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Near-infrared pyramid wavefront sensor for Keck adaptive optics: opto-mechanical design

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ABSTRACT

A near-infrared, high order pyramid wavefront sensor will be implemented on the Keck telescope, with the aim of providing high resolution adaptive optics correction for the study of exoplanets around M-type stars and planet formation in obscured star forming regions. The pyramid wavefront sensor is designed to support adaptive optics correction of the light to an imaging vortex coronagraph and to a fiber injection unit that will feed a spectrograph. We present the opto-mechanical design of the near-infrared pyramid wavefront sensor, the optical performance, and the alignment strategy. The challenges of designing the assembly, as well as a fiber injection unit, to fit into the limited available space on the Keck adaptive optics bench, will also be discussed.

Keywords: AO, KPIC, near-infrared pyramid wavefront sensor

1. INTRODUCTION

A near-infrared pyramid wavefront sensor (PWS) is being developed for the Keck II adaptive optics (AO) system with National Science Foundation funding to carry out a pilot L-band imaging coronagraph survey of 150 M dwarfs to identify exoplanet candidates. The abundance of M-type stars, their low close binary fraction, and the ubiquitous presence of massive proto-planetary disks at young ages imply that they are common sites of planet formation. Unfortunately the faintness of these stars at optical wavelengths has made them difficult to observe at the required contrast and spatial resolution to detect exoplanets with current AO systems. These stars are, however, sufficiently bright in the near-infrared to be used as AO guide stars. The planet to star contrast ratio is particularly favorable in L-band and a suitable L-band vortex coronagraph is implemented in the NIRC2 science camera that is fed by the Keck II AO system. The choice to develop a near-infrared PWS was driven by the high performance of visible PWS, the recent availability of near-infrared e-APD arrays, and measured performance improvements using a near-infrared tip-tilt sensor with the Keck I laser guide star (LGS) AO system. [1-3]

The near-infrared PWS will be a key component of the Keck Planet Imager and Characterizer (KPIC) project. The characterizer part of KPIC includes a fiber injection unit (FIU) that will feed exoplanet light to the NIRSPEC spectrograph. The PWS is closely integrated with the FIU to provide the wavefront sensing. [4-5]

The opto-mechanical design will also support the use of off-axis guide stars using a field steering mirror (FSM) assembly. This is not required for science with the NIRC2 vortex coronagraph or FIU. However, the use of off-axis guide stars will facilitate more general NGS AO science with NIRC2 (e.g. observations of the dust obscured galactic center) and provides a platform for the future use of the near-infrared system for low order sensing as part of the LGS AO system.

In this paper we will discuss the opto-mechanical design. Related papers at this conference will discuss the PWS performance, the PWS real-time controller, the FIU design and the overall KPIC program.[5-8]

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1.1 Implementation on the AO bench

For science with the vortex coronagraph, the PWS must share light with the NIRC2 science camera. This is done with a dichroic beamsplitter. To minimize the size of the dichroic, and given other space constraints, the PWS is located close to the front of NIRC2 as shown in Figure 1. The Keck II AO bench has very limited available space for new components, but sufficient space was identified behind the tip-tilt mirror and deployable fold mirror for NIRSPEC (items 2 and 10 respectively in Figure 1(a)).

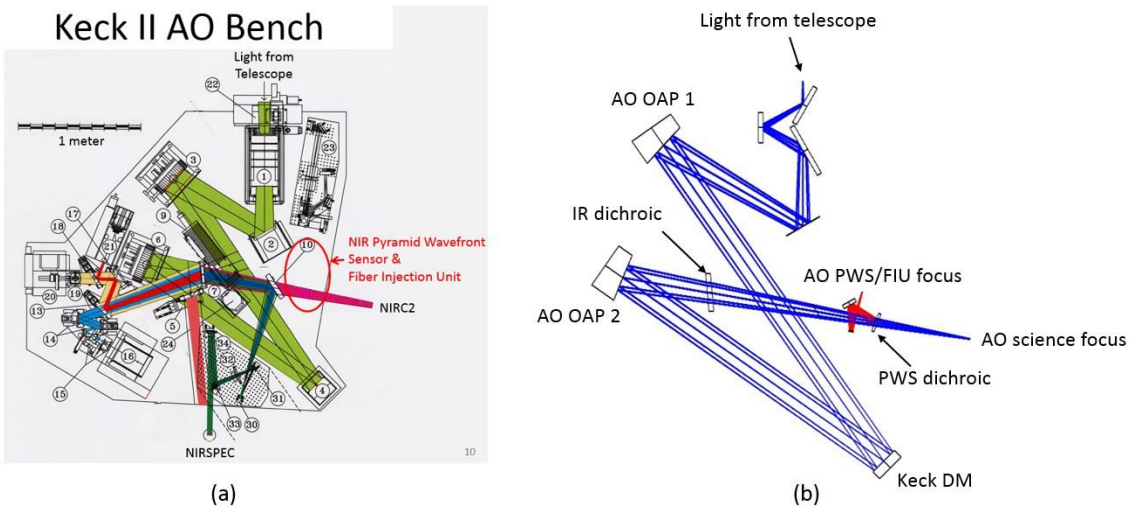

Figure 1. (a) Layout of the Keck II AO bench with location of the new components identified and (b) optical path of the AO bench with the dichroic pickoff and first two fold mirrors shown.

The first three new elements, referred to collectively as the FSM assembly, are shown just before the AO science focus in Figure 1(b). The FSM assembly feeds light to the PWS and FIU. The FSM assembly includes a dichroic beamsplitter and two fold mirrors. The dichroic and the last fold mirror are the field steering elements. J- and H-band light from the Keck AO system is picked off by the dichroic. Longer wavelengths are passed to the NIRC2 instrument for science. The FSM assembly also contains a fold mirror that moves in to replace the dichroic for science with the FIU and NIRSPEC instrument.

Light from the FSM assembly is re-imaged by a pair of identical off-axis parabola (OAP) mirrors. The FIU assembly contains the first OAP, a MEMS deformable mirror (DM) and a dichroic. The dichroic on the FIU plate reflects H-band light towards the PWS assembly and transmits longer wavelength light. Figure 2 shows how the light is split between the FIU and PWS.

