Keck AO High order Wavefront Sensing and Control: opto-mechanical design

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ABSTRACT

As part of the High order Advanced Keck Adaptive optics (HAKA) project, a state-of-the-art ALPAO 2844 actuator deformable mirror (DM) will replace the more than 25 years old 349 actuator DM on the Keck II Adaptive Optics (AO) bench. The increase in the number of DM actuators requires a new set of pupil-relay optics (PRO) to map the 2.5mm DM actuator spacing to the 200µm lenslet spacing on the Shack-Hartmann wavefront sensor (WFS). A new lenslet array with increased focal lengths will be procured in order to maintain current plate scales. HAKA will initially support science with the near-infrared camera (NIRC2), a single mode fiber fed spectrograph (KPIC + NIRSPEC) and a fast visible imager (ORKID).

In addition, a new infrared wavefront sensor ('IWA) is being designed to support science with ORKID and a suite of new science instruments: a mid-infrared coronagraphic integral field spectrograph (SCALES) and a fiber-fed high-resolution spectrograph (HISPEC).

We present the opto-mechanical design of the HAKA DM, Shack-Hartmann WFS upgrades and the 'IWA system. A mount for the HAKA DM will allow for quick integration and alignment to the Keck II AO bench. The upgrade to the WFS PRO includes a new set of optics and associated mounting that fits within the mechanical constraints of the existing WFS and meets the requirements of the HAKA DM.

Keywords: HAKA, adaptive optics, infrared wavefront sensing, deformable mirror

1. INTRODUCTION

A high-order deformable mirror (DM) is being procured as part of the High order Advanced Keck Adaptive optics (HAKA) project[1]. HAKA will enable science that will (1) directly image and spectroscopically characterize populations of old, cold exoplanets that are not accessible to any other ground or space-based direct imaging facility and (2) enable short wavelength (z-band) AO corrections to e.g. probe the atmospheres of our Solar System's ice giants and map the surfaces of the Galilean moons.

In conjunction with the HAKA DM, upgrades to the Shack-Hartmann wavefront sensor (SH WFS) include a new set of pupil relay optics (PRO) and lenslet arrays. The SH WFS upgrades are necessary to properly map the 2.5mm DM actuator spacing (20cm on the primary mirror) to the 200µm lenslet spacing. The new ALPAO DM contains 2844 actuators and replaces the 25+ years old 349 actuator DM on the Keck II AO bench. An all refractive optical design was utilized for the PRO to fit within the mechanical constraints of the SH WFS. HAKA will initially support science with the near-infrared camera (NIRC2), a single mode fiber fed spectrograph (KPIC + NIRSPEC) and a fast visible imager (ORKID)[2-3].

In addition, a new infrared wavefront sensor ('IWA) is being designed to support science with ORKID and a suite of new science instruments: a mid-infrared coronagraphic integral field spectrograph (SCALES) and a fiber-fed high-resolution spectrograph (HISPEC).[4-7] 'IWA will provide four wavefront sensing modes: high and low-order pyramid wavefront sensor (PyWFS) modes to support natural guide star AO science with SCALES and HISPEC; the low-order mode will also be used to replace the visible tip-tilt and truth sensors for laser guide star AO science; and a Zernike wavefront sensor will be used to periodically optimize primary mirror phasing. An NSF Major Research Instrumentation (MRI) proposal was submitted for ‘IWA in November 2023.

‘IWA utilizes a combination of refractive and reflective optics to relay the NGS light to the pyramid tip and Zernike mask location. A voice-coil actuated steering mirror provides a 30 arcsec radius field of regard and a piezo stage modulates the pupil on the pyramid tip. ‘IWA’s opto-mechanical requirements and space constraints presented many challenges for the design of the optics and mechanics. We discuss the performance of the optical design of ‘IWA as well as the performance of the new PRO optics. We also discuss the challenges of designing the ‘IWA assembly to fit within the limited available space on the Keck II AO bench. The Keck II AO bench layout is shown in Figure 1 with the various science instruments (current and future) highlighted.

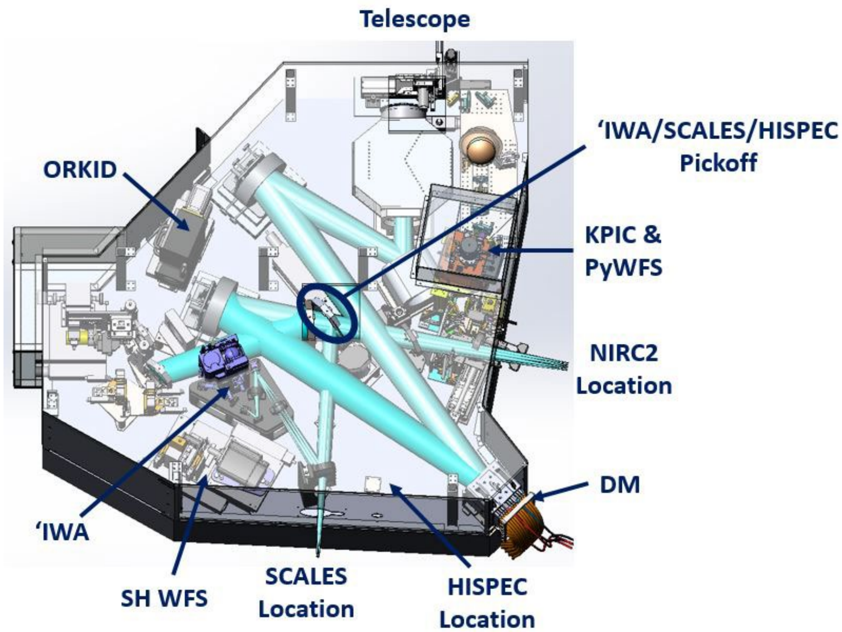


Figure 1: Keck II AO bench layout

1.1 HAKA design requirements and constraints

WMKO placed a two-phase contract with ALPAO in July 2022. Phase I, including the development of the DM technical proposal and compliance matrix, and demonstration of a suitable membrane has been completed. ALPAO’s final design review (FDR) was successfully completed on March 14, 2024. As of their FDR, ALPAO was predicting DM delivery in November 2024. The DM mounting mechanical detailed design was completed in April 2024 and fabricated components are expected to be delivered well before the ALPAO DM.

