# The Planetary Systems Instrument: Overview of the Instrument Architecture and Opto-Mechanical Design of the Red Arm, aka SCALES

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## ABSTRACT

The Planetary Systems Instrument (PSI) for the Thirty Meter Telescope (TMT) is comprised of 3 key modules: 1) an Adaptive Optics (AO) bench consisting of a large stroke, high actuator count ‘woofer’ Deformable Mirror (DM) and Wavefront Sensor (WFS) that is common to both the Red and Blue arms; 2) PSI-Red, covering 2-5 microns with a sophisticated suite of modular components based around a lenslet IFS coronagraph; and 3) PSI-Blue, covering 0.6 to 1.8 microns with its own suite of modular components including a ‘tweeter’ DM with its own WFS. An additional module is PSI-10, an 8-13 micron suite of modular components based around a lenslet IFS and is under consideration. The precursor to PSI-Red is currently being developed by UC Santa Cruz as SCALES (Santa Cruz Array of Lenslets for Exoplanet Spectroscopy) and will operate in the mid-IR from 2 to 5 microns at the WM Keck Observatory before being integrated with the remainder of PSI at TMT. Its fully cryogenic optical train uses a custom silicon lenslet array, selectable coronographs, and dispersive prisms to carry out integral field spectroscopy over a 3.6 arcsec field of view with low spectral resolution (50 to 200). A set of insertable mirrors relay light to and from a slicer module sitting behind the lenslet array allows for medium spectral resolution (5000 to 10,000), which has not been available at the diffraction limit with a coronagraphic instrument in the mid-IR before. The opto-mechanical design takes advantage of modern diamond-turning materials and machining techniques with minimal risk and cost while delivering diffraction-limited performance both at Keck and TMT. Unlike previous IFS-based exoplanet instruments, SCALES is capable of characterizing cold exoplanet and brown dwarf atmospheres (<600 K) at bandpasses where these bodies emit most of their radiation while capturing interesting molecular spectral features. We will discuss some of the technical challenges of designing a TMT-ready instrument that will first be deployed at Keck.

**Keywords:** Near-infrared, exoplanets, Thirty Meter Telescope, Keck Observatory, integral field spectroscopy

## INTRODUCTION

Directly imaging exoplanets is a technical challenge requiring a large aperture telescope to reach the angular resolution needed to separate exoplanets from their host stars as well as to collect photons from intrinsically dim exoplanets. Differentiating exoplanetary light from host starlight is challenging even at longer wavelengths where exoplanets emit most of their blackbody radiation, requiring extreme adaptive optics behind large-aperture telescopes, advanced coronagraphy, and sophisticated data reduction techniques to extract exoplanetary signal. In this paper we describe the PSI-Red (which is very similar to SCALES) instrument design beginning with an overview of the AO system and a detailed discussion of the modularized design approach of SCALES. Several novel design choices allow for SCALES to have a maximally flexible scientific grasp while minimizing technical

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risks. In particular, we have included what we dub a ‘slenslit’, which is a set of image slicer optics operating behind the lenslet array that reformats a subarray of lenslets from a rectangular grid into a staggered pseudo-slit; this reformatted pseudo-slit allows us to reach a spectral resolution of 5000 to 10 000 while preserving the fine spatial sampling of the lenslet array.

## 1. THE PLANETARY SYSTEMS INSTRUMENT FOR THE THIRTY METER TELESCOPE

PSI is designed to directly image exoplanets both in reflected visible light (PSI-Blue) and in infrared thermal emission (PSI-Red); a 10-micron channel (PSI-10) is under consideration and would allow for debris disc and exozodiacal light imaging. A block diagram of the PSI architecture is shown in Figure 1. While new techniques must be invented to reach the contrast goal in visible light of $10^{-10}$ (e.g., the contrast of Earth-like planets around Sun-like stars) at small angular separations approaching the diffraction limit of lambda/D, techniques for imaging exoplanets via their thermal emission have been around since 2004 [1] (2MASS1207b) and have been demonstrated on a variety of exoplanetary systems from nearly every large-aperture telescope on and off the world. It requires corongagraphs to block out the starlight and Lyot stops to prevent diffracted starlight from leaking around the coronagraphic dot impinging on the detector.

