5 um (mas)	Resolution at 2.2 um (mas)
HST	2.4	43	192[a]
JWST	6.5	16[b]	71
Gemini/Subaru/LBT/VLT	8	13	56
Keck/GTC	10	10	46
GMT	25.4	4.1[c]	18
TMT	30	3.5[c]	15
ELT	39	2.7[c]	12

a) HST historically had 2.2 um capability with NICMOS which has not been offered since 2008. WFC3 is capable of imaging at 1.7 um with a diffraction-limited resolution of 148 mas at a pixel scale of 130 mas / pix.

b) while JWST has no instrumentation capable of observations at 0.5 um. NIRCam is capable of imaging at 0.6 um with a diffraction-limited resolution of 19 mas at a pixel scale of 31 mas / pix.

c) none of the first light ELT instruments plan diffraction limited observations in the visible.

As is clear from Table 1 the Keck telescope and HST are well matched in angular resolution between IR(Keck) and visible (HST) observations. In the ELT era the Keck telescopes along with the other 8–10 meter telescopes will not be able to compete with the superior angular resolutions offered by ELTs in the IR. However, they will have the unique ability to offer visible observations at similar angular resolutions to the ELTs in the IR. In order to take advantage of this parameter space Keck and other 8-10 meter telescopes must make plans and investments now to get ready for the ELT era.

3. ADAPTIVE OPTICS IN THE VISIBLE

While it is simple enough to make the argument that Keck must push into visible AO the ability to do so is technically challenging. In the most general terms to have good AO correction in the visible several technical challenges must be overcome. The atmospheric fitting, measurement and bandwidth errors must be reduced, and the sky coverage and corrected field must be increased. Technological develops in Deformable Mirror (DM) and detector technologies have led to significant advancements. It is now possible to get DMs with thousands of actuators and detectors that can readout at several kHz. Similarly, CPU and GPU speeds have improved to the point where processing the wavefront sensor information and driving a deformable mirror at several kHz is also now possible. The last remaining issues of sky coverage and field of view have proved to be the most challenging. The amount of bright natural stars that can be used for wavefront sensing at a few kHz provides a sky coverage of ~1%. To increase this AO systems have employed the use of Laser Guide Stars (LGS) to create an artificial bright reference source near an object of interest. With current laser technology it is possible to generate artificial LGS with R-band magnitudes of 8. While this is acceptable for NIR observations, it remains too faint for visible AO. In addition to low flux LGS offer no tip/tilt information meaning a nearby natural star must still be used for tip/tilt. Additionally, LGS suffer from focal anisoplanitisum that reduce their performance compared to NGS. While there are systems that perform visible AO today, they offer limited targets, limited performance, and limited fields of view.

4. ORCAS

4.1 Overview

The ORbital Configurable Artificial Star (ORCAS)[6-10] mission is a first of its kind hybrid ground and space observatory. The goal is to overcome the final technical challenge mentioned in section 3 to enabling high resolution visible astronomy over most of the sky. The proposed mission would place a small cube satellite in a highly elliptical orbit around the Earth with an apogee of about 200,000 km. The satellite will carry a tunable laser payload that will be aimed to the observatory and produce a point source for AO wavefront sensing at an apparent magnitude from 0th to 8th at two wavelengths (532 nm, 1064 nm). The highly elliptical orbit will allow the satellite to be within the isoplanatic patch at apogee.