A CAD model of the DM showing the DM, top-mounted heat exchanger, cabling and coordinate system used for alignment is shown in Figure 2. The ALPAO DM membrane is the same diameter as the current DM to avoid changing the optics on the AO bench (i.e. to maintain the pupil size on the DM.) Table 1 lists the DM alignment requirements, which correspond to the coordinate system in Figure 2. The alignment goal is to reproduce the alignment of the existing DM, with better centering on the AO rotator axis, so as not to require realigning anything after the DM.

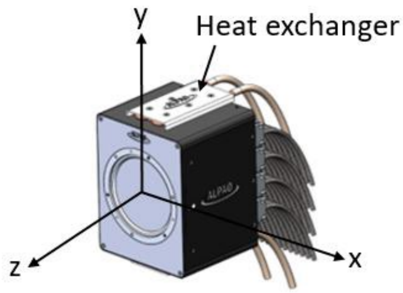


Figure 2: Coordinate system; x and y are in the plane of the DM facesheet. As seen looking at the front of the DM, x is horizontal pointing to the right, y is vertical pointing up and z is perpendicular to the face sheet pointing toward the viewer. Thetax, thetay and thetaz are rotations about these axes.

Table 1: Deformable mirror alignment requirements

DM #	HAKA Deformable Mirror (DM) Alignment Requirements
DM1	The DM shall be centered on the AO rotator axis to within ≤ 0.5mm in both x and y. Note: this is 20% of the actuator spacing. Note: the nominal height of the center of the DM above the optical bench is 305 mm.
DM2	The displacement of the new DM facesheet in z with respect to the existing DM's facesheet shall be ≤ 2 mm. Note: at 10° angle of incidence this will shift the AO rotator axis (and image) by 2 x sin(10) = 0.34 mm.
DM3	The x-axis of the DM shall be tilted (thetaz) with respect to the top surface of the AO bench by ≤ 0.5 mm between the center and edge of the DM. Note: 0.5 mm/30 actuators x 2.5 mm = 0.4°.
DM4	The tip-tilt (thetax,thetay) deviation shall displace the image by ≤ 0.4 mm (0.5") at the focal plane. Note: 0.4mm/1800mm = 46 arcsec.

The SH WFS, shown in Figure 3, needs to be modified to make use of the high-order DM. The F/13.66 beam comes to a focus at the field stop and is then collimated by the PRO, which re-images the pupil onto the lenslet array. The lenslet array has three different arrays with different focal lengths for various plate scales. The spots from the lenslet array are re-imaged onto the WFS detector by the reducer optics, by a factor of 0.48, to map the 200μm lenslet spacing to the 24μm pixel spacing on the camera.

The design choice we made is to change the PRO to expand the pupil by the ratio of the old actuator to new actuator spacing (i.e. 7 mm / 2.5 mm = 2.8). This expansion also requires changing the lenslet focal lengths by a factor of 2.8 to maintain the same field of view (i.e. plate scale). Based on past experience and performance expectations the new lenslets have the following specifications:

1. 200 µm lenslet spacing, f = 4.9 mm x 2.8 = 13.7 mm to correspond to 1.5″/pixel. This is the preferred plate scale with the current system.
2. 200 µm lenslet spacing, f = 2.4 mm x 2.8 = 6.7 mm to correspond to 0.75″/pixel. Finer plate scale for NGS AO correction with good seeing.
3. 400 µm lenslet spacing, f = 4.9 mm x 2.8 = 13.7 mm to correspond to 1.5″/pixel. This will provide improved NGS AO performance for R>9.

The PRO requirements are listed in Table 2.

Table 2: PRO requirements

PRO #	HAKA Pupil Relay Optics (PRO) Requirements
OPT1	The HAKA PRO shall reimage the deformable mirror (DM; i.e an image of the Keck telescope pupil) onto the existing wavefront sensor (WFS) lenslet array, for WFS focus stage (FCS) positions conjugate to sources from infinity to 85 km from the Keck telescope. Note: Requires a FCS range of 265 mm from the NGS focus.
OPT2	The HAKA PRO image of the 150 mm diameter (60x60-actuator) DM on the WFS lenslet array shall be unvignetted for field angles up to 6" diameter.
OPT3	The HAKA PRO magnification shall scale the 2.5 mm ALPAO DM actuator spacing, in the vertical direction, to be equal to the 200 µm lenslet spacing.
OPT4	The HAKA PRO shall produce lenslet-to-DM registration errors of ≤ 3% of a subaperture. This maximum allowable registration error may be distributed to define the tolerances on the other pupil re-imaging optics requirements.
OPT5	For the NGS case, with the FCS conjugate to infinity, the HAKA PRO shall meet the lenslet-to-DM registration error requirement for the pupil over a wavelength range of 0.5 µm to 1.0 µm.
OPT6	For the LGS case, with the FCS conjugate to altitudes from 85 km to 170 km, the HAKA PRO shall meet lenslet-to-DM registration error requirement at 0.589 µm, without adjusting the lenslet-to-DM registration.
OPT7	For the NGS case, the throughput of the HAKA PRO must be ≥ 95% for the wavelength range of 0.5 µm to 0.95 µm.
OPT8	For the LGS case, the throughput of the HAKA PRO must be ≥ 96% at 0.589 µm.
OPT9	The wavefront tilt introduced by the HAKA PRO shall be ≤ 0.1″ on-sky over an individual lenslet. Note: Small compared to the 0.6″ lenslet diffraction-limited spot diameter.
OPT10	The wavefront error introduced by the HAKA PRO shall be ≤ 40 nm rms over an individual lenslet. Note: Small compared to the 0.6″ lenslet diffraction-limited spot diameter.