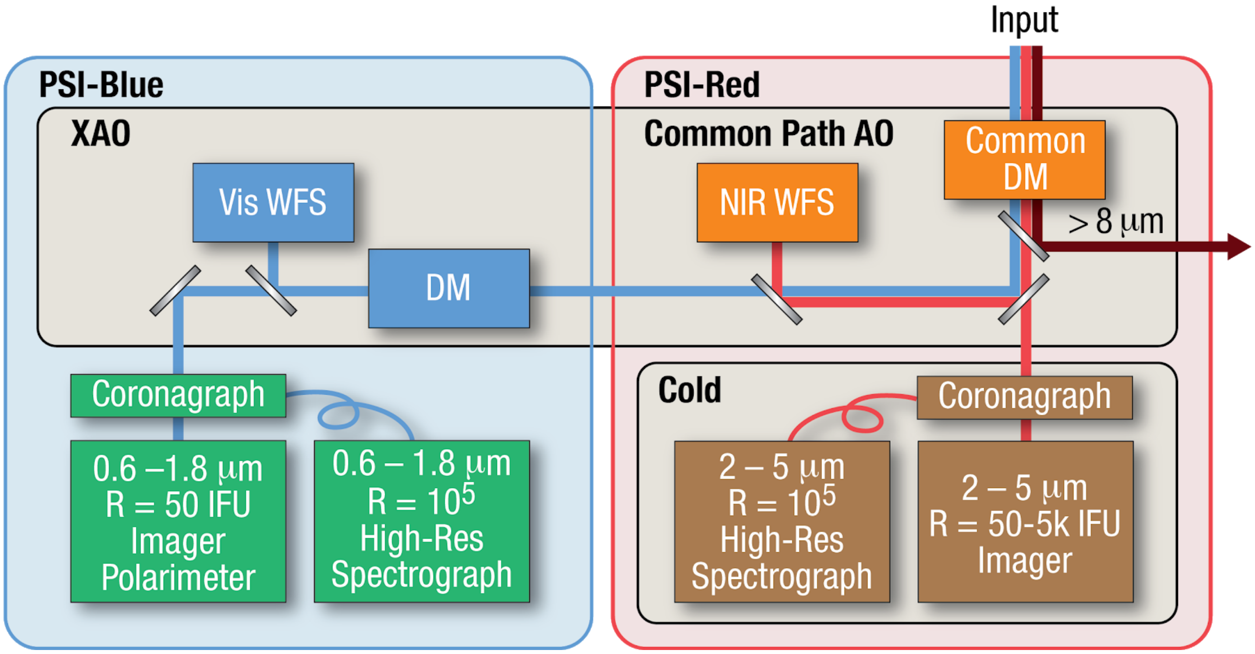


Figure 1: PSI Block Diagram. The AO system is split into a Common DM and DM-Blue; the Common DM, fed by an NIR WFS, corrects the wavefront for both PSI-10 and PSI-Red. Further correction needed for the extremely high contrast PSI-Blue science is performed by the DM-Blue tweeter, fed by the visible WFS. Note that for simplicity PSI-10 is not shown. The curly lines in both PSI-Blue and -Red represent Single Mode fibers feeding high resolution spectrographs.

The AO system for PSI is built on the success of SCExAO, the Subaru Coronagraphic Extreme AO system. PSI-AO is a woofer-tweeter design, with the woofer acting as a common DM for all the PSI channels. This DM must have high stroke and a minimum clear aperture of 100 actuators with no actuators in the clear aperture ‘dead’ or ‘stuck’; a 128x128 actuator DM from ALPAO is our baseline device. Currently a half-scale (64x64 actuator) proof of concept device has been delivered to ESO for testing and characterization, with the scaling-up representing a minor schedule and cost risk (ALPAO, private communication). The DM’s RTC is fed by an NIR WFS, which we expect to be a refractive pyramid wavefront sensor operating in H-band. We have our choice of detectors, from CRED2 to a SAPHIRA [2] to an MKIDs [3] device, although both the SAPHIRA and the MKIDs detectors need more development to increase the detector area and number of congruent active pixels. Regardless, the common AO system could be bought with extant technology. A high actuator count MEMS device from BMC is our baseline DM-Blue; the stroke required is on the order of 5 nm with speed being the greatest concern. The WFS camera may be an MKIDs device, but our baseline is an EMCCD. The exact

WFS bandpass has not been decided upon, which allows us maximum flexibility in our design. We are developing a simulation toolchain to run trade studies on sensing vs science bandpasses will deliver the most impactful science.

Without considering the reimaging optics, the light path up to the instrument windows is as follows. The common DM corrects the wavefront for PSI-Red and PSI-10. As shown in Figure 1, PSI-10 light is picked off with a reflective dichroic that sends light redward of 8 microns to PSI-10. Light from 2-5 microns is sent past the 10 micron dichroic and the red/blue dichroic; light redward of 2 microns is sent toward PSI-Blue and the NIR WFS. Another dichroic picks off the light for the NIR WFS, while sending light blueward of 1.8 microns toward the PSI-Blue and the DM-Blue system (with its own dichroic).

The size of the clear aperture of the Common DM is set by the actuator count and density. ALPAO is comfortable with the spacing of ~15 mm, which gives a pupil size of about 190 mm. Given the bandpass we hope to cover (0.6 - 13 microns), we will almost certainly use reflective reimaging optics (sans dichroics) in the Common DM section to minimize the chromatic effects of our optics. Diamond-turning machines are capable of turning mirrors with clear apertures of up to ~0.5 m and with very low RMS surface roughness (>0.5 nm RMS), so reflective reimaging optics represent little technical risk. The size of DM-Blue will be smaller, so some de-magnification will have to happen after the Common DM. However, those details are outside the scope of this paper.