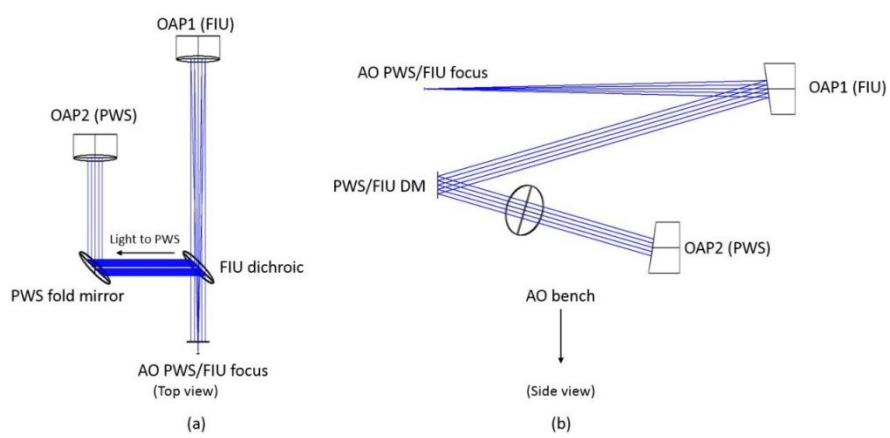

Figure 2. (a) Top view of the first FIU and PWS optics shows how the light is sent to the PWS from the FIU and (b) side view of the first optics showing the DM location.

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The PWS optics are designed to relay the output of the Keck II AO system to the pyramid tip and then relay the four pupils created by the pyramid to the near-infrared detector. The PWS camera dewar utilizes a SAPHIRA HgCdTe 320 X 256 pixel, 24 µm pixel pitch detector.[9] A modulator mirror is used to modulate the pupils on the detector and a piezo positioning stage is used for pupil centration on the detector. Figure 3 shows a CAD image of the FSM, PWS and FIU assembly (a) and a zoomed in view of the PWS assembly (b) and Figure 4 shows the top (a) and side (b) views of the model with dimensions for scale. The CAD model in Figure 3 (a) shows the FSM assembly with actuated mirrors. The first iteration of the KPIC project will have a fixed field for the PWS and the actuated field steering will be implemented in the second iteration.

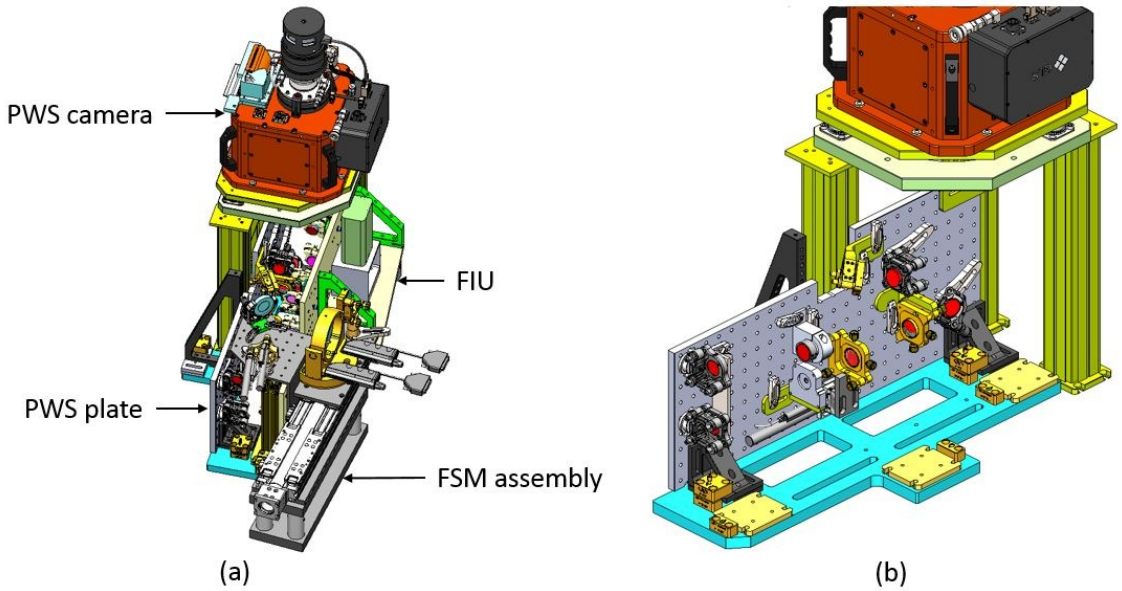

Figure 3. (a) CAD model of the assembled KPIC opto-mechanical components on the Keck II AO bench and (b) a zoomed in view of the PWS components.

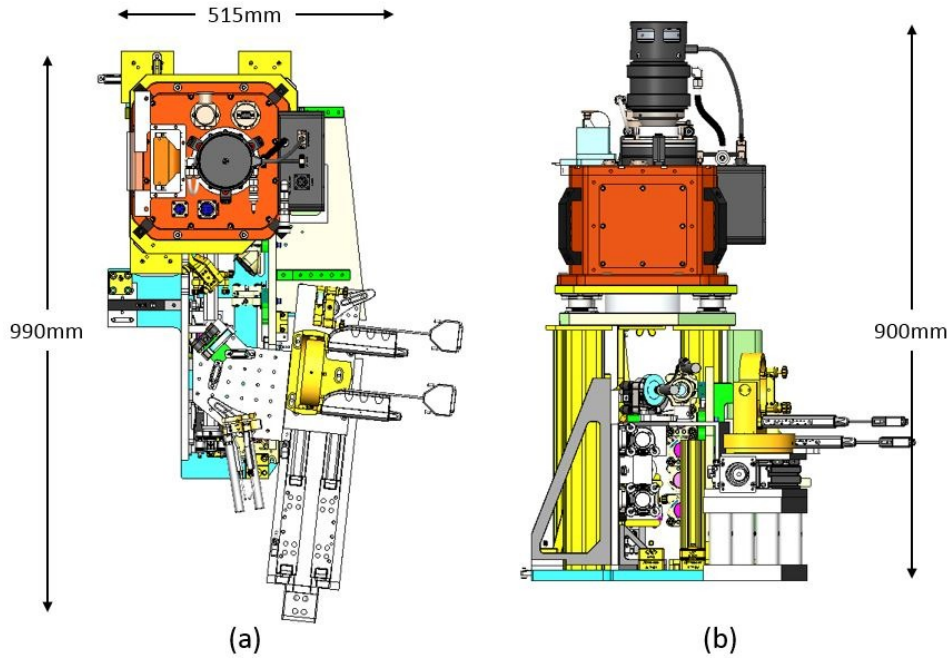

Figure 4. Top view (a) and side view (b) of the CAD model of the KPIC components with dimensions for scale.