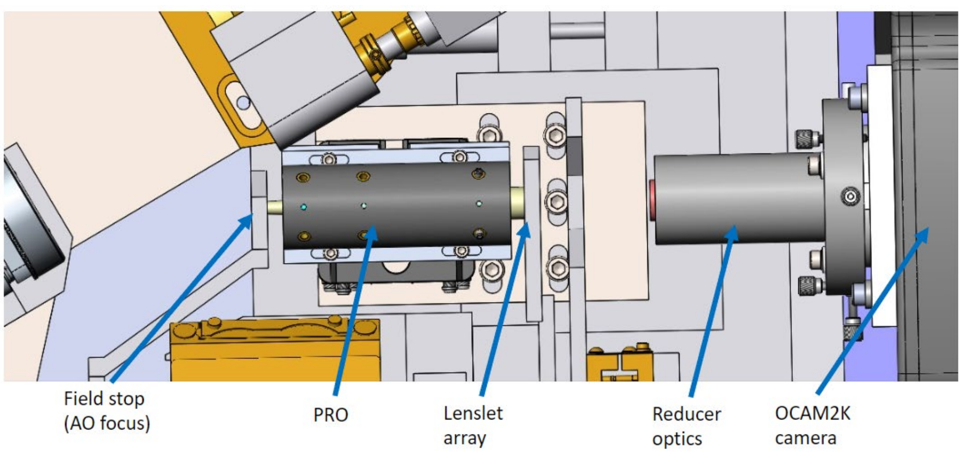


Figure 3: SH WFS opto-mechanical layout

1.2 ‘IWA design requirements and constraints

‘IWA is currently in the preliminary design phase while funding is being secured to move towards full-scale development. The primary design requirements for ‘IWA are shown in Table 3.

Table 3: Primary 'IWA requirements

‘IWA #	**‘IWA Requirements**
‘IWA1	Provide a high-order (HO) PyWFS for NGS AO science
‘IWA2	Provide a low-order (LO) PyWFS for LGS AO science
‘IWA3	Provide a Zernike WFS for primary mirror phasing
‘IWA4	Support K to M-band integral field spectroscopy with SCALES over a 2.2"x2.2" field centered on the AO optical axis
‘IWA5	Support Y to M-band imaging with SCALES over a 12.4"x12.4" field centered on the AO optical axis
‘IWA6	Support Y to K-band single mode fiber injection with HISPEC over a 6" diameter field centered on the AO optical axis, while sharing J- or H-band light with the PyWFS
‘IWA7	Support 0.6 to 0.95 um imaging with ORKID over a 10" diameter field
‘IWA8	A natural guide star selection field of ≥ 30" radius shall be provided (goal ≥ 60" radius)
‘IWA9	The design shall degrade the image quality provided by the Keck AO system by ≤50nm RMS

Several options and locations were considered for a new PyWFS on the Keck II AO bench, including upgrading the existing PyWFS, replacing the existing PyWFS at its current location and installing a new PyWFS at a different location. Ultimately, it was decided to install a new PyWFS (‘IWA) at the location shown in Figure 1. This decision was mainly driven by the pickoff mirror location for HISPEC and SCALES (Figure 1). The current pickoff mirror would have needed to be replaced by a complicated dichroic (or multiple dichroics) that would need to pass the shorter J-H wavelengths and reflect longer K-M wavelengths. This would have limited the PyWFS FOV as well as the HISPEC and SCALES science cases.

A three-position dichroic changer located approximately 450mm in front of the AO focus is used to send the desired wavelength to ‘IWA. The three options for the pickoff are:

1. Reflect J-band light to ‘IWA, transmit H-M to SCALES & HISPEC
2. Reflect H-band light to ‘IWA, transmit K-M to SCALES & HISPEC
3. Transmit y-M light to SCALES & HISPEC

Figure 4 shows a top-view CAD model of the pickoff assembly on the AO bench (left) and a front view of the pickoff assembly with the three positions shown (right). The opto-mechanical design of ‘IWA is detailed in section 3 of this paper.

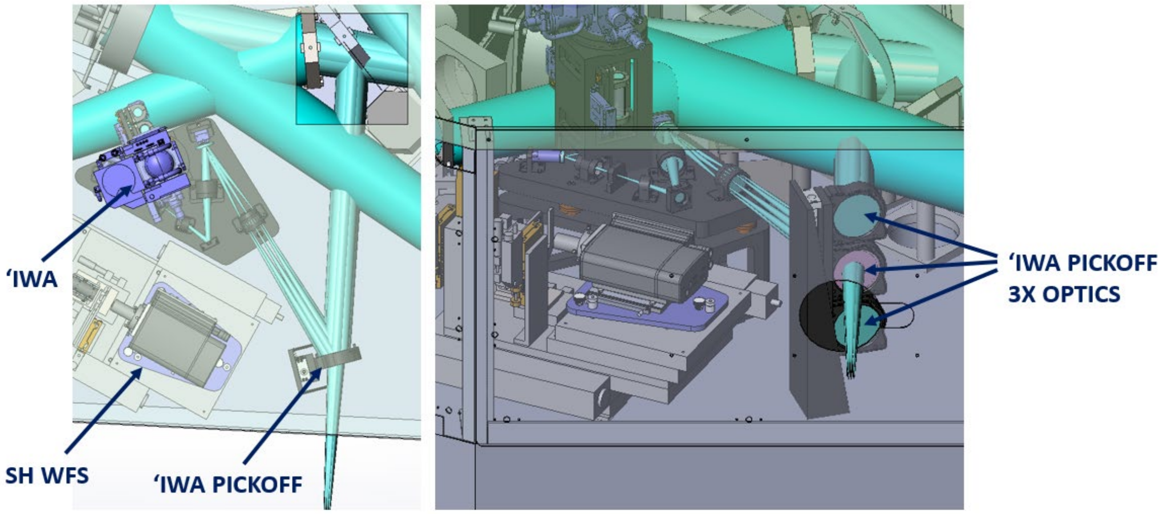


Figure 4: CAD model showing 'IWA pickoff top view (left) and the pickoff assembly with the three optics (right)

2. HAKA OPTO-MECHANICAL DESIGN

The HAKA opto-mechanical upgrades to the Keck II AO bench include a new DM, PRO and lenslet array. All components were designed to be drop-in replacements for the current hardware, with as little modification to the AO bench as possible.

2.1 DM

The overall DM mounting scheme is shown in both a collapsed and exploded view in Figure 5. This design can be separated into five individual entities: the top plate, the base, the alignment adjusters, the locking mechanism, and the cable support ladder. The top plate, shown in Figure 6, supports the DM without putting weight on the heat exchanger. A set of four through holes and a hole and slot pair machined into the top of the 6061-aluminum plate receive the reference pins and match the hole pattern on the underside of the DM. The use of reference pins allows the DM to be removed without impacting the alignment. The reference hole is strengthened with a press-fit hardened steel drill bushing to protect the aluminum when locating the DM.

