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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**TECHNOLOGICAL DEVELOPMENTS FOR EXOPLANET AND
PROTOPLANETARY DISK SCIENCE**

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ASTRONOMY AND ASTROPHYSICS

by

Dominic Francisco Sanchez

June 2025

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Abstract

Technological Developments for Exoplanet and Protoplanetary Disk Science

by

Dominic Francisco Sanchez

This dissertation presents the design, development, and demonstration of novel technologies for advancing wavefront sensing and spectropolarimetric instrumentation in support of high-contrast astronomical observations. The work centers on three primary contributions: (1) a three-sided reflective pyramid wavefront sensor (3RPWFS) optimized for compact and achromatic pupil-plane wavefront sensing; (2) the integration of Wynne correctors to broaden the spectral bandwidth of focal-plane wavefront sensing with the Self-Coherent Camera (SCC); and (3) the implementation of a reflective dispersive Wollaston prism to enable near-infrared spectropolarimetry in the SCALES instrument. The 3RPWFS offers a reflective alternative to conventional transmissive sensors and is compatible with systems constrained by chromatic or spatial limitations. Its first-generation implementation in ShaneAO achieved on-sky closed-loop performance, while a second-generation system incorporating a pyramidal concave mirror (PCM) reduced the pupil footprint and enhanced spatial compactness. Despite the presence of fabrication-induced spiral features, the system maintained linearity across 20 Zernike modes and demonstrated stable closed-loop correction at 100 Hz. To overcome the chromatic limitations of SCC wavefront sensing, Wynne correctors were introduced to maintain fringe coherence over broad spectral bands. Designs for both visible and

near-infrared bands were developed and tested, enabling SCC operation over bandwidths exceeding 20% while preserving image quality and fringe visibility for speckle correction. A reflective dispersive Wollaston prism was designed to split orthogonal polarization states while matching the low-resolution spectral format of SCALES, targeting the 2–4 μm bandpass. This configuration enables simultaneous acquisition of polarized spectra, supporting the detection of weak features such as the 3 μm water ice band in protoplanetary disks. Collectively, these developments enhance the capability of adaptive optics and polarimetric systems to detect and characterize exoplanets and their formation environments, with direct applications to ground-based and future space-based observatories.

To those who came before me—
the ones who dreamed without boundaries,
who worked, sacrificed, and endured so that I could stand where I do.
This work is not mine alone; it is the continuation of yours.

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Chapter 1

Introduction

1.1 Scientific Motivation

1.1.1 Why Exoplanets and Protoplanetary Disks?

One of the most profound scientific questions we continue to face is whether we are alone in the universe. While Earth serves as our only example of a habitable planet, life may not be exclusive to environments where liquid water is sustained by the Earth-Sun separation. Alternative mechanisms—such as tidal heating from gravitational interactions—could produce habitable conditions even at large orbital distances or in subsurface oceans. However, the limitations of current technology and interstellar travel make such environments extremely challenging to explore. To date, no direct evidence of extraterrestrial life has been confirmed, nor do we fully understand the processes that created life on Earth. In the absence of such knowledge, searching for Earth analogs remains the most logical and observationally feasible path forward.

We typically associate Earth’s surface temperature and its stable reservoir of liquid water as the primary ingredients for life. If a planet is too cold, water freezes and becomes less chemically reactive, while a complete lack of water precludes the formation of life as we know it. Identifying environments where liquid water can exist remains a key criterion in exoplanet science.

Beyond the search for life, understanding how planets form is equally vital. Planetary formation is thought to originate in turbulent environments surrounding young stars. These regions, known as protoplanetary disks, consist of gas and dust that gradually coalesce into larger bodies. Over time, these planetesimals grow and undergo complex thermal and chemical processes. How does the spatial distribution of solids and volatiles in the disk influence planet formation? Can we detect observational signatures of these early processes, and how do they inform our understanding of Earth’s own origin?

1.1.2 Exoplanet Atmospheric Characterization

As of the time of this writing, there are approximately 6000 confirmed exoplanets, with only a small fraction—about 360—located within their respective habitable zones, where conditions may support liquid water. While water vapor has been detected in the atmospheres of several exoplanets, the unambiguous detection of liquid water remains unresolved[8, 9]. Establishing the habitability of these distant worlds requires detailed characterization of their atmospheric composition, typically through spectral analysis. This approach allows us to probe for the presence of molecules and atomic

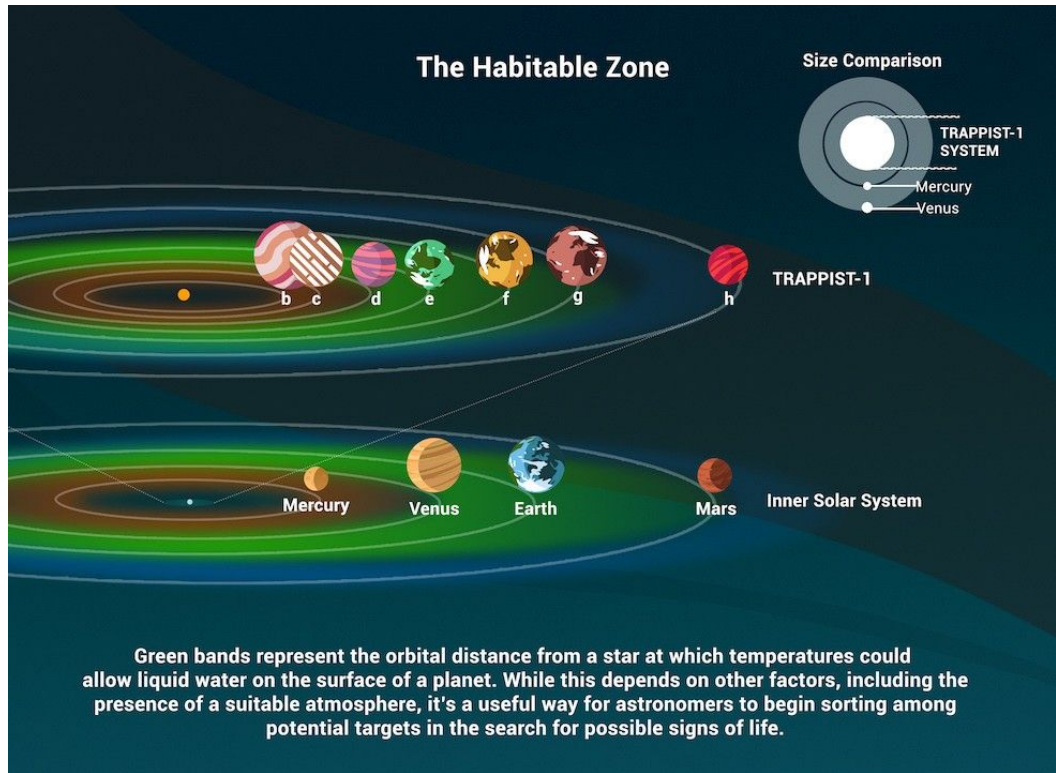


Figure 1.1: Comparison of the habitable zones in the TRAPPIST-1 system and the inner Solar System. Green regions illustrate the range of orbital distances around each star where liquid water could exist on a planet's surface, assuming an appropriate atmospheric composition. The TRAPPIST-1 system hosts multiple Earth-sized exoplanets within this zone and makes systems like TRAPPIST-1 valuable targets in the search for potentially habitable exoplanets (Figure Credit: NASA/JPL-Caltech/Lizbeth B. De La Torre).

species that may be indicative of geophysical, chemical, or even biological processes.

Molecular signatures such as H_2O , CO_2 , CH_4 , O_2 , and N_2O are considered

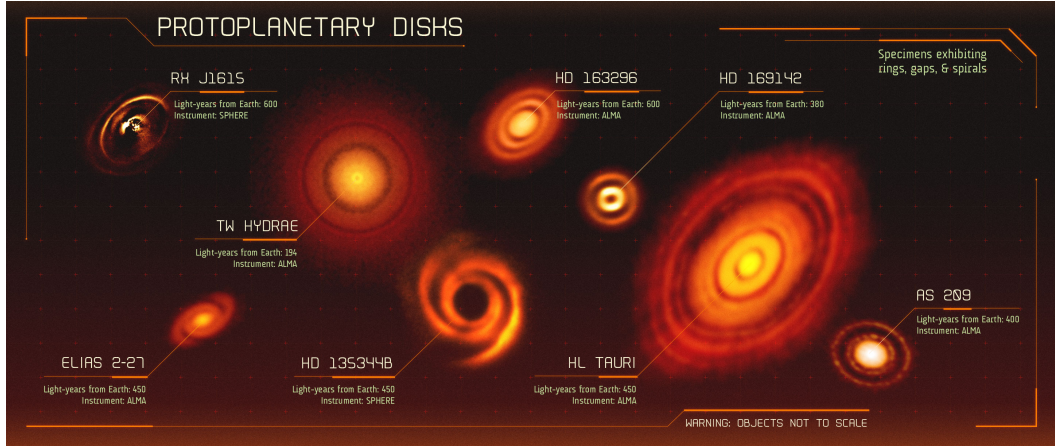


Figure 1.2: Images of protoplanetary disks observed by ALMA and SPHERE, illustrating the diverse morphologies including rings, gaps, and spirals. These substructures are interpreted as signatures of disk evolution, grain growth, and potential planet formation. Systems shown include TW Hya, HL Tau, AS 209, HD 163296, Elias 2-27, and others, with distances ranging from 194 to 600 light-years. These spatially resolved observations provide critical insight into the processes governing the early stages of planetary system formation (Figure Credit: Disk images by ESO; Adapted by Olena).

potential biosignatures, especially when they appear in disequilibrium abundances [10, 1, 11]. However, defining a definitive set of biosignatures remains an open challenge in the field. Many of these markers are observable in the visible to near-infrared (VIS–NIR) regime, where numerous detections of water vapor have already been made in exoplanet atmospheres[12, 13, 14]. Constraining elemental abundances further informs models of planetary formation and migration, offering insight into a planet’s chemical history and physical structure.

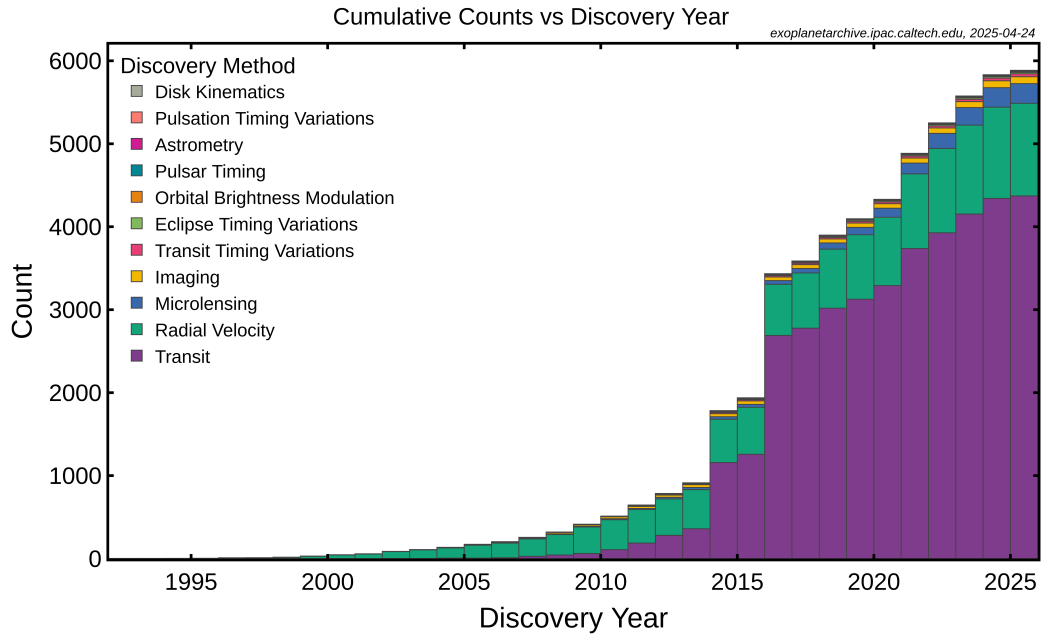


Figure 1.3: Cumulative number of confirmed exoplanets as a function of discovery year, categorized by detection method. The data, obtained from the NASA Exoplanet Archive (as of April 2025), show the increase in discoveries. Transit and radial velocity methods dominate, particularly following the launch of space-based observatories such as Kepler and TESS. The chart also highlights the diversity of detection techniques—including microlensing, direct imaging, astrometry, and others (Figure Credit: NASA Exoplanet Archive).

Although not a primary focus of this thesis, polarization offers an additional and complementary pathway to characterize exoplanetary atmospheres. Polarized light signals — particularly from self-luminous exoplanets observed with direct imaging—are sensitive to asymmetries in the planet’s atmosphere, such as patchy clouds or haze

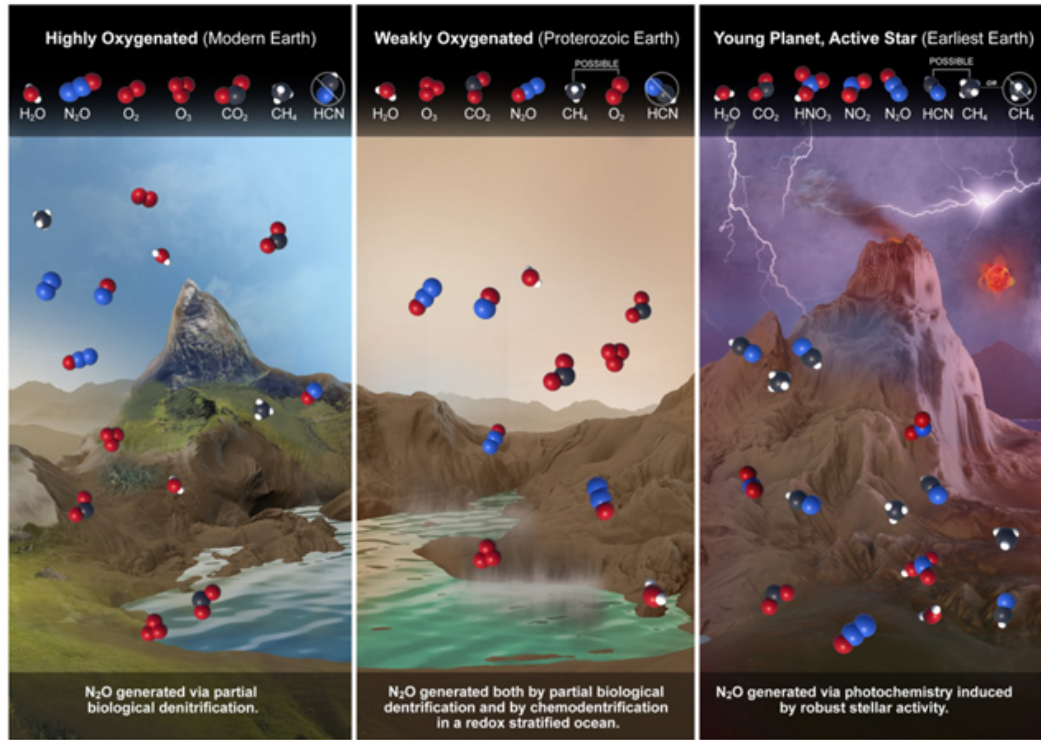


Figure 1.4: Illustration of potential biosignature gases in the atmospheres of terrestrial planets at different stages of Earth's evolution. (Left) A modern, highly oxygenated Earth-like planet dominated by O_2 , O_3 , and N_2O produced by biological denitrification. (Middle) A Proterozoic-like planet with weak oxygen levels and stratified ocean chemistry enabling both biological and abiotic N_2O production. (Right) An early Earth analogue orbiting an active young star, where atmospheric composition is shaped by intense photochemistry, including the abiotic generation of N_2O . Each scenario illustrates how the detection of specific molecules and their abundances could signal potential biological activity depending on the planet's evolutionary stage (Figure Credit:[1])

layers. Time-resolved polarization measurements can help disentangle degeneracies between atmospheric structure and surface features. For example, variations in polarized reflected light across an orbital phase can produce a diagnostic phase curve, potentially revealing features such as surface oceans or cloud belts through phenomena like specular glint [15].

1.1.3 Protoplanetary Disks and Planet Formation

In addition to studying mature exoplanets, it is essential to understand the conditions under which planets form. Protoplanetary disks provide a direct observational window into the early stages of planetary system development. Water-ice plays a particularly important role in shaping disk chemistry and planet-building processes. Classical models of planet formation suggest that the outer disk regions are rich in icy solids, which enhance the surface density of solids and accelerate the formation of planetary cores. These icy grains also serve as great environments for chemical reactions that can lead to complex organic compounds [16, 17, 18, 19, 20].

Water-rich solids may drift inward and deliver volatiles — including water — to the inner disk, potentially seeding terrestrial planets with essential ingredients for habitability. The distribution and abundance of ice are therefore critical parameters in assessing planet formation environments. Measuring the location of the snow line—the distance from the central star at which water transitions from vapor to solid—offers valuable insight into where planets form and what materials they accrete [21, 22, 23, 24].

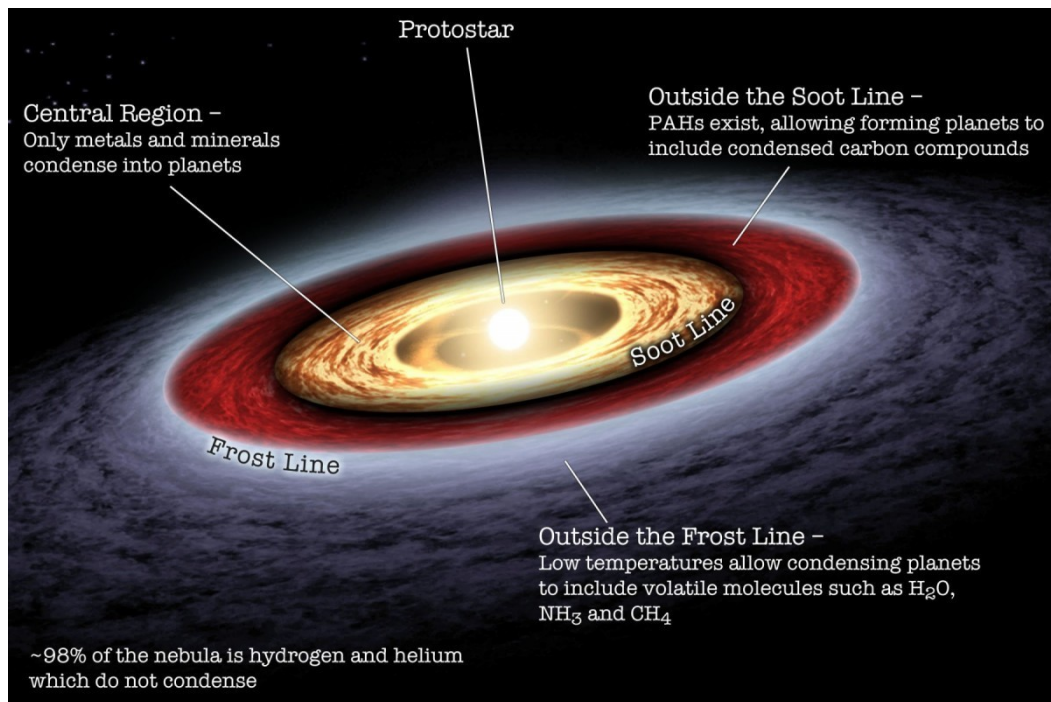


Figure 1.5: Schematic of a protoplanetary disk illustrating disk transitions that influence planet formation. The innermost region near the protostar is too hot for volatile compounds to condense, allowing only metals and minerals to form solid grains. Outside the “soot line,” polycyclic aromatic hydrocarbons (PAHs) and other carbon compounds condense, enabling carbon-rich planetesimal formation. Beyond the “frost line” or “snow line”, temperatures are sufficiently low for volatile molecules such as H_2O , NH_3 , and CH_4 to freeze and incorporate into icy grains (Figure Credit: NASA/JPL-Caltech, InvaderXan, design und mehr).

1.2 Detecting Exoplanets

1.2.1 Indirect Methods

Detecting exoplanets is inherently difficult due to their small size, faint luminosity, and close proximity to their much brighter host stars. Despite these challenges, several observational techniques have proven effective, each with its own sensitivities and limitations.

In transit photometry, a periodic dip in the observed brightness of a star signals the presence of an orbiting planet that momentarily blocks a fraction of the starlight (Fig.1.6). Even for large gas giants, the drop in stellar intensity is typically only about 1% or less, making this a high-precision measurement. This technique is inherently biased toward detecting large, close-in exoplanets that are more likely to transit from our line of sight. Additionally, a transit can only be observed if the orbital plane of the exoplanet is closely aligned with the observer's perspective. Despite these geometric constraints, transit photometry provides a wealth of information: exoplanet radius, orbital period, inclination, and, when combined with radial velocity data, planetary density. It remains the leading method for exoplanet detection, and the first potentially habitable zone exoplanet was discovered using this approach [25]. Transit photometry has also enabled transmission spectroscopy, in which stellar light filters through the planetary atmosphere during transit. By comparing in- and out-of-transit spectra, astronomers can infer the composition of the exoplanet's atmosphere, offering insights into habitability and atmospheric dynamics [26].

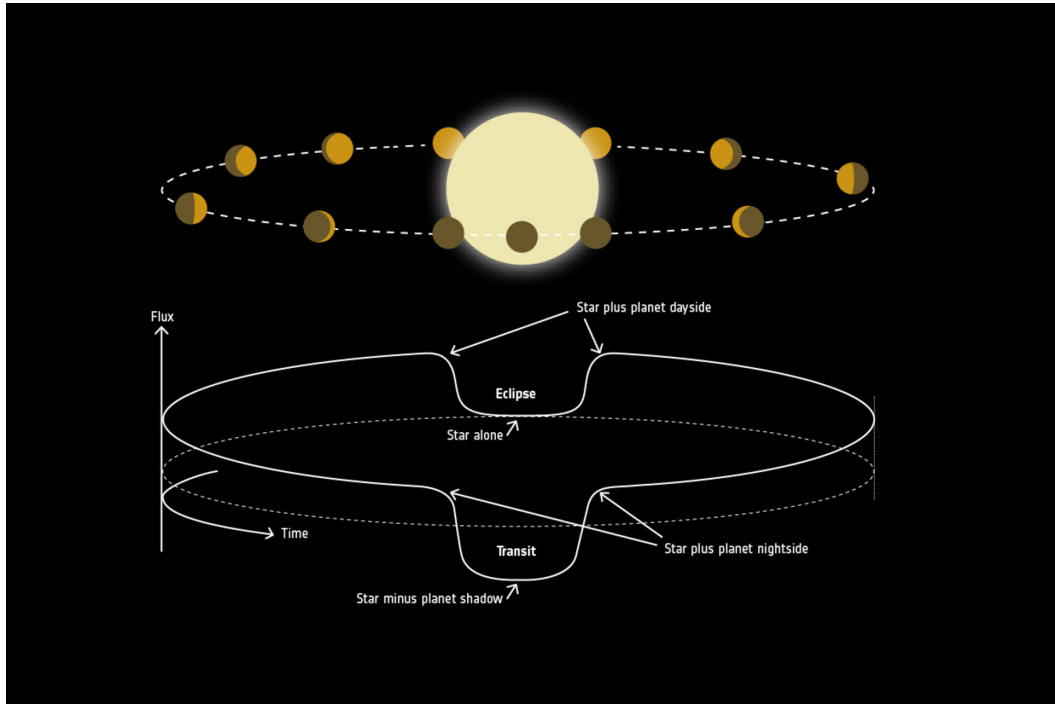


Figure 1.6: **Transit Photometry:** A planet crossing in front of its host star causes a small, periodic dip in the observed brightness. The transit light curve provides information about the planet’s size and orbital period (Figure Credit: ESA).

Another major detection technique is the radial velocity (RV) method, which observes the motion of a star induced by the gravitational pull of an orbiting planet. Rather than tracking the planet directly, the RV method measures periodic Doppler shifts in the stellar spectrum—blueshifts when the star moves toward the observer and redshifts when it moves away (Fig.1.7). These shifts reveal the presence of a planet and provide constraints on its mass and orbital period. Like transits, this technique is most sensitive to large, close-in planets and also requires a favorable orbital inclination. The

RV method remains the second most productive exoplanet detection technique, especially valuable when combined with transit measurements to derive planetary densities.

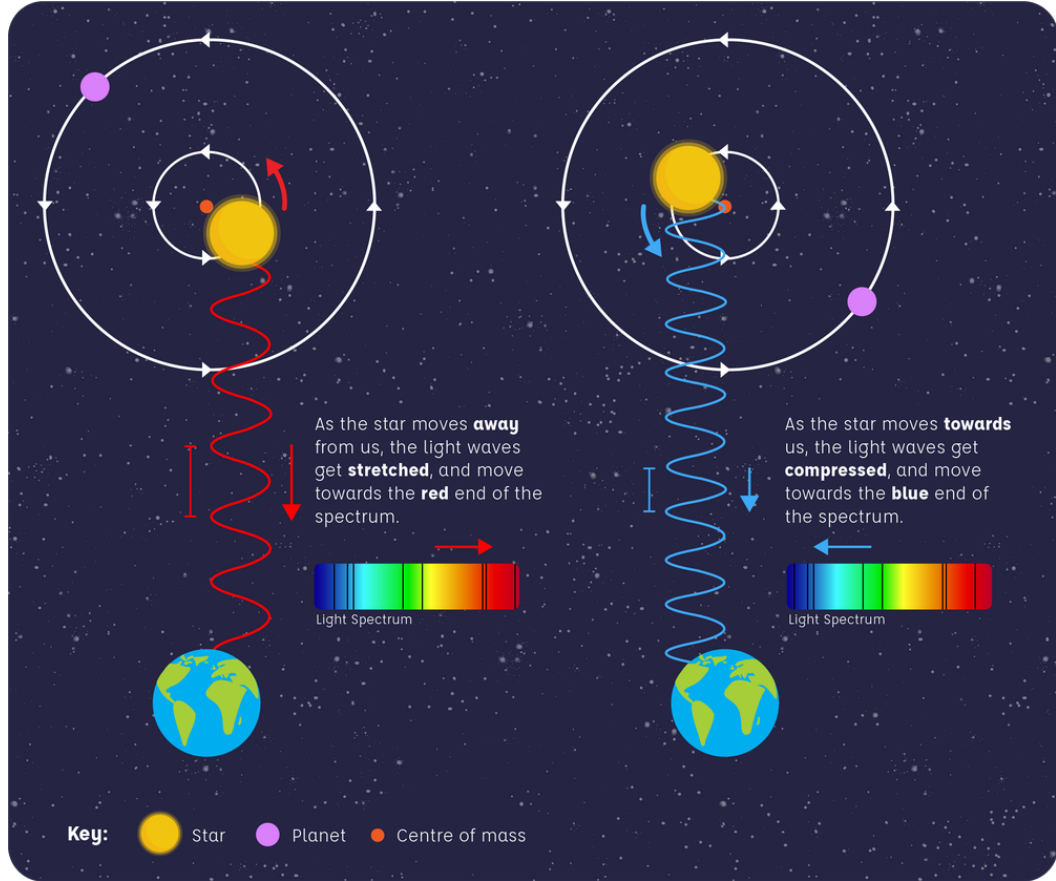


Figure 1.7: **Radial Velocity:** The gravitational pull of an orbiting planet causes the host star to move toward and away from the observer. This motion produces Doppler shifts in the stellar spectrum, detectable as periodic changes in radial velocity (Figure Credit: Alice Hopkinson, LCO; Jessica Barton, LCO).