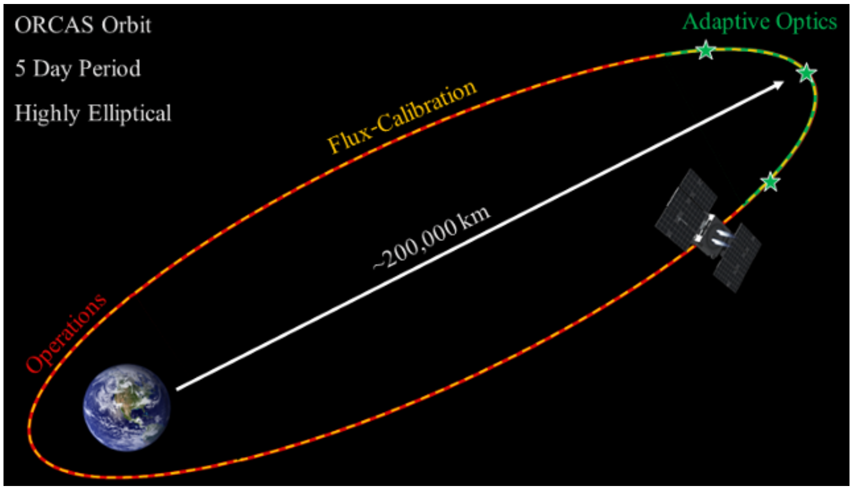

Figure 1: Illustration or elliptical orbit of ORCAS CubeSat

With the ability to define the orbit of the satellite prior to launch, and the ability to steer the satellite post launch, previously inaccessible areas of the sky will now be open to observing across all wavelengths. Thanks to the brightness of the source, it will also be possible to do so at extremely fast speeds to account for bandwidth error. Lastly, given its distance, ORCAS provides an unresolved point source. Meaning that the issues with ground based LGS of no tip/tilt information and of focal anisoplanatism are no longer present.

4.2 Feasibility

The use of a non-siderial object as an AO reference source is routinely done at most observatories. The most common example is when taking data on solar system objects. The Keck Twilight Zone[11-14] program is one example of such observations. The opportunistic use of passing objects such as asteroids was proposed by Ribak and Rigaut (1994)[15]. Since then these kinds of observations have come to be known as appulse. In January 2023 we demonstrated with Keck that we can do appulse observations to look at objects for which there are no viable natural guide stars nearby for either NGS or LGS AO. Figure 2 shows a demonstration done at Keck on UGC 4729.

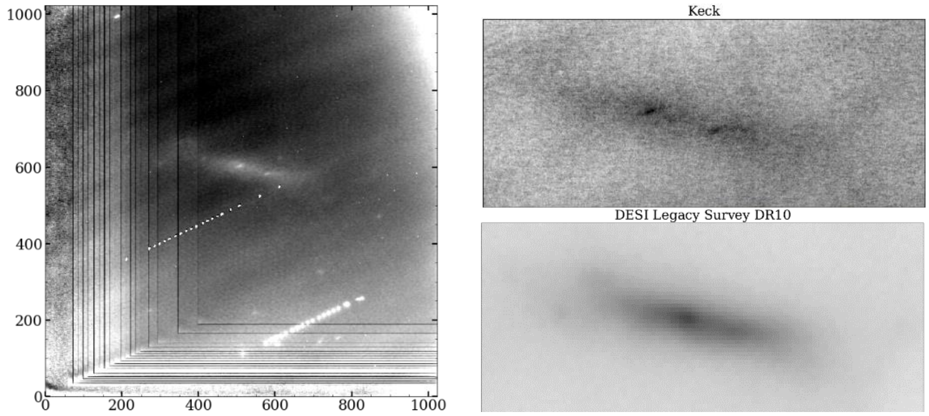

Figure 2: Keck appulse demonstration on UGC4729. Left: raw stacked NIRC2 Kp frames of 45second each, for a total of 2550s of integration. Top Right: processed Keck image showing two bright areas to the galaxy UGC4729. Bottom right: DESI legacy survey where it is not possible to see the two bright areas. The Keck images have a FWHM of 0.14" as the telescope was tracking the asteroid elongating the PSF in the direction of the asteroids motion.

4.3 Science Drivers

ORCAS and high-resolution visible AO will open exciting new science. While synergistic observations with the ELTs will be possible there are also stand-alone science cases to consider. There are four main science goals we are exploring at this point of the project. [1] Solar system, [2] Binary stars, [3] Accreting Exoplanets, and [4] Active Galactic Nuclei (AGN).