The two holes located in the front corners of the plate provide a means of attaching slotted dowel rods on either side of the front face of the DM that support a pupil mask when in use (also shown in Figure 6). The mask will be located 9.33 mm from the DM membrane. Since the DM is at an angle of incidence of 10° the mask is designed to minimize shadowing (a central obscuration, matching the Keck pupil, was not included since the support struts would also cause shadowing and horizontal struts would need to be too thick). As designed, the mask is 0.25 mm thick and made of 1095 hardened spring steel to ensure stiffness. The mask is 2*(9.33+0.25)mm*tan(10°) = 3.38 mm wider in the horizontal direction than in the vertical direction.

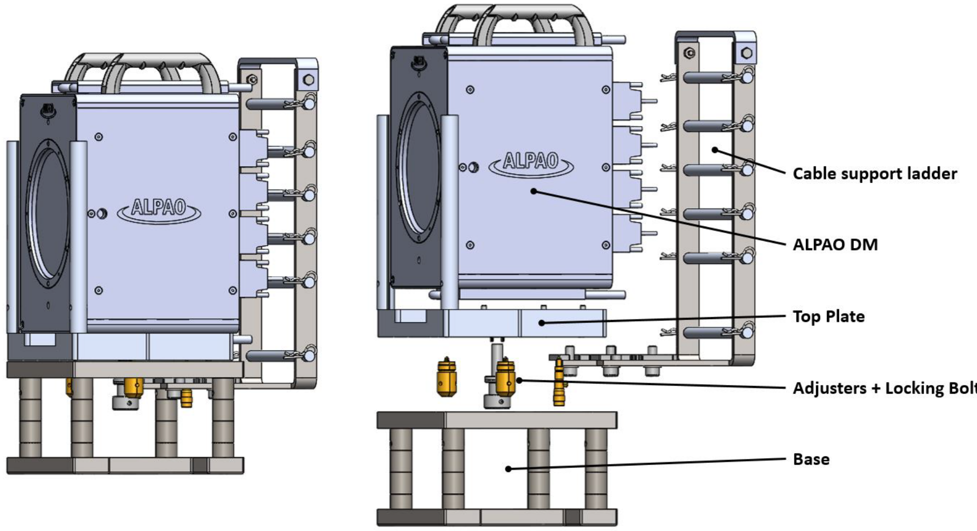


Figure 5: DM mounting scheme

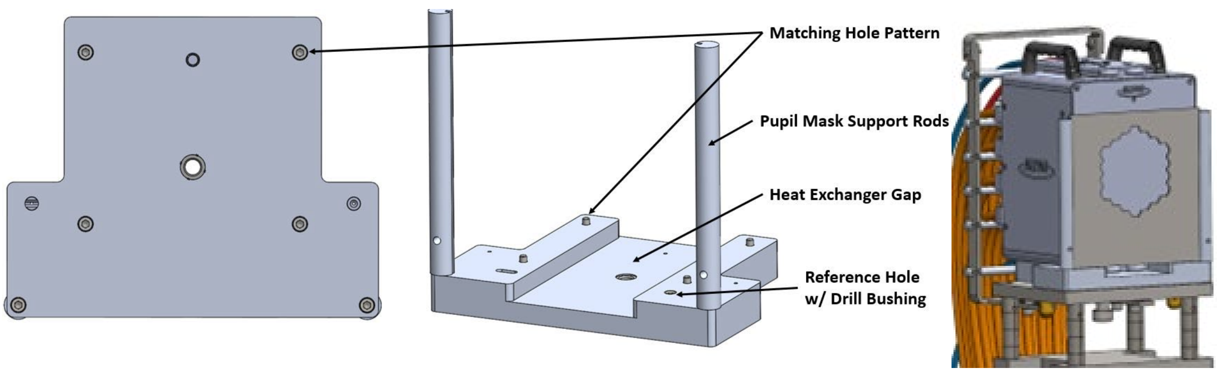


Figure 6: Top plate of DM mount (left and center). A mounted pupil mask is shown at right.

The base of the mount, shown in Figure 5, acts as a heavy AISI 1018 steel riser that sets the initial height of the DM and holds the alignment adjusters, locking bolt, bench clamps, and cable support ladder. The recesses cut into the bottom allow room for side adjusters to mount directly to the AO bench and push on either side. Linked with identical adjusters pushing on the front face of the base, the x, z, and thetay degrees of freedom can be aligned appropriately. Once aligned, the adjusters will be swapped with bench clamps that lock the mount in those three degrees of freedom.

The three alignment adjusters, shown in Figure 7, thread into the base and support the top plate at an initial gap of 1.5 mm above the base. A kinematic cone-vee-flat arrangement of tool steel press-fit inserts provide defined, hard locations that each adjuster can push on. Together they align the mirror in the y, thetax, and thetaz degrees of freedom. The type of adjuster and its position under the mirror were chosen through an optimization of load capacity and resolution.

The two front adjustment screws are the primary drivers of the thetaz adjustment, which requires < 0.4˚ resolution (DM3 in Table 1). The 1.4 µm sensitivity of the adjusters is more than capable of achieving this type of resolution. The location of the mirror along the y axis can be set by raising or lowering all three adjusters simultaneously, easily making changes within the 0.5 mm requirement of DM1 in Table 1.-The rear pusher is placed as far back as reasonable directly along the mirror's z axis. This location places it as the primary driver of the thetax adjustment, which requires the finest resolution of < 46 arcsec (requirement DM4 in Table 1). With the fine sensitivity of the micrometer head, this adjuster can rotate the mirror in 0.92 arcsecond steps around the x axis.