Two additional indirect methods, though less commonly used, have also contributed to exoplanet discoveries. The first is astrometry, which involves precise mea-

surements of a star’s position on the sky (Fig.1.8). A detectable periodic wobble may indicate the gravitational influence of an orbiting planet. Unlike transit and RV techniques, astrometry does not require the observer to be in the orbital plane, allowing detection of planetary systems missed by other methods. When successful, astrometry can provide both mass and orbital characteristics.

The second is gravitational microlensing, which leverages Einstein’s theory of general relativity. If a foreground planetary system passes directly in front of a background star, its gravitational field acts as a lens, magnifying and distorting the light of the background object. A unique intensity signature—sometimes with brief perturbations caused by orbiting planets—can reveal the presence of an exoplanet (Fig.1.9). Microlensing is particularly sensitive to low-mass planets and planets at large separations but suffers from low detection yield due to the rarity and unpredictability of lensing alignments.

1.2.2 Direct Method

Finally, direct imaging aims to observe exoplanets by resolving their light from that of their host stars. This technique requires a telescope with sufficient angular resolution to spatially separate the two sources (Fig.1.10). While direct imaging is not yet competitive as a detection method, it is uniquely powerful for characterization. By separating stellar and exoplanetary light, direct imaging provides direct access to an exoplanet’s thermal emission or reflected spectrum, enabling measurements of temperature, atmospheric composition, orbital parameters, and even surface features. Due to

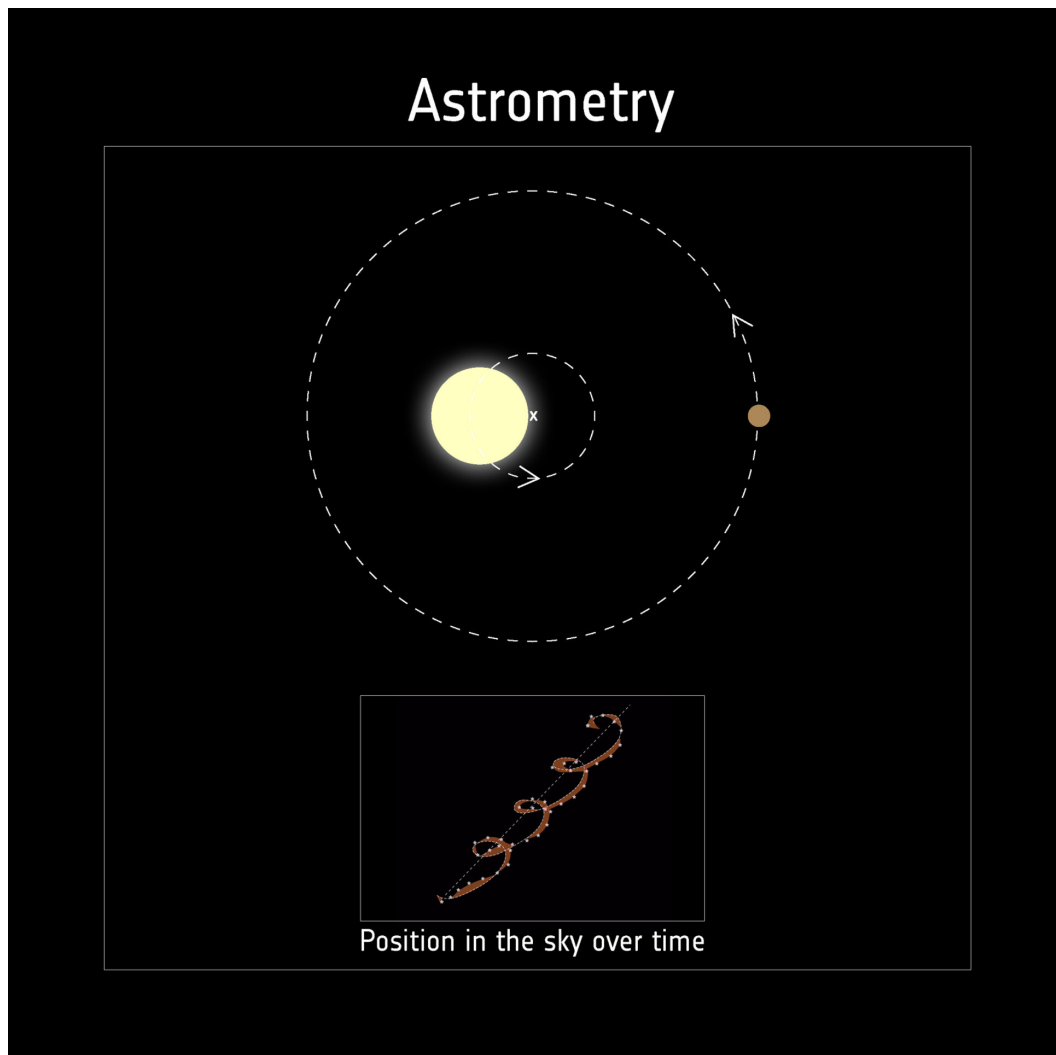


Figure 1.8: **Astrometry:** The presence of a planet is inferred by measuring periodic changes in a star's position on the sky, caused by the gravitational influence of an orbiting companion (Figure Credit: ESA).

this, direct imaging is often used as a follow-up technique, applied to systems already identified with indirect methods. It is also the primary method for studying protoplan-

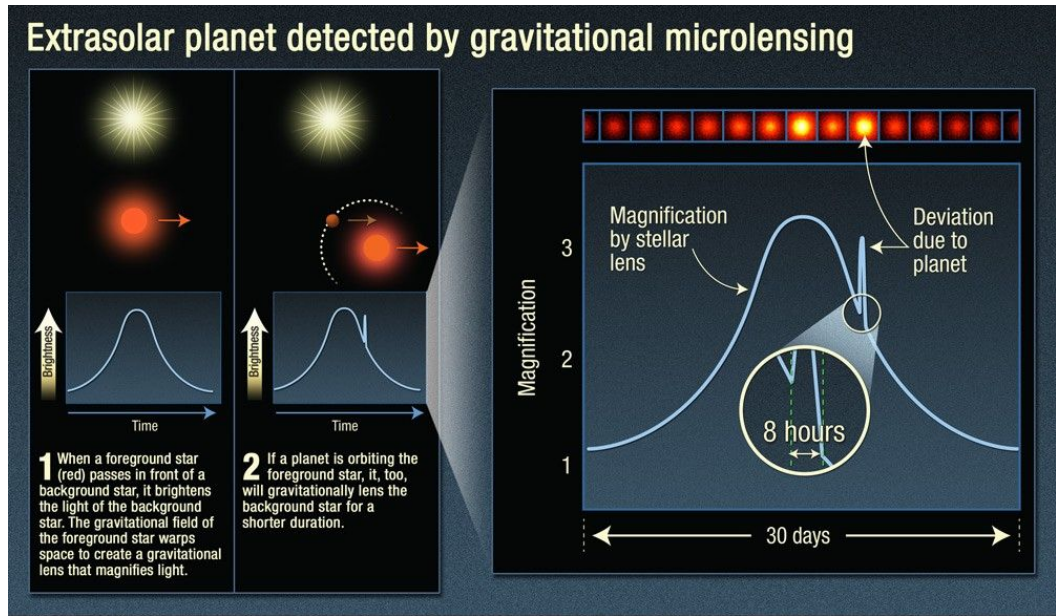


Figure 1.9: **Microlensing:** When a foreground star passes in front of a background source, the gravitational field of the foreground system magnifies the light. A planet induces a secondary lensing event, revealed as a short-duration anomaly in the light curve (Figure Credit: NASA, ESA, and A. Feild (STScI)).

etary disks, where resolving spatial structures is critical to understanding early planet formation.

1.3 Technological Foundations

1.3.1 Adaptive Optics

Telescopes in astronomy serve two essential functions: to collect light from faint sources and to resolve the angular structure/separation of distant objects. In

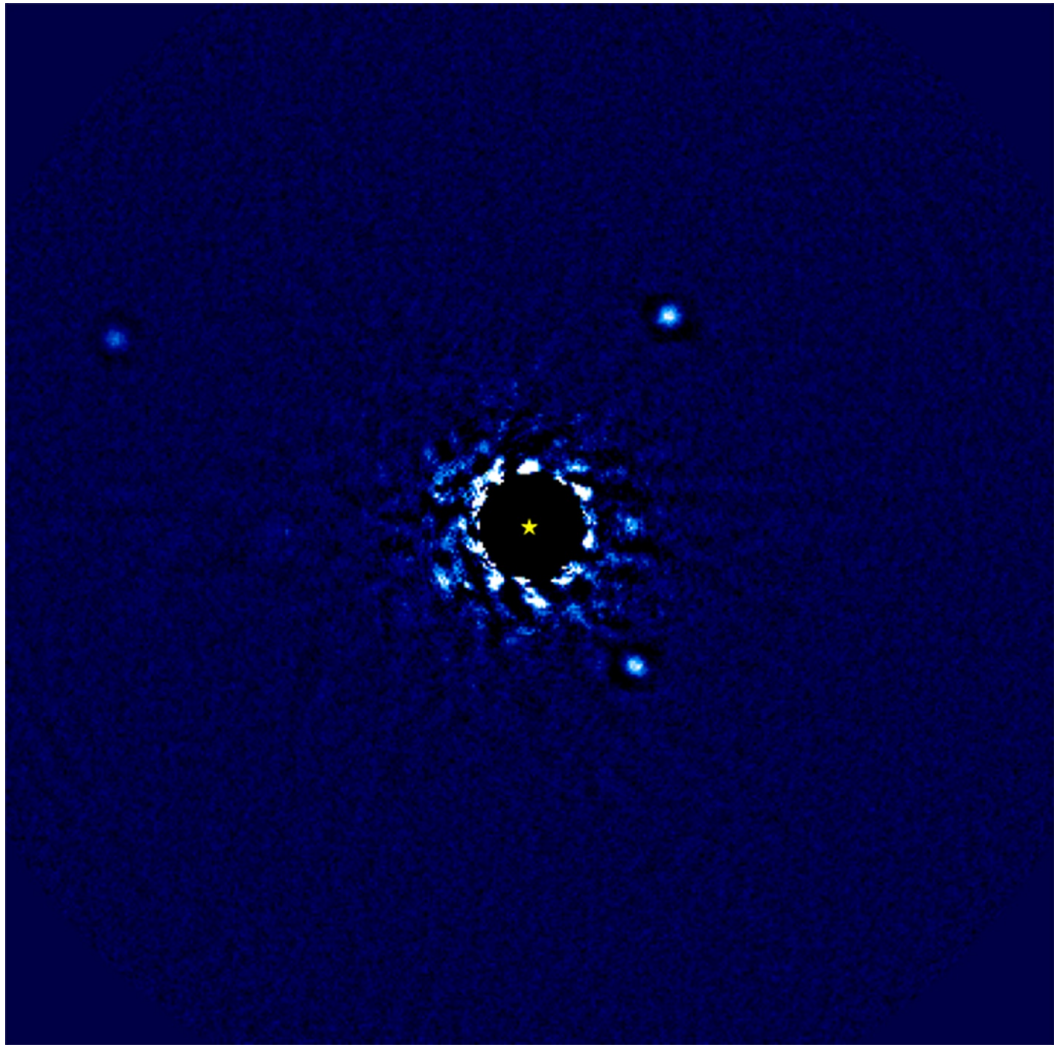


Figure 1.10: **Direct Imaging:** Exoplanets are detected by spatially separating their light from the host star using high-contrast imaging techniques such as coronagraphy and adaptive optics. The image shows the HR 8799 system, with four directly imaged planets (Figure Credit: Jason Wang; Christian Marois).

the context of exoplanet direct imaging, both capabilities are crucial. Exoplanets are much fainter than their host stars, and achieving high angular resolution is required to distinguish the planetary signal from the stellar glare. However, the resolution is limited not only by telescope aperture but also by distortion introduced by Earth’s atmosphere.

From a wave optics perspective, distant astronomical sources emit spherical wavefronts. As these wavefronts propagate over astronomical distances, they become effectively planar across the scale of a telescope aperture. In an ideal optical system with no atmospheric disturbance, these flat wavefronts would focus to a diffraction-limited point spread function (PSF). However, the finite size of the aperture imposes a diffraction limit, resulting in an Airy pattern in the focal plane:

$$E(r) = E_0 \left(\frac{2J_1(\pi r/\lambda f/\#)}{\pi r/\lambda f/\#} \right)^2 \quad (1.1)$$

where r is the radial coordinate in the image plane, λ is the wavelength, and $f/\# = f/D$ is the system’s f-number. The angular resolution is determined by the Rayleigh criterion:

$$\alpha = \frac{1.22\lambda}{D} \quad (1.2)$$

indicating that resolution improves with larger apertures and shorter wavelengths.

In practice, this idealized imaging scenario is disrupted for ground-based telescopes due to atmospheric turbulence. Fluctuations in temperature and pressure lead to spatial and temporal variations in the refractive index of the atmosphere, which distort the phase of the incoming wavefront. These distortions break the phase uniformity of the wavefront and degrade the resulting image, producing a blurred PSF populated with speckles. The effective resolution under these conditions is limited by the Fried

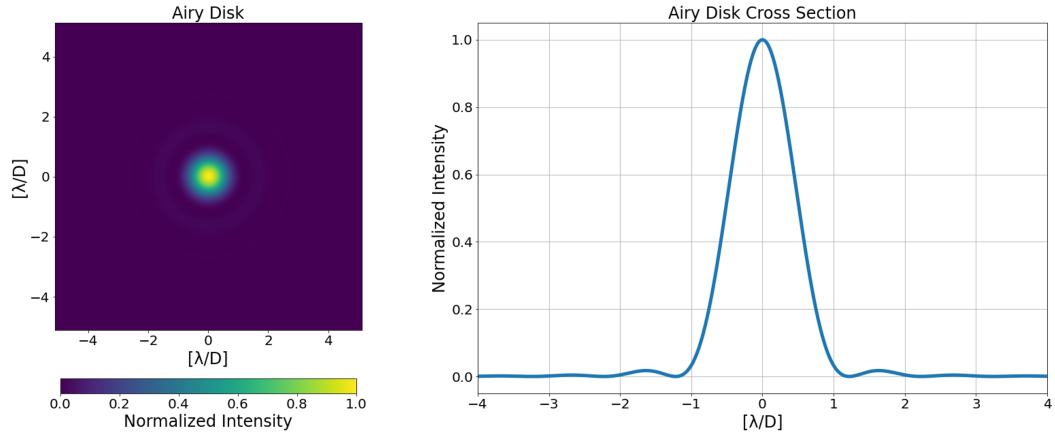


Figure 1.11: (Left) Image of the monochromatic diffraction-limited impulse response from a circular aperture, called an Airy disk. (Right) Cross-sectional profile of the PSF. The first zero of the Airy pattern occurs at an angular radius of $1.22\lambda/D$.

parameter (r_0), which represents the atmospheric coherence diameter:

$$\alpha_b = \frac{1.22\lambda}{r_0} \quad (1.3)$$

For example, if $r_0 = 10$ cm at $\lambda = 1 \mu\text{m}$, the resolution is limited to about 5 arcseconds—orders of magnitude worse than the diffraction limit of modern large telescopes.

To recover diffraction-limited performance, astronomers implement adaptive optics (AO) systems that correct wavefront aberrations in real time. A standard AO system consists of three key components: a wavefront sensor (WFS) to measure phase errors, a deformable mirror (DM) to apply compensating phase shifts to reflatten the wavefront, and a real-time control computer to close the feedback loop. The AO control loop must operate at high speed to track the rapid evolution of atmospheric turbulence and maintain effective correction.

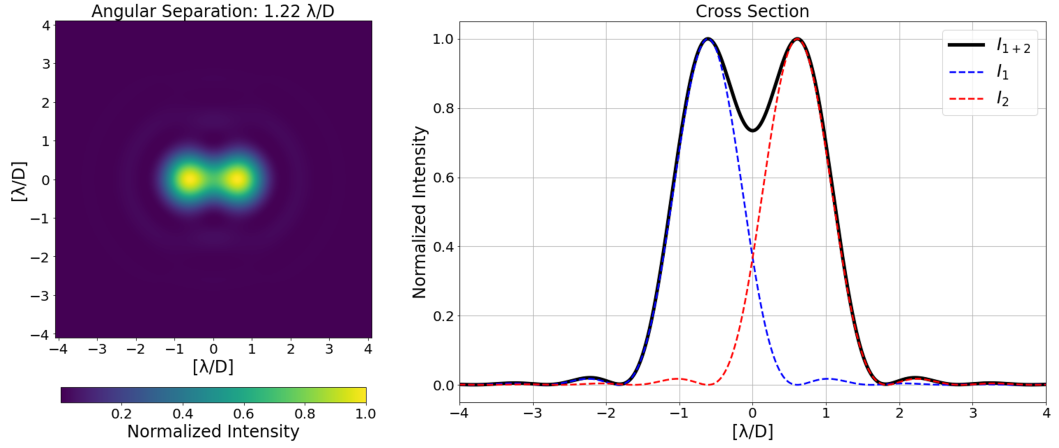


Figure 1.12: (Left) Composite PSF image showing two equally bright sources separated by $1.22\lambda/D$, the classical Rayleigh limit for a circular aperture. (Right) Cross-sectional intensity profile. The blue and red dashed lines represent the individual Airy patterns I_1 and I_2 , while the black solid line shows the combined intensity I_{1+2} . At this separation, the peak of one PSF coincides with the first zero of the other, meeting the Rayleigh criterion.

As shown in Fig. 1.13, incoming starlight reflects off the DM, which dynamically adjusts its surface using an array of actuators. The beam is then split into two arms: one directed toward the science camera and the other toward the wavefront sensor. The WFS measures the aberrated wavefront, typically by imaging a reimaged telescope pupil and analyzing intensity or phase variations. These measurements are used by the control system to compute actuator commands that "flatten" the wavefront, i.e. cancel the measured aberrations to restore a planar wavefront.

For effective correction, both the DM and the WFS must be optically conju-

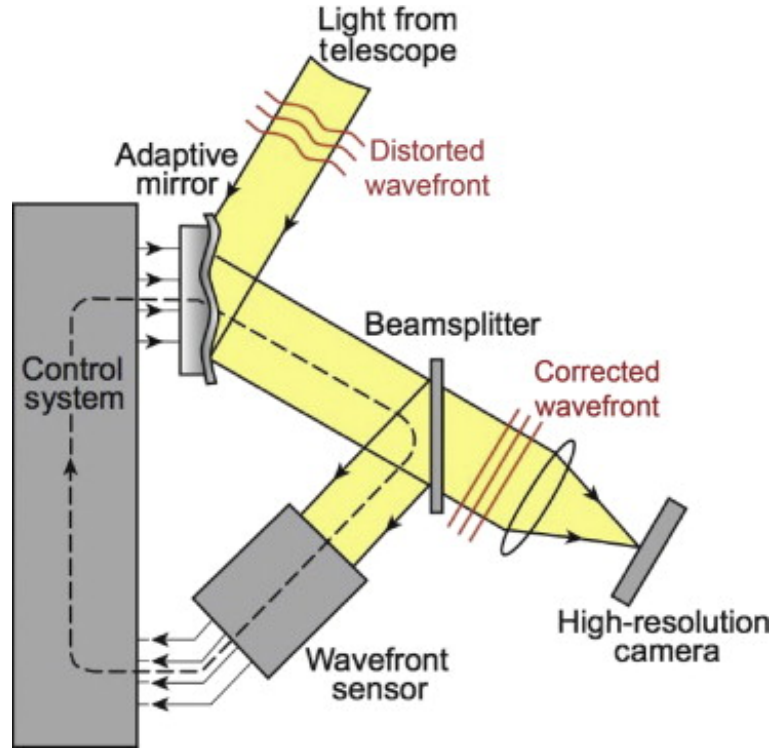


Figure 1.13: A conceptual diagram of an adaptive optics (AO) system. Light from the telescope arrives with atmospheric aberrations, measured by a wavefront sensor. The control system computes corrections that are applied to a deformable mirror in real time, producing a corrected wavefront that is directed toward the science camera for high-resolution imaging[27].

gated to the same plane in the system — the telescope pupil. Optical conjugation ensures that the aberrations measured by the WFS correspond directly to those corrected by the DM. Additional relay optics are often required to reimage the telescope pupil onto the DM and WFS. Pupil-plane wavefront sensors, such as the Shack-Hartmann (SHWFS) and pyramid WFSs (PWFS), are widely used in astronomy and will be dis-

cussed in detail in Chapter 2.

Most AO systems operate in a closed-loop configuration, where corrections are applied continuously based on residual wavefront measurements. In contrast, open-loop AO systems operate without feedback from corrected light.

The degree to which an AO system restores diffraction-limited performance is generally quantified by the Strehl ratio (S), defined as the ratio of the peak intensity of the corrected PSF to that of an ideal, unaberrated PSF:

$$S = \frac{I'}{I_0} \quad (1.4)$$

where I' is the peak intensity of your measured PSF and I_0 is the peak of the diffraction limited PSF. $S = 1$ corresponds to perfect correction, while values below 0.1 reflect poor image quality. In practice, AO systems achieve S ranging from 0.2–0.6 in the near-infrared, depending on atmospheric conditions, correction speed, and WFS performance. Higher Strehl ratios indicate more concentrated PSFs, which are especially valuable for high-contrast imaging. In exoplanet detection, a high S not only enhances the planet signal relative to the stellar halo, but also improves spectroscopic and polarimetric measurements by reducing contamination from residual starlight.

A key limitation of conventional AO systems arises from non-common path aberrations (NCPAs). Since the light paths to the science camera and the WFS diverge after the beam splitter, aberrations introduced downstream — such as by filters, coronagraph optics, or detector surfaces — are not seen by the WFS and therefore remain uncorrected. These residual aberrations can manifest as quasi-static speckles that

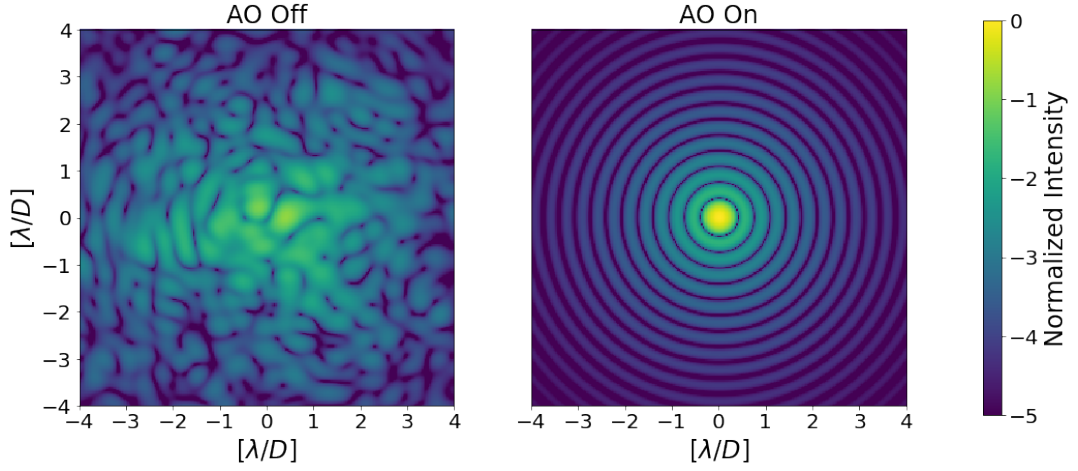


Figure 1.14: Simulated point spread functions (PSFs) with adaptive optics (AO) off (left) and on (right). Without AO correction, atmospheric turbulence distorts the incoming wavefront, producing an aberrated PSF and decrease angular resolution. With AO correction, the wavefront is flattened, ideally restoring a diffraction-limited PSF. Intensity is shown on a logarithmic scale and normalized to the PSF peak.

persist in the science image and may mimic or obscure exoplanetary signals.

To address this, advanced AO systems increasingly rely on focal-plane wavefront sensing (FPWFS) techniques, which use the science image itself to infer residual aberrations. FPWFSs operate in the common optical path and are particularly valuable for applications requiring high-contrast imaging, such as direct exoplanet detection. These methods are nonlinear and computationally intensive but offer the advantage of correcting errors that conventional pupil plane WFSs cannot detect. A detailed overview of focal plane wavefront sensing strategies will be presented in Chapter 4.

Finally, it is important to note that classical AO assumes a single dominant turbulent layer. In reality, atmospheric turbulence is distributed over altitude. Techniques such as multi-conjugate adaptive optics (MCAO) and ground-layer adaptive optics (GLAO) address this by using multiple DMs conjugated to different atmospheric layers or having the DMs conjugated to the atmospheric ground layer respectively, though such architectures are beyond the scope of this thesis. AO will also be an integral part of the next generation of extremely large telescopes (ELTs), such as the Thirty Meter Telescope (TMT), Giant Magellan Telescope (GMT), and the European Extremely Large Telescope (E-ELT). These facilities require high-order AO systems to fully realize their diffraction-limited potential, especially for direct imaging and spectroscopy of exoplanets at small angular separations.

1.3.2 Coronagraphy

Exoplanet direct imaging faces a fundamental challenge: even when AO systems correct for atmospheric turbulence and angularly resolve the exoplanet from its host star, the planet remains orders of magnitude fainter. The overwhelming brightness of the star — and its diffraction pattern - dominates the image and contaminates nearby regions where an exoplanet signal may lie. In addition to suppressing atmospheric distortions, any practical high-contrast imaging system must also suppress the starlight itself. This is the primary role of a coronagraph.

Coronagraphy is essential for direct imaging because it reduces the intensity of on-axis starlight while preserving the signal from off-axis sources like exoplanets. A

well-designed coronagraph reshapes or blocks the electric field associated with the stellar PSF so that less light reaches the science detector near the star’s location. This improves contrast and increases sensitivity to faint companions. Without a coronagraph, photon noise from the star and diffraction spillover would dominate the detector, making direct detection of planets nearly impossible — especially for high-contrast systems targeting small inner working angles.

A coronagraph typically consists of one or more optical elements placed in the focal and/or pupil planes. Focal plane masks are positioned at the star’s PSF and attenuate the core and surrounding diffraction rings, while pupil-plane masks—such as Lyot stops—filter the re-collimated beam to block diffracted starlight. When designed together, these elements selectively remove the star’s light while allowing off-axis planet light to pass through relatively unaffected — provided the planet lies beyond the coronagraph’s inner working angle (IWA), usually specified in units of (λ/D) , where (λ) is the wavelength and (D) is the telescope diameter.

Despite their effectiveness, coronagraphs do not achieve perfect suppression. Residual wavefront errors — such as uncorrected atmospheric aberrations, quasi-static optical misalignments, and thermal drifts — create speckles in the focal plane that vary in time. These dynamic speckles can mimic or obscure exoplanet signals and are often the dominant source of noise in high-contrast images. Furthermore, most coronagraphs are designed for narrow spectral bands and are susceptible to chromatic effects, as diffraction and optical phase vary with wavelength. These chromatic limitations degrade performance across broad bandpasses.