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2. PWS OPTO-MECHANICAL DESIGN REQUIREMENTS AND CONSTRAINTS

Several performance and volume constraints drove the opto-mechanical design of the PWS. The primary optical requirements that drove the design are listed in Table 1.

Table 1. Primary PWS optical requirements

PWS #	Requirement
1	Relay the output of the Keck II AO system to the tip of the pyramid.
2	Operate in H-band wavelengths (1.5-1.8 µm).
3	Produce a pupil at which a modulator can be located.
4	The pupils on the detector shall be 40 pixels across.
5	The as-built system shall degrade the image quality provided by the Keck II AO system by < 150 nm rms.
6	Provide a means of maintaining the pyramid tip to be conjugate to the science focal plane.
7	The pupil distortion shall be < 80 mm (peak-to-peak) on the Keck primary mirror.
8	The chromatic aberrations in the pupil shall be less than 80 mm (peak-to-peak) on the Keck primary mirror.
9	Support an unvignetted FOV of 2.0 arcsec diameter.

The space allocated for the PWS and FIU assemblies has a footprint of about 500 mm wide by 1000 mm long. This limited space was the driving factor behind the layout of the optical design. The two optical plates (PWS and FIU) and SAPHIRA camera had to fit side-by-side in the 515 mm allocated width which drove the vertical layout of the optical design.

3. PWS OPTICAL DESIGN

The starting point for the optical design was to have the Keck AO deformable mirror optimize the image quality at the NIRC2 AO science focus to correct for the astigmatism introduced by the two dichroics in this path. This results in non-common path aberrations (NCPA) of 45 nm RMS WFE at a wavelength of 1.6 µm at the AO PWS/FIU focus (AO Input in Figure 5). Figure 5 shows the PWS optical layout. Two sets of OAPs relay the AO input to a collimating lens and a focusing lens (the first OAP is on the FIU plate). Two relays were chosen to match the relays on the FIU plate. The two lenses relay the OAP output to the pyramid and a third lens is used to relay the pupils to the SAPHIRA detector.

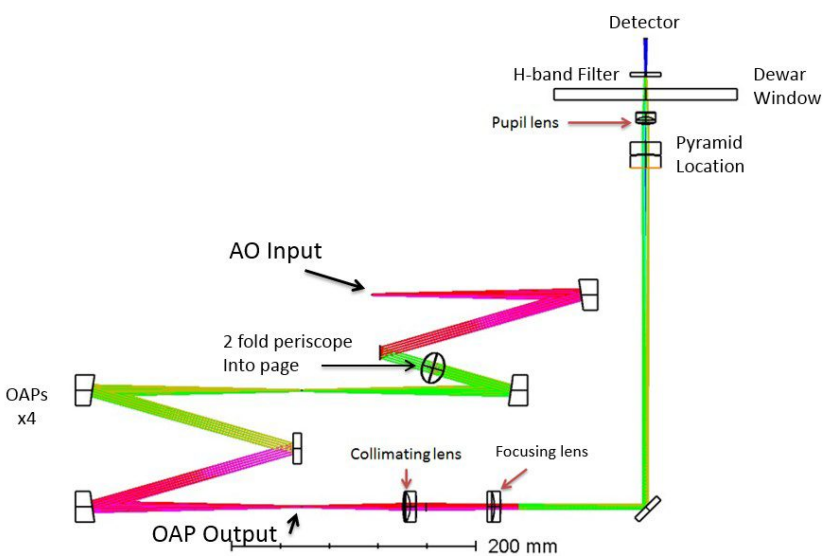

Figure 5. Side view of the PWS optical layout.

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3.1 OAP design

A reflective OAP design was desirable due to its compact horizontal size and performance capabilities.[10] Both assemblies (FIU and PWS) share the same set of OAP relays and the FIU plate contains the first OAP, MEMS DM (initially just a fold mirror) and dichroic that sends H-band light to the PWS plate. The OAPs have a nominal parent focal length of 168.3 mm and an offset of 48 mm. The 48 mm offset provides enough room for the DM and modulator mirror mechanics. In this case, having two pairs of identical OAPs was necessary in order to have two pupil locations with the same size pupils. The first pupil location is used for the MEMS DM on the FIU plate and the second for the modulator for the PWS. Additionally, the second set of OAPs serves to correct the tilted focal plane created by the first set of OAPs. This design results in a RMS WFE of 46 nm at a wavelength of 1.6 μm at the OAP output focal plane, which is identical to the input RMS WFE from Keck AO. Figure 6 shows the reflective portion of the PWS optical design.

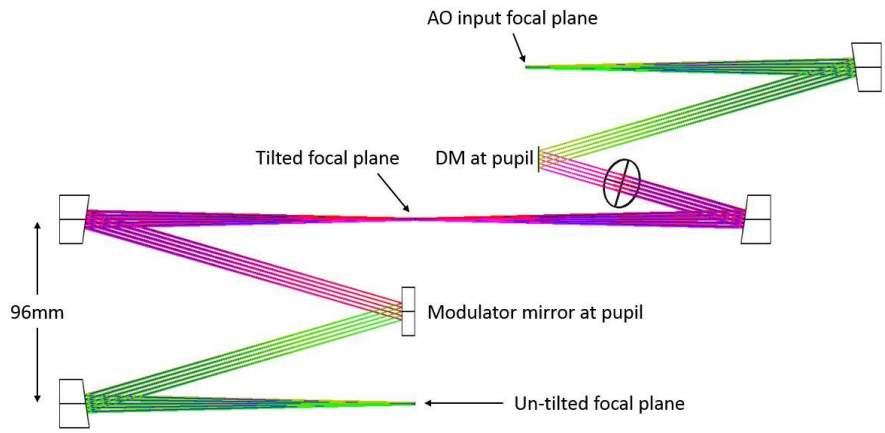

Figure 6. PWS reflective optics.