We chose our lenslet images to be well-separated on the detector (once dispersed), and chose a 180x180 format for a field of view of 1.2 arcseconds. The lenslets are made of silicon, are square and thus subtend 6.7 milliarcseconds on a side. The physical spacing of the lenslets is 340 microns center-to-center, with a beam speed of f/8. Modern photolithography makes our lenslet array perhaps the most easily manufacturable (although certainly not the cheapest) out of all the optics in PSI-Red.

## 2. PSI-RED OPTO-MECHANICAL OVERVIEW

PSI-Red was designed from the outset to be optimized for IFU spectroscopy from 2-5 microns with a field of view of 1.2 arseconds. From the start we intended to build an all-reflective optical train, with the obvious exceptions of the entrance window (calcium fluoride), a 180x180 lenslet array (silicon), and dispersing prisms (sapphire and ZnSe). An all-reflective system means that we can build our optics, their mounts, and optical bench out of the same material, namely aluminum-6061. Al-6016 is both cheap and eminently machineable. After diamond-turning, Al-6061 mirrors are easily coated with gold, which is highly reflective over the 2-5 micron bandpass. This sets the stage for our design work. Additionally, we are focused on working at small angular separations of a few lambda/D (approximately 30 milliarcseconds) out to about 1 arcsecond. Larger separations do not require the high contrast needed at small separations and have different technical drivers, so our field of view is 1.2 arseconds. We found it useful to begin thinking about the design by identifying the number and type of planes (focal, pupil/Lyot) needed in a lenslet-based IFS.

### 2.1 Focal planes

In order to perform coronagraphic spectroscopy, we need a coronagraphic plane, a lenslet plane, and a detector plane. Each of these planes should follow a 'cold stop' pupil plane in order to minimize background light. Additionally, in order to function properly, our detector (a Teledyne HAWAII4-RG device) must be cooled cryogenically. This means that the instrument must be in a cryogenic vacuum vessel, as warm optics emit light at these wavelengths. In total we need 3 focal planes, although additional ones may be added at the cost of throughput due to more optics. In practice, we will have the focal plane of the AO system internal to the cryostat, giving us 4 focal planes in total.

### 2.2 Pupil planes

As noted above, we need a cold stop before the coronagraphic focal plane. Following the cold stop and coronagraph, we need a Lyot stop. This pupil plane apodizes the pupil, meaning that we can limit how much starlight that diffracts around the coronagraphic dot in the focal plane makes it to the detector plane. We also need a disperser plane in order to disperse the lenset images into spectra on the detector. In sum, we need 3 pupil planes, although as before more may be added at the cost of throughput due to additional optics.

## 2.3 Baseline instrument

Thus we arrive at the baseline instrument. There is a natural split of the optical train at the lenslet array; the fore-optics, which magnify the beam from the telescope from f/15 to f/350, and the spectrograph, which reimages the spots produced by the lenslets onto the detector, and operates at f/8 (the f/# of the lenslets). PSI-Red uses Off-Axis Parabolas (OAPs) and Off-Axis Ellipses (OAEs) as its reimaging optics in the fore-optics, and off-axis aspheres in the spectrograph. A selectable linear slide will carry several coronagraphic masks, and will be able to be moved out of the field of view entirely. The Lyot stop is populated with a selectable wheel allowing for a range of bandpass-optimized Lyot stops of various flavors: Apodizing Aperture Pupils, Non-Redundant Masks, and Vortex Apodizing Pupil Plane masks, with room for others. The dispersers ride on a selectable carousel and are sapphire and ZnSe matched prisms, with sapphire acting as the disperser and ZnSe acting as the beam deviation corrector.

## 2.3 Additional modes

Our design philosophy is science-driven, with a ‘do no harm’ approach to additional modes, meaning nothing we add may affect the low-resolution lenslet IFS mode. Figure 2 shows the PSI-Red layout with the added modes, which we will discuss in detail one at a time.

### *7x7 arcsecond imager*

We have deliberately oversized our fore-optics before the Lyot plane to accept a 7x7 arcsecond field of view in order to be able to feed a broadband imager. The optics up to the Lyot plane are used both for the IFS and for the imager, with a reflective Lyot plane feeding rejected light to the imager, or alternatively, a mirror may be placed at the Lyot plane feeding the whole field of view to the imager. This requires the use of a double-stack of filter wheels after the cold stop, but there is ample room for it. Our filter slots are sized for standard 1” round filters and we can accommodate up to 18 filters at once. The imager has been designed to be diffraction-limited at 1 micron using a Teledyne HAWAII2-RG across the entire field of view with minimal distortion, making it an attractive option for monitoring stars at the Galactic Center, among other science cases.