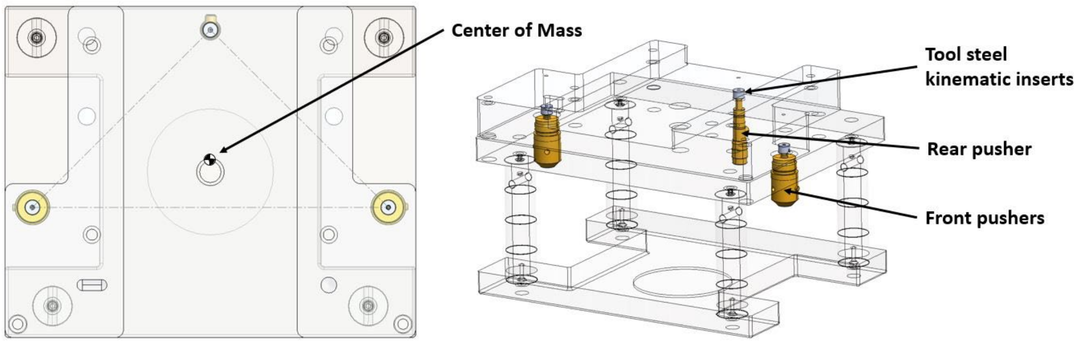


Figure 7: Leveling adjusters of DM mount relative to center of mass

The final component of the mount is the cable support ladder. Fifty-two cables plus four glycol lines add a non-trivial mass to the back of the mirror that would overload the rear HR-6 adjuster if not accounted for. The support system, shown in Figure 8, contains six rods spanning the rear face of the mirror that each support one row of cables. The rods slide into vertical bars on either side and are secured with a hitch pin inserted into each end. The rods are still free to spin and wiggle side to side once secured. The vertical bars on either side attach directly to the underside of the base, which transfers the cable weight from the sensitive alignment adjusters to the steel base. Each bar is machined with slots where they attach to the base to allow for movement along the z axis. Each bar is also designed to receive a ¼" shim which can be added to or removed to allow for movement along the y axis. The whole system can be adjusted in y and z to line up the support rods in the optimal position that recovers the cable weight without pushing up on the mirror.

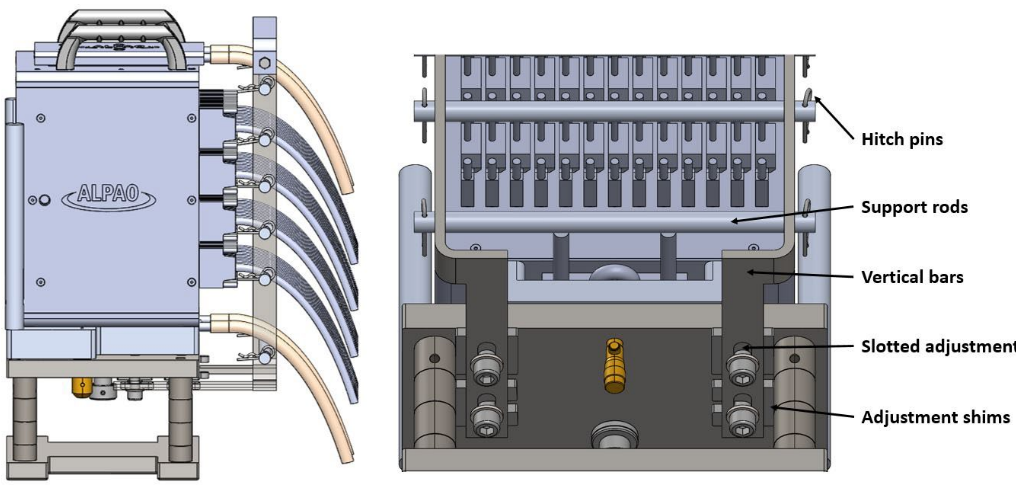
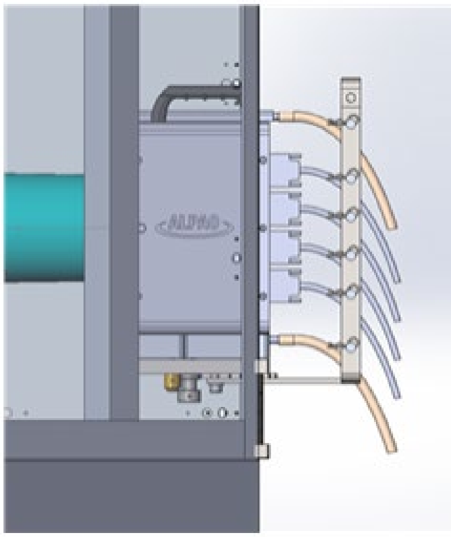


Figure 8: Cable support ladder of DM mount

The ALPAO DM extends farther along the x axis than the Xinetics DM, creating interference with the AO bench corner support post shown with the red arrow in Figure 9. There is 100.5 mm of space between the focal point and the edge of the left support post, and the DM measures 110 mm to either side of the focal point, creating 9.5 mm of interference. The current proposed solution is to move this post to a location where it doesn't interfere with the DM, which can be done in conjunction with the redesign of the front bench panel being done for the SCALES project.



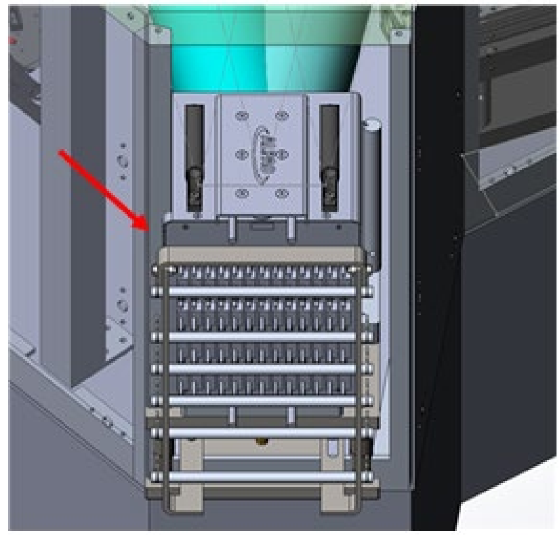


Figure 9: DM overhang in z axis (left) and interference in x axis (right)

2.2 SH WFS

The HAKA PRO optical design was optimized to fit within the 110mm space on the WFS and to produce a pupil magnification of 12.5X while minimizing the RMS WFE. The optical layout for the PRO is shown in Figure 10.