3.2 Refractive optics design

The refractive optics were designed to relay the output of the OAPs to the pyramid tip and re-image the pupils created by the pyramid onto the SAPHIRA detector. A 100 mm focal length commercial off-the-shelf (COTS) doublet lens is used to collimate the output of the OAP relay and provide focus control. The telescope focus can change between NIRC2 filters or between NIRC2 and FIU science. This will shift the output focus of the OAP relay by up to 2 mm. The collimating lens is used to compensate the focal shift by moving along the optical axis so that the beam is once again collimated. A custom collimating lens was designed, but a performance analysis showed little difference between the custom and COTS lens and the COTS lens was an order of magnitude cheaper than the custom doublet.

The combination of the COTS collimating lens and the custom focusing lens is used to relay the output of the OAPs to the pyramid. A slow f-number (f/56) at the pyramid tip was desirable to create the proper magnification and reduce the effects of focus misalignment. It was necessary to fold the beam after the focusing lens in order to get the SAPHIRA camera to fit in the allotted volume.

A pair of fused silica roof prisms creates the pyramid and separates the pupils. The pupil re-imaging lens is a custom designed doublet that places the four pupils created by the pyramid on the SAPHIRA detector. One of the main challenges in designing the pupil lens was to have enough space between the last surface of the pyramid prisms and the dewar window to allow for mechanical mounting of the pyramid prisms, pupil centration stage and pupil lens. The merit function for the pupil re-imaging constrained the separations to a minimum to allow for the mechanics while also optimizing the doublet to reduce pupil distortion and chromatic shear.

3.3 Optical design performance

The optical performance of the PWS can be analyzed at two points: the focus at the pyramid tip and the pupils on the detector. The performance at the pyramid is evaluated in terms of RMS WFE and the performance at the pupil is evaluated in terms of pupil distortion, chromatic pupil shear, and pupil size.

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The design goal for the collimating lens and f/56 focusing lens was to minimize the WFE at the pyramid tip. Requirement PWS 5 in Table 1 states that the NCPA at the pyramid of the as-built system should be less than 150 nm RMS. The nominal optical design shows a RMS WFE at the pyramid of 48 nm, nearly the same as the input WFE from Keck AO. A tolerance analysis for the PWS optics shows a RMS WFE at the pyramid tip of 135 nm for > 90% of 50 Monte Carlo tolerance runs.

Manufacturing tolerances for the OAPs were based on discussions with the vendor and were set well before the optical design of the PWS was completed. The manufacturing tolerances for the doublets were set based on "typical" tolerances that would keep the cost reasonable without impacting performance. Tolerances for the position of each element were based on the sensitivity of the mounts, the height tolerance of the optical posts and an estimation of how accurate the posts could be adjusted by hand.

Pupil distortion for the final toleranced optical design was calculated to be 205 mm (peak-to-peak) for the full 2 arcsec field and 68 nm (peak-to-peak) for a field of 0.7 arcsec diameter. Even though the requirement for pupil distortion is less than 80 mm peak-to-peak, it was deemed acceptable for the design to meet the requirement for the 0.7 arcsec field and not the full 2 arcsec field. The chromatic pupil shear in H-band was calculated to be 68 mm peak-to-peak for the toleranced system, which meets the requirement. Figure 7 shows the size of the Keck pupils on the SAPHIRA detector.

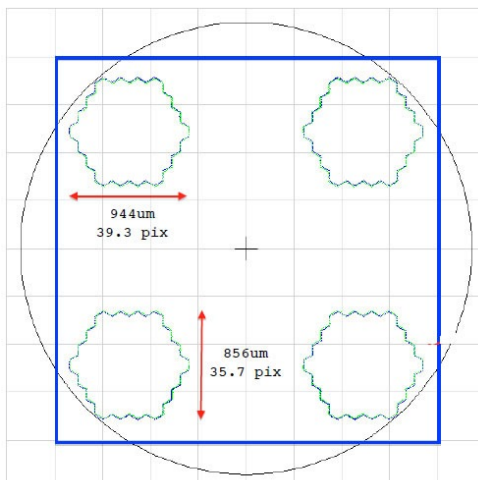

Figure 7. Keck pupils on the SAPHIRA detector outlined by a box of 128x128 pixels.

4. PWS MECHANICAL DESIGN

The mechanics for the PWS plate and SAPHIRA camera were designed to utilize several COTS components in order to reduce cost and complexity. A kinematic mounting interface is used to couple the PWS plate to the FIU plate and mount both plates to the AO bench. The SAPHIRA camera mounting utilizes three risers to mount the camera above the AO bench. There are two adapter plates with kinematic mounts that allow the camera to be removed and replaced with repeatability.

4.1 PWS plate

Figure 8 shows the PWS plate assembly which contains all the PWS opto-mechanical components except for the SAPHIRA camera. All the optics, excluding the pyramid prisms and pupil re-imaging lens, are mounted in COTS mounts. The OAPs are mounted in 3-axis (θ_X, θ_Y, Z) mirror mounts and clamped to the plate using standard posts and clamps. The modulator mirror is glued to a piezo tip/tilt stage which is then mounted to the PWS plate using a custom designed clamping mechanism. Five-axis adjustable lens mounts are used to hold the collimating and focusing lenses. The collimating lens mount is attached to a linear stage driven by a motorized actuator. An iris is placed at the OAP output to control the field of view seen by the SAPHIRA camera. This will be a fixed iris in the first iteration and motorized later on.

A separate assembly for the pyramid prisms and pupil re-imaging lens is bolted to the PWS plate. The two prisms are mounted in a housing that holds the prisms orthogonal to each other to create the pyramid. The pupil re-imaging lens is

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mounted to the moveable portion of the piezo positioning stage. The fixed portion of the stage is mounted to the prism housing and allows the pupil re-imaging lens to be moved in X and Y while the pyramid assembly remains fixed.