### *Focal plane wavefront sensing & cryogenic DM*

Focal plane wavefront sensing may allow for advanced techniques such as quasi-static speckle nulling, non-common path aberration (NCPA) correction, and electric field conjugation (EFC, eg, digging a dark hole). In PSI-Red, we use the lenslet array to sample the focal plane, so our non-common path relative to the NIR WFS runs from the dichroic that feeds PSI-Red all the way to the lenslet array - a sizable distance. The focal plane WFS may feed back into the RTC loop running the Common DM in order to minimize NCPA to the lenslet array, as there is only one optic, a dichroic, between the wavefront sensor and the lenslet array.

Additionally, replacing one of the fold mirrors with a DM internal to PSI-Red’s vacuum jacket (DM-cryo) is being considered. This DM will only make slow corrections at the rate of ~1 Hz due to the lack of dampening on the MEMS surface from the lack of atmosphere. This control loop, particularly the DM operating at speed in a cryogenic environment, is currently in the conceptual stage. Several benefits of having an additional DM, such as performing NCPA corrections or offloading quasi-static speckle nulling from the Common DM to the DM-cryo, are appealing While we have no easily recoverable phase information, we should be able to correct much of the NCPA present in the PSI-Red optical train, with quasi-static speckle nulling being a tantalizing goal in extreme AO.

### *High-dispersion high contrast coronagraphy*

This mode requires feeding a single-mode (SM), phase-preserving fiber with exoplanetary light (KPIC [6]). We plan on including a linear slide with a selectable beam-splitter or dichroic in-between the Lyot stop and the lenslet array that sends light to a high-resolution spectrograph about the size of a breadbox; several spectrographs or SM fiber feeds may be necessary to cover the 2-5 micron bandpass. This mode requires a fast tip-tilt mirror stage in order to ‘steer’ the exoplanet light onto the fiber and to do fast tip-tilt corrections to maximize throughput. A fast guide camera using rejected starlight may be necessary in order to close this control loop. This mode is very promising because it can potentially deliver $10^{-10}$ contrast between the host star and its exoplanet by allowing for much finer discrimination between stellar and exoplanetary light, although this has yet to be demonstrated on-sky. Additionally this method is only effective for point sources, as extended sources will not match the dominant mode of the SM fiber and will be largely filtered out by the SM fiber.

*The SLENSLIT (Sliced LENslet pseudo-SLIT)*

The slenslit concept arose out of the frustration felt at the lack of spectral resolution offered by traditional lenslet IFUs. The limitation of lenslet IFUs like OSIRIS or ALES is that the spectra they produce are very short (10s to 100s of pixels), with the density of lenslets for any given field of view trading off with spectral resolving power. This trade space is not new. However, if one were able to geometrically rearrange the regularly-spaced grid of lenslet spots into something resembling a pseudo-slit before dispersing them, it is conceivable that one could produce much higher spectral resolution. Indeed, without needing to cross-disperse, spectral resolutions of up to 10 000 are achievable limited only by the bandpass and size of the detector.

As it happens, image slicing optics perform fantastically well at geometrically rearranging a focal plane into a pseudo-slit. Figure 2 shows a schematic of a lenslet, slicer, and hybrid lenslet-slicer (slenslit) IFS. PSI-Red will have a slenslit that reimages 24x24 lenslets into pseudo-slit made up of 3x8 sets of 24 field mirrors (one for each slice). The lenslets will be staggered such the spacing between lenslets along the pseudo-slit direction will be decreased by a factor of 3, allowing us to pack in more spectra while preserving a row of unilluminated spectra. Figure 3 shows a simplified version of this stagger. This concept preserves spatial information, unlike an SM fiber feeding a higher-resolution spectrograph.