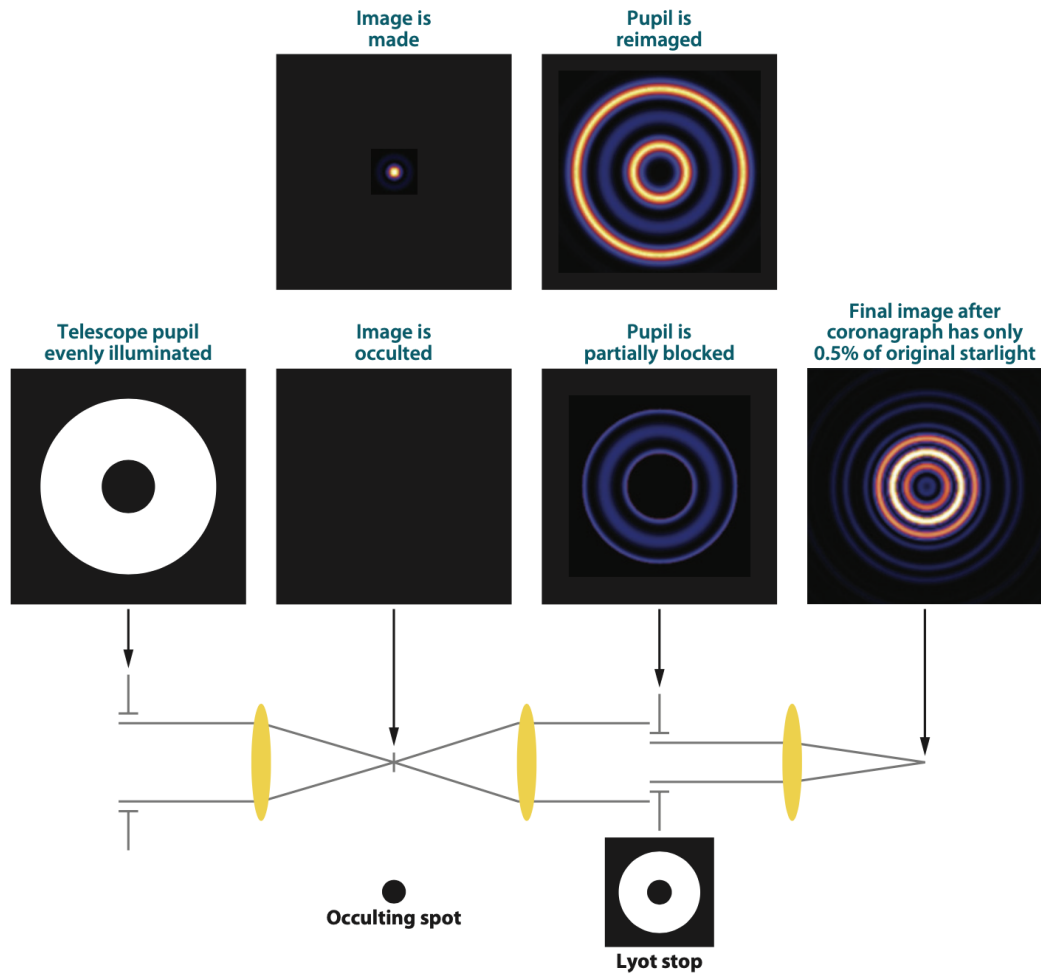


Figure 1.15: An optical layout of a focal plane and pupil plane hybrid coronagraphic optical system. Light from an unresolved star is focused onto an occulting mask in the focal plane, blocking the core of the PSF. The reimaged pupil shows diffracted starlight redistributed outside the pupil. A Lyot stop blocks this residual light at the pupil plane, allowing only the remaining flux to pass. The final image contains only a small fraction of the initial light, significantly enhancing contrast for detecting faint companions near the star [2].

Nonetheless, coronagraphy remains a cornerstone of ground-based and space-based high-contrast imaging. Several coronagraph types — such as the vortex, apodized pupil Lyot, and PIAA coronagraphs — have demonstrated deep starlight suppression and are routinely used in conjunction with AO systems for exoplanet and circumstellar disk observations.

In Chapter 4 of this thesis, I will introduce a coronagraphic instrument that integrates a focal plane wavefront sensor to actively correct dynamic speckles. This design expands upon traditional coronagraphy by enabling starlight suppression over a significantly broader spectral bandpass than previous systems. Such an approach is essential for spectroscopic and polarimetric characterization of exoplanets, where sensitivity across a wide wavelength range is critical.

1.3.3 Spectropolarimetry on Protoplanetary Disks

Astronomy is fundamentally a science of light. Nearly all information about celestial objects is inferred by collecting and analyzing electromagnetic radiation. By dispersing this light into its constituent wavelengths — spectroscopy — we gain access to the physical and chemical properties of the source and any intervening material. In the context of exoplanetary systems and protoplanetary disks, spectroscopy enables measurements of composition, temperature, velocity structure, and chemical evolution — parameters that directly inform models of planet formation and habitability. These capabilities motivate the development of new instruments capable of capturing spectral information across a broad wavelength range, including those optimized for moderate-

or low-resolution applications.

In protoplanetary disks, light from the central star scatters off or passes through the surrounding gas and dust, imprinting spectral features from a variety of molecular and solid-phase species. Depending on the wavelength, light can excite vibrational, rotational, or electronic transitions, resulting in unique absorption or emission lines. For example, water vapor, carbon monoxide, methane, and silicates exhibit strong and distinguishable vibrational bands in the near- and mid-infrared, making this spectral region particularly valuable for tracing volatiles and dust mineralogy. By analyzing the shape, strength, and position of these features, one can determine temperature gradients, radial and vertical composition, and disk structure.

While spectroscopy offers compositional properties, it is often insensitive to geometric and morphological properties—such as disk flaring, grain porosity, or the vertical distribution of scattering layers. This is where polarimetry becomes a powerful complementary tool. Light becomes polarized when it scatters off asymmetric particles or surfaces. Measuring the degree and angle of polarization provides insight into the scattering geometry (e.g., disk inclination and morphology) grain size distribution, and surface structure [28, 29, 30].

Combining both techniques yields spectropolarimetry, which captures the polarization state of light as a function of wavelength. This hybrid method improves sensitivity to faint or spatially extended features embedded in stellar glare, and helps disentangle overlapping spectral and geometric signatures. In protoplanetary disks, spectropolarimetry in the 2–4 μm band is particularly effective for detecting the promi-

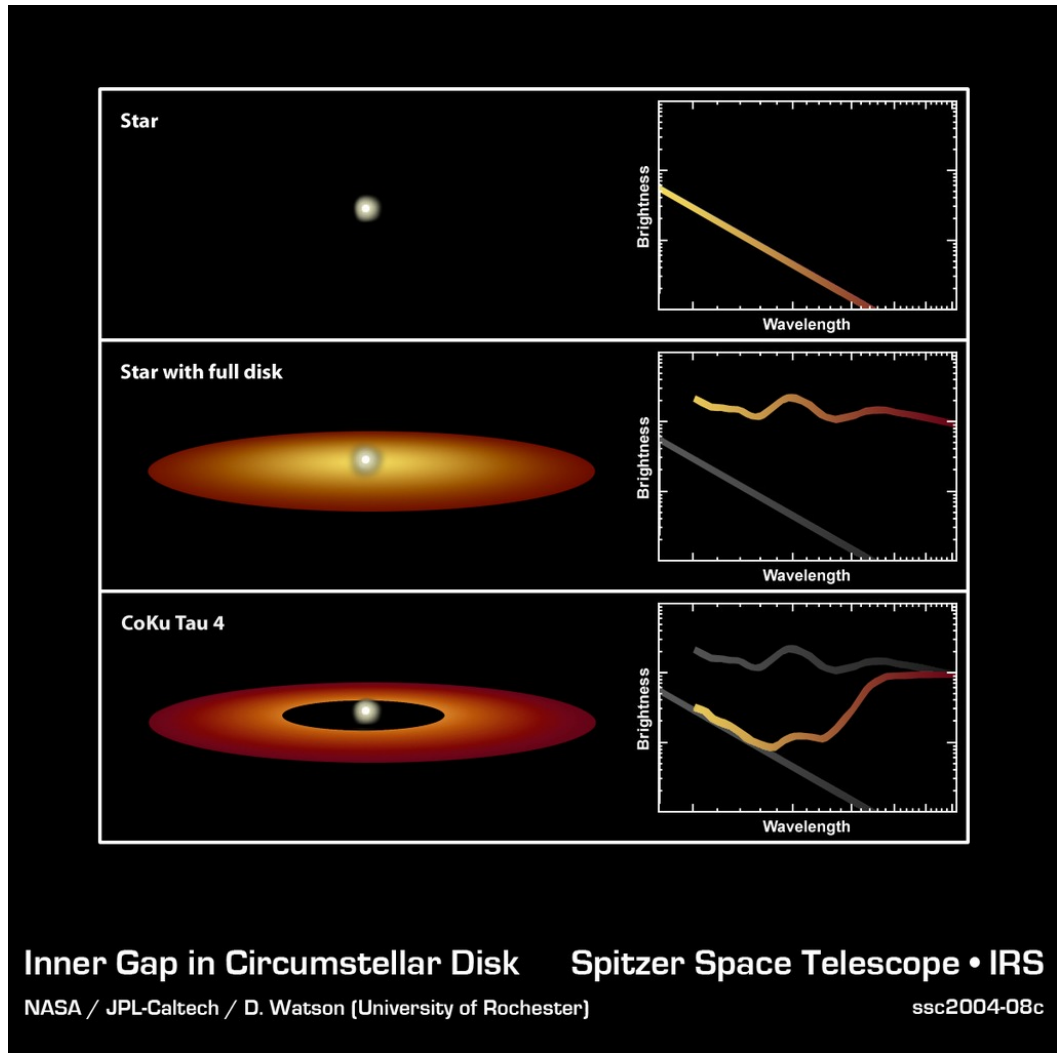


Figure 1.16: Infrared spectra of a star without a disk (top), a star surrounded by a protoplanetary disk (middle), and CoKu Tau 4 (bottom), a system exhibiting an inner disk gap. The presence or absence of dust near the star produces distinct spectral energy distributions. The deficit of emission in CoKu Tau 4 indicates a cleared inner region, consistent with disk evolution or planet formation processes (Figure Credit: NASA/JPL-Caltech/D. Watson (University of Rochester)).

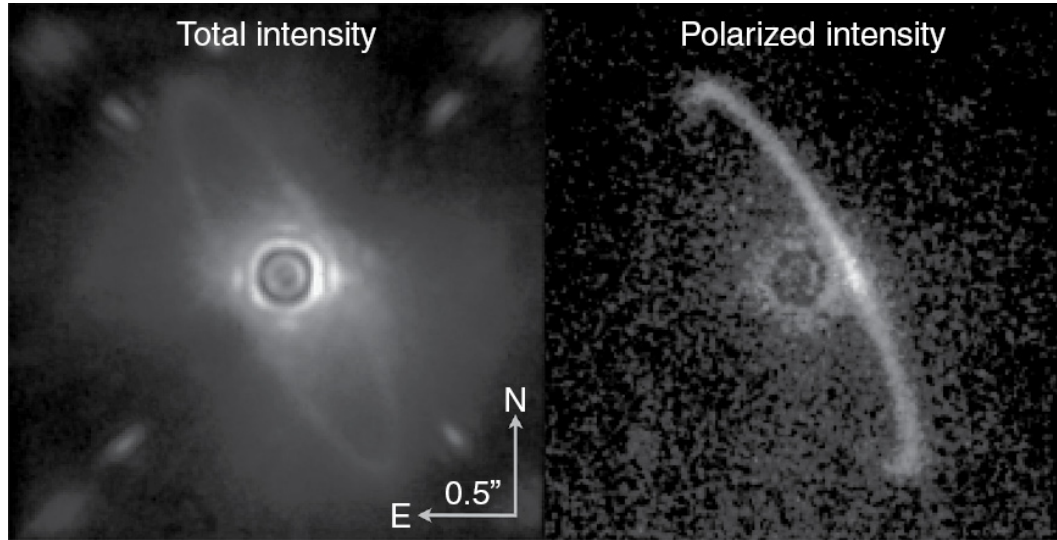


Figure 1.17: (Left) Total intensity image of a circumstellar disk showing the stellar PSF and disk emission. (Right) Polarized intensity image isolating the scattered light component from the disk. Polarization enhances disk visibility by subtracting unpolarized stellar light, revealing fine structures in the disk[3].

ment 3 μm water ice absorption feature in polarized scattered light. This capability enables direct measurement of the snow line—the radial distance from the star at which water transitions from vapor to ice—and supports constraints on water distribution and delivery mechanisms relevant to planet formation.

1.4 Aims and Scope of This Thesis

This thesis presents the development and analysis of novel wavefront sensing and characterization technologies designed to advance ground-based direct imaging of exoplanets and protoplanetary disks. Each chapter focuses on addressing a specific limitation in current instrumentation — ranging from sensitivity and chromaticity in wavefront sensing to the integration of polarimetry in disk characterization. Collectively, these efforts aim to improve contrast, expand spectral coverage, and bring theoretical models of planetary system formation into closer contact with observations.

In the first two chapters, I focus on wavefront sensors used in high-contrast AO systems. Chapter 2 introduces the pyramid wavefront sensor (PWFS), outlining its advantages over traditional Shack-Hartmann designs and presenting an alternative three-sided reflective geometry. This novel design improves achromatic performance and simplifies alignment while maintaining the PWFS’s high sensitivity to low-order aberrations — making it a promising candidate for future AO systems on large telescopes.

Chapter 3 shifts to focal-plane wavefront sensing using the Self-Coherent Camera (SCC). This technique enables complex electric field estimation in the focal plane

by modulating the speckle pattern with spatial fringes. A key limitation of the SCC is its sensitivity to chromaticity, which reduces fringe visibility across broad spectral bands. To address this, I propose and implement a Wynne corrector to mitigate chromatic phase variation and extend the usable spectral bandpass of the SCC. This work is performed in the context of REDWOODS, a focal-plane wavefront sensing instrument under development for the Shane Telescope at Lick Observatory.

In Chapter 4, I address exoplanet and protoplanetary disk characterization through the development of a spectropolarimeter for the Santa Cruz Array of Lenslets for Exoplanet Spectroscopy (SCALES), a near-infrared instrument being developed for the Keck Telescope. The proposed design targets the (2-4 μm) spectral range to capture vibrational features of water ice and hydrocarbons, enabling spatially resolved measurements of the snow line. A description of a dispersive Wollaston prism proposed for spectropolarimetry, characterize its optical performance, and assess its viability for tracing grain growth and volatile distribution in planet-forming disks.

The overarching goal of this thesis is to overcome current technological barriers in AO-based exoplanet imaging and characterization. By developing new wavefront sensing architectures and extending the spectral and polarimetric capabilities of existing instruments, this work contributes toward the scientific readiness of next-generation ground-based observatories.

Part I

Pupil Plane Wavefront Sensing

Pupil-plane wavefront sensors are a class of optical devices used to measure phase aberrations in a beam of light by analyzing its structure at a plane conjugate to the entrance pupil of the system. Unlike focal-plane sensors that operate at the image plane, pupil-plane sensors are positioned where the spatial coherence of the wavefront can be directly sampled, making them especially suitable for AO systems that require fast, accurate, and localized measurements of wavefront distortions.

Several types of pupil-plane wavefront sensors have been developed for astronomical and laboratory AO applications. Among the most widely used is the Shack-Hartmann Wavefront Sensor (SHWFS), which samples the pupil using a lenslet array to measure local wavefront slopes. The curvature wavefront sensor operates by measuring intensity changes near on either side of the focal plane to estimate second-order wavefront curvature. Other designs include the shearing interferometer, the Mach-Zehnder interferometer, and phase-diversity techniques, each with their own advantages and trade-offs in sensitivity, complexity, and robustness.

One particularly versatile and sensitive variant is the pyramid wavefront sensor (PWFS), which uses a refracting or reflecting pyramid placed at the focal point to split the beam into multiple pupil images. The differential intensity between these images encodes the phase gradients across the pupil, enabling high-precision reconstruction of the incoming wavefront. The PWFS is of special interest in this work due to its high sensitivity and adaptability to various observing conditions.

The following chapters will focus on the design, development, and testing of a novel three-sided reflective pyramid wavefront sensor (3RPWFS), implemented as a

compact, achromatic alternative to traditional transmissive designs.

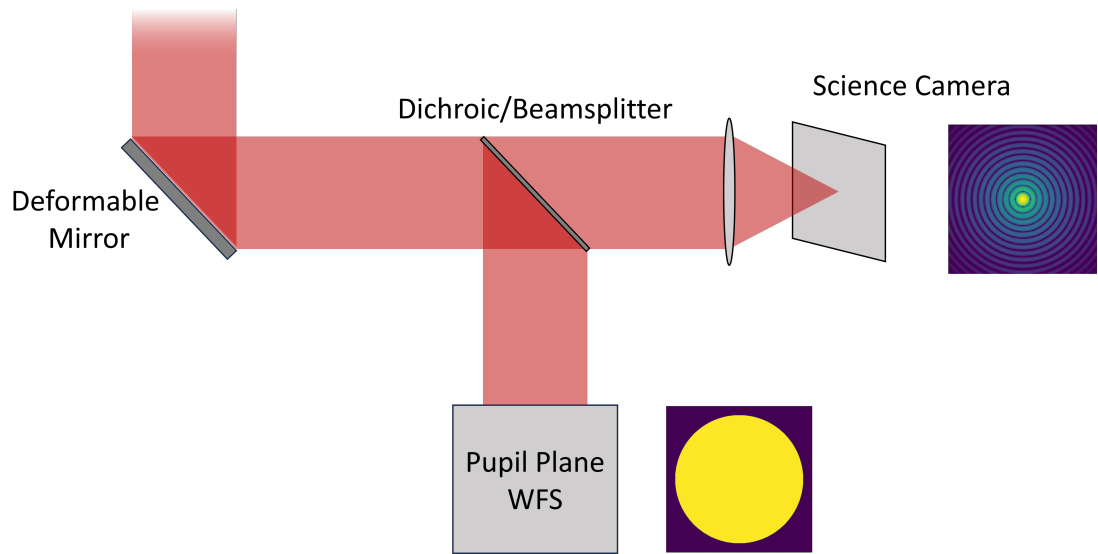


Figure 1.18: Optical layout of a pupil-plane wavefront sensor (WFS) system. The incoming beam is split along two paths: one directed to the pupil-plane WFS for wavefront sensing, and the other toward the science camera. Because the science path bypasses the WFS, this configuration introduces non-common path aberrations that are not directly sensed or corrected, potentially limiting final image quality.

Chapter 2

First-Generation 3-sided Reflective Pyramid Wavefront Sensor

2.1 Traditional Pyramid Wavefront Sensors

Among the pupil plane wavefront sensors, SHWFS remains the most widely adopted and mature. Under ideal, aberration-free conditions, each lenslet focuses light into a spot centered on its optical axis. Aberrations introduce local phase gradients that laterally displace these spots. A detector records these shifts, and from them, the wavefront slopes are inferred. The global phase is then reconstructed by integrating the local slope measurements across all sub-apertures.

The performance of a SHWFS is critically dependent on its pupil sampling. Increasing the number of pixels per sub-aperture improves dynamic range and enables measurement of steeper gradients but increases read noise. Reducing pixel count im-

proves sensitivity but can lead to spot overlap, signal saturation, and increased crosstalk between adjacent sub-apertures.

A more sensitive alternative—particularly attractive for extremely large telescopes (ELTs)—is the pyramid wavefront sensor (PWFS). First proposed by Ragazzoni [31], the conventional PWFS (4PWFS) uses a four-sided glass pyramid placed at the telescope focus. The incoming point spread function (PSF) is focused onto the pyramid apex, where it is split into four beams by the prism faces. These beams are reimaged as four pupil images on a detector, and differences in their intensity distributions encode the wavefront slopes. Unlike the SHWFS, the PWFS analyzes all pupils collectively to determine the wavefront map; you cannot effectively reconstruct the incoming wavefront while missing a pupil image. A conceptual layout of a typical pyramid wavefront sensor (PWFS) is shown in Fig. 2.1.

However, the PWFS is inherently nonlinear in the presence of large aberrations. When a strong tip/tilt displaces the PSF off the apex, light may illuminate only one face of the pyramid, saturating that corresponding pupil image and results in aberration magnitude ambiguity [32]. This occurs when the PSF shifts by more than approximately one resolution element ($1.22\lambda/D$), causing signal degeneracy and reducing the accuracy of phase reconstruction.

To extend the linear dynamic range, the beam is modulated around the apex, typically using a fast steering mirror upstream of the pyramid. This circular modulation broadens the effective PSF and ensures more uniform illumination of all four faces, recovering linearity at the cost of reduced sensitivity. The modulation radius can be

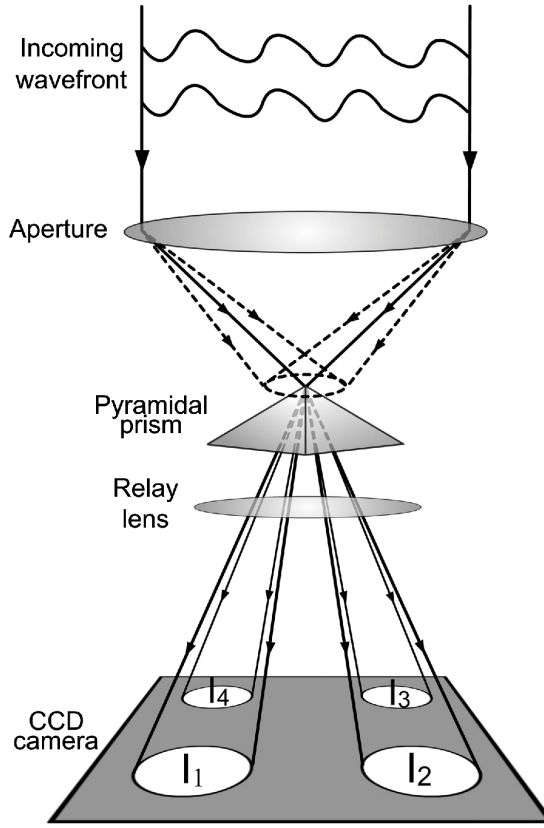


Figure 2.1: Schematic showing a traditional four-sided pyramid wavefront sensor. An incoming wavefront is focused onto the apex of a glass pyramid, where it is split into four beams. A relay lens re-images the beams into four pupil images onto a WFS detector. Intensity distribution between the pupils yields wavefront information, enabling reconstruction of the optical aberrations (Figure Credit: [4]).

tuned to match seeing conditions: smaller modulation improves sensitivity in good seeing, while larger modulation increases robustness under poor seeing. Importantly, this modulation must occur in a pupil conjugate plane to avoid lateral shifts of the pupil images on the detector (Fig.2.2) [33, 34].

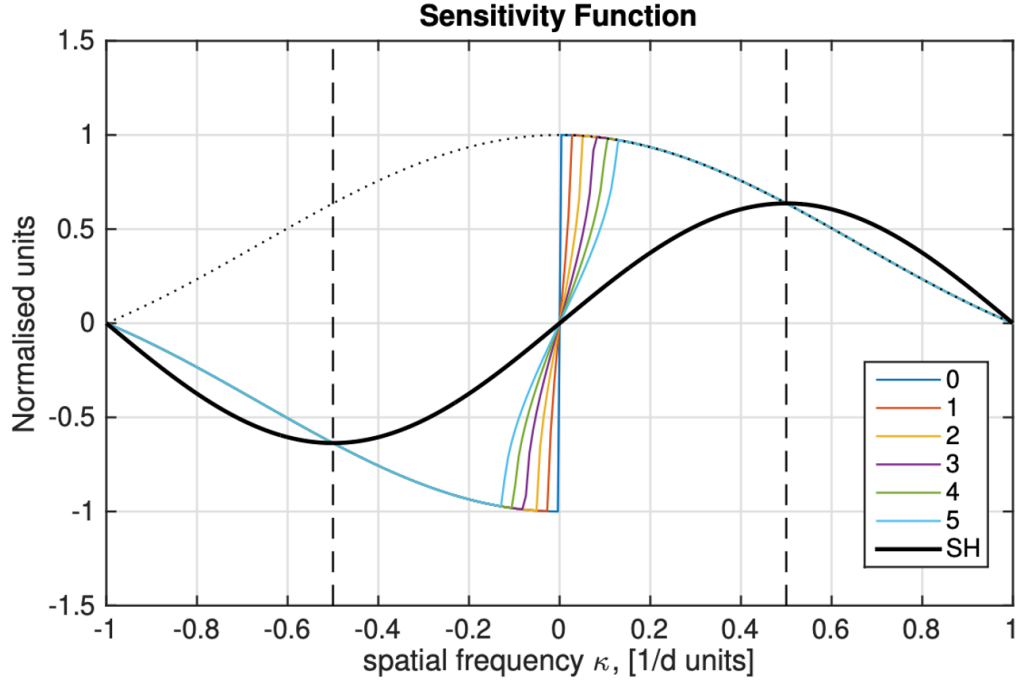


Figure 2.2: Comparison of the spatial frequency response for a WHWFS and PWFS at increasing modulation radii. Higher modulation radii reduce PWFS sensitivity at low spatial frequencies, trading sensitivity for increased linearity (Figure Credit: Correia et al. 2020).

Despite its advantages, traditional PWFS faces two major limitations: chromaticity and fabrication complexity. Being refractive, its response varies with wavelength. The wavelength dependence of the glass refractive index causes lateral chromatic smearing of the pupil images in polychromatic light, degrading sensor performance (Fig.2.3). Achromatic designs have been developed using pairs of glasses with matched dispersion properties, but these are limited to narrow spectral ranges and require careful

control of geometry and material choice [35].

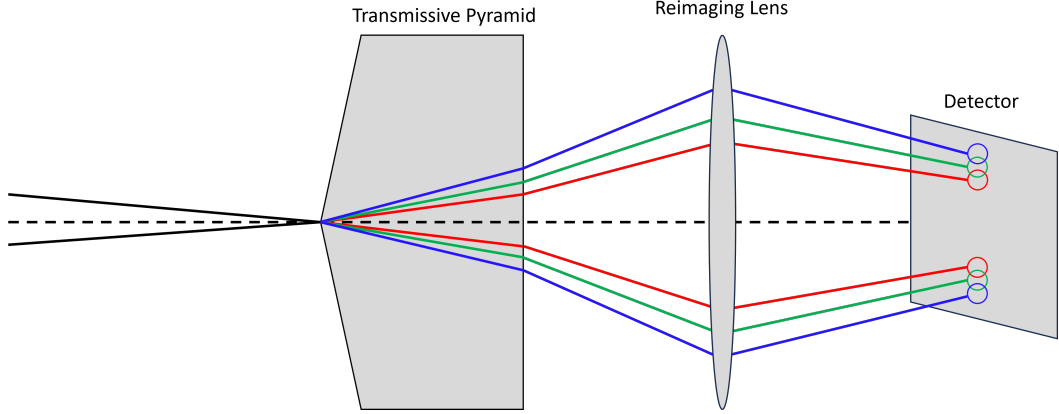


Figure 2.3: Block diagram illustrating the lateral chromatic dispersion in a traditional refractive PWFS. Due to wavelength-dependent refraction, polychromatic light experience dispersion when transmitting through the glass pyramid and results in chromatic pupil image shear. This chromaticity reduces sensitivity and complicates wavefront reconstruction in broadband applications.

Manufacturing the four-sided glass pyramid also presents challenges. The apex must be as sharp as possible to maintain sensitivity and avoid diffractive artifacts. In practice, small misalignments between prism faces often result in a roof-like structure rather than a true point apex (Fig.2.4)[36]. These imperfections skew the light distribution among the pupils and introduce signal degeneracies — particularly problematic in unmodulated configurations. To mitigate these effects, the focused PSF is typically made significantly larger than the apex imperfection scale, reducing sensitivity to the defect.