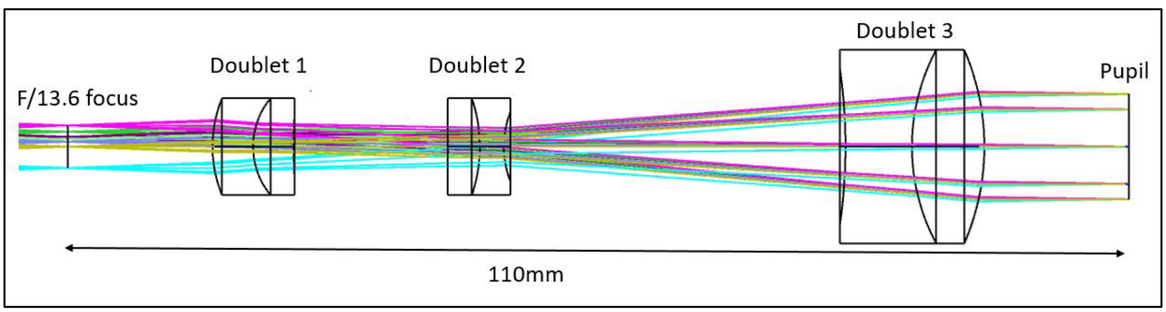


Figure 10: HAKA PRO optical layout

The nominal performance of the HAKA PRO compared to the current PRO is shown in Table 4. The HAKA PRO nominal design meets all requirements and outperforms the current PRO. The increase in wavefront error (WFE) for LGS is due to the AO optics (off-axis parabolas to be specific) and not a product of the PRO.

Table 4: PRO performance

Criterion	Current K2 PRO	HAKA PRO
Primary mirror diameter (m)	10.95	
F/#	13.6	
Pupil diameter at DM (mm)	136.26	
NGS Pupil diameter at lenslet (mm)	3.86	10.90
Pupil magnification	35.27	12.5
NGS RMS WFE (589nm, on axis) (nm)	41	22
LGS RMS WFE (589nm, on axis) (nm)	93	85
LGS Pupil diameter at lenslet (mm)	3.82 (98.8% of NGS)	10.77 (98.8% of NGS)

The mechanical layout of the HAKA PRO is shown in Figure 11. An adapter plate (base) allows the assembly to mount to the wavefront sensor stage with the riser setting the nominal height of the optical axis. The lens barrel attaches to a mount which is then bolted to a second adapter which then bolts to a 5-axis Thorlabs stage (PY005). The stage allows for fine alignment of the lens barrel to the WFS optical axis.

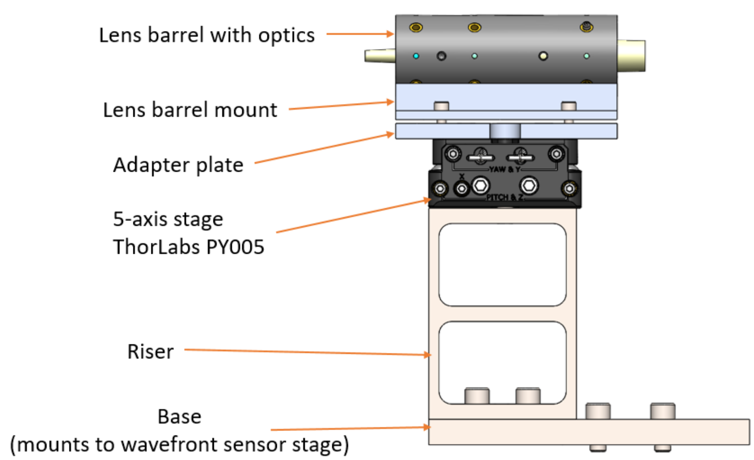


Figure 11: HAKA PRO mechanical layout

The lenses are installed and aligned in the lens barrel using spacers and lateral adjusters. Figure 12 through Figure 14 shows the layout of the lens barrel assembly. The spacers will be machined to the proper thickness after the lens metrology (RoC, CT, nd, vd) reported by the optic vendor. The as-built lenses will be input to Zemax and the proper lens spacing will be determined based on the Zemax analysis.

Alignment of the lenses within the lens barrel will be done with a rotary air bearing and point-source microscope. The lateral pushers will be used to center each lens and the retainers will hold the lenses in place during alignment. Lens manufacturing tolerances will ensure the tilt of each lens is within tolerance.