- There are several solar system objects of interest in the visible. Neptune, Uranus, Titan, Io and many smaller asteroids and Kuiper belts objects are all of scientific interest at high resolutions in the visible.
- The high angular resolution offered by visible AO will allow new compact binaries to be discovered and the orbits of known binaries to be monitored with high astrometric precision.
- Accretion processes in planet formation are not well known. These systems are bright at H-alpha (656nm). High resolution in the visible can enable these detections.
- Dual AGN are bound below 50 parsec resolution which is the limit of current IR AO. By moving to the optical it will be possible to observe bound AGN at higher resolutions.

5. ORKID

5.1 Overview

In support of the ORCAS mission, we have developed and installed the ORKID (ORCAS Keck Instrument Demonstrator) camera. This is a visible light camera located on the Keck II telescopes AO bench. The camera was quickly developed using an Andor Marana sCMOS[16] sensor and a simple optomechanical design that allows it to be on the same light path as the AO visible acquisition camera. Table *2* goes over the main parameters of the camera.

Table 2: ORKID camera parameters

Field of View	10” Full Configurable sub-array
Readout	10ms in 2”x2” or smaller sub-array
Min exposure time	0.5 us
Pixel Scale	6.65 mas/pix (Nyquist sampled at 650nm)
Wavelength range	600nm – 950nm

The cameras optical design was done in collaboration between NASA Goddard and the Keck Observatory, with the opto-mechanical assembly built by OMP Inc. The camera was tested and integrated into Keck II AO in August of 2022. Figure 3 shows a cutaway of ORKID. There are narrow band filters over the entire spectral range as well as a set of Risley prisms for atmospheric dispersion correction. The camera is placed on the same optical path as the Keck II AO acquisition camera and sits vertically above the acquisition camera. A dichroic beam splitter sends light redder than 600nm to ORKID while bluer light is passed to the acquisition camera.

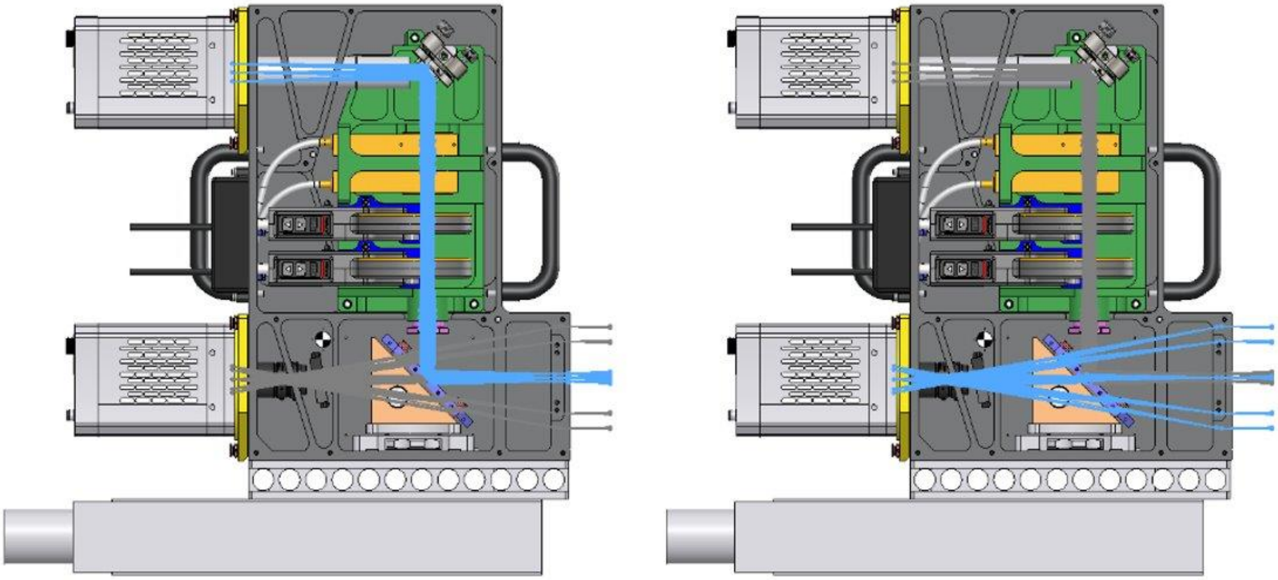

Figure 3: ORKID camera rendering. Left: light is reflected off a dichroic beam splitter and sent to ORKID. Right: Light is transmitted through the beam splitter and sent to the AO acquisition camera.