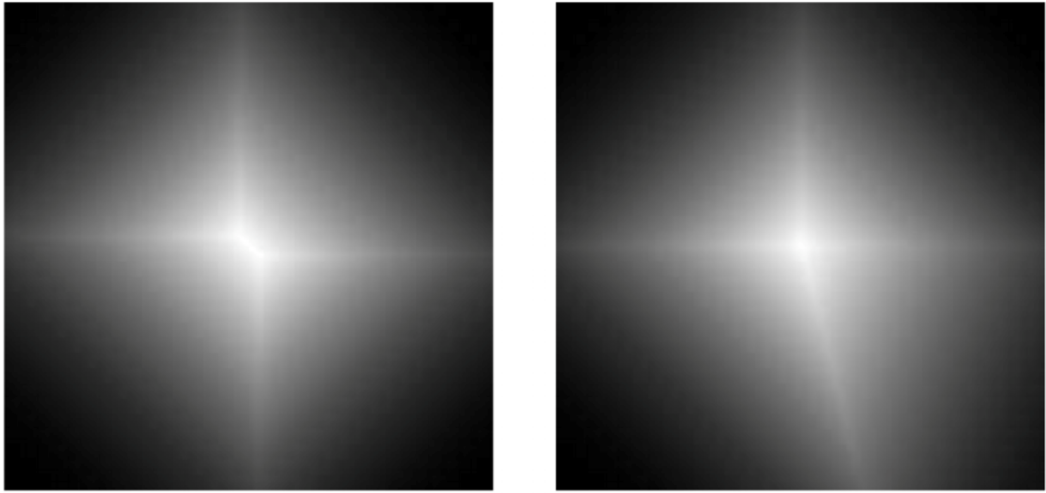


Figure 2.4: (Left) Misalignment of pyramid surfaces produces a roof-like feature rather than a sharp apex, causing asymmetric light distribution. (Right) Unequal crest alignment results in one side being larger than the others, further contributing to asymmetric pupil intensity. In both cases, these manufacturing imperfections introduce signals that can be degenerate with true wavefront aberrations, reducing the fidelity of wavefront sensing (Figure Credit: Fauvarque et al 2017).

To address fabrication challenges, an alternative configuration using orthogonally oriented roof prisms has been proposed. Separated by the depth of focus of the incident beam, this pair of prisms approximates the function of a four-sided pyramid without requiring a monolithic structure. Roof prisms are more straightforward to fabricate, offer better edge quality, and are less prone to chipping or misalignment, making them a practical substitute for traditional designs [37].

These limitations — chromatic dispersion, fabrication complexity, and reliance

on precise modulation optics — motivate the development of reflective pyramid architectures. The next section introduces a novel three-sided reflective pyramid wavefront sensor (3RPWFS), designed to address these challenges while retaining the high sensitivity and wavefront sensing capabilities of the traditional PWFS.

2.2 Motivation

The three-sided reflective pyramid wavefront sensor (3RPWFS), originally proposed by Mark Chun, was developed as a compact, achromatic alternative to the 4PWFS. Unlike the 4PWFS, which splits the incoming PSF into four pupil images, the 3RPWFS forms only three. This reduction in pupil count can yield a higher signal-to-noise ratio (SNR) in the readout noise-limited regime because fewer detector pixels are required to extract wavefront information.

In support of this approach, simulations comparing a 4PWFS and a 3PWFS — both transmissive — have shown only minor differences in performance under read-noise-limited conditions [38, 39]. These results suggest that a three-sided design may offer comparable wavefront sensing capability while simplifying the detector layout and reducing the photon budget required for accurate slope estimation.

From a theoretical standpoint, a three-sided pyramid is the minimum number of intersecting planes required to fully encode wavefront gradients in two dimensions. This is rooted in the origins of the PWFS itself, which evolved from the Foucault knife-edge test. In the classical Foucault configuration, a single edge provides differential

information along one axis, but cannot fully resolve two-dimensional wavefront structure. Adding a second orthogonal edge improves coverage, but still leaves ambiguities — particularly at the intersection. Only with a third edge, forming a point, can one define a unique solution for the localized intensity distribution and fully reconstruct the 2D wavefront.

In this sense, the three-sided pyramid serves as the simplest geometric shape that can produce complete 2D slope information through differential pupil illumination. It is not only theoretically sufficient but also easier to fabricate. Geometrically, three planes are the minimal number required to define a single point in space. This reduces the complexity of achieving a sharp, symmetric apex compared to the four-plane design, which is more sensitive to angular misalignments and fabrication defects. The increased manufacturability and potential SNR benefits make the 3RPWFS an attractive architecture for both ground-based and space-based AO systems.

2.3 Theory

The incoming electromagnetic field in the pupil plane can be written as:

$$\Psi_p = P(x_p, y_p) \exp [i\phi(x_p, y_p)], \quad (2.1)$$

where $P(x_p, y_p)$ represents the pupil function, and $\phi(x_p, y_p)$ is the wavefront phase. The focal plane field is related to the pupil field through a Fourier transform. For a circular unobstructed pupil, this yields an Airy pattern; in the case of the Shane Telescope, the pupil includes a central obscuration from the secondary mirror, resulting in a modified

PSF shape (see Fig. 2.6, 2.7).



Figure 2.5: Image of the 3-meter Shane Telescope in Lick Observatory.

Following the formalism described in [36], the pyramid mask can be described as a complex transmission function in the focal plane:

$$m(f_x, f_y) = a(f_x, f_y), \exp \left[\frac{2\pi i}{\lambda_{WFS}} M(f_x, f_y) \right], \quad (2.2)$$

where $a(f_x, f_y)$ is an amplitude mask (set to unity in the idealized case) and $M(f_x, f_y)$

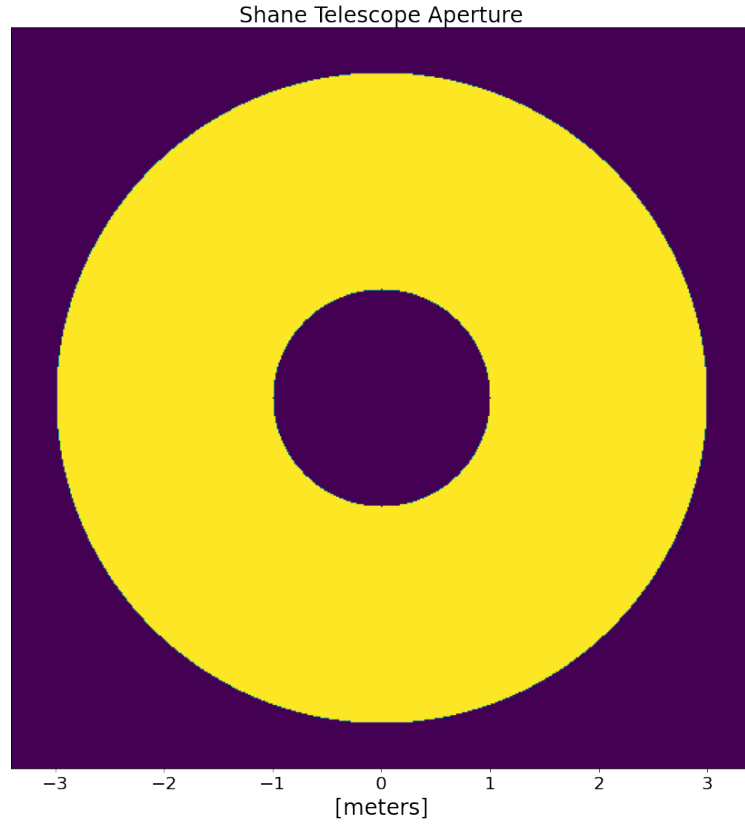


Figure 2.6: Pupil geometry of the Shane Telescope, modeled with a central obscuration ratio of 0.3. The annular aperture is used in AO simulations for the 3RPWFS. The outer diameter corresponds to the full telescope aperture, while the central obstruction represents the secondary mirror.

encodes the phase geometry of the pyramid structure. For a reflective pyramid wavefront sensor (RPWFS), M describes the surface height profile of the reflective faces. In simulations, assuming monochromatic light and a perfectly transparent mask, the RPWFS and PWFS are mathematically equivalent, with M representing phase shifts imparted by either transmission (in the 4PWFS) or reflection (in the RPWFS).

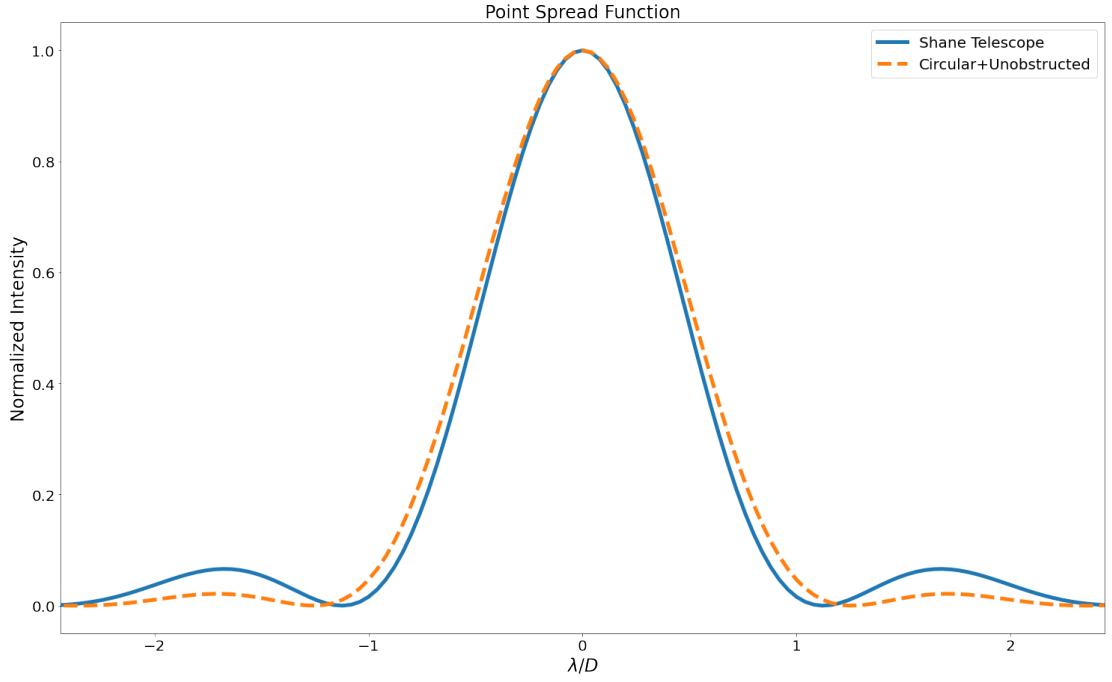


Figure 2.7: Cross-sectional profile of the point spread function (PSF) for the Shane Telescope aperture (blue), compared with the Airy pattern from a circular unobstructed pupil (orange, dashed). The two PSFs show high similarity near the core, while the Shane Telescope PSF exhibits slightly increased sidelobe intensity due to the central obscuration.

The field in the detector plane is the convolution of the pupil field with the Fourier transform of the phase mask:

$$\Psi_d = \Psi_p \circledast \mathcal{F}[m(f_x, f_y)], \quad (2.3)$$

and the resulting intensity recorded by the detector is:

$$I(x_p, y_p) = |\Psi_d|^2 = |\Psi_p \circledast \mathcal{F}[m]|^2. \quad (2.4)$$

This intensity distribution across the re-imaged pupil contains information about the input wavefront phase $\phi(x_p, y_p)$. The PWFS converts phase gradients into measurable intensity variations by spatially separating portions of the PSF in the focal plane. The number and orientation of pyramid faces—encoded in M —determine the number and geometry of the resulting pupil images. In the reflective case, each facet deflects the beam in a different direction, forming multiple pupil images on a common detector.

To enhance linearity and extend dynamic range, the PSF is typically modulated around the pyramid apex. In practice, this modulation is implemented with a fast steering mirror (FSM) that traces a circular or raster pattern in the focal plane. In simulations, modulation is modeled by averaging over a set of tip/tilt offsets applied to the PSF:

$$I_{\text{mod}} = \left\langle |\Psi_p \circledast \mathcal{F}[m_\delta]|^2 \right\rangle_\delta, \quad (2.5)$$

where m_δ represents the phase mask shifted by a small tip/tilt offset δ , and the angle brackets denote averaging over a modulation cycle. This process artificially enlarges the PSF footprint on the pyramid, reducing nonlinear effects and increasing the sensor's tolerance to large aberrations.

The measured intensity differences between the reimaged pupils encode the spatial derivatives of the wavefront. For small phase perturbations, these differences are approximately proportional to the local wavefront slopes:

$$\Delta I(x_p, y_p) \propto \nabla \phi(x_p, y_p). \quad (2.6)$$

This allows phase reconstruction using linear estimation or modal decomposition tech-

niques. Unlike the SHWFS, which samples the wavefront locally and independently in each sub-aperture, the PWFS globally mixes phase information across the entire pupil. This coherent mixing enhances sensitivity to small aberrations but also introduces strong nonlinearity at larger phase errors.

Overall, the PWFS performance depends on several critical parameters, including the apex sharpness, modulation radius, detector sampling, and the spectral bandwidth of the incoming light. In the next sections, we explore the implementation of this framework in a novel three-sided reflective geometry and evaluate its performance in simulation, laboratory, and on-sky environments.

2.4 Simulation

This section presents simulation results for a 3RPWFS intended for integration into the Shane Telescope’s adaptive optics module (ShaneAO). The goal of these simulations is to assess expected performance, inform optical design choices, and determine system parameters for future on-sky testing. Simulations were conducted using the HCIPy Python package, which provides a modular environment for modeling high-contrast imaging and wavefront control systems. A key performance metric in this analysis is the Strehl ratio (S), evaluated over 1-second exposures.

2.4.1 Assumptions

The simulation parameters are based on the specifications of the ShaneAO system at Lick Observatory on Mount Hamilton, California. The Shane Telescope is

a 3-meter optical telescope with typical seeing values typically ranging from 1-1.5". To model realistic atmospheric conditions, the simulations include a multi-layered Kolmogorov turbulence profile with scintillation.

The WFS arm operates in the 600–900 nm bandpass, selected using a dichroic mirror. The detector used in the simulation is a Lincoln Laboratories CCID66, which has a quantum efficiency (QE) of approximately 80% in this range and a read noise of 5.1 electrons per pixel. The science wavelength is assumed to be 2.2 μm (K-band), and the WFS operates at 750 nm. A full summary of simulation parameters is provided in Table 2.1.

Table 2.1: HCIPy Simulation Parameters.

Science Wavelength (λ_{obs})	2.2 μm
WFS Wavelength (λ_{WFS})	750 nm
Telescope Diameter (D_T)	3 m
Fried Parameter (r_0)	7.5 cm, 11 cm
Transmission (T)	50%
Quantum Efficiency (QE)	0.8
Read Noise (N_r)	5.1 e-
Number of DM actuators (n_{act})	121 (11x11)
Modulation Steps (n_{steps})	18
Number of AO Time Steps (t_{steps})	200

The ShaneAO system employs a two-stage deformable mirror (DM) setup using a woofer-tweeter configuration. To simplify the simulation architecture, we approximate this configuration using a single DM modeled after the ALPAO DM97, featuring a rectilinear 11 $\times$ 11 actuator array. This simplification allows us to approximate closed-loop behavior with a single correction layer. A detailed discussion of on-sky loop closure

with this sensor is provided in Sec. 2.8.

2.4.2 Modulation Radius

The PWFS’s sensitivity and linear dynamic range are controlled with the modulation radius (r_{mod}), which defines the lateral displacement of the PSF around the pyramid apex. A smaller r_{mod} results in higher sensitivity to small aberrations but reduced tolerance for large wavefront errors, while a larger r_{mod} increases linear range at the cost of sensitivity. Maximum sensitivity is achieved at $r_{mod} = 0$, or the unmodulated PWFS.

In the case of ShaneAO, optical and mechanical constraints preclude reflective modulation adjustment during operation. Therefore, we simulate system performance across a fixed range of r_{mod} values to determine an optimal setting. Simulations were performed assuming 1.5 arcseconds seeing—representing a conservative scenario for Lick Observatory.

Simulation results in Fig. 2.8 show that S performance peaks for modulation radii between $3\text{--}7 \lambda/D$. Outside this range, performance degrades due to either insufficient sensitivity (at high r_{mod}) or insufficient linearity (at low r_{mod}). To balance these effects, we select $r_{mod} = 5 \lambda/D$ for subsequent simulations and proposed on-sky testing, as it offers robust performance under both favorable and adverse seeing conditions.

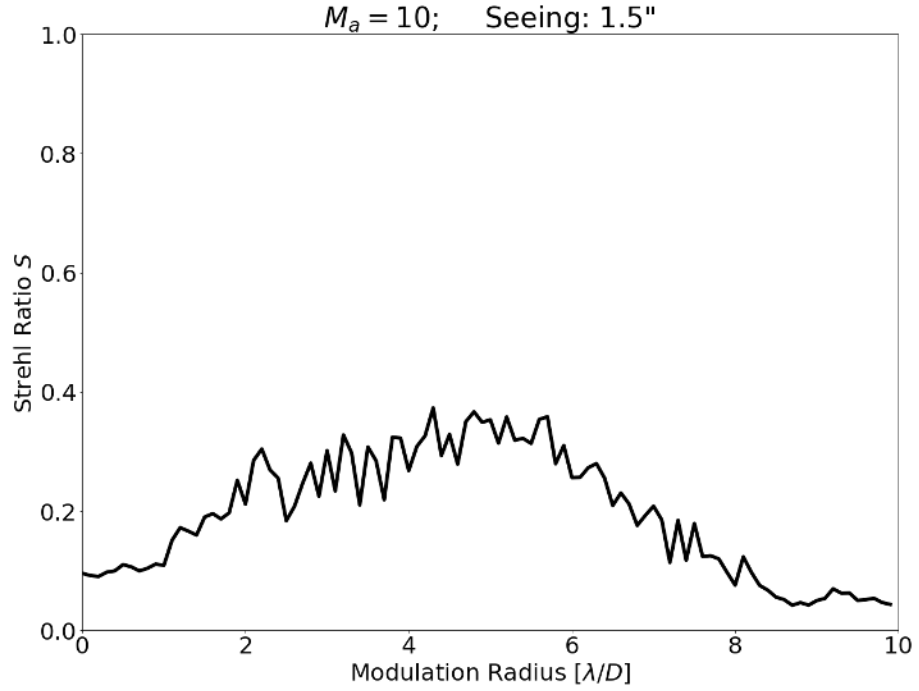


Figure 2.8: Simulated S as a function of modulation radius for the 3RPWFS under 1.5 arcsecond seeing.

2.4.3 Limiting Guide Star Magnitude

To evaluate faint-end performance of the 3RPWFS, we simulate S as a function of guide star magnitude (M_a) and wavefront sensor frame rate. For reference, ShaneAO’s existing SHWFS achieves $S \approx 0.6$ at $M_a = 10$ under good conditions.

As M_a increases (i.e., dimmer stars) SNR decreases due to lower incident light, particularly in the read-noise-limited regime. To mitigate this, we simulate 3RPWFS operation at 100 Hz and 500 Hz—two feasible speeds for the CCID66 detector. Reducing frame rate increases photon collection per frame, enhancing sensitivity for faint stars,

though at the cost of temporal bandwidth. This ultimately lowers the performance ceiling, but increases the performance floor and achieves decent AO performance.

Results are shown in Fig. 2.9. At 500 Hz, the 3RPWFS achieves $S \geq 0.4$ for guide stars with $M_a \leq 11$, comparable to current SHWFS performance. At 100 Hz, performance improves for fainter targets, reaching $S = 0.51$ at $M_a = 11$ and maintaining $S \geq 0.2$ for $M_a \leq 13$. These results indicate that the 3RPWFS can extend ShaneAO’s faint star limit by more than one magnitude without sacrificing performance at the bright end.

S values below 0.2 are generally not considered reliable for analytical or empirical interpretation due to their poor PSF quality. Nonetheless, the ability to maintain $S \geq 0.2$ for $M_a = 13$ suggests the 3RPWFS could operate on a significantly larger fraction of sky than the current SHWFS, particularly at lower frame rates.

2.5 Optical Design

2.5.1 Concept

Traditional PWFSs employ a focusing optic to image the PSF of a guide star onto the apex of a transmissive four-sided glass pyramid. A relay system then re-images the four resulting pupils onto a detector, forming the basis for wavefront slope estimation. This configuration benefits from a shared optical axis: all elements in the system, from input to detector, operate within a common coordinate frame without reflection or beam folding. As a result, the optical axis remains undeviated throughout

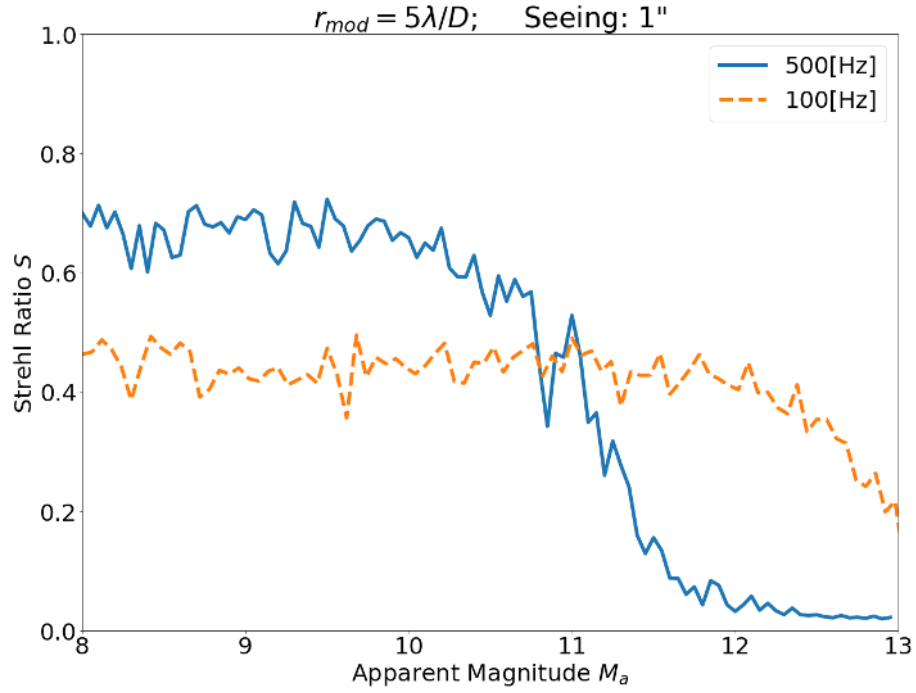


Figure 2.9: Strehl ratio versus guide star magnitude at 100 Hz and 500 Hz frame rates. The lower speed enables deeper limiting magnitude at the cost of temporal resolution. Current ShaneAO capabilities allows for 100-500 Hz loop speeds using the 8x and 16x SHWFS.

the system, which simplifies alignment and integration.

In contrast, the RPWFS is a completely reflective system. As shown conceptually in Fig. 2.10, light is redirected by mirrors and reflected from the pyramid surface, rather than transmitted. After the initial re-imaging optic—which is shown as transmissive, but can just as easily be reflective—focuses the PSF onto the reflective apex, the pyramid reflects the light back toward the upstream optics. This reflection includes

the three diverging pupil beams that encode the wavefront information.

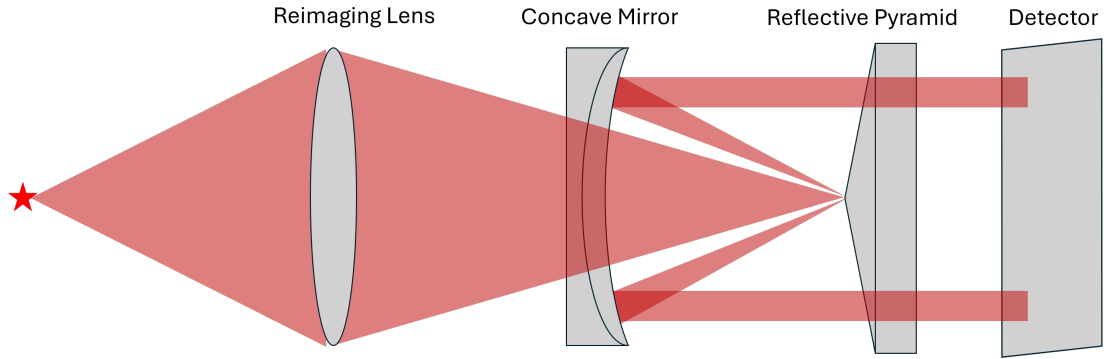


Figure 2.10: Proposed optical layout of a RPWFS. Light from the telescope is focused onto the apex of a three-sided reflective pyramid, where the incoming beam is split into multiple pupils upon reflection. The diverging beams are then recollimated and collimated by a re-imaging lens to form separated pupil images downstream. Both the reflective pyramid and the re-imaging mirror have drill holes to allow the incoming and outgoing beams to pass through without vignetting, ensuring unobstructed pupil formation and compact optical packaging.

A naive approach might suggest placing a dedicated detector behind each reflected pupil beam. However, such a design is inefficient in both space and resources. Instead, a single-detector configuration is preferred. To achieve this while maintaining a compact, collinear optical path, we introduce a concave mirror to re-collimate the reflected beams. This concave mirror functions analogously to the re-imaging lens in transmissive PWFS designs but operates in reflection.

To allow unvignetted access to the pyramid apex, the concave mirror is fabri-

cated with a central through-hole at its vertex. This enables the incident $F/21.08$ beam to focus onto the apex without obstruction. Similarly, the pyramid substrate must be drilled with three symmetrically spaced holes — one corresponding to each of the reflected pupil beams — to allow their passage toward the re-imaging optics and detector. These through-holes are aligned parallel to the system’s optical axis and are sized to accommodate the full extent of the beam envelope after reflection.

This architecture forms the foundation of the 3RPWFS optical design. It preserves an undeviated optical axis while ensuring that all three pupils are simultaneously reimaged onto a single detector. This is a key requirement for integration with the existing ShaneAO system, which has limited optomechanical degrees of freedom and strict spatial constraints.

2.5.2 Motivating Parameters

The optical design of the 3RPWFS is governed by a set of key performance constraints, primarily dictated by the ShaneAO module’s existing infrastructure and operational requirements. Table 2.2 summarizes the relevant specifications of the ShaneAO system, while Table 2.3 outlines the design targets for the 3RPWFS.

Within ShaneAO, the DM architecture consists of a two-stage system: a low-order woofer DM with 6 actuators across the pupil and a high-order tweeter DM with 32 actuators across the pupil diameter. To ensure that the 3RPWFS is capable of resolving wavefront distortions at the level of the tweeter DM, we select a pupil sampling of 30 pixels across the diameter. This choice ensures adequate pupil sampling while

minimizing footprint and still fit within the WFS detector.

Given the 30-pixel sampling and a detector pixel size of 21 μm , the projected pupil diameter on the detector must be 0.63 mm. Furthermore, since the 3RPWFS splits the input beam into three pupil images, all three pupils must be accommodated within the detector’s active area without vignetting. The detector, a 160 x 160 pixel format sensor, provides sufficient space provided the optical design constrains the beam footprints appropriately.

The operating wavelength band for ShaneAO’s wavefront sensor is 600–900 nm, covering the visible regime where the atmospheric turbulence induced phase aberrations. A representative wavelength of 632.8 nm, corresponding to a HeNe laser, is used as the reference wavelength for optical design and optimization in Zemax.