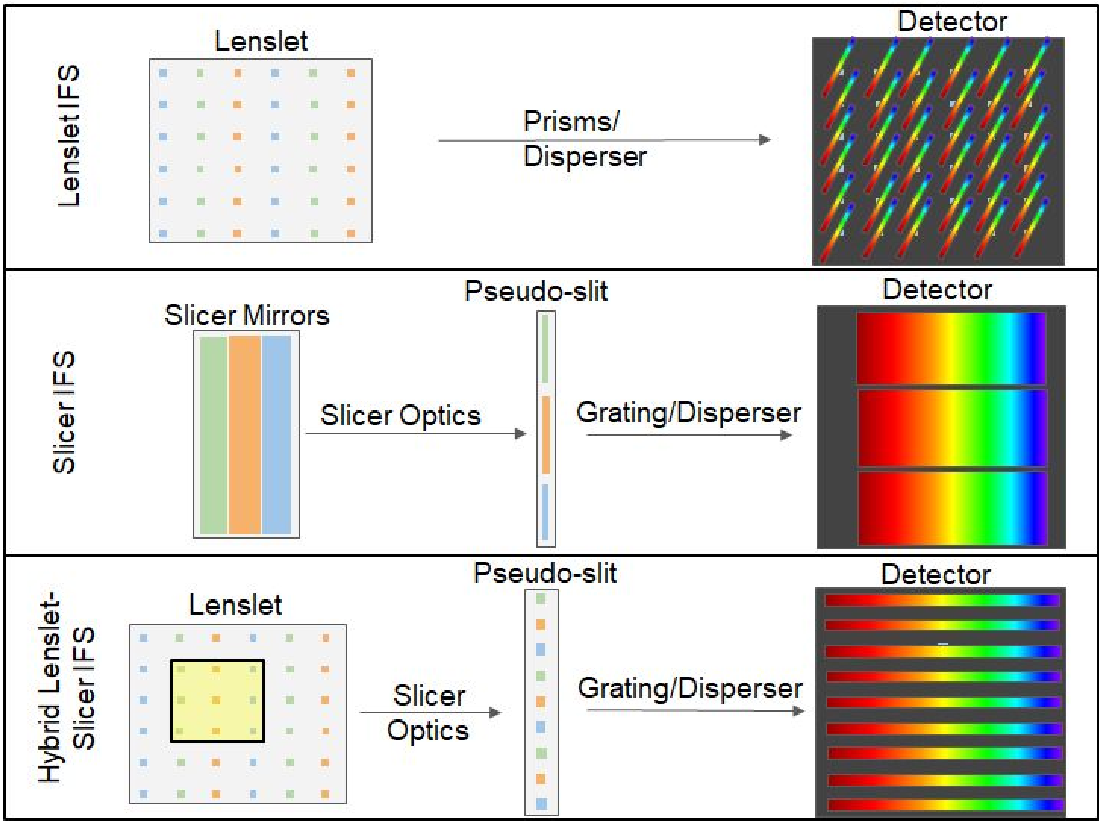
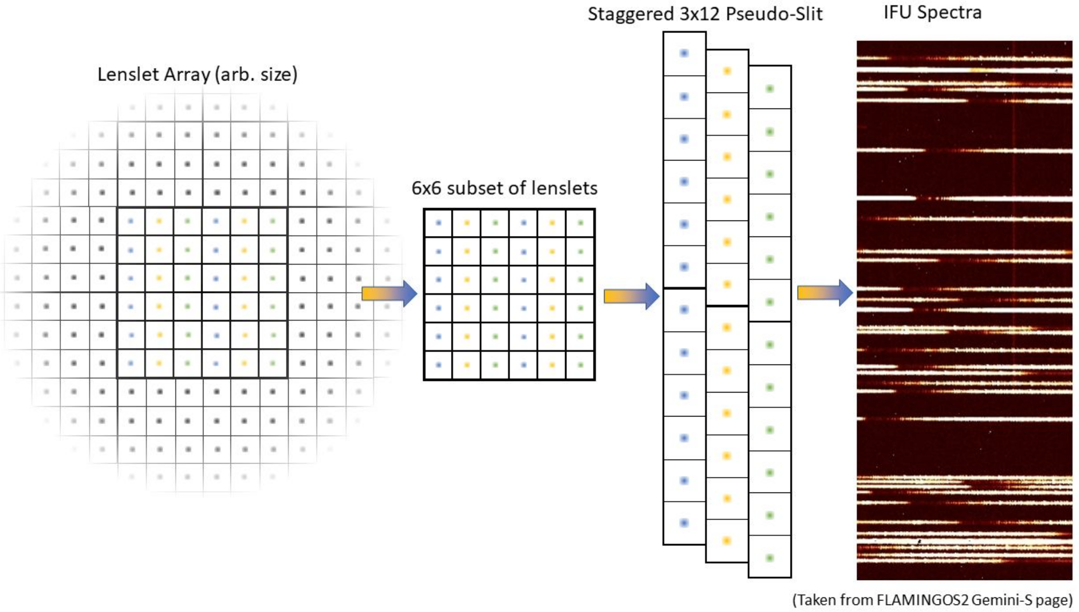


Figure 2: Schematic comparison among a lenslet, slicer, and hybrid lenslet-slicer (slenslit) IFS. Note the lengths of the spectra are akin to the spectral resolution, as the sampling of the spectra is limited by the pixel size and number. A slenslit represents a happy medium of spatial and spectral sampling.

In order to perform this optical juggling, we use an insertable pick-off mirror that sends a 24x24 subarray of lenslet images to a set of magnifying optics. The magnifying optics, a Schwarzchild array, magnify the beam from f/8 to f/64.