5.2 Early Results

The first targets we explored with the ORKID camera during engineering nights were known compact binaries. One of these Theta Ori C is a well-known compact binary that has been observed in the visible with the MagAOsystem[17]. The

MagAO observations taken at the 6.5 meter Clay telescope have a FWHM of 29 mas and a Strhel ratio of 31% at H-alpha (656 nm). At this resolution the binary is visible, but the PSF is still merged with the brighter star (Figure 4). The binary does have a variable separation and it is likely that the orbital separation was smaller than the 29mas raw resolution at the time.

Figure 4: H-Alpha MagAO observations of Theta Ori C, figure from Close (2016)[17]

With ORKID we are unable to get high Strehl ratio long exposure images due to the limited number of actuators on the Keck AO system (349). Additionally, as we are splitting the visible light between ORKID and the Shack-Hartman WFS we are unable to go faster than a few hundred Hz. Instead, we use several short exposure images and shift and add them together to form a final stacked low Strehl ratio, but high-resolution image. With ORKID we observed Thera Ori C with a resolution of 15.2 mas at H-alpha or about half that of the MagAO observation (Figure 5)

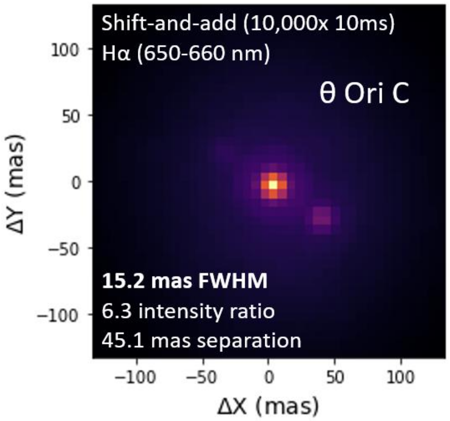

Figure 5: ORKID image of Theta Ori C with 15.2mas FWHM

The separation of the binary at the time of the ORKID observation was 45.1 mas which would have been observable with the MagAO system. However, the superior FWHM shows the potential for visible AO at the Keck observatory. The shift-and-add technique we employ with ORKID is most often associated with lucky imaging. While developing the camera we had thought that we would have to employ lucky imaging techniques to get the performance we wanted. Once we started to observe with ORKID it became clear that doing a shift-and-add of all the images in the set was sufficient and there was no need to use traditional lucky imaging. We were able to stack 100% of the raw data. Figure 6 shows an open loop image, and an 100% shift-and-add stack on a calibration target.

These data were taken with the facility Shack-Hartmann wavefront sensor. Keck II AO is also equipped with an infrared pyramid wavefront sensor[18]. Using the pyramid with ORIKD offers several advantages over the Shack-Hartmann. With the ability to do the wavefront sensing in the IR we no longer have to split light between the wavefront sensor and the science camera, allowing us to run at faster loop rates. The pyramid also offers superior AO performance to the Shack-Hartman. Subsequent to the data presented here we have done test with the pyramid wavefront-sensor that show superior performance to the Shack-Hartmann.