In terms of mechanical layout, the ShaneAO WFS assembly is constrained by a maximum optical track length of 226.35 mm between the focal point of the incoming telecentric F/21.08 beam and the wavefront sensor detector. This defines the maximum allowable space for all optical components in the 3RPWFS path. Table 2.2 lists the key geometric and detector parameters, while Table 2.3 presents the derived optical performance goals.

Table 2.2: ShaneAO Specifications.

Pixel Size	21 μm
Detector Dimensions	160 x 160 pixels
Available Track Length	226.35 mm

Table 2.3: Optical Design Requirements.

Pixel Sampling	30 pixels per pupil
Pupil Diameter	0.63 mm
Wavelength Coverage	500–900 nm

Additionally, the optomechanical design must coexist with two SHWFS modes already housed in ShaneAO. These sensors are mounted in parallel within a v-groove rail system (Fig. 2.11). The 3RPWFS must not mechanically interfere with these existing modules or their support structures, including the field stop and detector housing. The minimum clearance between neighboring OTAs, determined from existing SHWFS modules (Fig. 2.12), provides a baseline for spatial integration of the 3RPWFS OTA.

Figures 2.11, 2.12, and 2.13 illustrate the current mechanical layout and the projected integration of the 3RPWFS. These considerations strictly constrain the available footprint and necessitate a compact and collinear optical path.

2.5.3 Working F-number

In the ideal case, the RPWFS would feature a perfectly sharp apex and edge intersections, such that incident light reflects cleanly from well defined planar surfaces. In this configuration, the apex effectively behaves as a geometric point with negligible surface area, and the edges form mathematically exact lines. This minimizes diffractive scatter and ensures that all incoming light is split and directed cleanly into the desired pupil images for downstream detection.

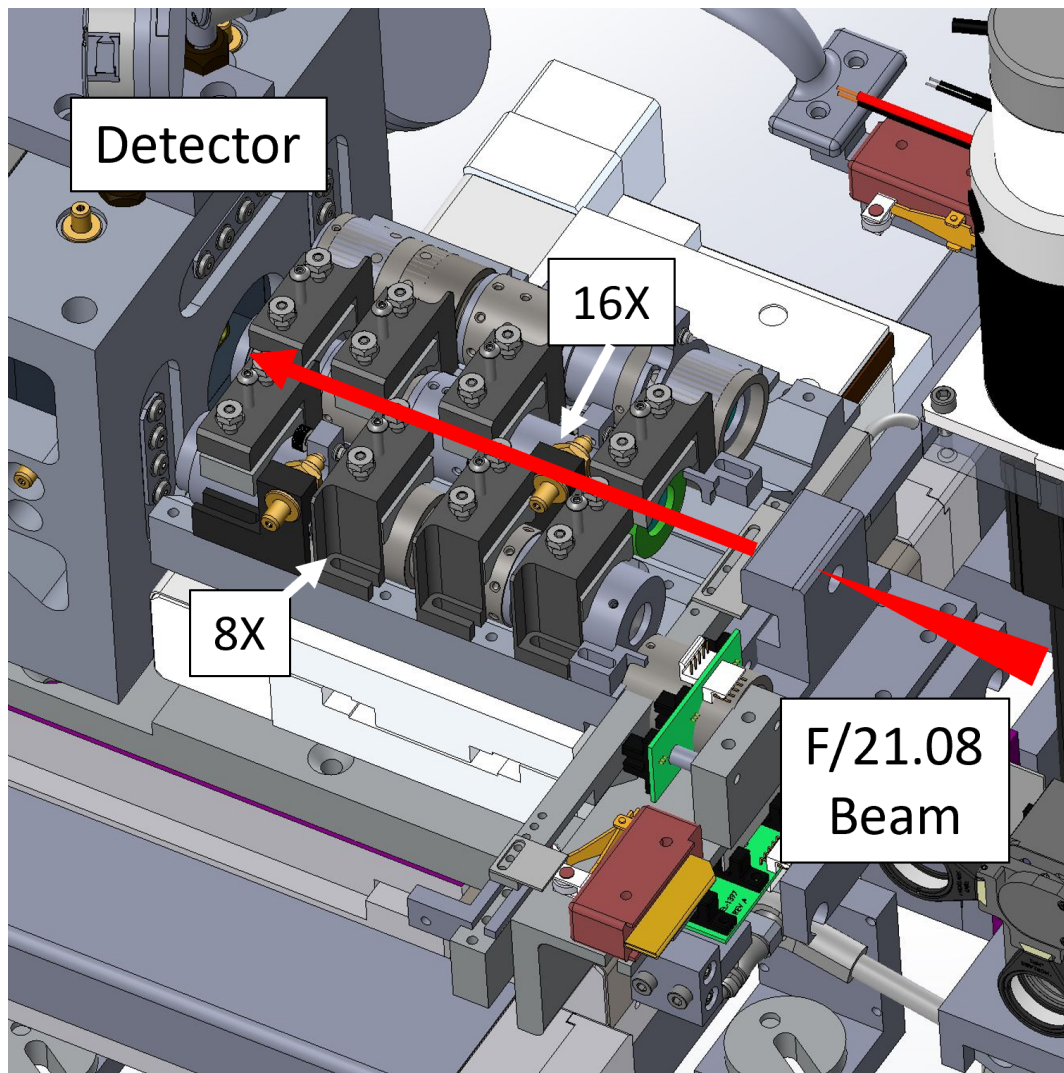


Figure 2.11: Schematic of the ShaneAO v-groove rail assembly for mounting multiple wavefront sensor modes.

However, practical fabrication techniques impose limitations. In reality, the sharpness of the apex and its intersecting edges are constrained by the machining tolerances achievable with standard optical polishing or diamond-turning methods. Rather

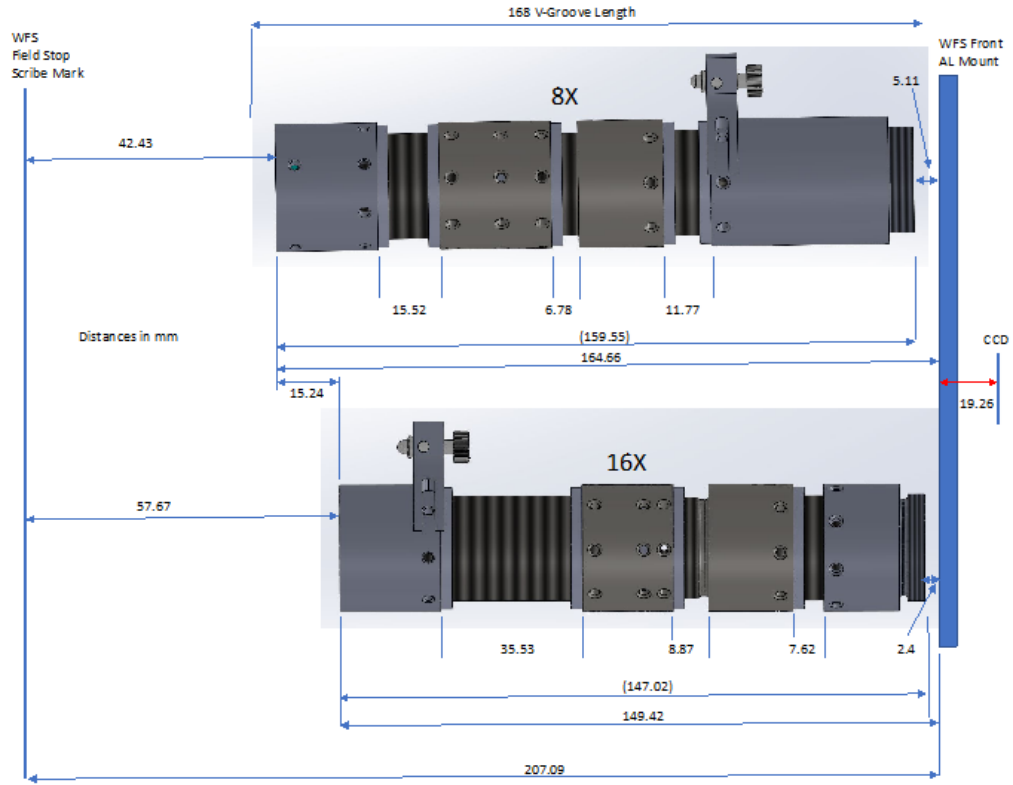


Figure 2.12: Clearance configuration between the dual SHWFS OTAs. The minimum inter-OTA spacing serves as a constraint for 3RPWFS integration (Figure Credit: Daren Dillon; Renate Kupke).

than converging to an infinitesimal point, the three reflective surfaces terminate in a rounded apex with a finite radius of curvature, denoted d_r . This non-ideal geometry can substantially degrade optical throughput.

From a geometrical optics perspective, any portion of the focused beam that falls within the rounded apex area will be reflected at undefined angles or scattered outside the capture cone of the re-imaging optics. If the focal spot size is comparable

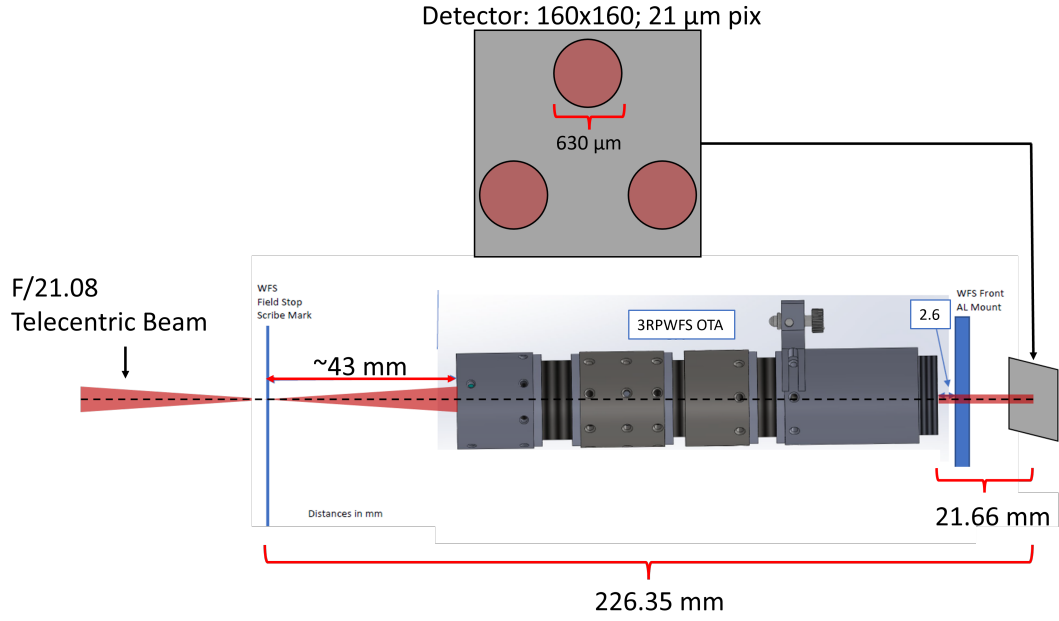


Figure 2.13: Modeled clearance envelope for the proposed 3RPWFS OTA within the ShaneAO v-groove WFS stage.

to the apex diameter, a significant fraction of the wavefront may not be redirected into the pupil-forming directions, leading to signal loss. From a wave optics standpoint, the rounded apex acts as a spatial filter that suppresses high spatial frequencies and redistributes energy outside of the primary pupil footprints. This manifests as a loss in SNR and a potential failure to recover high-order aberration terms—especially problematic when working with faint guide stars (Fig 2.14).

To mitigate these losses, the focused beam must be sufficiently wide relative to the apex imperfection. Specifically, the Airy disk diameter (d_s) of the focused spot must be large enough such that most of the energy avoids the rounded region. This

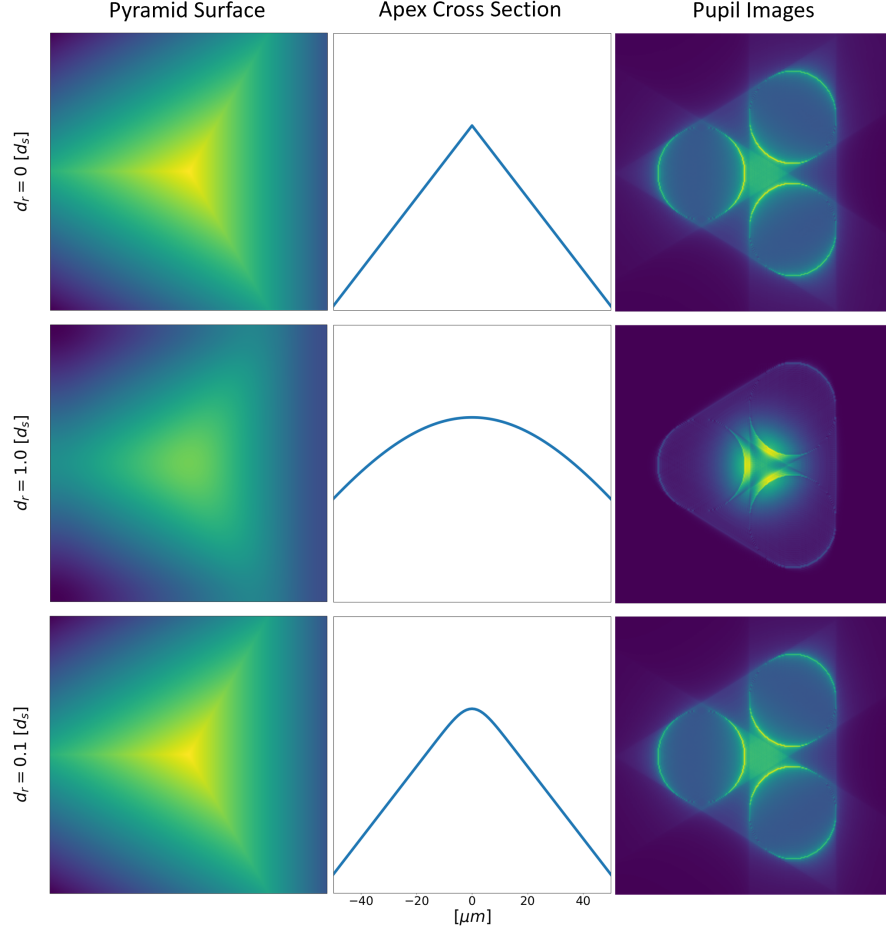


Figure 2.14: Simulated impact of apex rounding on the resulting pupil images of a 3PWFS. Each column illustrate the pyramid mask M (left), the one-dimensional cross-section of the apex profile (center), and the corresponding pupil image (right). The top row represents an infinitely sharp apex. The middle row corresponds to an apex roundness diameter that is equal to the PSF core ($d_r = d_s$). The bottom row shows an intermediate case with negligible rounding $d_r = \frac{1}{10}d_s$, which preserves performance while easing fabrication constraints.

motivates the use of a slower working f-number ($f/\#_w$), which increases the focal spot size at the cost of total system length. A trade study was conducted to quantify the relationship between throughput and $f/\#_w$, given a conservative estimate of d_r .

Assuming that all light incident within a diameter d_r is lost, the throughput was modeled by attenuating the PSF core with a top-hat mask. The PSF was computed as a diffraction-limited Airy pattern for a circular aperture at a wavelength $\lambda_H = 632.8\text{nm}$. To ensure convergence, the PSF was sampled to include energy out to the fourth zero ring, capturing approximately 95% of the total intensity. The mask representing the rounded apex was applied multiplicatively to the PSF (Fig.2.15), and throughput was calculated as the ratio of the integrated filtered PSF to the total unfiltered PSF.

The results of this simulation are shown in Fig.2.16, which plots throughput as a function of both d_r and $f/\#_w$. Manufacturers using precision diamond turning techniques quote typical apex rounding diameters of $d_r = 10\mu\text{m}$. At this threshold, an $f/\#_w$ of approximately 50 is required to maintain a throughput of at least 70%, which we adopt as the minimum acceptable value for science operations. This 70% threshold reflects a practical trade-off between sensitivity, integration time, and acceptable guide star magnitude.

Although increasing $f/\#_w$ further would improve throughput, it also increases the spot size d_s and therefore the back focal distance (BFD) required to capture the full PSF without vignetting. The total track length of the AO optical system is fixed at 226.35mm, which places an upper limit on $f/\#_w$ and BFD. The resulting spot size

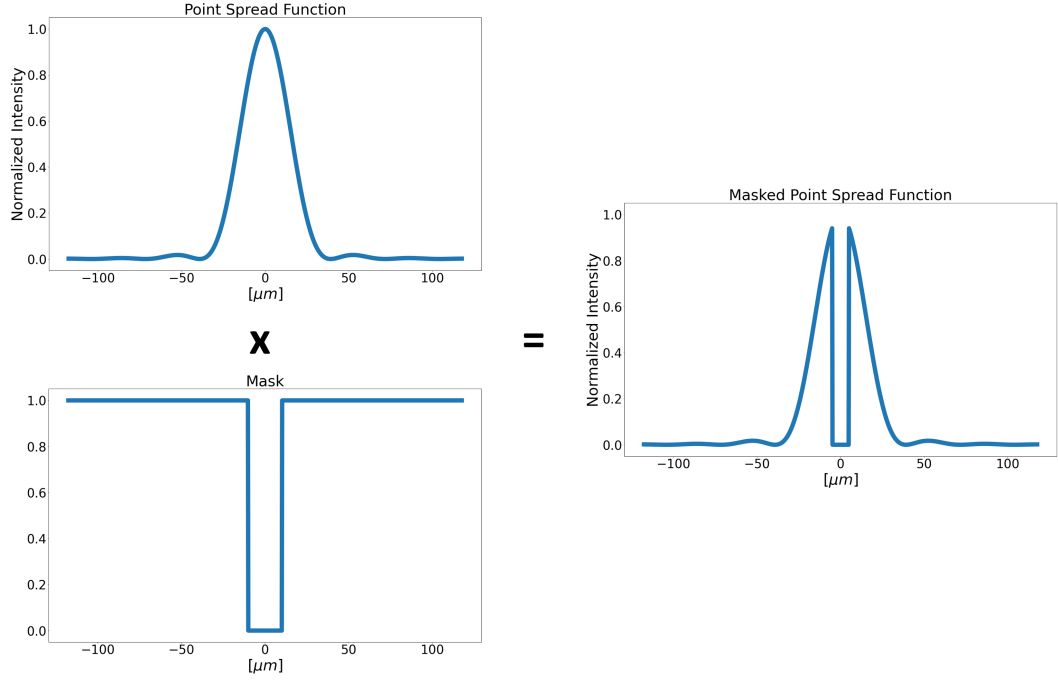


Figure 2.15: Diffraction-limited PSF (left) and its attenuation using an opaque top-hat mask (right), simulating light loss from a rounded reflective pyramid apex.

using λ_H and $f/\#_w = 50$ is calculated to be $77.2\mu\text{m}$.

Microscope images of a fabricated 3-sided reflective pyramid, provided by CMM Optic, are shown in Fig.2.17. These images suggest that the true apex roundness is in fact smaller than the quoted $10\mu\text{m}$, indicating even sharper apex formation and a better-than-expected fabrication outcome.

2.5.4 Re-imaging Lens

To achieve the desired $F/50$ beam at the reflective pyramid apex, the incoming telecentric $F/21.08$ beam from ShaneAO must be reimaged using an optical element of

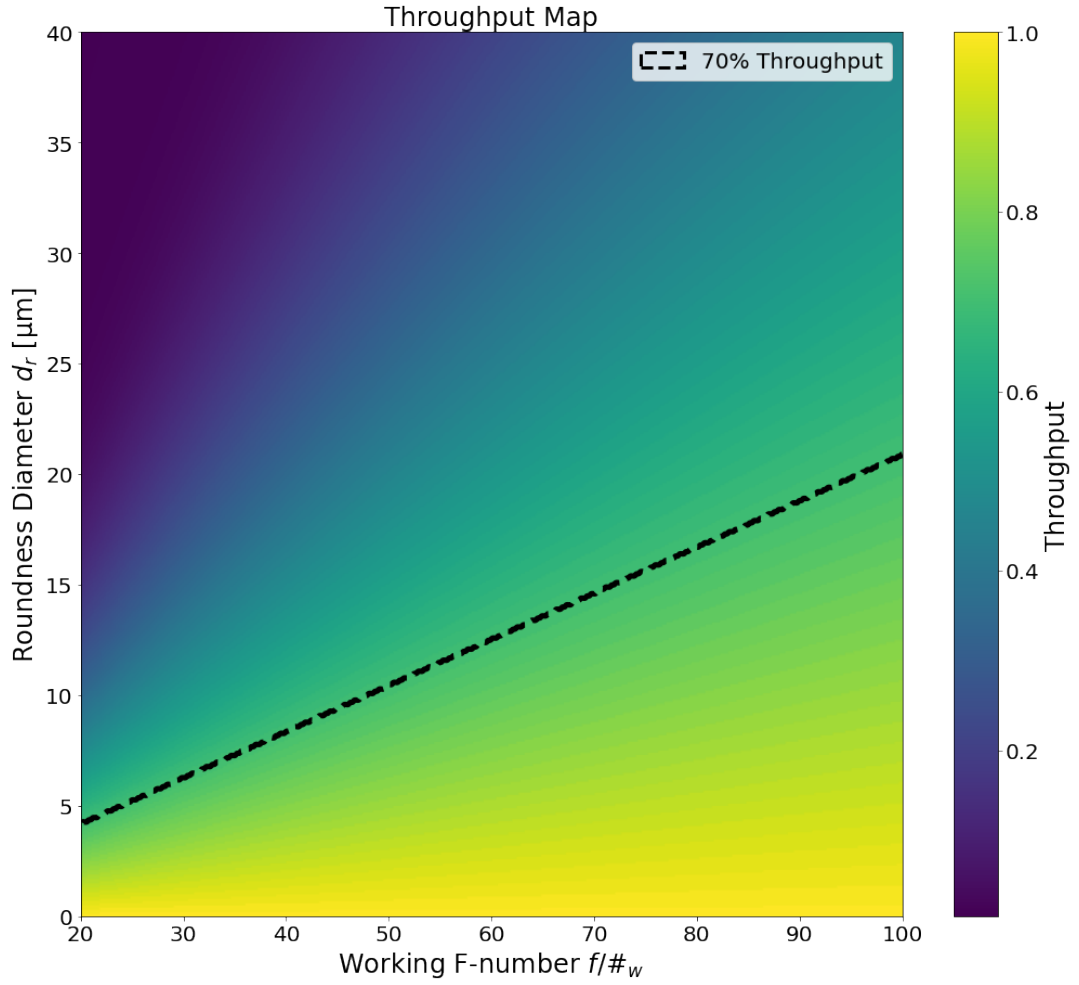


Figure 2.16: Simulated throughput as a function of apex rounding diameter (d_r) and working f-number ($f/\#_w$). Higher f-numbers lead to larger PSFs, reducing light loss to the rounded apex.

suitable power. This section details the derivation of the lens parameters using thin lens approximations, while also accounting for spatial constraints imposed by the existing ShaneAO optomechanical layout.

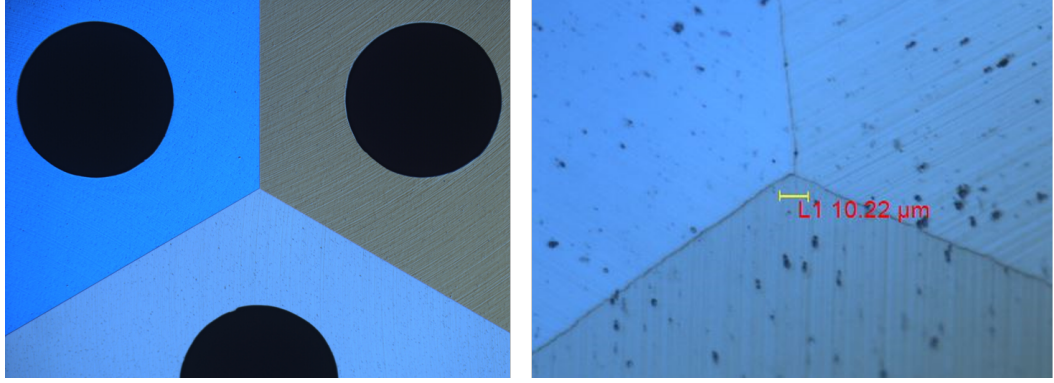


Figure 2.17: (Left) Microscope image of the fabricated 3-sided reflective pyramid. (Right) Close-up view showing apex quality, illustrating $<10 \mu\text{m}$ apex rounding.

The AO bench imposes a critical physical constraint: a minimum axial clearance of 45 mm between the final focusing location of the $F/21.08$ beam and the entrance surface of the re-imaging lens. This ensures mechanical compatibility with field stops and other structural elements. Using this distance as the object distance z in the thin lens equation:

$$\frac{1}{f} = \frac{1}{z'} - \frac{1}{z}, \quad (2.7)$$

aims to solve for the focal length f of the re-imaging lens, which we denote as f_1 . To do this, relate the desired change in $f/\#$ to the angular magnification m via the slope of marginal rays U and U' in object and image space:

$$m = \frac{z'}{z} = \frac{U}{U'}, \quad (2.8)$$

where U and U' are related to the numerical apertures (NAs) of the incident and out-

going beams by:

$$NA = \frac{1}{2 \cdot F/\#_w}, \quad (2.9)$$

$$NA = n \cdot \sin(U), \quad (2.10)$$

assuming air ($n \approx 1$). Substituting $F/21.08$ and $F/50$ yields U and U' , and thus a magnification $m \approx -2.37$. With $z = -45$ mm, the resulting image distance $z' \approx +106.7$ mm, which then determines the focal length as:

$$f_1 = \left(\frac{1}{z} + \frac{1}{z'} \right)^{-1} \approx +31.7 \text{ mm}. \quad (2.11)$$

While increasing $f/\#_w$ might improve throughput (as discussed in Sec. 2.5.3), doing so would also increase z' , lengthening the optical path beyond the 226.35 mm track length available in ShaneAO. Thus, a compromise of $f/\#_w = 50$ is selected as an optimal balance between performance and spatial constraints.

A custom triplet lens, designated L_1 , is designed with this 31.7 mm focal length to generate the $F/50$ beam. The lens is optimized in Zemax for diffraction-limited performance across the 600–900 nm bandpass. Fig. 2.18 shows the Zemax layout of the triplet assembly, including the transmissive modulating wedge. The optical performance, assessed with spot diagrams and RMS wavefront error across the field, is shown in Figs. 2.19 and 2.20.

Note that although ShaneAO has a 20" FOV, the RPWFS FOV is restricted to 0.74", or $14\lambda_H/D$, to avoid vignetting by downstream optics (Sec. 2.5.6). Nonetheless, L_1 is designed to be diffraction-limited across the full 20" field as a future-proofing measure (Fig. 2.21 and 2.22).

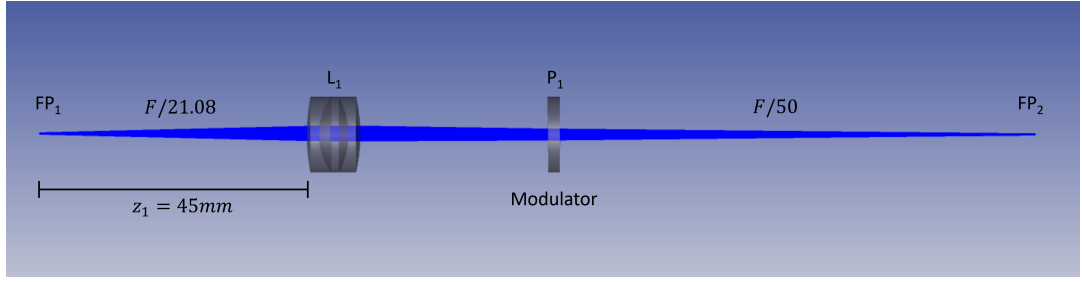


Figure 2.18: Zemax model of the custom triplet re-imaging lens (L_1), used to transform the incoming $F/21.08$ beam to $F/50$. The modulator wedge is placed at the reimaged pupil position.