The slicer, located at the focal plane of the Schwarzchild array, sends pupil images to the pupil mirror array, each slice having its own pupil mirror located at its exit pupil. The pupil mirrors reimage their respective slices onto a field mirror array while speeding up the beam to f/32. The field mirrors can be powered to correct for telecentric errors as needed. The field mirror array performs the final tweaks to the reformatted focal plane-to-pseudo-slit transformation, and reflects the light into another set of reimaging optics that de-magnify the beam from f/32 to f/8, whereupon a reinsertion optic places the pseudo-slit beam back into the spectrograph optical train, with the spectrograph none the wiser. The disperser carousel will carry several gratings operating in the 1st order to deliver the desired spectral resolution over the bandpass selected by the filter wheels after the cold stop. These filter wheels function as both the imager and the slenslit bandpass selectors. The slicer optics are monolithic advanced image slicers [4]. The opto-mechanical design is based on the FRIDA image slicer integral field unit [5].



(Taken from FLAMINGOS2 Gemini-S page)

Figure 3: Schematic of the slenslit pseudo-slit stagger. Note that this shows a restricted subset of 6x6 lenslets for simplicity.

We show a view of the fully-populated optical bench without vacuum jacket or thermal shields in Figure 4. The optical bench measures 1x2 meters. The cold volume is approximately 1x2x1 m$^3$. Figure 5 shows an isometric view of the rear of the instrument. A CAD engineer gives a sense of scale of the instrument on its cart. We have chosen to make the instrument serviceable by putting all vacuum interfaces on ‘fixed’ portions of the vacuum jacket. To service the instrument, the vacuum lid (domed portion) must be removed, but the rest of the vacuum jacket does not have to be removed.

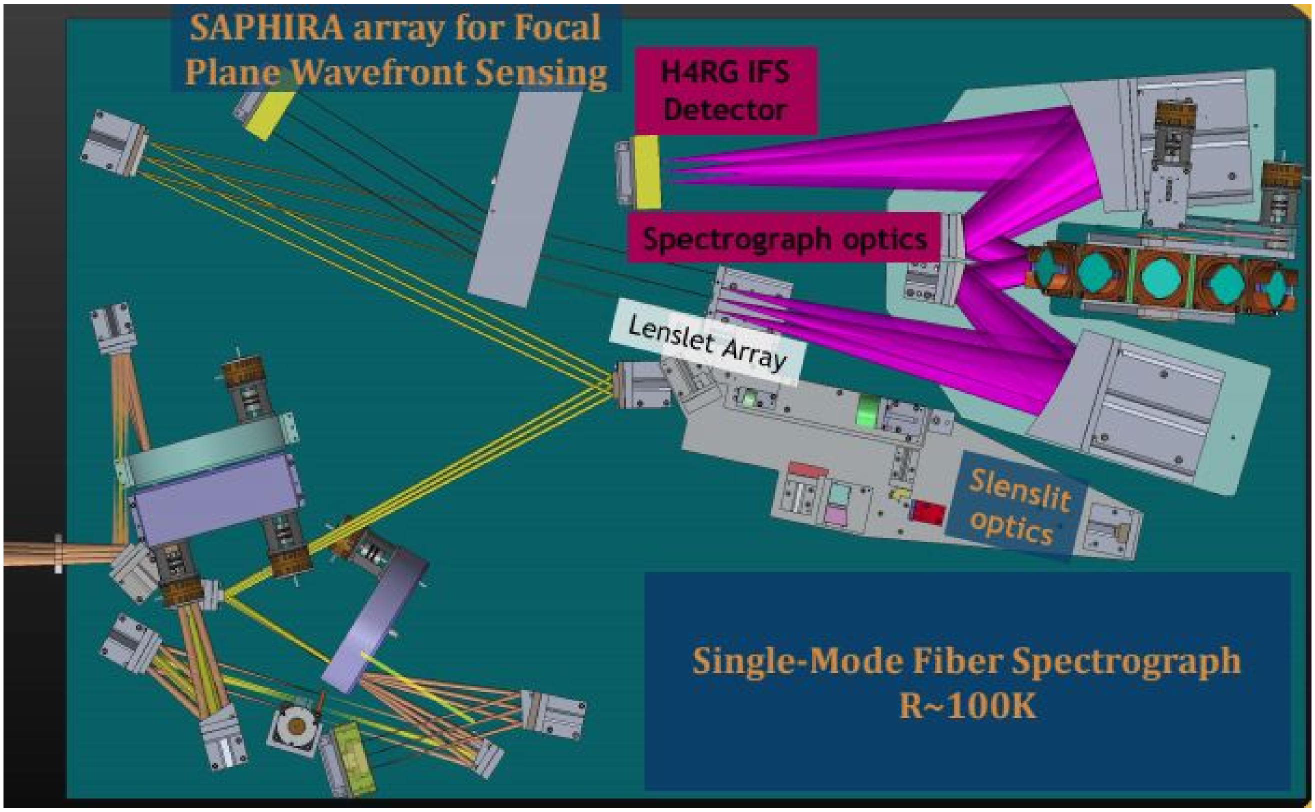


Figure 4: The PSI-Red optical bench. For simplicity the SM fiber feed system is not shown, nor is the DM-Cryo. Light enters from the AO system from the left. The yellow beams show the fore-optics for the lenslet IFS, while the magenta beams show the spectrograph optics. The orange beams trace out the 7x7 arcsecond field of view for the imager, which is shown to the lower left (translucent yellow box).