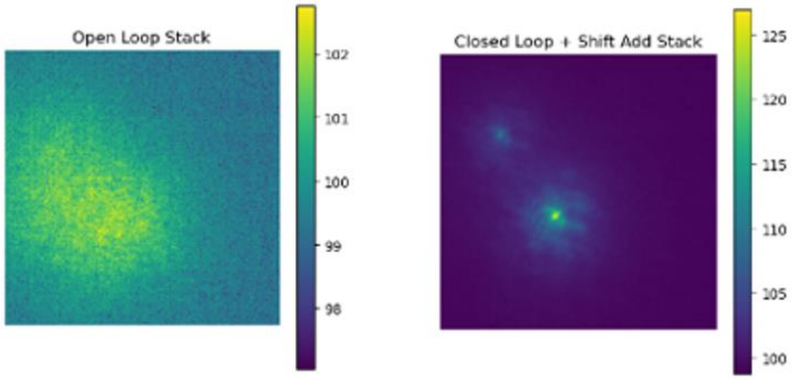

Figure 6: Left: Open loop image, Right:100% Shift-and-add Stack.

These early results show the potential for high resolution visible AO with the Keck Observatory. and show that even today we can start to do high resolution visible science at the Keck Observatory.

6. FUTURE DEVELOPMENTS

To enable more regular and stable visible AO observatory the observatory must embark on a set of upgrades to the existing AO systems. As part of the strategic plan Keck I and Keck II AO will take different approaches to getting to visible AO. On Keck I the plan is to develop an Adaptive Secondary Mirror with 1000-4000 actuators. This will serve as the DM for a Ground Layer AO (GLAO) system and as the ground layer conjugate DM for a future Multi-Conjugate AO (MCAO) system. Additional LGS capabilities will also be implemented on the telescope with up to six side launched sodium LGS for use in the GLAO system and later in the visible MCAO system.

On Keck II the High order Advanced Keck Adaptive optics (HAKA) project has been funded by the NSF MRI program to implement a 2844 actuator ALPAO DM to replace the existing 349 actuator Xinetics DM. In addition, the Shack-Hartmann WFS will be upgraded to match the high order DM. A new high order infrared pyramid wavefront sensor is being designed to work with the HAKA. There are also several advanced wavefront control projects to improve AO performance that are outlined in Wizinowich et al. (2023)[5] and Guthery et al. (2023)[19].

Both telescopes will be able to take advantage of the ORCAS mission, with Keck II being able to leverage HAKA with the ORCAS mission. With the ORCAS mission and the planned upgrades to both Keck I and Keck II AO we will enable high resolution visible AO at the Keck Observatory.

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REFERENCES

[1] Wizinowich, P. et al., “First Light Adaptive Optics from the Keck II Telescope: A New Era of High Angular Resolution Imagery,” PASP 112, 315 (2000).

[2] Wizinowich, P. et al., “The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Overview,” PASP 118, 297 (2006).

[3] National Academies of Sciences, Engineering, and Medicine 2021. *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26141.

[4] W. M. Keck Observatory Science Strategic Plan (2023).

[5] Wizinowich, P., et al., “Keck Adaptive Optics Current and Future Roles as an ELT Pathfinder,” AO4ELT7 (2023).

[6] Peretz, E., Hamilton, C., Mather, J., Pabarcius, L., Hall, K., Michaels, A., Pritchett, R., Yu, W., Wizinowich, P., and Golliher, E., “Orcas–orbiting configurable artificial star mission architecture,” UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts X. 11819 (2021).

[7] Peretz, E., McCormick, K., Moehring, E., Hamilton, C., Mather, J., Hall, K., Hyland, D., Freeman, A., Russin, T., Nash, J., and Robie, D., “Orbiting configurable artificial star multi-wavelength laser payload,” Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems III 11820 (2021).

[8] Peretz, E., Mather, J. C., Hamilton, C., Pabarcius, L., Hall, K., Fugate, R. Q., Green, W. A., and Klupar, P., “Orbiting laser configuration and sky coverage: coherent reference for Breakthrough Starshot ground-based laser array,” Journal of Astronomical Telescopes, Instruments, and Systems 8(1), 017004 (2022).

[9] Peretz, E., Hamilton, C., Mather, J. C., D’Amico, S., Michaels, A., Pritchett, R., Yu, W., and Wizinowich, P., “Astrostationary orbits for hybrid space and ground-based observatories,” Journal of Astronomical Telescopes, Instruments, and Systems 8(1), 014004 (2022).