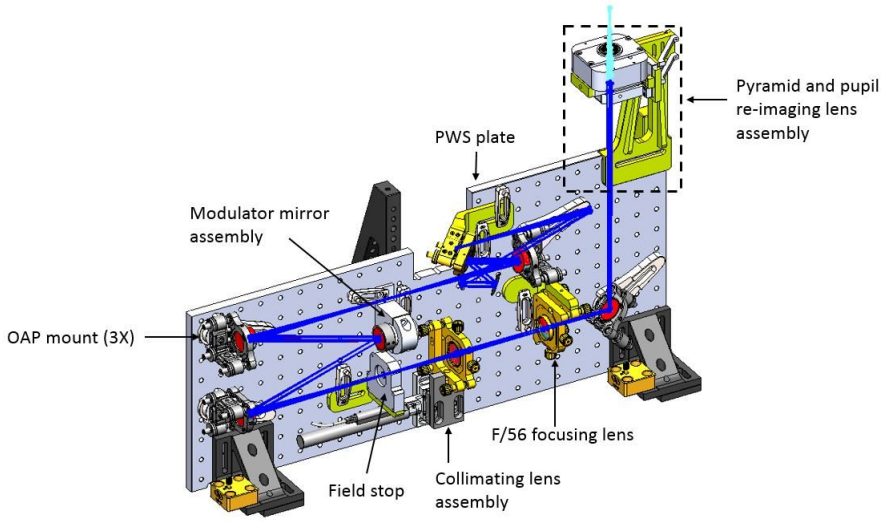

Figure 8: CAD model of the PWS plate assembly with the optical path shown.

4.2 PWS and FIU kinematic mounting

A kinematic baseplate was designed to allow co-mounting of the PWS and FIU plates. This allows for the two plates to be co-aligned in the lab before being installed on the Keck II AO bench. The baseplate can be roughly aligned to the AO bench without the PWS and FIU plates attached. The plates can then be placed on the kinematic points and the entire assembly can then be aligned to the incoming beam from Keck II AO. Once the alignment is complete the plates can be removed and replaced without having to re-align the entire system. Figure 9 shows the kinematic baseplate and mounts for the PWS plate and FIU plate.

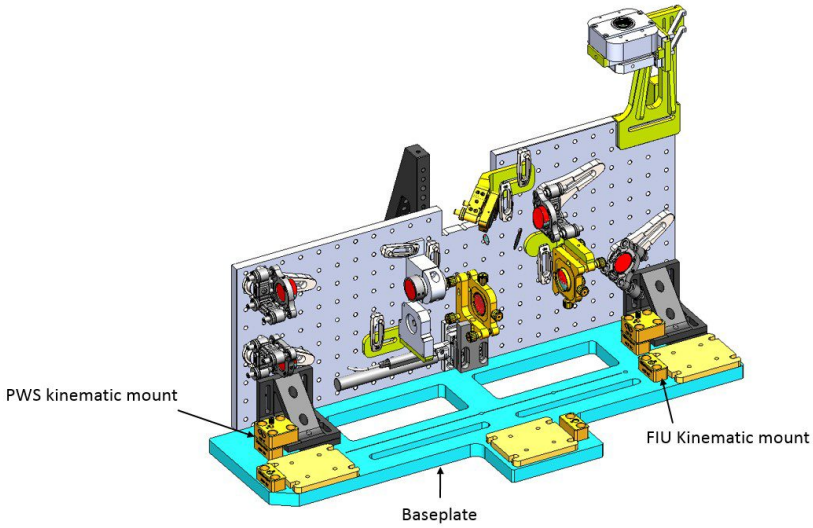

Figure 9. CAD model of the PWS plate assembly with the kinematic baseplate and mounts shown (rear PWS kinematic mount not shown).

4.3 SAPHIRA camera mounting

Due to the long focal length of the focusing lens, the SAPHIRA camera is mounted approximately 470 mm above the surface of the AO bench. The camera is raised to the appropriate height by three risers mounted to the AO bench. Figure

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10 shows the locations of the three camera risers on the AO bench. The tight space limited the available locations for the camera risers and they were not able to be placed in a typical 120 degree configuration.

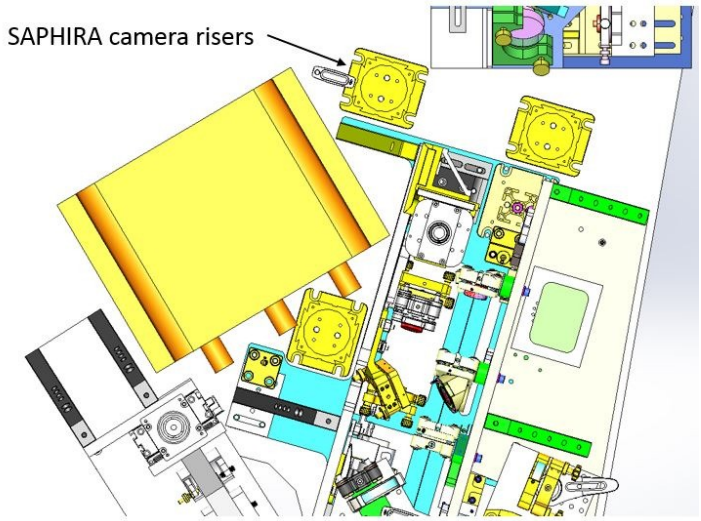

Figure 10. Top view of the KPIC CAD model with the SAPHIRA camera assembly hidden to show the location of the camera risers

An adapter plate attaches to the risers and contains kinematic points that mate to a second adapter plate that attaches to the SAPHIRA camera. The two plates are held to the kinematic points using several thumb screws. The thumb screws provide enough clamping force to prevent the camera from tipping off the kinematic points and dislodging from its kinematics. Figure 11 shows the two adapter plates and the kinematic points for the SAPHIRA camera.