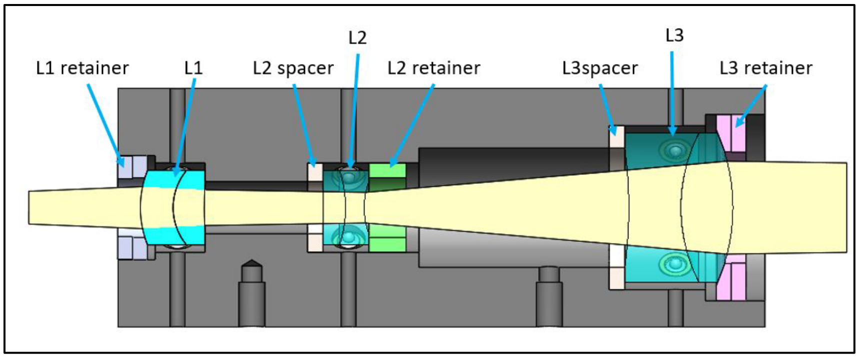


Figure 12: HAKA PRO lens barrel cross-section

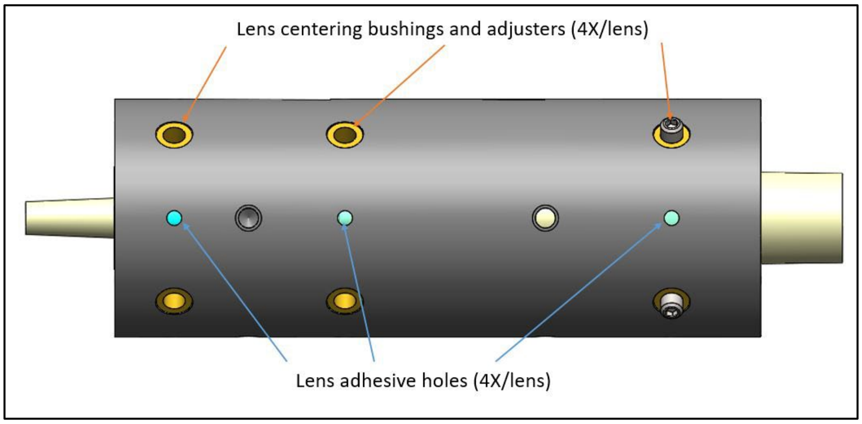


Figure 13: HAKA PRO lens barrel outside view

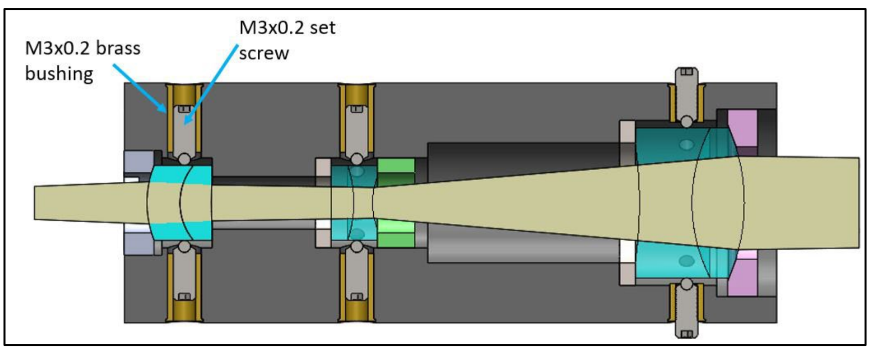


Figure 14: HAKA PRO lens barrel section showing lateral adjusters

Initial alignment of the lens barrel will utilize the lens retainers to hold the lenses in place while the pupil diameter and location is measured. After verification of the pupil diameter and location, adhesive will be used to secure each lens in place. After the adhesive is cured the pushers will be removed and the pusher holes will be sealed.

A lab is being set up at Keck headquarters (HQ) to support the integration and test of the HAKA DM and PRO with a spare real-time controller and SH WFS prior to summit install. Assembly and closed loop testing of the full system will occur in the lab starting in December 2025.

3. 'IWA OPTO-MECHANICAL DESIGN

'IWA has been designed to fit within a limited space on the Keck II AO bench while meeting the requirements listed in Table 3. The 'IWA optical layout is shown in Figure 15 and includes a combination of refractive and reflective optics to meet the requirements and space constraints. The optical design assumes the incoming beam from the HISPEC/SCALES fold mirror is corrected by the AO system's DM for the astigmatism in the science path caused by the AO infrared transmissive dichroic plus the 'IWA pickoff dichroic. Figure 15 shows the layout of the 'IWA optical design and Figure 16 shows a 3-D layout of the optical design for the PyWFS mode.

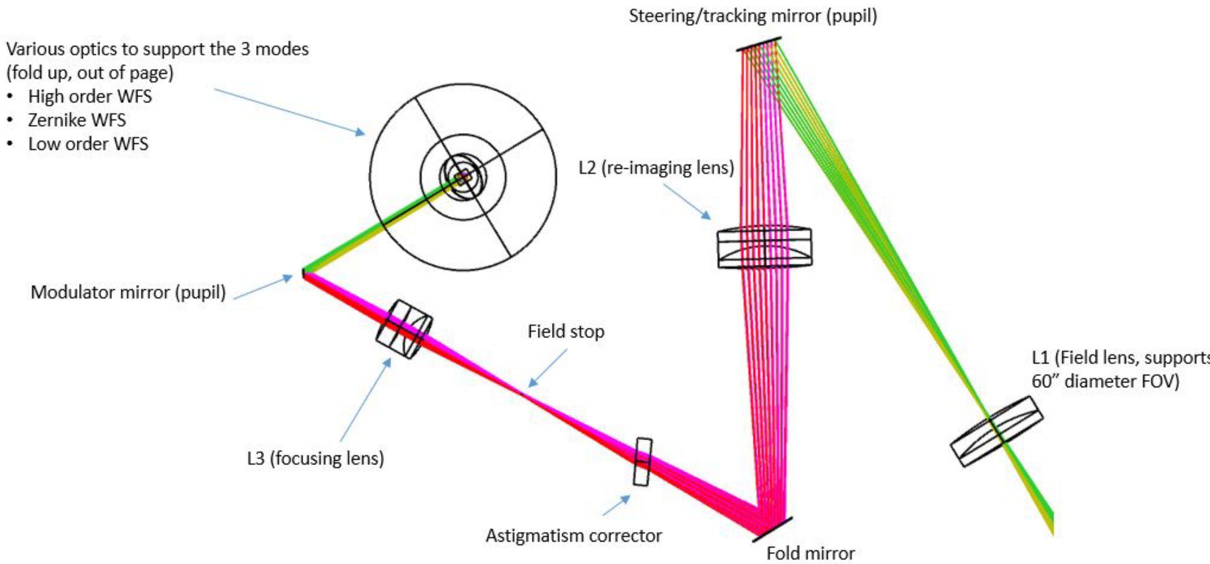


Figure 15: 'IWA optical layout

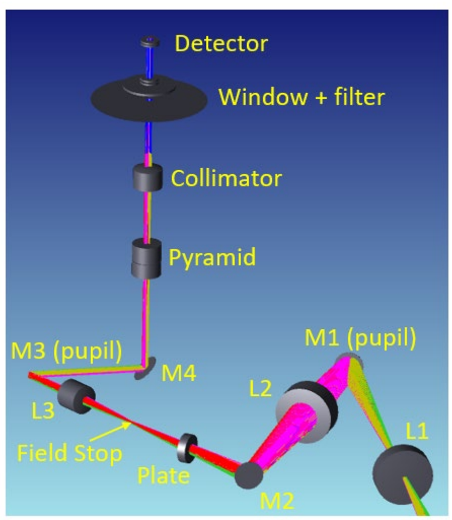


Figure 16: 3-D layout of 'IWA optical design. A custom field lens (L1 in Figure 15) is located near the AO focus and creates an 18mm diameter pupil where a steering/tracking mirror (M1) is located. The field lens is sized to accept a 60″ diameter field. All optics after the field lens are sized to accept a 7″ diameter FOV.

Next, a re-imaging lens (L2 in Figure 15) relays the AO focal plane to an intermediate image plane where a field stop can be located. This custom re-imaging lens is 50mm in diameter and creates a f/12 output. The re-imaging lens is also used as focus compensation between the J and H-bands as well as to keep the pyramid tip conjugate to the science focal plane. An astigmatism corrector plate is located before the f/12 focal plane. The corrector is designed to counter the astigmatism put on the DM when correcting the HISPEC/SCALES focus for the 'IWA pickoff dichroic.

The next optic is the pyramid focus lens (L3 in Figure 15). This lens forms a 7mm diameter pupil, at which a modulator mirror is located, and creates an F/47 focus at the pyramid tip location, with a plate scale of 0.395″/mm. A 25mm diameter fold mirror is placed between the modulator mirror and the pyramid for packaging purposes. Figure 17 shows the RMS WFE at the pyramid tip for J-and H-band. The re-imaging lens (L2) is moved approximately 2mm between the two bands. The RMS WFE is 14nm (worst case) for J-band and 18nm (worst case) for H-band, which meets the 50nm requirement.