2.5.5 Modulator

In pyramid wavefront sensors, variable sensitivity and linear dynamic range are achieved through modulation—typically by oscillating the focal spot around the pyramid apex. This is commonly implemented using fast steering mirrors (FSMs), which introduce small, high-speed angular displacements in the pupil plane. However, to preserve the undeviated optical axis of the 3RPWFS, we introduce an alternative modulation strategy using a transmissive glass wedge.

As illustrated in Fig. 2.23, the glass wedge is positioned at the exit pupil of the re-imaging triplet lens L_1 . This location is chosen to minimize lateral shifts of the reimaged pupils during modulation. When placed at this pupil conjugate plane, the wedge induces angular tilts in the converging beam without significantly altering the spatial alignment of the pupil images on the detector.

The wedge functions similarly to a shear plate or prism: the angled surface

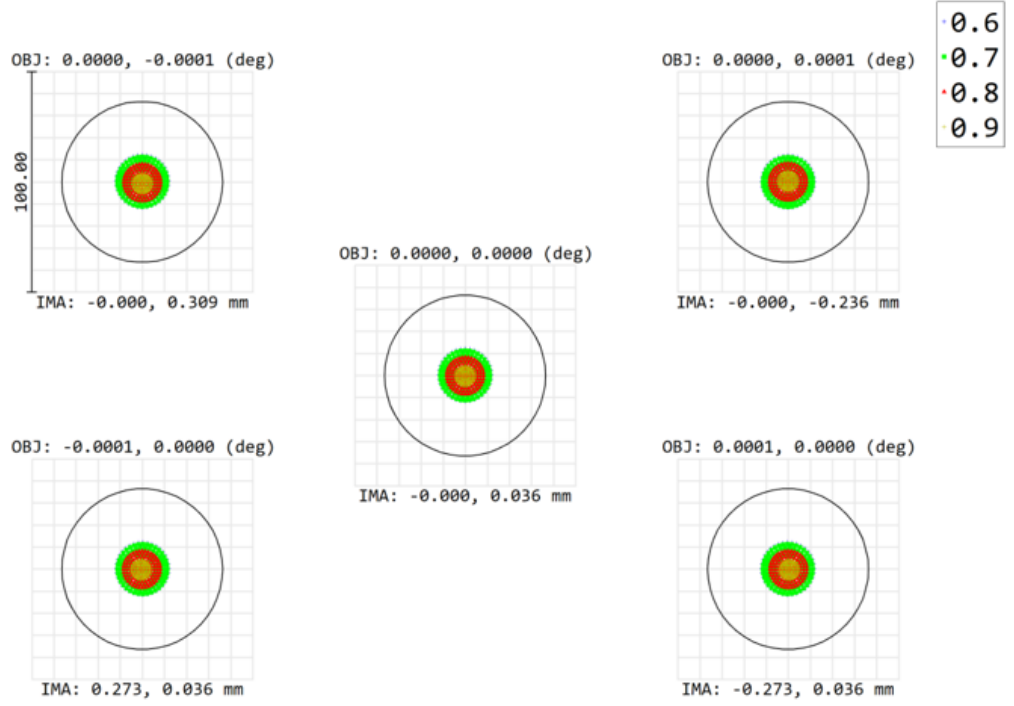


Figure 2.19: Spot diagrams of the re-imaging triplet at multiple field positions, illustrating diffraction-limited performance across the narrow RPWFS field.

introduces a small deviation in the chief ray proportional to the wedge angle and refractive index. As the wedge is rotated about the optical axis, it sweeps the PSF in a circular path over the apex, producing circular modulation. The modulation radius is primarily controlled by the wedge's angle, and is fixed for a given wedge.

Using the modulation radius value $r_{\text{mod}} = 5 \cdot \frac{1.22\lambda}{D}$ determined in Sec. 2.4.2, and the separation between the exit pupil and the focal plane ($t_{\text{sep}} = |z'_1| - |\text{EP}|$), the

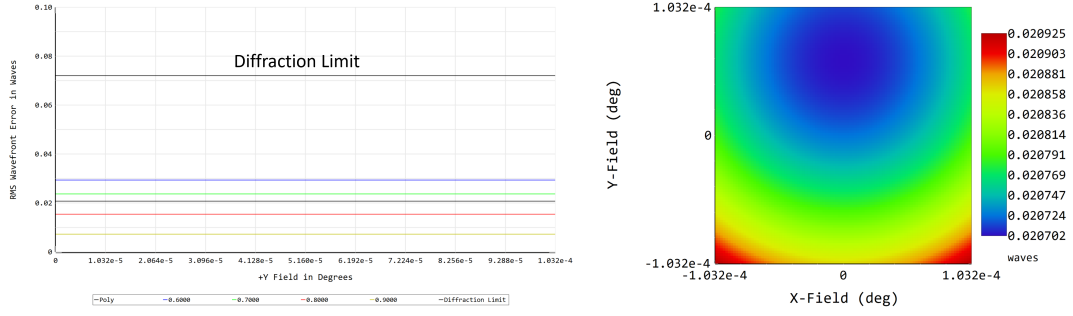


Figure 2.20: RMS wavefront error vs. field position for the triplet lens, confirming image quality within the RPWFS's FOV.

required angular deviation δ introduced by the wedge is:

$$\delta = \arctan\left(\frac{r_{mod}}{t_{sep}}\right) \quad (2.12)$$

This angular deviation is wavelength-dependent due to dispersion in the glass, introducing chromatic modulation errors.

To minimize chromatic effects, an achromatic wedge system could be constructed by combining two materials with different Abbe numbers ν and refractive indices n :

$$\frac{\alpha_1}{\delta} = \left(\frac{1}{\nu_2 - \nu_1}\right) \left(\frac{\nu_1}{n_1 - 1}\right) \frac{\alpha_2}{\delta} = \left(\frac{1}{\nu_2 - \nu_1}\right) \left(\frac{\nu_2}{n_2 - 1}\right) \quad (2.13)$$

However, to simplify implementation and reduce costs, only a single BK7 wedge is used in this design. Chromatic aberrations introduced by this wedge are compensated in the triplet lens optimization (Sec. 2.5.4).

The relationship between the deviation angle δ , the wedge angle α_w , and the

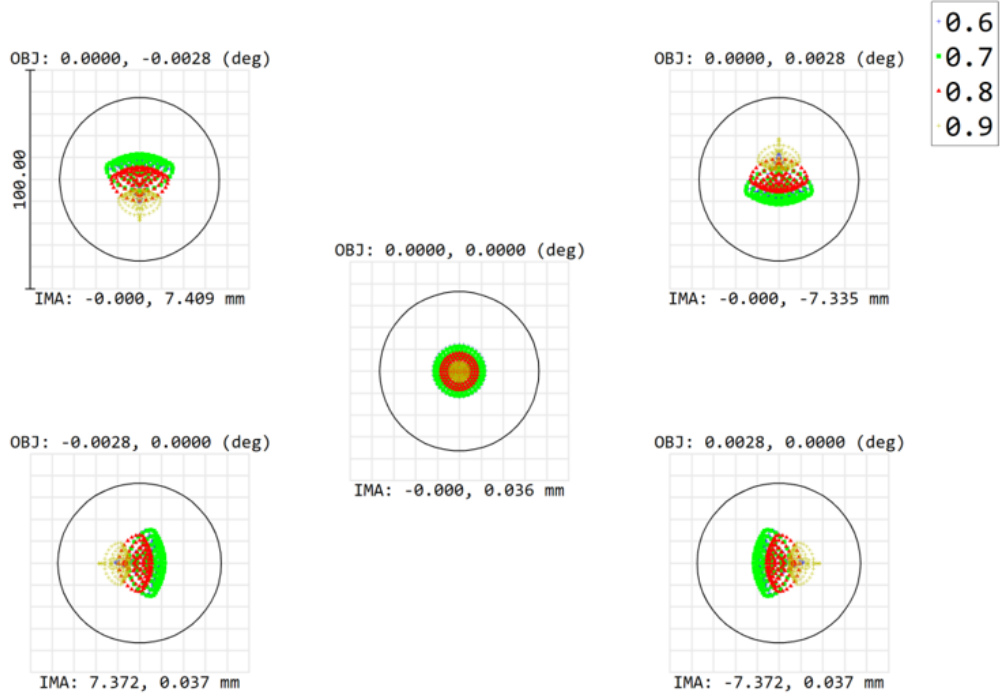


Figure 2.21: Spot diagrams of the triplet lens across the full 20° field, illustrating diffraction-limited design for future scalability.

refractive index $n(\lambda)$ is given by:

$$\delta = (n(\lambda) - 1)\alpha_w \quad (2.14)$$

Solving this equation allows us to select a wedge angle α_w appropriate for the design wavelength $\lambda = \lambda_H = 632.8\text{nm}$, which lies within the WFS bandpass of 500–900nm.

A notable limitation of wedge-based modulation is that the modulation radius is fixed for a given wedge. In contrast, FSMs allow continuous adjustment of the modulation radius. To overcome this limitation while maintaining the undeviated optical

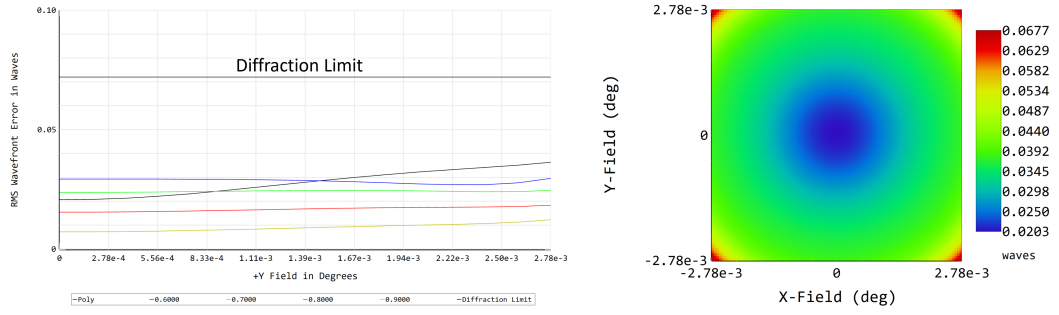


Figure 2.22: RMS wavefront error vs. field for full 20" FOV, verifying high image quality across the broader field of the triplet lens.

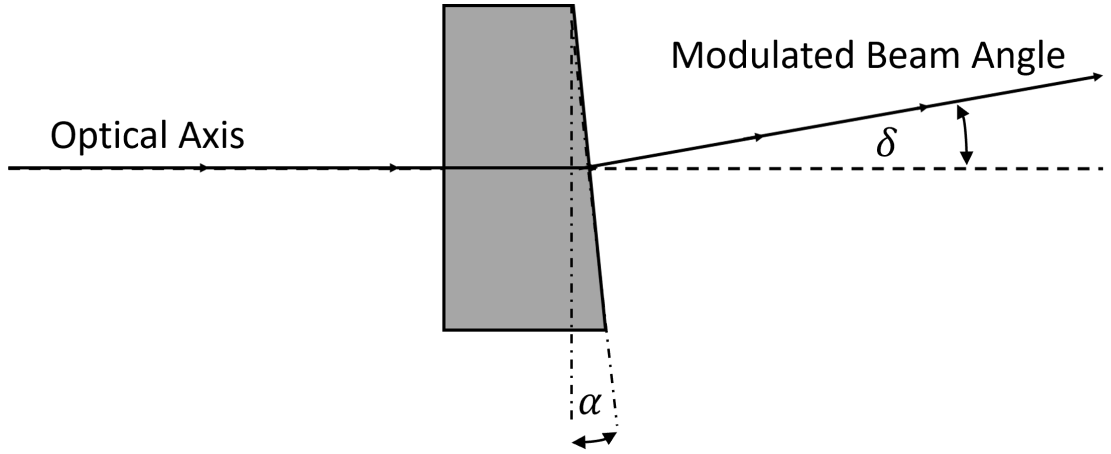


Figure 2.23: Above is a block diagram illustrating the modulating wedge. This diagram shows how the chief ray is deviated from the shear surface, effectively creating a tilt. Rotating this circular wedge will produce a circular modulation, with its radius being dependent on the shear angle.

axis, we propose a discrete modulation mechanism: a chopper-wheel assembly. This mechanism holds multiple wedges with varying shear angles. By rotating the wheel to

insert a specific wedge into the beam path and spinning it around the optical axis, different modulation radii can be achieved in a modular and repeatable manner. Each wedge is balanced for optical quality, and residual aberrations are accounted for in the design of the re-imaging optics. Considering the tight mechanical restrictions in ShaneAO, this will not be implemented and the 3RPWFS will have only one modulation radius mode.

This approach offers a compact, passive modulation scheme compatible with the reflective 3RPWFS architecture and avoids the complexity and alignment sensitivity of FSM-based systems.

2.5.6 Re-imaging Mirror

To form distinct pupil images after reflection from the pyramid apex, the 3RPWFS requires a re-imaging optic that captures and collimates the diverging rays. This is analogous to the transmissive pupil imaging lens in a traditional PWFS. However, because the 3RPWFS uses reflective optics to maintain an undeviated optical axis, a concave mirror is used for this re-imaging task.

The three pupil images are reflected from the three faces of the pyramid. To capture and redirect these beams toward downstream imaging optics, the re-imaging mirror must be carefully designed to satisfy several criteria:

- Collimate each of the diverging pupil beams and avoid vignetting.
- Provide sufficient mechanical clearance for both the incoming focusing beam and the outgoing reimaged beams.

- Be compact enough to fit within the 226.35 mm optical track length of the ShaneAO module.
- Avoid additional off-axis aberrations, particularly coma and astigmatism, introduced by misaligned reflective surfaces.

2.5.6.1 Design Configuration

A parabolic concave mirror is chosen due to its ability to collimate on-axis beams without introducing spherical aberration. This is especially advantageous because the diverging rays from the pyramid apex remain close to the optical axis, minimizing off-axis aberrations even when modulation is applied. To allow the incident $F/50$ beam to reach the reflective pyramid unvignetted, a central through-hole is machined into the mirror at its vertex.

In parallel, each of the three pupil beams reflected by the pyramid exits through dedicated drill holes in the pyramid substrate, aligned parallel to the optical axis. These beams are directed radially outward, and the mirror must be positioned such that all three beams fall within the reflective area and are redirected along parallel, collimated paths toward the re-imaging doublets.

2.5.6.2 Mirror Focal Length

The pupil size at the detector must be 0.63 mm in diameter, corresponding to the spatial sampling requirement of 30 pixels per pupil. To achieve this pupil diameter

from a focused $F/50$ beam, we use the relation:

$$d = 2f_M \cdot \tan U \quad (2.15)$$

where $U = \arctan\left(\frac{1}{2F/\#}\right) \approx 0.57^\circ$, and f_M is the mirror focal length. Solving this yields a required mirror focal length of approximately 31.5 mm.

2.5.6.3 Optical Path Considerations

Figure 2.24 shows a ray diagram illustrating the key planes and surfaces in the RPWFS configuration. The re-imaging mirror M_i is located between the reflective pyramid and the downstream doublet optics. The conjugate pupil plane P_2 lies beyond the mirror and must be imaged onto the detector using a $4f$ relay.

The optical path from the initial beam focus FP_1 to the final pupil image plane must be managed within the 226.35 mm mechanical constraint. The working distance from the re-imaging lens to the reflective pyramid, combined with the back focal distance and fold path through the mirror, requires careful spacing of all components.

To calculate the remaining optical distance l , sum the distance from the focusing triplet to the pyramid apex, then to the re-imaging mirror, and finally to the pupil conjugate:

$$l_0 = |z_1| + z'_1 + (z'_2 - f_M) \approx 165 \text{ mm} \quad (2.16)$$

This falls short of the full track length, so an additional optical element—such as a second lens in a $4f$ system—is required to extend the optical track and project the pupil image onto the detector.

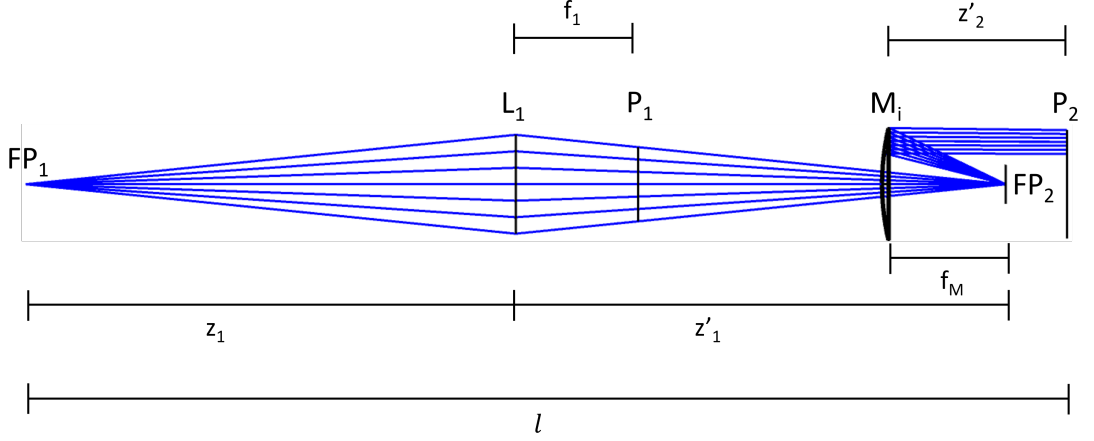


Figure 2.24: First-order optical layout of the 3RPWFS design for ShaneAO. The input telecentric beam is reimaged to the pupil plane P_1 , with object distance z_1 relative to the re-imaging lens L_1 , and its conjugate image formed at z'_1 . The collimating mirror M_1 (focal length f_M) relays this pupil to a second conjugate pupil at z'_2 . The focal planes FP_1 and FP_2 define the primary and secondary focus locations of the system. The total track length l defines the axial space required to integrate the system within the ShaneAO optomechanical envelope. The design must satisfy the technical constraints specified in Table 2.2 and Table 2.3.

2.5.6.4 Solution Space for Optical Layout

A parametric solution for the optical configuration is defined by:

$$l(z_1, f/\#_w) = |z_1| - \frac{z_1 \cdot f/\#_w}{21.08} + c \quad (2.17)$$

where z_1 is the object distance, $f/\#_w = 50$, and $c = 35$ mm is the mechanical clearance required to avoid collisions with the WFS stage. These constraints are visualized in

Fig. 2.25, which shows the set of solutions that satisfy both mechanical and optical requirements. The corresponding drill hole radius $d_F \approx 3.1$ mm is chosen to avoid pupil vignetting.

Critically, the footprint of each pupil image must fit within the active detector area (160×160 pixels at $21 \mu\text{m}$ per pixel), and the spacing between WFS optical assemblies must respect the 42.24 mm separation enforced by the translation stage mechanics. Without an additional pupil relay lens, the complete RPWFS optical path would exceed the allowed mechanical length or risk vignetting. Therefore, the inclusion of a second relay lens becomes essential.

2.5.7 Apex Angle

Once the $F/50$ beam is focused onto the reflective pyramid, the apex angle α must be chosen to ensure efficient separation of the reflected rays (Fig.2.26). From basic geometric optics, the condition $U < \alpha$ must be met, where U is the marginal ray angle of the incident beam. If $U = \alpha$, the marginal ray reflects directly back toward the incoming beam, leading to overlap and potential signal loss. For $U > \alpha$, the reflected rays converge and are vignetted by the collimating mirror's central hole, preventing accurate pupil formation. Therefore, α must be sufficiently large to cleanly separate the incident and reflected rays while avoiding overlap or vignetting. For the $F/50$ beam, this implies a maximum marginal ray angle of $U = \arctan(1/(2 * F/\#)) \approx 0.57^\circ$, setting a lower bound on the apex angle.

To define this angle in practice, we refer to the modulated beam footprint on

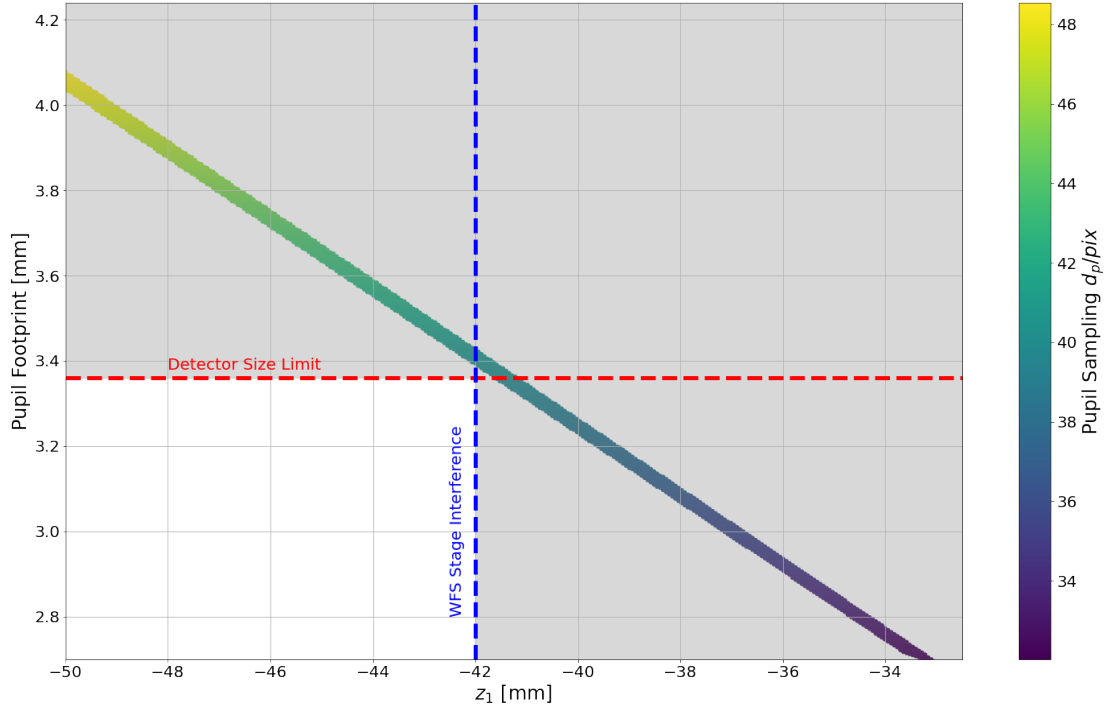


Figure 2.25: Solution space for pupil footprint diameter and sampling as a function of z_1 , based on the first-order 3RPWFS design shown in Fig. 2.24. The color scale represents the number of detector pixels spanning the pupil diameter (d_p/pix). The red dashed line marks the maximum pupil size that fits within the available detector area, while the blue dashed line indicates the shortest permissible z_1 before mechanical interference with the WFS stage occurs. The absence of overlap between these constraints indicates that no valid solution exists within this design space, necessitating additional optics to meet design requirements.

the parabolic collimating mirror, located 31.5 mm behind the pyramid apex. This beam radius, r_H , determines the necessary separation between incoming and reflected rays. Using trigonometry, we calculate the required apex angle with:

$$\alpha = \arctan\left(\frac{r_H}{f_M}\right) \quad (2.18)$$

where f_M is the focal length of the re-imaging mirror. Including a modest tolerance for alignment, we select an apex angle of approximately 1.09° to ensure robust optical separation and avoid ray overlap.

The reflected beam is deflected by 2α , and its offset at the mirror surface is given by $f_M/\cos(2\alpha)$. This geometry yields a pupil footprint of roughly 3.1 mm, which comfortably fits within the collimated system and clears the mirror's drilled aperture.

2.5.8 Doublet Lenses

The remaining optical path length, defined as $t_r = l - l_0 \approx 61$ mm, must accommodate a compact $4f$ imaging system to relay the three reflected pupils onto the detector with unit magnification ($m = -1$). To meet this requirement, each lens must have a focal length of $f_2 = t_r/4 \approx 15$ mm, and the resulting back focal distance (BFD) must exceed 21.66 mm to clear downstream optomechanical components.

A doublet lens design is chosen to reduce both axial and lateral chromatic aberrations over the 600-900 nm bandpass. Initial attempts to use a single shared doublet lens for all three pupils proved infeasible: the radius of curvature required to simultaneously achieve the desired focal length and pupil size would result in a non-

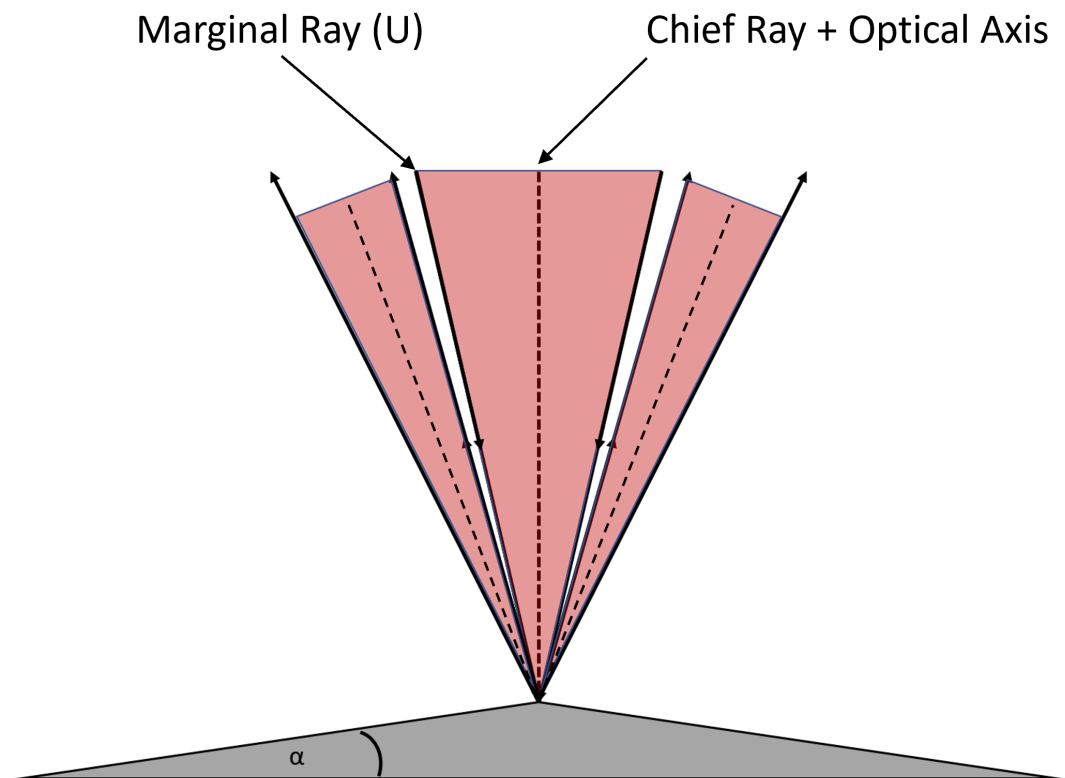


Figure 2.26: Above is a block diagram illustrating the marginal ray paths upon reflection. The apex angle, α , must be large enough to separate the incident and reflected rays.

physical lens profile. Moreover, off-axis pupils would experience unacceptable levels of off-axis aberration induced by the decentered pupils.