[10] Peretz, E., Mather, J. C., Albert, J., Aldering, G., Kurczynski, P., Lafon, R., Milam, S., O’Meara, J., de Pater, I., Perlmutter, S., Plavchan, P., Satyapal, S., Windhorst, R., Wizinowich, P., Barth, A., Campbell, R., Canalizo, G., Cristina, M., Rico, G. D., Duncan, J., Freeman, A., Gebhardt, K., Gilchrist, K., Golliher, E., Hall, K., Hamilton, C., Hicks, E., Hyland, D., Juneau, S., Kassis, M., Koss, M., Kusters, D., Laha, S., Lu, J., Malkan, M., Mawet, D., Max, C., McCormick, K., Michaels, A., Michelson, D., Millar-Blanchaer, M., Moehring, E., Sanchez, F. M., Newman, P., Oppenheimer, R., Pabarcius, L., Pachowicz, P., Portaluri, E., Pritchett, R., Rice, J., Rothberg, B., Seager, S., Slonaker, R., Stephen, M., Storm, M., Vermilion, D., Villanueva, G., U, V., and Yu, W., “The orbiting configurable artificial star (orcas) mission,” tech. rep., NASA/GSFC (2021)

[11] de Kleer, K., de Pater, I., Molter, E. M., Banks, E., Davies, A. G., Alvarez, C., Campbell, R., Aycock, J., Pelletier, J., Stickel, T., Kacprzak, G. G., Nielsen, N. M.+, Stern, D., Tollefson, J. (2019). Io's Volcanic Activity from Time Domain Adaptive Optics Observations: 2013-2018. The Astronomical Journal, 158(1), 29.

[12] Molter, E. de Pater, I., Luszcz-Cook, S., Hueso, R., Tollefson, J., Alvarez, C., Sanchez-Lavega, A., Wong, M. H., Hsu, A. I., Sromovsky, L. A., Fry, P. M., Delcroix, M., Campbell, R., de Kleer, K., Gates, E., Lynam, P. D., Ammons, S. M., Coy, B. P., Duchene, G., Gonzalez, E. J., Hirsch, L. Magnier, E. A., Ragland, S., Rich, M., Wang, F. (2019). Analysis of Neptune's 2017 bright equatorial storm. Icarus, 321, 324-345.

[13] Chavez, E., de Pater, I, Redwing, E., Molter, E. M., Roman, M. T., Zorzi, A., Alvarez, C., Campbell, R., de Kleer, K., Hueso, R., Wong, M. H., Gates, E., Lynam, P. D., Davies, A. G., Aycock, J., Mcilroy, J., Pelletier, J., Ridenour, A., Stickel, T. (2023). Evolution of Neptune at near-infrared wavelengths from 1994 through 2022. Icarus, in Press.

[14] Chavez E., Redwing, E., de Pater, I., Hueso, R., Molter, E. M., Wong, M. H., Alvarez, C., Gates, E., de Kleer, K., Aycock, J., Mcilroy, J., Pelletier, J., Ridenour, A., Sanchez-Lavega, A., Rojas, J. F., Terry Stickel, T. (2023). Drift rates of major Neptunian features between 2018 and 2021. Icarus, 404, 115667.

[15] Ribak, E. M., Rigaut, F., “Asteroids as references stars for high resolution astronomy.” Astronomy and Astrophysics, Vol. 289, p. L47-L50 (1994)

[16] https://andor.oxinst.com/products/scmos-camera-series/marana-scmos

[17] Close, L, " A review of astronomical science with visible light adaptive optics ", Proc. SPIE 9909, Adaptive Optics SystemsV, 99091E (July 26, 2016); doi:10.1117/12.2234024; http://dx.doi.org/10.1117/12.2234024

[18] Bond, C. et al., “Adaptive optics with a pyramid wavefront sensor at Keck,” JATIS 6, 039003 (2020).

[19] Guthery, C. et al., “High Contrast Imaging Tools at Keck Observatory”, AO4ELT7 (2023).