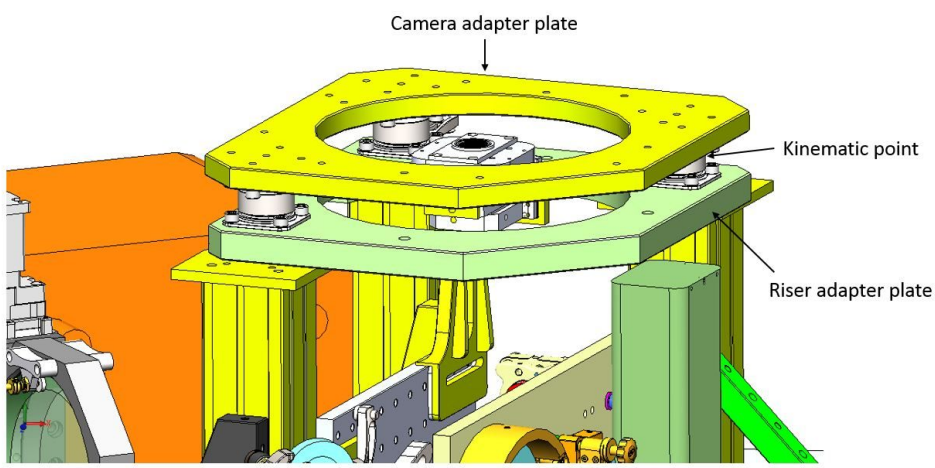

Figure 11. SPAHIRA adapter plates and kinematic points.

The SAPHIRA camera is cooled by a Stirling cooler mounted on the back of the camera (top side in this case). Several tests were performed during the design phase to determine if the vibration from the cooler had any impact on the AO bench. The camera was mounted inside the Keck II AO bench with the Stirling cooler running. The AO bench was set up to collect data with several instruments to determine what effect the SAPHIRA camera had on the system. It was found that the AO bench was able to fully operate in closed-loop with no negative effects from the Stirling cooler on the SAPHIRA camera.

The COTS and custom components are largely fabricated from 6061-T6 aluminum. This material is used extensively throughout the Keck AO bench and does not pose an issue for the other opto-mechanical assemblies on the bench. Due to time and resource constraints, a detailed Finite Element Analysis (FEA) was not performed on the PWS plate

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mounting components or the SAPHIRA camera mounting components. If deemed necessary, additional analyses will be performed during the next phase of the project, including thermal and structural FEA.

5. PWS ALIGNMENT STRATEGY

The PWS plate was built and aligned at the Institute for Astronomy (IfA) in Hilo, Hawaii and the FIU plate was built and aligned at the California Institute of Technology in Pasadena, CA. The FIU plate was then brought over to IfA and the two plates were co-aligned on the kinematic baseplate. The alignment strategy for both the PWS and FIU plates utilized a combination of mechanical and optical reference to align each optic.

5.1 PWS OAP/reflective optics alignment

An extension plate was built to bolt to the PWS plate to hold the first OAP and a fold mirror, prior to integration with the FIU. This allowed the two plates to be aligned separately before integration at IfA. Precision machined rods were used to set the initial alignment between the PWS OAP mounts. Figure 12 shows the OAP mounts and the precision machined tools used to set the initial alignment. The OAPs are back surface registered in the mounts and the OAP thickness is known from the manufacturer. The OAP mounts were set so that the three adjustment screws were in the middle of their range of travel. Two precision rods and a spacer were used to set the position of the OAP3 mount relative to the OAP2 mount. A second alignment tool was used to set the position of OAP4 mount relative to the positon of the OAP3 mount. The second alignment tool for OAP 3 and 4 was then used to set the position of the mount for OAP1 on the dummy plate.

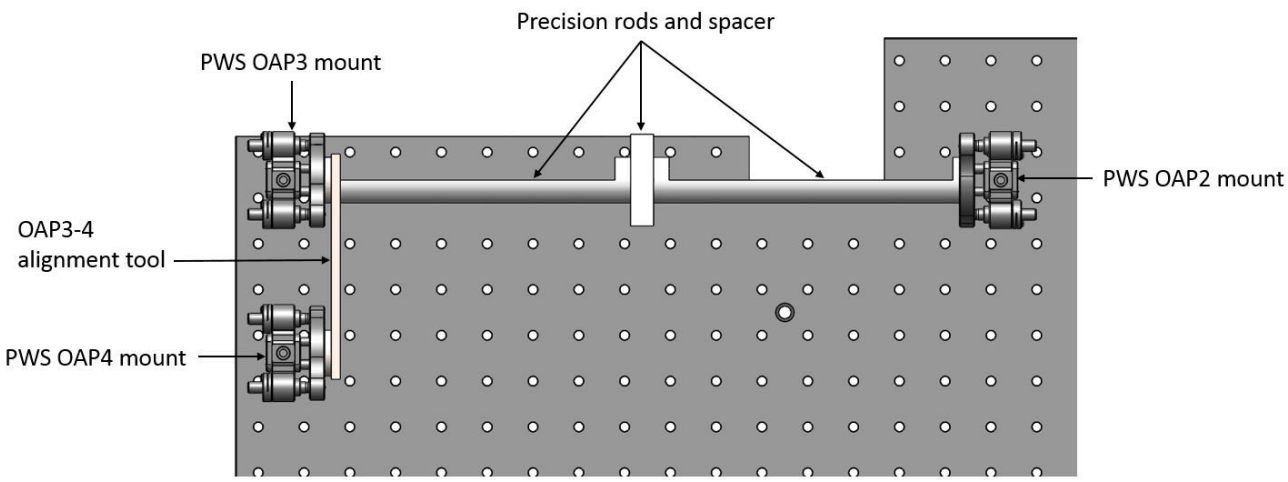

Figure 12: PWS OAP mounts and precision alignment tools

Next, the OAPs were aligned using a Zygo interferometer and a precision reference sphere. The precision sphere was placed at the focus of the OAPs and used to reflect the beam back into the interferometer. The incoming interferometer beam was obscured so that two beams were formed. The following steps were utilized to fine align the PWS reflective optics:

a. Align PWS plate, with the extension plate bolted on, to be parallel to the beam from the interferometer.

b. Place a flat mirror in OAP1 mount and align using the Zygo.

c. Remove the flat mirror and place OAP1 into the mount. Carefully clock the OAP so that the reflected beam is at the proper height relative to the PWS plate.

d. Use the reference sphere to back-reflect light from OAP1 into the Zygo. Adjust OAP1 mount to minimize the wavefront error measured by the interferometer.

e. Align OAP2 using the second beam from the interferometer following steps b – d.

f. Replace the reference sphere with a flat mirror and adjust to minimize the WFE.