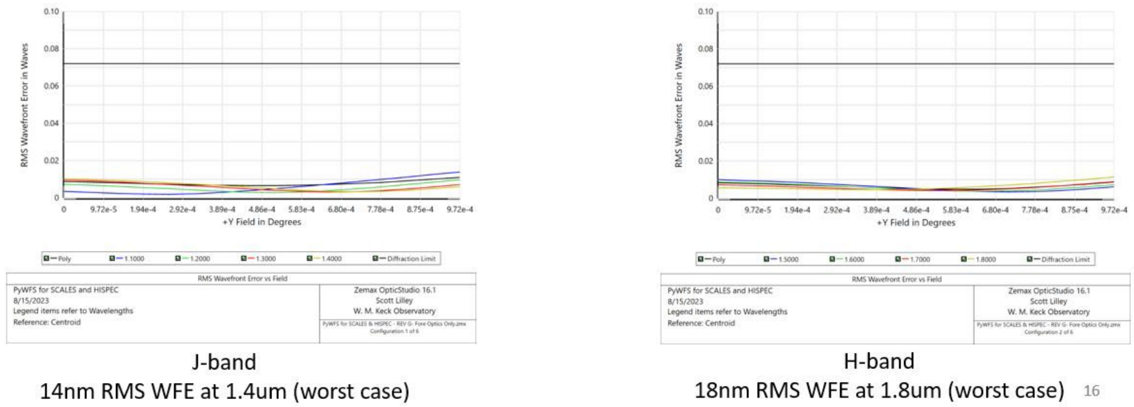


Figure 17: RMS WFE at pyramid tip location showing J-band (left) and H-band (right)

After the final fold (M4 in Figure 16) are a set of changeable optics to support the various modes. Figure 16 shows the optics for the high-order (HO) PyWFS mode plus the camera window, filter and detector. The pyramid prisms remain the same for the HO and low-order (LO) PyWFS modes and are then switched out for a Zernike mask for the ZWFS mode. Each of the three modes have different collimating lenses.

A First Light C-RED One camera has been baselined as the detector for ‘IWA.[8] Figure 18 details the structural layout for ‘IWA including the C-RED One camera. A riser with kinematic points is clamped to the Keck II AO bench to get the ‘IWA optics to the proper height. The majority of the optical components are mounted to the baseplate which has the mating kinematic points. In this configuration the riser can be fixed to the Keck II AO bench while the ‘IWA assembly is lifted out for servicing. The camera support serves to support the C-RED One camera and as an attachment point for the optical switching assembly. A vertical orientation for the camera and PyWFS optics was chosen due to the very tight space allotted for ‘IWA. The camera itself rises above the AO bench roof and modifications to roof and roof supports are necessary.

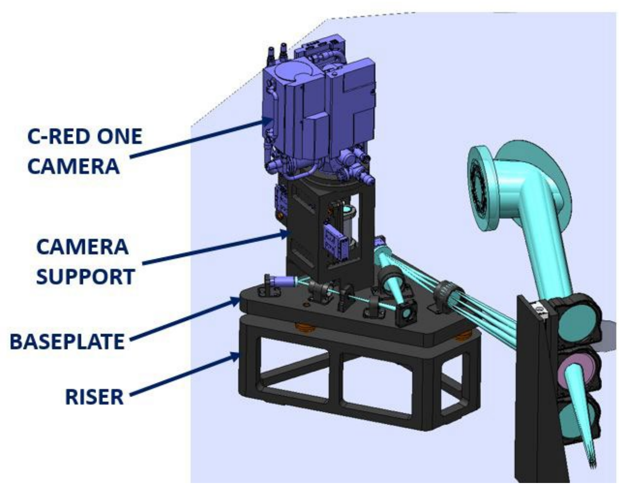


Figure 18: 'IWA structural layout

Figure 19 shows a detailed opto-mechanical layout of ‘IWA. A linear stage supports the opto-mechanics for the various modes. M1 (Figure 19) is a voice-coil actuated mirror capable of steering the 30arcsec radius FOV on-axis. M3 (Figure 19) is a piezo-actuated mirror capable of modulating the beam on the pyramid tip. Three modes are baselined for ‘IWA, but the optics mode stage has room for two additional future modes.

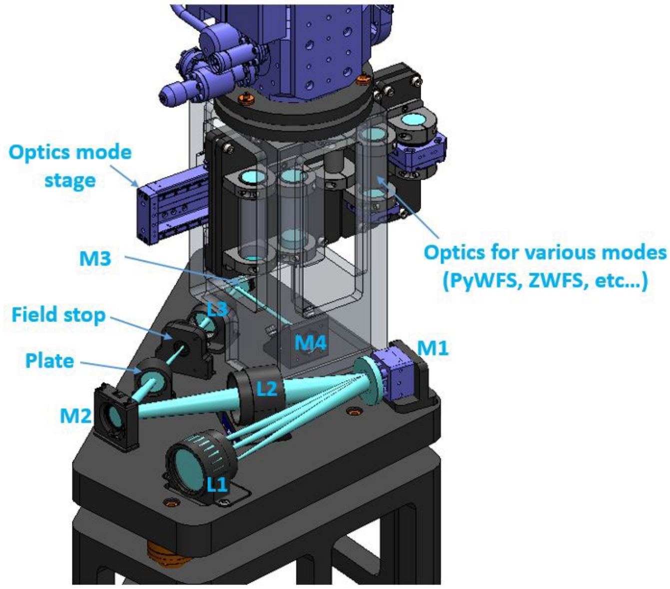


Figure 19: 'IWA detailed opto-mechanical layout

4. SUMMARY

A new DM is being procured as part of the HAKA project and is scheduled to be delivered in November 2024. The DM mechanical mounting as well as the PRO opto-mechanical design has been completed and components are being procured. The upgrades to the Keck II AO bench (DM, PRO, new lenslets) are scheduled to be begin in August 2025. Assembly and closed loop testing of the full system will occur in the lab starting in December 2025.

A new infrared wavefront sensor (‘IWA) has completed the conceptual design phase and an MRI proposal was submitted in November 2023. ‘IWA includes several PyWFS modes as well as a Zernike WFS mode. The design includes provisions for future upgrades, including additional modes and capabilities. ‘IWA is currently waiting on additional funding to move forward.

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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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