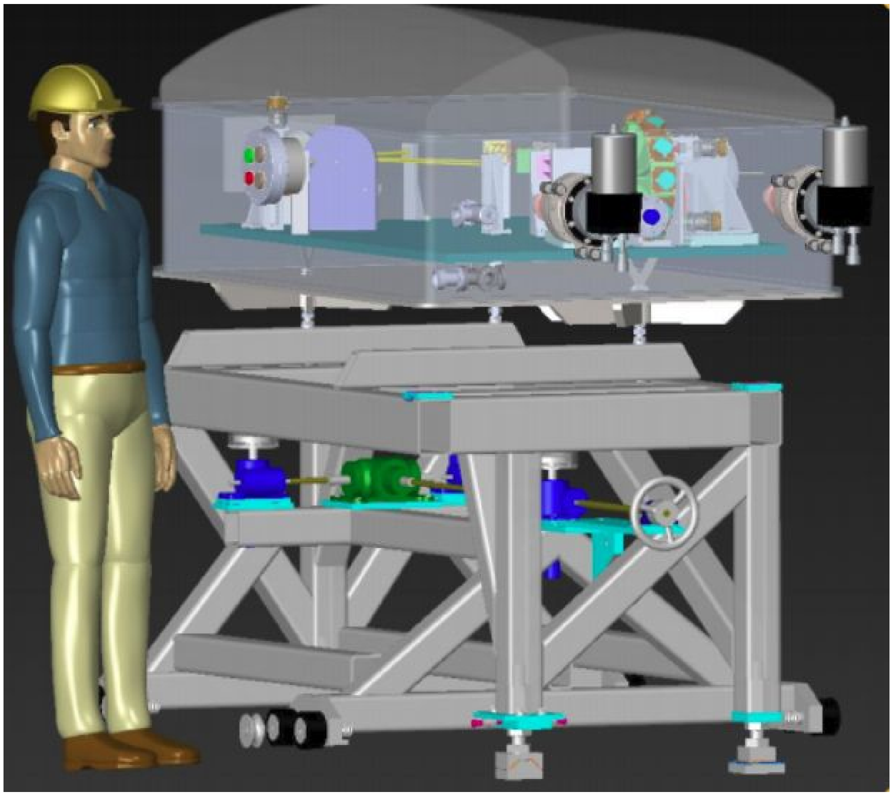


Figure 5: View of the PSI-Red instrument with a CAD engineer for scale. Note the COTS stubs and flanges for the vacuum interfaces, and how all interfaces are kept to the middle of the vacuum jacket; this makes servicing the instrument simple.. The vacuum jacket has been made transparent to allow for a view of the interior mechanisms, and the thermal shields are not shown.

## 3. BOLT-AND-GO ALIGNMENT APPROACH

PSI-Red has been designed with its optics substrates carrying alignment features using a semi-kinematic mounting scheme referred to as 'Bolt-and-Go' developed at the University of Florida (MIRADAS, [7] CIRCE [8], FISICA [9]). The mounting scheme is as follows: the mirror substrate, aluminum-6061, has three square bolt pads measuring 10-20 mm on a side (larger pads are used for larger optics) that define the plane of contact with the mount; a transitional pinhole meant to slip-fit a precision-ground round 2 mm stainless steel dowel pin defines the position of the optic on the plane of contact, and a transitional pin slot meant to slip-fit a precision-ground 2 mm stainless steel dowel pin defines the clocking angle of the optic (the slot's long axis is oriented toward the pinhole, such that the pin is free to move along the pin slot without affecting the optic's clocking due to thermal contraction). Similarly, each optical mount uses a similar mounting scheme, with the alignment features machined to match pins located in the optical bench. The bolts are required to only hold the optics in place, and they provide no location information. A slight worry is the CTE mismatch between the Al-6061 mirror substrate and stainless steel pin, but the shrinkage of a 2 mm pin is much smaller than the machining tolerances in Al-6061. A larger worry is potential galling due to the different materials used, but as long as care is taken when installing or removing the Al-61061 part, galling is not a concern.

This semi-kinematic approach has several advantages over a proper kinematic mounting scheme. First, each one of the alignment features is easy to machine, especially if no movement of the part during the final machining step is required. Second, the bolt-and-go method depends largely on the relative accuracy of the milling machine over the size of the optical substrate's size instead of relying on absolute accuracy, which is very difficult. In other words, once the pin hole and slot have been machined, the height of the bolt pads matters far less as shims may be used to adjust the height, tip, and tilt (although it is preferable that the pads are accurately machined to be coplanar). A potential drawback is that the relative accuracy of the optical alignment features to that of the mount's is less certain; however, careful machining should get those features to within ~50 microns. The bench's pins, used for the locating of each optical mount, are machined via CNC in series and require no re-homing of the toolhead; their relative accuracy will be excellent.