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g. Repeat steps b-f for the second OAP relay (OAPs 3 and 4) and install the modulator mirror as the flat mirror in step f.

Figure 13 shows a layout of the alignment strategy for the OAP relays on the FIU plate (similar for the PWS plate).

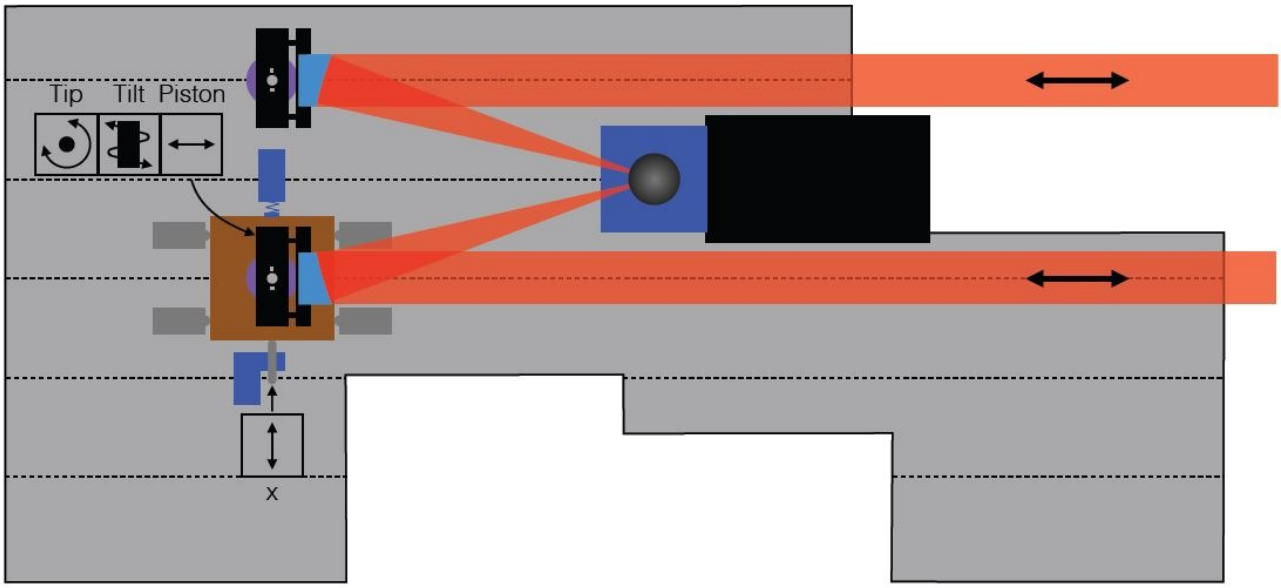

Figure 13: Alignment strategy utilizing an interferometer and a precision ball

A telescope "simulator" was used to send a f/13.66 beam to OAP1. A camera was placed at the output of the combined OAP relays and used to check the point-spread function (PSF) of the system. The PSF was very uniform and at this point the reflective portion of the PWS plate was aligned to an incoming beam that simulated the Keck AO F-number.

5.2 PWS refractive optics alignment

The refractive PWS optics were aligned in sequential order; collimating lens, f/56.5 focusing lens, PWS. The initial alignment of the PWS plate was done using visible light, not near-infrared (NIR) light. This was not an issue for alignment as everything except the focus at the pyramid should be in similar positions in the visible and NIR.

5.2.1 Collimating lens alignment

The following steps were used to align the collimating lens to the output of the OAP relays:

a. Place the collimating lens in its mount and mount on the PWS plate at the design position. Check that the beam from the OAP output is centered on the lens.

b. Fine tune the lens position by monitoring the optical height and lateral position of the beam after the lens.

c. Use a Shack-Hartmann wavefront sensor (HASO) to measure the beam after the collimating lens. The Z-position of the lens along the optical axis was adjusted to produce a collimated beam. The lens was finely adjusted to minimize the WFE measured by the HASO.

Steps a-c were used to align the collimating lens in the visible. The position was adjusted later to accommodate for the focus shift between the visible and NIR wavelengths.

5.2.2 Focusing lens alignment

The following steps were used to align the focusing lens to the output of the collimating lens:

a. Position the lens in its mount at the design location on the PWS plate. Check that the collimated beam is centered on the lens.

b. Fine tune the lens position by monitoring the optical height and lateral position of the beam after the lens.

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c. Place a camera at the focus and monitor the quality of the PSF. Use the fine adjustments in the lens mount to form a uniform PSF.

5.2.3 Alignment of the PWS

The following steps outline the alignment procedure for the fold mirror, pyramid prisms, pupil re-imaging lens and the SAPHIRA camera:

a. Position the final fold mirror according to the CAD model and use it to direct light towards the pyramid location.

b. Mount the pyramid prisms and pupil re-imaging lens according the CAD model and attach the sub-assembly to the PWS plate.

c. Use the fold mirror to direct light to the pyramid tip. This was done by eye using visible light.

d. Install the SAPHIRA camera behind the pupil re-imaging lens. Switch the light from the telescope simulator to a NIR laser (1550 nm).

e. Steer the final fold mirror so that the light intensity is balanced between the four pupils created by the pyramid and pupil re-imaging lens.

f. Adjust the pyramid/pupil lens stage so that the pupil plane is on the SAPHIRA detector (conjugated to the modulator mirror).

g. Adjust the collimating lens to focus light on the pyramid tip, whilst monitoring the pyramid pupil images for focus errors.

The collimating lens was adjusted in focus to accommodate for the NIR wavelength. At this point the PWS plate, including the SAPHIRA camera, was aligned in the NIR and ready for integration with the FIU plate.

5.3 PWS/FIU co-alignment

The PWS and FIU plates were brought together in the lab at IfA for co-alignment. The FIU plate was designed to have a fiber input at the Keck AO focus location and it was internally aligned to the fiber output. The following steps outline the procedure used to align the two optical plates:

a. Remove the adapter plate containing the first OAP and fold mirror from the PWS plate.

b. Position the first fold mirror on the PWS plate (see Figure 2) at the design location.

c. Use the dichroic on the FIU plate and the PWS fold mirror to steer the beam from the FIU plate through the PWS optics. A visible laser was used to positon the beam in the center of the optics.

d. Insert a visible camera at the focus of OAP2 on the PWS plate. Fixing the optical height at 1.5”, the beam was aligned using the dichroic and fold mirror to minimize aberrations in the PSF (mostly astigmatism and coma).

e. Examine the PSF at the pyramid focus in both the visible and NIR.