To resolve this, the final design uses three independent doublet lenses—one per pupil—each centered on its respective optical axis and optimized to deliver diffraction-limited performance across the full spectral bandpass. Each doublet satisfies the BFD requirement and projects a 0.63 mm pupil onto the detector with minimal chromatic distortion.

Figure 2.27 and Figure 2.28 show the Zemax model of an individual doublet lens and the resulting focal spot diagrams across the design wavelengths. These simulations confirm that the optical quality is diffraction-limited and field distortion is well-controlled. The measured pupil diameters at the detector plane are consistent with design specifications, as shown in Figure 2.29. The complete configuration, with all three doublets radially displaced and aligned to focus the respective pupils onto the shared detector, is illustrated in Figure 2.30.

2.6 Mechanical Design

The existing ShaneAO module is equipped with optical tube assemblies (OTAs) that house SHWFSs, each mounted within a v-groove rail. This mechanical infrastructure permits translation and limited rotation along the z-axis (optical axis). A SolidWorks rendering of the OTA and v-block mounting system is shown in Fig. 2.31[40]. This configuration imposes mechanical constraints that informed the development of

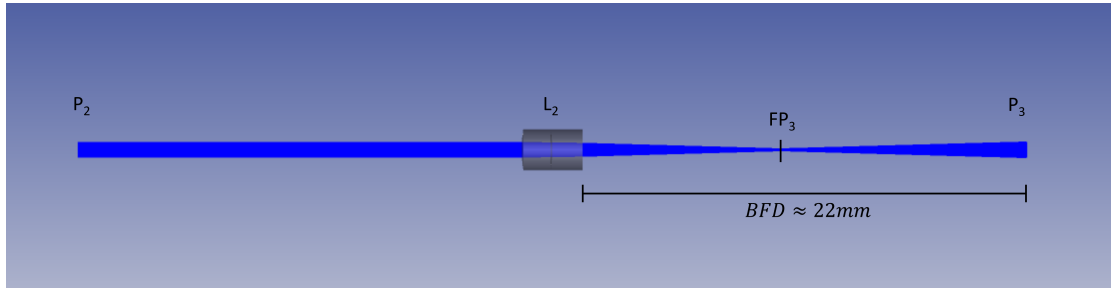


Figure 2.27: Zemax optical layout of a single doublet lens used to reimage one of the three reflected pupils in the 3RPWFS. The doublet minimizes axial and lateral chromatic aberration across the 600–900 nm bandpass.

the 3RPWFS; specifically, the undeviated optical axis and linear motion system preclude bulky beam-folding optics or off-axis relays commonly used in fully reflective AO systems.

To enable direct integration into this v-groove rail, the 3RPWFS is also designed as a self-contained OTA. A cross-sectional model of the proposed optomechanical layout is shown in Fig. 2.32. The design supports modular alignment of all key optical components: the reflective pyramid, re-imaging mirror, and the three doublet lenses. Each doublet is independently mounted in a flexure or kinematic cell that provides tip, tilt, and X - Y translation, allowing precise alignment of the reimaged pupils on the shared detector. This flexibility compensates for any asymmetries introduced during alignment or fabrication and is essential to maintaining diffraction-limited imaging across all three pupil channels.

To generate circular beam modulation around the pyramid apex, the modu-

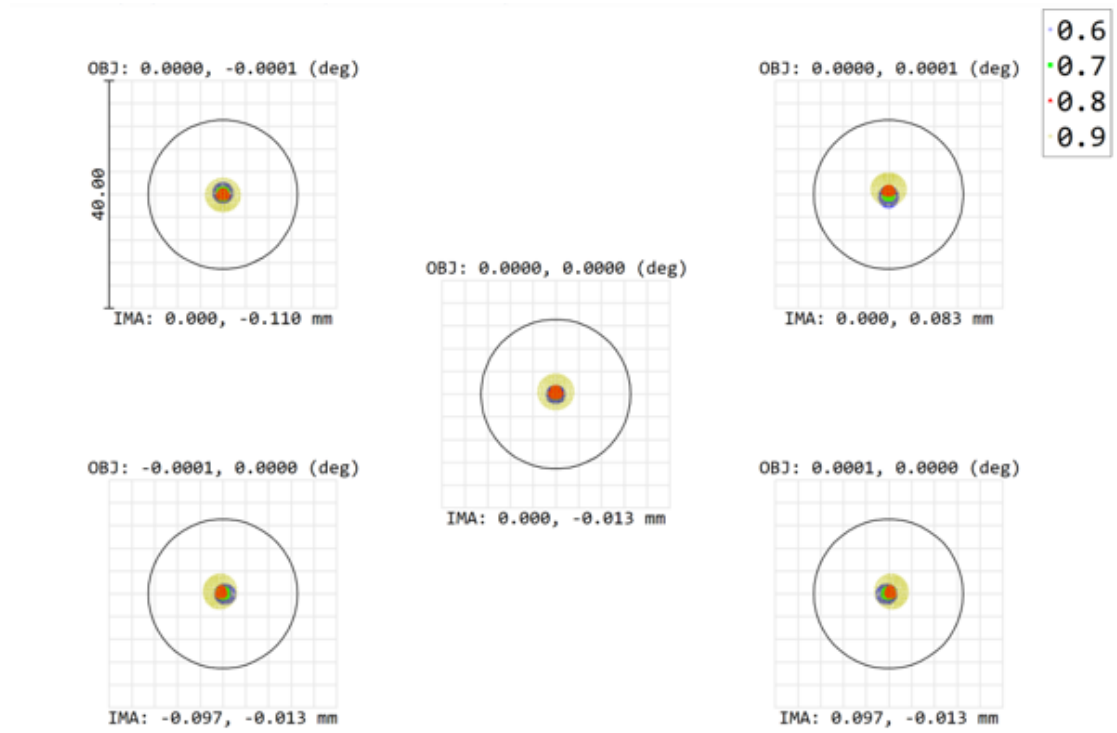


Figure 2.28: Spot diagrams for the doublet lens show diffraction-limited focusing performance across the visible bandpass.

lating wedge must be rotated at high speed along the optical axis. The modulation frequency must match the detector's exposure time in order to evenly distribute light over a full modulation cycle—up to 500 Hz. To achieve this, a compact friction drive system was developed, as shown in Fig. 2.33. A brushless DC (BLDC) motor drives a Viton O-ring that is friction-coupled to the rotating glass wedge. This design minimizes backlash and mechanical complexity while remaining compatible with the existing OTA housing.

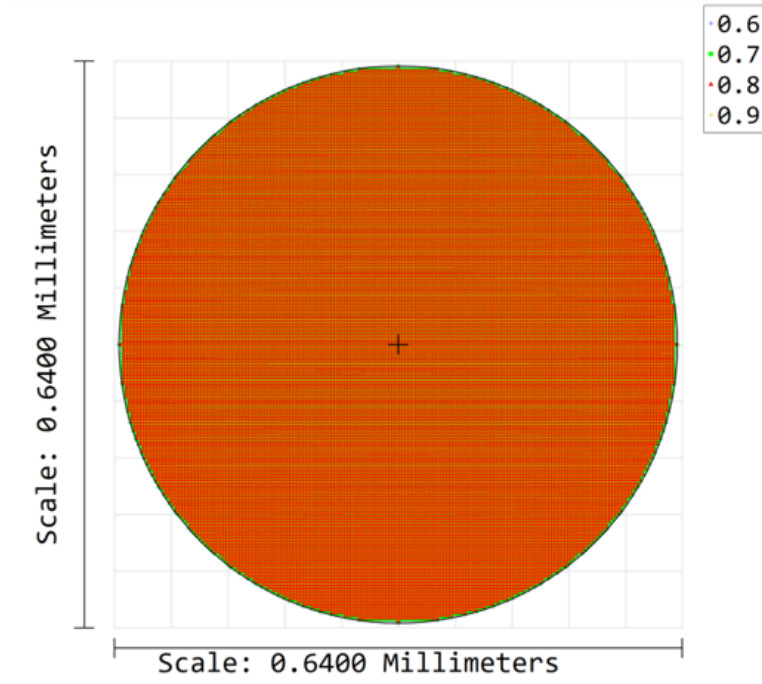


Figure 2.29: Pupil images at the detector plane showing consistent diameter of 0.63 mm across all three beams.

The modulator is controlled by a Raspberry Pi 3B microcontroller, which governs the drive current and feedback loop. Bench testing has verified stable operation up to ~ 200 Hz, meeting the minimum requirement of 100 Hz on ShaneAO for initial on-sky testing. Importantly, the compact volume of this modulation mechanism allows the 3RPWFS OTA to occupy one of the existing slots in the v-groove rail without mechanical interference.

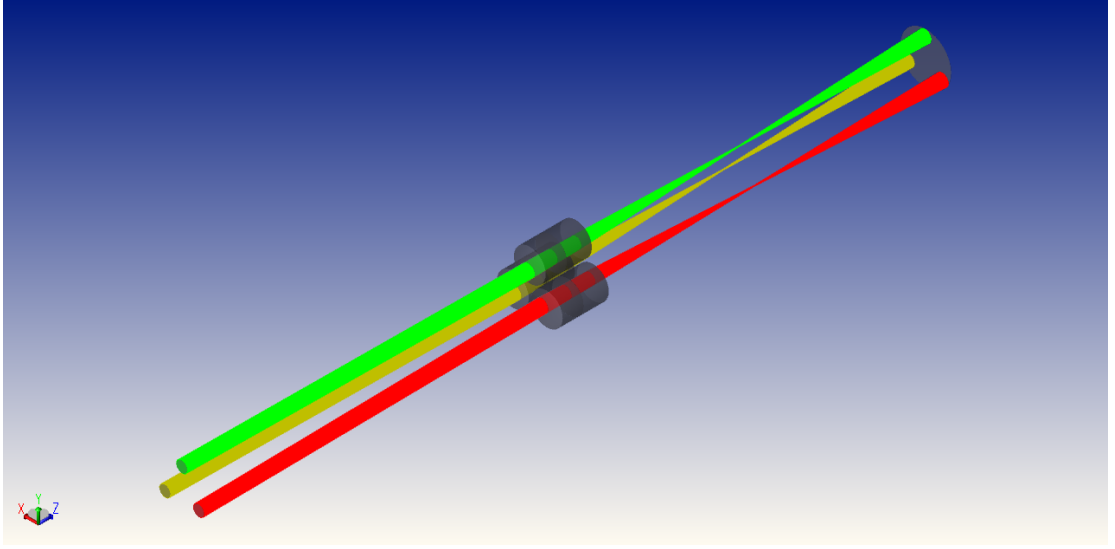


Figure 2.30: Complete configuration of three independent doublet lenses, each aligned with a reflected pupil and re-imaging it onto a shared detector. This approach avoids high curvature single lenses sensitive to aberrations induced by decentration, and maintains diffraction-limited image quality.

2.7 SEAL Demonstration

2.7.1 Optical Setup

An in-lab demonstration of a 3RPWFS is performed using the SEAL testbed, which supports wavefront sensing development through its modular design and stability. SEAL was used to validate the 3RPWFS reconstruction pipeline and to assess its closed-loop performance under controlled laboratory conditions. A SHWFS was used to generate a high quality reference flat, which the 3RPWFS then used to calibrate its pupil response. The ultimate goal of this demonstration was to test whether the

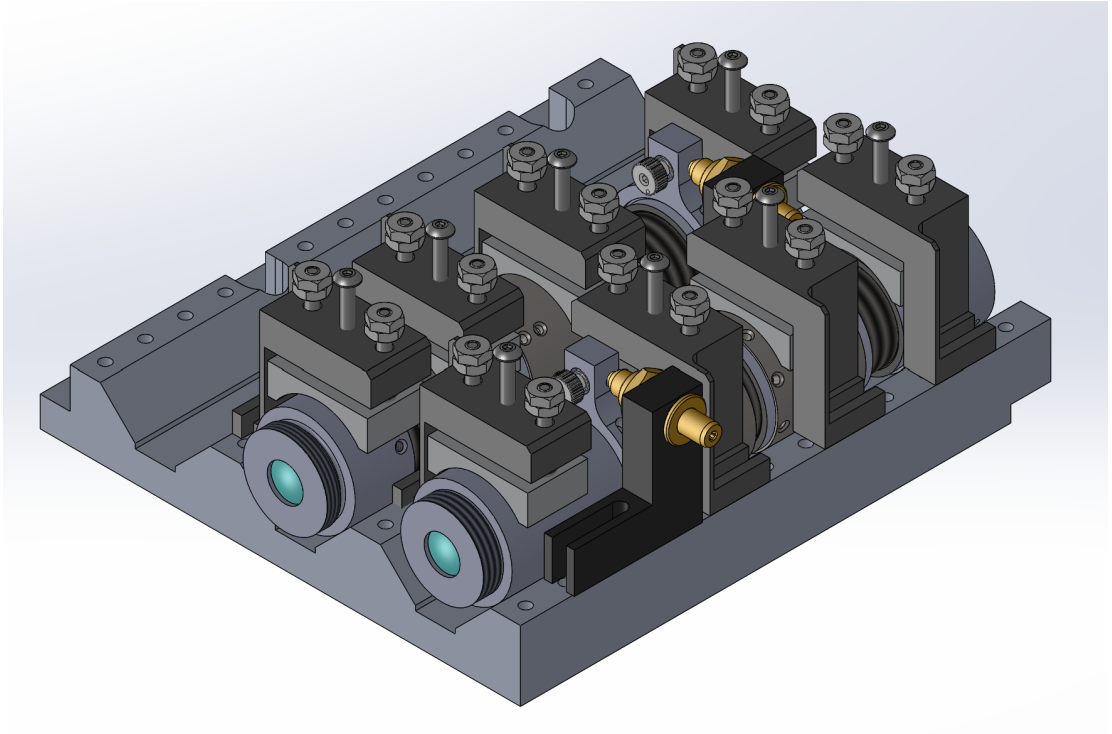


Figure 2.31: SolidWorks model of the ShaneAO v-groove mounting system. The two populated OTAs (center and right) house the 16x and 8x SHWFS modes, respectively. The 3RPWFS will be installed in the open slot on the leftmost v-groove track, sharing the same mechanical base and motion platform.

3RPWFS could achieve closed-loop performance comparable to the SEAL SHWFS.

The optical outline of the 3RPWFS configuration within SEAL is shown in Fig. 2.34. We use an ALPAO97 DM with a 13.5 mm circular aperture and 97 actuators — 11 actuators across the pupil. After beamsplitting the light, a pair of relay lenses reduces the beam size. Additional optical elements—an air-spaced doublet lens—are introduced to simulate the $F/21.08$ telecentric beam present in the ShaneAO module,

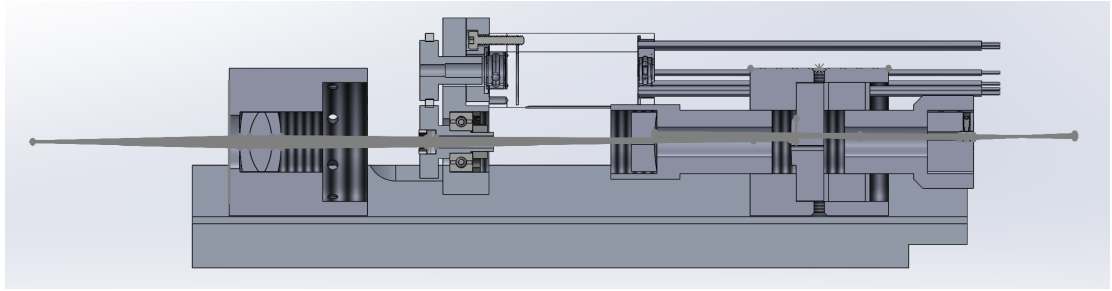


Figure 2.32: Cross-sectional view of the proposed 3RPWFS optomechanical assembly. The system integrates into the ShaneAO v-groove WFS stage and allows independent alignment of the pyramid and each of the three re-imaging doublets.

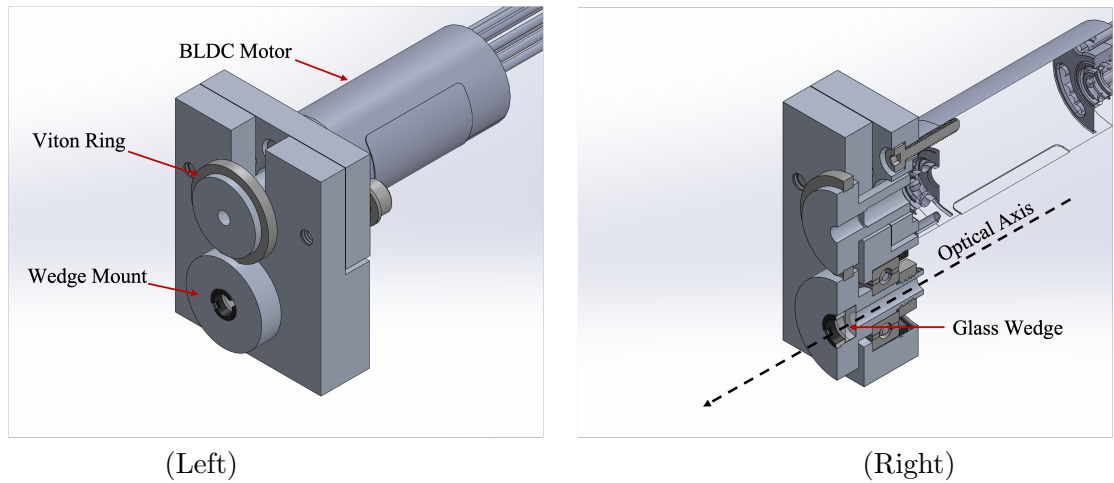


Figure 2.33: (Left) SolidWorks model of the modulator assembly, showing the Viton O-ring mounted on the BLDC motor shaft. The O-ring drives the glass wedge holder through friction contact. (Right) Cross-section view of the rotating wedge along the optical axis, showing its placement in the 3RPWFS optical path.

ensuring the 3RPWFS meets the space and pupil footprint requirements detailed in the previous section.

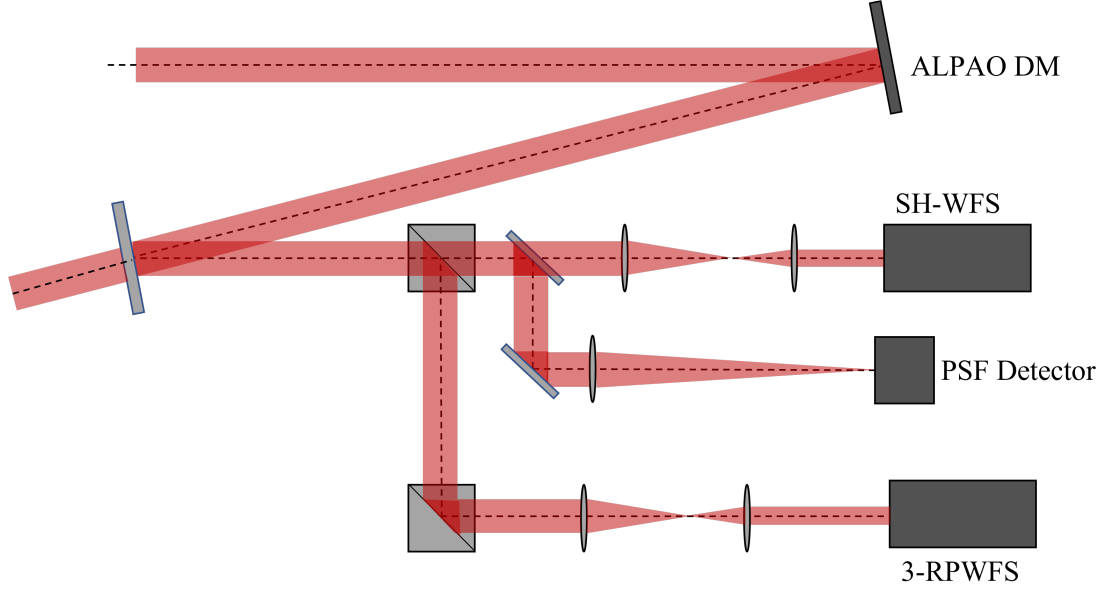


Figure 2.34: 3RPWFS SEAL layout used for lab demonstration. Additional optical elements were installed to mimic a F/21.08 telecentric beam before inserting the 3RPWFS.

Fig. 2.35 shows the physical 3RPWFS setup in SEAL. While the optomechanical OTA described in Sec. 2.6 had not yet been implemented, an analogous arrangement was tested. Instead of three doublet lenses used in the final design, the three pupil beams were relayed using two 100 mm focal length lenses. The system used a FLIR Blackfly detector with 1920x1200 resolution and 5.86 μm pixels.

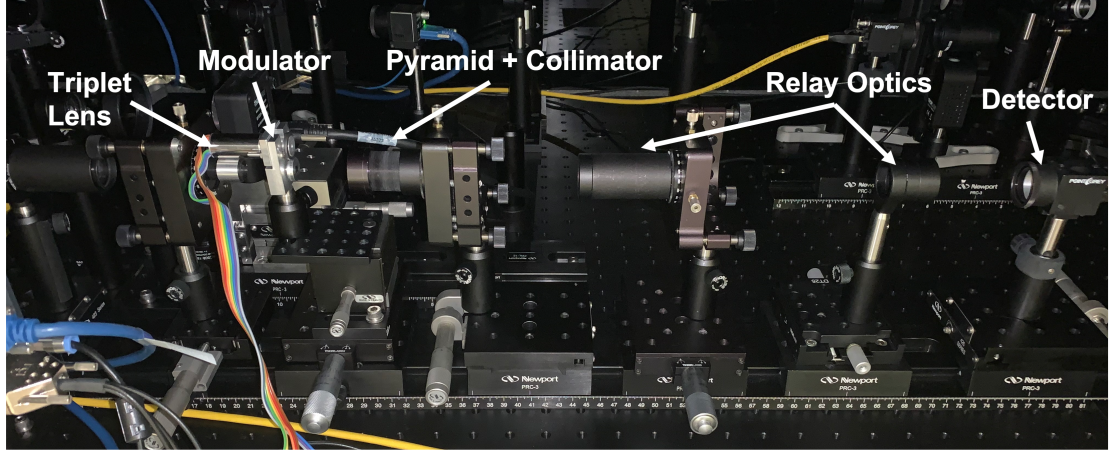


Figure 2.35: Lab setup for the SEAL 3RPWFS demonstration. One-to-one conjugate relay lenses are used to reimage the pupils onto the detector.

2.7.2 Calibration

The calibration began by flattening the DM using the SHWFS in SEAL, achieving a wavefront error of approximately 50 nm RMS. The modal interaction matrix was then constructed by measuring actuator influence functions using a poke matrix. Each actuator was individually poked, and the resulting pupil images were collected. These images were referenced against the flattened state to isolate phase-induced intensity variations.

The Moore-Penrose pseudoinverse was calculated for the poke matrix, and a Zernike modal basis of 100 modes was used to create the interaction matrix. A comparison of simulated and measured pupil images is shown in Fig. 2.36, with each row depicting the DM shape, the HCIPy simulation, and SEAL measurements, respectively.

Differences in pupil geometry arise due to unmodeled upstream optics and a secondary DM footprint seen only in the SEAL system.

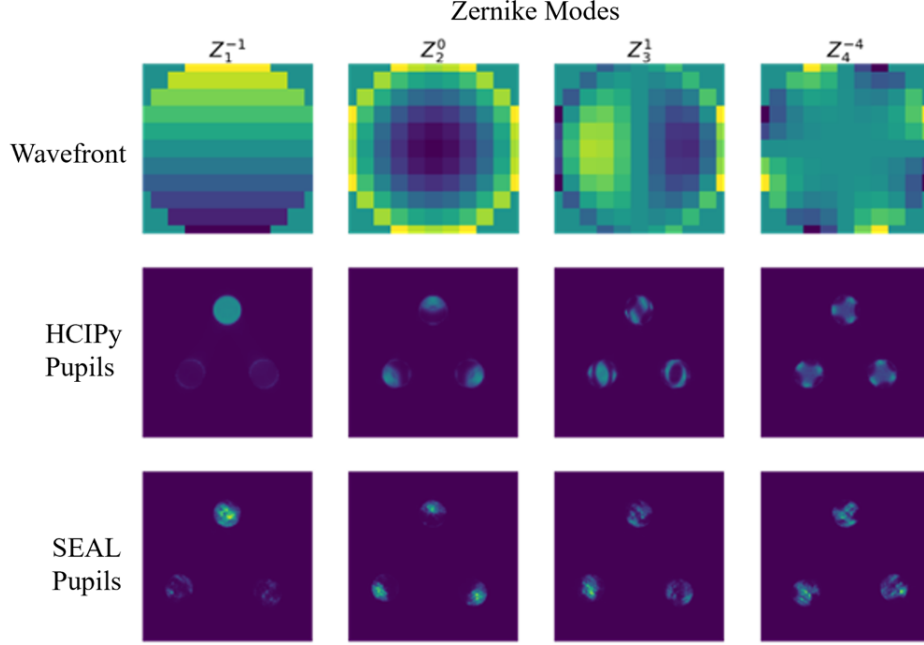


Figure 2.36: (Top) The wavefront applied to the ALPAO DM after flattening. (Middle) The expected 3RPWFS pupil images simulated using HCIPy. (Bottom) The pupil images collected using SEAL testbed. An 80 μm P-V is applied for each Zernike mode.

2.7.3 Closing the Loop

The modulation frequency was set to 100 Hz, with eight modulation cycles per exposure. Control was managed using a Raspberry PI 3B. A leaky integrator controller was implemented with a gain of 0.5 and a leakage factor of 0.01. Fig. 2.37 shows the PSFs before (top row) and after (bottom row) closed-loop correction across various

Zernike modes.

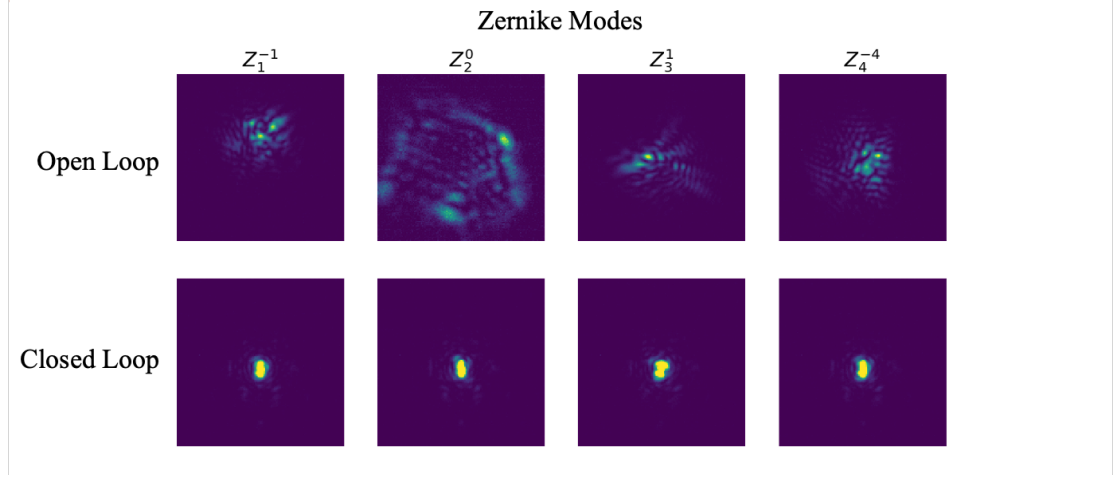


Figure 2.37: (Top) The PSF images for each Zernike mode before closed loop correction. (Bottom) The resulting PSFs after closed loop correction.