Previous instruments built at the University of Florida have used the Bolt-and-Go method with great success. CIRCE and FISICA are both infrared instruments, and like PSI-Red operate cryogenically in vacuum. The Bolt-and-Go method allowed for much easier alignment than one might have naively expected (FISICA's alignment process was to bolt together the mirror blocks onto a common mount, which took 15 minutes; verifying alignment took much longer). Additionally, given that PSI-Red's optics are largely reflective, we can use optical light such as HeNe lasers and optical detectors operating at room temperature to align our optics with the expectation that the performance of PSI-Red when cold will be similar.

## 4. DIAMOND-TURNED MIRRORS

During diamond-turning, the alignment features (pin hole and slot, bolt pads) define the substrate's position in XYZ-space relative to the diamond-turning tool. Thus, the optical surface is defined with exquisite accuracy relative to these alignment features. Experience with the bolt-and-go approach has shown that the pins and bolt pads do well enough at defining the absolute position that each optic may be removed from its mount and replaced many times, even re-machined, without affecting the alignment in a noticeable way (given care not to gall the aluminum substrate on the steel pins).

This alignment method works well for classical mirrors (OAPs/off-axis aspheres) as well as free-form optics, such as image slicer optics, whose surfaces are not contiguous nor have co-located mirror vertices or centers of curvature. In the case of a slicer mirror, the different optical prescriptions of each slice is definable relative to the shared alignment features. This is also true for the pupil and field mirrors of a slicer. After the final diamond-turning process, we will coat the mirrors in protected gold, which is highly reflective over the 2-5 micron bandpass.

## 5. VACUUM JACKET AND FEEDTHROUGHS, THERMAL ISOLATION SYSTEM, AND COOLING SYSTEM

The vacuum jacket as designed is meant to mate to the existing Dual Star Module cart donated by Keck Observatory. The PSI-Red vacuum jacket resembles a domed rectangular box or coffin, and will hold the interior in vacuum. Thermal isolation is managed by using G-10 fiberglass bipod stand-offs attached to the base plate of the vacuum jacket and bench. Vacuum penetration is made via commercial off the shelf (COTS) stubs welded to the middle section of the vacuum jacket; these stubs come with COTS gaskets and interface plates which can be modified to suit our electrical connectors, which are standard mil-spec hermetic connectors.

Interior to the vacuum jacket are two thermal shields, each wrapped in two layers of super-insulating aluminized Mylar (emergency blankets). The outer thermal shield is passively cooled and rests on nylon or delrin bumpers that mechanically isolate it from the inner thermal shield. The inner thermal shield is attached via copper strapping to the helium cold heads, which provide the cooling power required to keep the instrument at cryogenic temperatures. The two cold heads, CTI CryoDyne Model 1020, provide 80 W of cooling at 77 Kelvin (1st stage) and 24 W of cooling at 20 Kelvin. This gives an estimated cooling margin of ~25% while operating at Maunakea and ~18% while operating on a warm day at UCSC. As demonstrated on NIRSPEC, speed controllers for the cold heads will offer some cooling control to account for the varying thermal load due to temperature fluctuations, and we are considering adding heaters on a PID control loop on the bench to help stabilize the thermal environment of PSI-Red.

## 6. CONCLUDING REMARKS

We have introduced PSI-Red for the TMT, aka SCALES for Keck, and placed it within the context of the PSI instrumentation suite. We focused primarily on the opto-mechanical design in this paper. PSI-Red will operate from 2-5 microns in a cryogenic environment, enabling detailed characterization of exoplanetary atmospheres at low spectral resolution. Additionally, we have described the slenslit concept, which will allow PSI-Red to achieve unprecedented spectral resolutions of 5000 to 10 000 for bright exoplanets while preserving the fine spatial sampling afforded by the lenslet array. Our design for PSI-Red is congruent with the design for SCALES, which will be deployed in advance of TMT's completion at W. M. Keck Observatory.

## ACKNOWLEDGEMENTS

The authors acknowledge that the land on which we work on at UCSC is the traditional and unceded territory of the Uypi Tribe of the Awaswas Nation. Today these lands are represented by the Amah Mutsun Tribal Band who are the descendants of the Awaswas and Mutsun Nations whose ancestors were taken to Mission Santa Cruz and Mission San Juan Bautista during Spanish colonization of the Central Coast. Today the Amah Mutsun are working hard to fulfill their obligation to the Creator to care for and steward Mother Earth and all living things through relearning efforts and the Amah Mutsun Land Trust.

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