The co-alignment of the two plates was challenging. It took several iterations of steps c-e to get the alignment correct. Eventually, a high quality PSF was formed at the pyramid focus and the two plates were co-aligned on the kinematic baseplate.

6. PWS PERFORMANCE

The detailed performance of the PWS is discussed in another paper at this conference.[6] Figure 14 shows images of the PSF at the pyramid focus in visible (a) and NIR (a) light. The PSF images were recorded after the two plates (PWS and FIU) were co-aligned using the fiber input on the FIU plate. Figure 15 shows an image of the four pupils on the SAPHIRA detector. The PSF images show a symmetrical PSF with well-defined diffraction rings.

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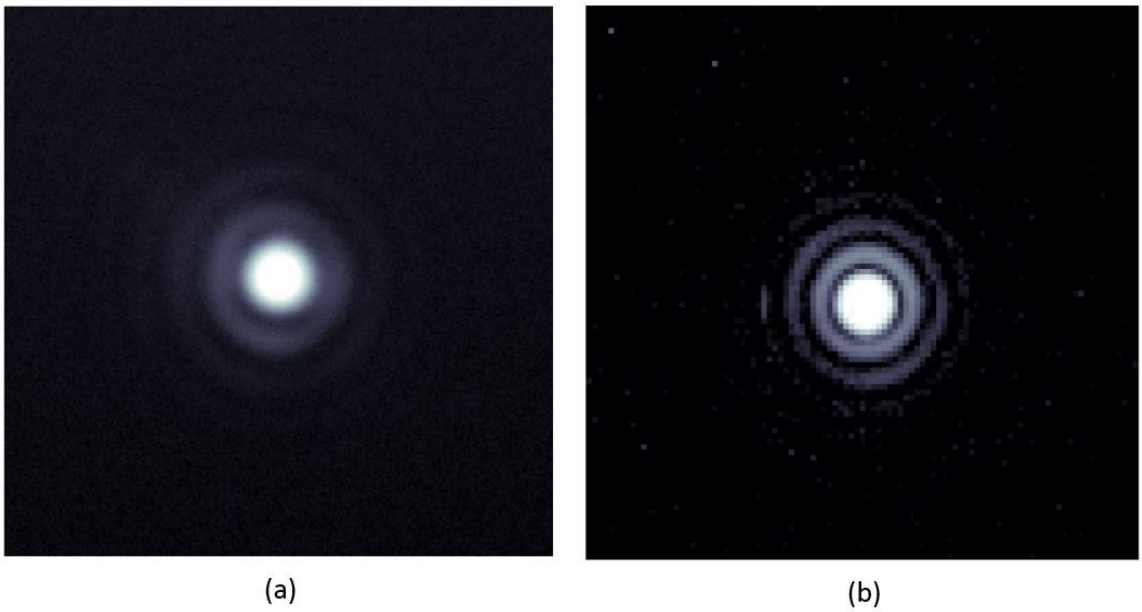

Figure 14: PSF images at the pyramid focus in (a) visible and (b) IR

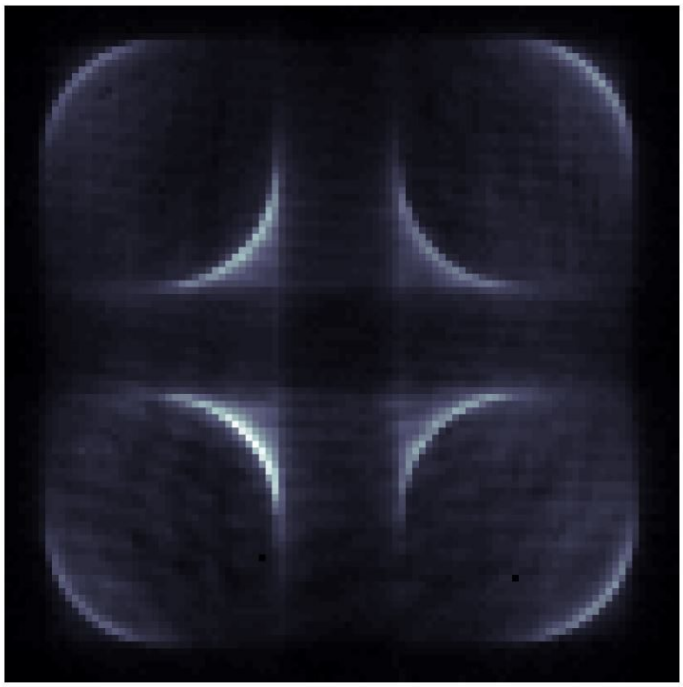

Figure 15: IR pupil image on the SAPHIRA detector

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7. SUMMARY

A near-infrared pyramid wavefront sensor (PWS) has been successfully designed, assembled and aligned in the lab. The optical design was optimized by using a combination of off-axis parabolas and refractive doublets. The PWS opto-mechanical layout, and how it fits within the Keck II AO bench, have been described in this paper. The PWS was aligned using an interferometer and analysis of the PSF at several locations. Co-alignment of the PWS and fiber injection unit (FIU) plates was achieved using a fiber source on the FIU plate while analyzing the PSF on the PWS plate.

The next step for the KPIC project, planned for September 2018, will be to install the PWS and FIU on the Keck II AO bench in support of exoplanet imaging science with the NIRC2 vortex coronagraph and fiber-fed spectroscopic science with NIRSPEC. The PWS and its real-time controller will be tested and validated on the AO bench using internal AO calibrations sources as well as on-sky testing. Testing on the AO bench will also determine whether or not additional analyses, like thermal and structural FEA, will be required to improve the mechanical design of the PWS. Several areas of improvement have been identified for the PWS for the second iteration of the project. These include upgrading the pyramid prisms to a material and coating optimized for the near-infrared, adding motion control capabilities to the field steering mirror assembly to support usage of off-axis guide stars, and adding a motorized iris to the PWS plate to reduce sky background.

8. ACKNOWLEGEMENT

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The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain

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