Qualitatively, the 3RPWFS effectively senses and corrects wavefront aberrations. Classical PSF signatures associated with defocus and spherical modes are clearly mitigated. In the case of Z_1^{-1} (tip), additional high-order features are observed, which are attributed to imperfect DM flattening and produces a superposition of Zernike modes. These do not reflect a failure of the sensor but rather an error in DM command signals. The testbed demonstration successfully achieved its primary goal: validating the 3RPWFS closed-loop feasibility against a known SHWFS baseline.

2.8 On-sky Demonstration on Shane Telescope

2.8.1 Calibration

The ShaneAO system employs a dual DM configuration consisting of a woofer and a tweeter, controlling 52 and 144 modes, respectively. Prior to on-sky observations, calibration was performed using the system’s internal light source. This involved synchronizing the 3RPWFS modulator to 100 Hz, ensuring that exactly one modulation cycle was captured per exposure. Proper synchronization between the modulation and the wavefront sensor (WFS) detector is critical, as desynchronized operation can lead to uneven light distribution across the three pupils, with effects that are degenerate with tip and tilt aberrations.

To prepare for wavefront sensing, iterative DM flattening was performed, starting with low-order woofer modes and incrementally increasing the number of active modes. Using the internal calibration source, the existing 8x and 16x SHWFS modes achieve Strehl ratios of $S_{16x|8x} = 0.65$ at 100 Hz. These modes sample the telescope pupil with 8 and 16 lenslets across the diameter, respectively.

The 3RPWFS was originally designed to sample the pupil with 30 pixels across each re-imaged pupil. However, initial tests showed closed-loop instability due to pixel misregistration, poor pupil edge quality, and non-uniform illumination. For accurate wavefront reconstruction, each pixel must correspond to the same relative location across all three pupils. Due to time constraints and alignment limitations, the sampling resolution was reduced to 25 pixels across each pupil. With this adjustment,

stable closed-loop operation was achieved, and the system matched the 16x SHWFS performance with $S_{3RPWFS} = 0.65$ using the internal source.

2.8.2 Observations

The 3RPWFS was tested on-sky over three nights at the 3-meter Shane Telescope at Lick Observatory. The science detector used is a 1976x1453 Teledyne HAWAII-2RG with a pixel scale of 0.033 arcsec/pixel, observing through the Br- γ filter centered at 2.16 μm . The WFS detector was a 160x160 pixel CCID66 with 21 μm pixels, and the 3RPWFS operated across a 600-900 nm spectral band.

Targets were selected based on brightness ($m_V < 9$) and proximity to zenith to maximize SNR. For each target, closed-loop AO performance was recorded using both the 3RPWFS and the 16x SHWFS, with both sensors operating at 100 Hz. Table 2.4 summarizes the observing log, including Strehl ratios achieved at 2.16 μm .

Table 2.4: Observed targets using the 3RPWFS. Strehl ratios marked with an asterisk denote peak performance achieved during gain and bleed optimization.

Date	Target	m_V	RA	Dec	S_{RP}	S_{16x}
2023-08-07	HR 6169	6.4	16:35:26.21	+17:03:33.8	0.54*	0.59
2023-08-07	HD 175425	7.89	18:53:38.11	+37:59:06.9	0.41 ± 0.03	0.55
2023-08-07	HD 180396	8.99	19:14:43.8	+37:42:31.8	0.20 ± 0.04	0.57
2023-10-01	HD 196642	6.2	20:37:23.58	+38:19:43.2	0.11*	0.21
2023-10-01	HD 173169	7.4	18:42:19.99	+36:33:06.4	—	—
2023-10-02	HD 176133	6.69	18:57:10.57	+36:28:11.5	0.17*	0.23

2.8.3 Gain-Bleed Study

The woofer-tweeter architecture of ShaneAO necessitates a more complex control strategy to account for the differing temporal response characteristics of the DMs. Woofer DMs typically exhibit slower response times, and overlapping spatial modes can be dynamically offloaded to the faster tweeter DM, which is the bleed. Both woofer and tweeter DMs contribute to this offloading, with lower bleed values enabling faster redistribution of shared modes [41].

To assess closed-loop performance under varying control configurations, an empirical study of the gain and bleed parameters using the bright natural guide star HR6169 is conducted. On UT 2023 August 7, under 0.9''-1.0'' seeing conditions, the performance of the 3RPWFS was evaluated as a function of AO control parameters. As expected, the Strehl ratio (S_{RP}) decreased with increasing guide star magnitude (m_V), consistent with reduced photon flux.

The results are shown in Fig. 2.38. The top row illustrates S_{RP} as a function of controller gain for fixed bleed, while the bottom row shows variation with bleed at fixed gain. Results indicate that S_{RP} is relatively robust across a wide gain range (0.4–0.8) but is more sensitive to bleed settings. Notably, lower bleed values slightly improved S_{RP} , contrary to expectations from SHWFS performance.

One possible explanation is that noisy or imprecise measurements from the 3RPWFS introduce spurious DM commands. Allowing these to persist through high bleed coefficients may accumulate wavefront error, whereas lower bleed settings sup-

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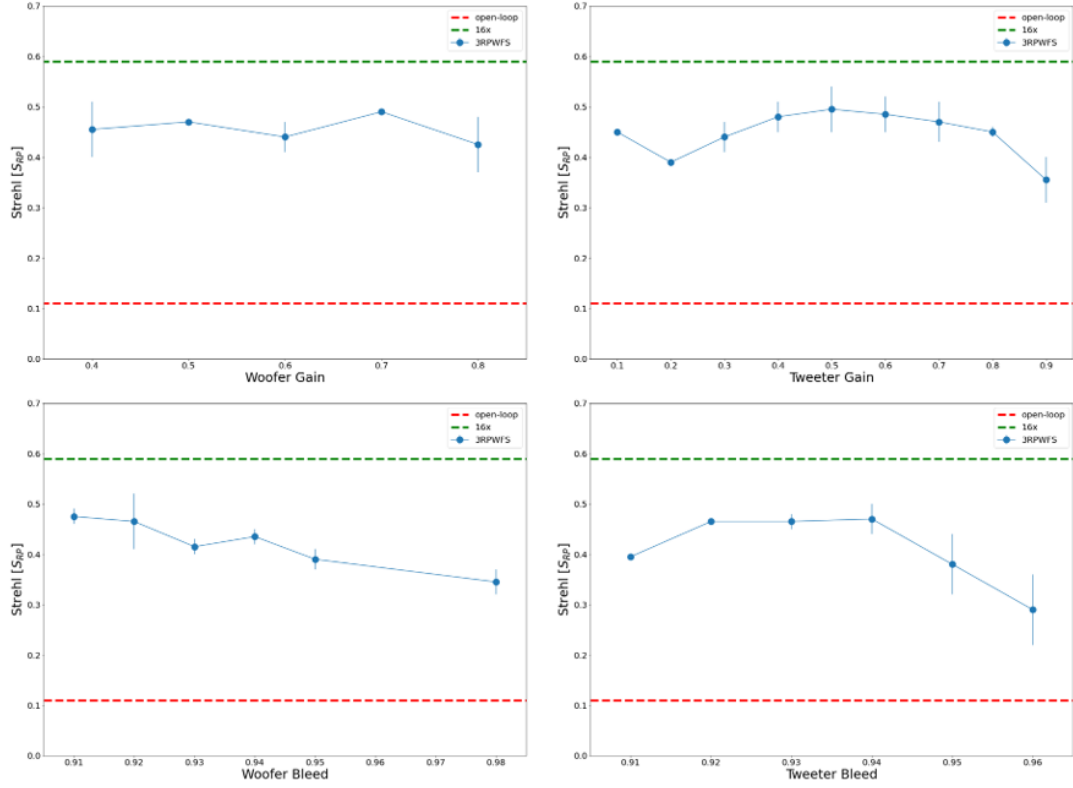


Figure 2.38: AO performance on HR 6169 as a function of controller gain (top row) and bleed (bottom row) for both woofer and tweeter deformable mirrors.

press these signals more quickly. This suggests that tuning control parameters for the 3RPWFS may benefit from more aggressive damping.

2.8.4 Throughput

A persistent issue during on-sky testing was poor loop stability when transitioning between calibration and WFS modes. This was not observed during SHWFS

operation and was ultimately traced to control software instability. Reinitializing the AO control software restored stable loop closure with the 3RPWFS.

Despite closing the loop, the 3RPWFS consistently delivered lower S_{RP} than the 16x SHWFS under similar conditions. To investigate this discrepancy, the optical throughput of both systems was compared using the internal calibration source. WFS images were reduced by subtracting the mean noise level from each of the 20 rectangular readout regions of the CCID66 detector. The summed flux across all sub-apertures showed that the 3RPWFS achieved only 32% of the signal level recorded by the SHWFS (Fig.2.39).

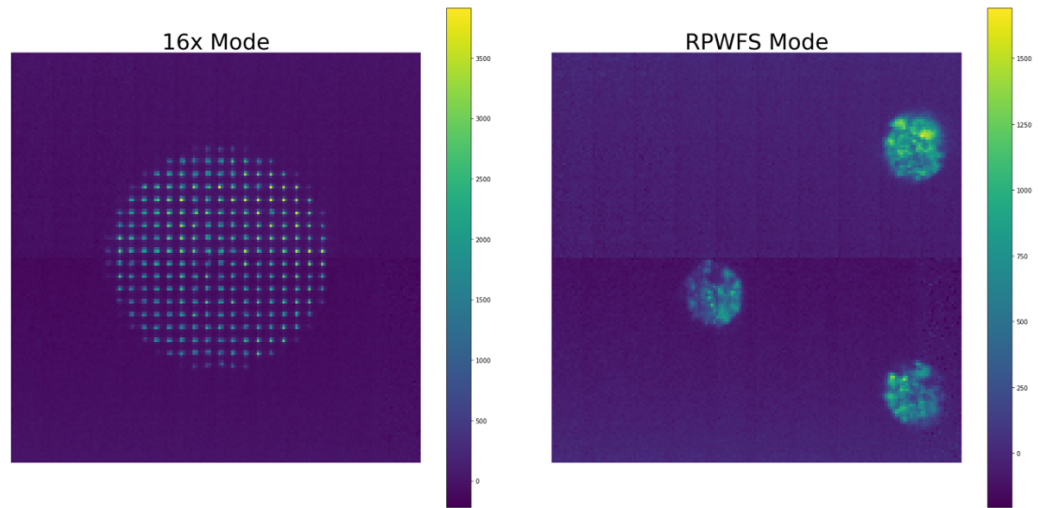


Figure 2.39: Comparison of signal throughput between the 3RPWFS and 16x SHWFS using the ShaneAO internal calibration source.

This throughput loss is likely due to uncoated optical surfaces in the 3RPWFS path—including the triplet lens, glass wedge, and parabolic mirror. While the reflective

pyramid itself has high efficiency, the cumulative losses from upstream elements are significant. Future iterations of the instrument will benefit from broadband anti-reflection and enhanced metallic coatings to mitigate this issue.

2.9 Conclusion

This work presents the design, modeling, implementation, and testing of a novel three-sided reflective pyramid wavefront sensor (3RPWFS) for ground-based adaptive optics (AO), culminating in a successful on-sky closed-loop demonstration at Lick Observatory’s Shane Telescope. The progression from conceptual development to real-world testing illustrates both the versatility and feasibility of this approach to wavefront sensing within the constraints of a working astronomical observatory.

A compact, reflective wavefront sensor architecture was developed and inspired by the traditional pyramid wavefront sensor (4PWFS), but modified to address specific limitations in optomechanical integration. Unlike the conventional transmissive four-sided glass pyramid, which requires downstream pupil imaging optics and a change in optical axis orientation, the 3RPWFS maintains an undeviated optical axis using a transmissive wedge for beam modulation which simplifies alignment and integration in existing systems with fixed mechanical footprints. Initially proposed by M. Chun, the reflective pyramid concept was adapted and re-optimized to meet the functional and spatial requirements of the ShaneAO module. These adaptations included new considerations in modulation, beam re-imaging, and throughput optimization.

The optical design process began with first-order ray-tracing approximations to evaluate candidate configurations under the constraint of a 226.35 mm optical path length in ShaneAO. This constraint, along with the requirement to achieve pupil diameters of 0.63 mm at the detector with 30 pixels across the pupil, was used to derive an effective working f-number of 50 ($F/\#_w = 50$). This value was selected to ensure sufficient spot size at the apex of the pyramid to reduce sensitivity to apex rounding while preserving throughput above 70% in an unmodulated configuration, a threshold determined by simulations that accounted for realistic fabrication tolerances.

A key innovation in this design is the use of a transmissive glass wedge for beam modulation rather than the traditional FSMs. By placing the wedge at the exit pupil of a triplet re-imaging lens, the system achieves circular modulation with minimized pupil walk, which would induced lateral pupil movement as a function of modulation radius r_{mod} . Because the ShaneAO architecture does not permit additional beam folding due to its undeviated optical axis design, the glass wedge modulator provides an elegant solution without requiring deviations from this constraint. The wedge modulator is actuated with a compact friction drive assembly capable of achieving rotation frequencies up to 1 kHz; however, the Viton O-ring can only maintain contact at speeds below 400 Hz. This is sufficient to match the 100 Hz frame rate of the ShaneAO detector, with room for future performance expansion.

Pupil re-imaging is performed using a concave parabolic mirror with a central drill hole to accommodate the incoming $F/50$ beam. This mirror collimates the three reflected beams from the pyramid apex, which are passed through additional radially

spaced drill holes in the pyramid substrate. The use of three spatially separated doublet lenses allows for discrete re-imaging of each pupil onto a single detector, further optimizing space and simplifying downstream optical design. The doublets are aligned using precision tip-tilt and translation stages to ensure diffraction-limited performance across the 600–900 nm bandpass.

The resulting optical configuration was initially validated in Zemax using both sequential and non-sequential ray tracing. The PSF size, modulation behavior, and pupil footprint were simulated and optimized, ensuring that each of the design criteria could be met in the constrained volume. A key challenge in this modeling effort was to manage the tradeoff between optical performance and system compactness. For instance, although a larger $f/\#_w$ increases throughput, it also leads to larger system lengths that may no longer fit within ShaneAO’s available optical track. By constructing a solution space from the magnification equation and thin lens optics, we identified an optimal configuration that balanced beam footprint, re-imaging distances, and mechanical clearance from other WFS components.

Following the design, the 3RPWFS was implemented in a laboratory setting using the Santa Cruz Extreme AO Laboratory (SEAL) testbed. A flat ALPA097 DM with 97 actuators was used to apply known Zernike modes to the incoming wavefront, and the 3RPWFS pupil images were recorded using a FLIR Blackfly detector with 5.86 μm pixels. A modal interaction matrix was constructed by poking each actuator and recording the differential intensity response across the pupil images. These images were flattened, registered, and compared to simulations generated using the HCIPy

framework. The observed agreement, especially in low-order modes such as defocus and astigmatism, confirmed that the 3RPWFS could detect spatial phase aberrations consistent with theory.

Importantly, the SEAL experiments revealed discrepancies for certain modes — particularly Z_1^{-1} (tip) and high-order spherical terms — where PSFs exhibited asymmetric behavior and apparent mode mixing. This was attributed to non-common path aberrations in the SEAL optical train, possible errors in DM shape modeling, and slight deviations in pupil registration. Nevertheless, the ability to produce closed-loop correction using a leaky integrator controller with 100 calibrated Zernike modes confirmed the viability of the sensor in practice. Modulation frequency in these early experiments was limited to 100 Hz due to mechanical drive limitations, but the system showed stable loop closure under these conditions, with improved PSFs and restored core intensities in corrected images.

Simulation work complemented these laboratory efforts by characterizing the effect of modulation radius (r_{mod}) on sensitivity and linear range. We determined that a conservative choice of $r_{mod} = 5 \lambda/D$ provides a balance between linearity and photon throughput. Simulations showed that under median seeing conditions and with sufficiently bright guide stars (up to $M_R \leq 13$), the 3RPWFS could achieve Strehl ratios exceeding 0.2 at 750 nm. These results were validated using a range of pupil sampling densities and modulation steps, with the caveat that coarse sampling can introduce artificial light imbalances between pupil images. For accurate simulation results, finer spatial resolution and increased angular modulation sampling (e.g., 40–50 steps per

modulation cycle) were found to be necessary at the cost of longer computation times.

The final phase of this work was an on-sky demonstration of the 3RPWFS in ShaneAO. After integrating the reflective pyramid, re-imaging optics, and modulator into the existing WFS optomechanical framework, we performed closed-loop AO correction under good seeing conditions. The 3RPWFS mode was tested against the 16x SHWFS, ShaneAO’s standard high-order sensor, and demonstrated comparable Strehl performance when operating with bright natural guide stars. We observed Strehl fluctuations within 10% between the two systems after software reinitialization, suggesting that performance differences were initially affected by software-related factors rather than fundamental sensor limitations.

During on-sky operation, we also explored the impact of AO control parameters, including woofer and tweeter gain and bleed values. We found that reduced bleed coefficients introduced excess temporal noise into the loop, particularly with fainter stars or poor seeing, indicating that 3RPWFS sensitivity is indeed sufficient to pick up this variation. These findings motivate further optimization of control algorithms tailored to the 3RPWFS’s signal characteristics.

One area of concern is optical throughput. Comparison between the 3RPWFS and 16x SHWFS modes revealed a loss factor of approximately 3 in total detected flux for the former. This discrepancy can be traced to uncoated optical surfaces in the triplet lens, glass wedge, and parabolic re-imaging mirror. These components were left uncoated due to time constraints prior to installation. Applying broadband anti-reflection and reflective coatings will be essential for improving sensitivity, particularly

for faint star targets. Addressing this issue is especially critical if higher modulation frequencies are to be pursued, as increased beam motion further spreads light and reduces peak intensities.

Another challenge encountered during integration was managing the pupil footprint on the detector. The 3RPWFS naturally spreads the three pupils radially across a larger field, making detector usage less efficient compared to transmissive designs. Modifications to the doublet lens spacing and focal length were introduced to reduce this footprint while preserving diffraction-limited performance. Although further optimization is warranted, these refinements make the sensor more compatible with compact detector formats and increase the dynamic range for tilt and focus correction.

In conclusion, this work successfully demonstrates the feasibility and flexibility of the 3RPWFS design. From conceptual design to Zemax modeling, from laboratory implementation in SEAL to final on-sky testing in ShaneAO, the sensor has proven capable of robust wavefront sensing under both controlled and real-world conditions. The architecture provides a compact, reflective alternative to traditional pyramid sensors, with the added benefit of maintaining a collinear optical path suitable for systems like ShaneAO with limited optomechanical degrees of freedom.

The next stages of development will focus on three key areas. First, the mechanical modulation assembly will be upgraded to a gear-driven system to support continuous operation at 500–1000 Hz. Second, all optical surfaces should be coated to recover throughput losses and improve performance at low SNR. Finally, updated pupil registration, control software calibration, and high-speed interaction matrix recalibra-

tion should be implemented to support rapid switching between SHWFS and 3RPWFS modes. These improvements will allow the 3RPWFS to serve as a viable next-generation WFS option for ShaneAO and other systems seeking compact, achromatic, and reflective alternatives to conventional PWFS architectures.

Ultimately, the 3RPWFS platform introduced in this thesis provides a foundation for broader applications, including future ELT-scale wavefront sensing, multi-object AO, and potentially space-based applications where chromatic performance and packaging constraints demand non-traditional sensing solutions. The successful combination of optical modeling, lab testing, and on-sky validation establishes the 3RPWFS as a mature, experimentally validated technology poised for further integration in adaptive optics systems.

Chapter 3

Second-Generation Three-Sided Reflective Pyramid Wavefront Sensor

The three-sided reflective pyramid wavefront sensor (3RPWFS) was introduced in a previous work as a compact, achromatic alternative to the traditional four-sided transmissive pyramid wavefront sensor (PWFS) [42, 40]. The initial design employed a concave mirror positioned behind a reflective three-sided pyramid to reimage the three deflected pupil beams. This configuration required that the marginal ray slope remain shallower than the apex angle to avoid self-vignetting by the pyramid structure. As a result, the size of the reimaged pupils scaled linearly with the distance between the pyramid apex and the concave mirror. However, increasing this distance simultaneously enlarged the radial pupil separation on the detector, leading to inefficient use of detector space. Higher sampling density required larger-format detectors, which introduced additional cost and complexity while leaving significant portions of the detector unused.

In this chapter, we present a second-generation design for the 3RPWFS that addresses the limitations of the first-generation layout, particularly the expansive pupil footprint and extended optical path length. The new design replaces the conventional concave re-imaging mirror with a pyramidal concave mirror (PCM) that features three tilted facets angled inward toward the optical axis. This geometry allows the reimaged pupils to be placed closer together, reducing the footprint on the detector without sacrificing sampling resolution or optical throughput.

The optical design is described in Section 3.1, including the motivation for the PCM and its impact on system compactness. Section 3.2 details the implementation of the second-generation system in a laboratory AO testbed and outlines the calibration methodology used to measure pupil responses. Section 3.2.3 presents laboratory results demonstrating closed-loop performance, while Section 3.3 discusses performance limitations and future improvements.

3.1 Optical Design

The first-generation 3RPWFS design utilized a continuous concave mirror to reimage the three pupil beams after reflection from the pyramid. In this configuration, the collimating mirror was placed downstream of the pyramid to create a parallel beam that preserved pupil geometry. Since the pupils are formed by a relationship with the apex angle, the pupil sizes scaled linearly with the effective focal length and working f-number ($f\#_w$) of the system. However, this also meant that the radial separation

between the pupils remained fixed in angle but increased in physical size with longer propagation distances. As the desired sampling resolution increased, the footprint of the re-imaged pupils quickly grew beyond the bounds of the available detector area. To reduce the footprint, one could introduce folding mirrors to reposition the pupils, but this adds mechanical complexity and optical surfaces, reducing throughput and introducing additional alignment challenges.

To overcome these limitations, the conventional concave mirror is replaced with a three-facet pyramidal concave mirror (PCM), shown conceptually in Fig. 3.1. In this configuration, each facet of the PCM is angled inward toward the optical axis, such that the diverging rays from each pyramid face are directed back toward the centerline of the system. This inward tilting reduces the radial pupil separation without requiring an increase in optical track length or beam collimation. Importantly, the PCM design relaxes the requirement for infinite conjugation — the reflected beams do not need to be strictly collimated — since pupil separation becomes primarily dependent on the PCM facet tilt rather than beam divergence alone. This decouples the re-imaging geometry from the constraints of focal length scaling, allowing a more compact and efficient design.

Furthermore, increasing the apex angle in the original design would have led to greater pupil separation without increasing pupil size, reducing detector efficiency. In contrast, the PCM configuration enables us to tune pupil spacing independently by adjusting the facet tilt, all while maintaining pupil size. This improvement makes the second-generation 3RPWFS more suitable for use with standard-format detectors and better aligned with the compact mechanical constraints of AO instrumentation.

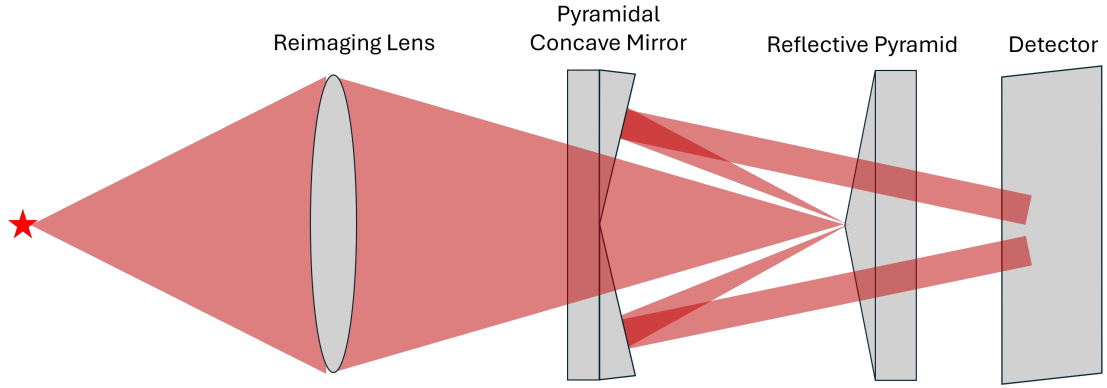


Figure 3.1: Conceptual layout of the second-generation 3RPWFS showing the reflective pyramid and pyramidal concave mirror (PCM) for pupil re-imaging. The inward-tilted PCM facets reduce radial pupil separation, enabling a more compact and efficient optical design.

This second-generation 3RPWFS is specifically designed for a laboratory testbed that receives an incoming telecentric F/50 beam, and thus it does not share the same optical configuration as the first-generation 3RPWFS implemented in ShaneAO. Key design modifications include an increased pyramid apex angle (α) of 10 degrees and a PCM drill hole radius of 6.35 mm. These represent increases of approximately $10\times$ and $12\times$, respectively, relative to the earlier prototype. Each PCM facet is tilted inward by 8.9 degrees, a geometry that yields a significantly larger unvignetted FOV and a more compact optical layout with a reduced pupil footprint. In this configuration, the image clearance is 45 mm, with a pupil footprint of 4.5 mm and a pupil diameter of 2 mm. These optical parameters are governed by the working f-number ($f/\#w$), pyramid angle (α), PCM focal length (f_{PCM}), and facet tilt angle. The design delivers detector limited

image quality across the near-infrared (NIR) spectral bandpass of 1–1.4 μm . However, the transmissive focusing optic imposes chromatic limitations due to focal shift. A fully achromatic design would require a reflective focusing element. For this implementation, an achromatic paraxial lens is used to illustrate usable bandwidth while maintaining compactness and alignment simplicity (Fig. 3.2 and 3.3).

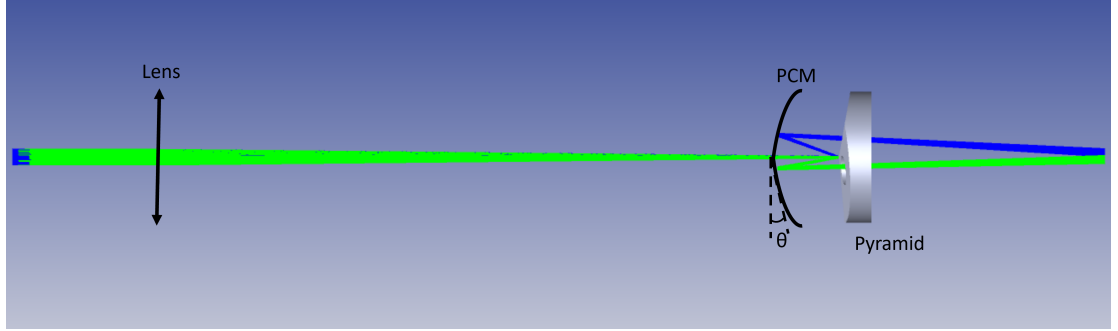


Figure 3.2: Optical layout of the second-generation 3RPWFS. A paraxial lens generates a telecentric F/50 beam and focuses onto the reflective pyramid. The three beams are then collected by a pyramidal concave mirror (PCM), whose curved facets tilt inward by an angle θ . The PCM physically redirects the three pupil beams closer together, enabling a compact sensor layout with reduced pupil separation. This architecture allows for tighter pupil spacing without compromising pupil sampling or introducing additional optical elements.

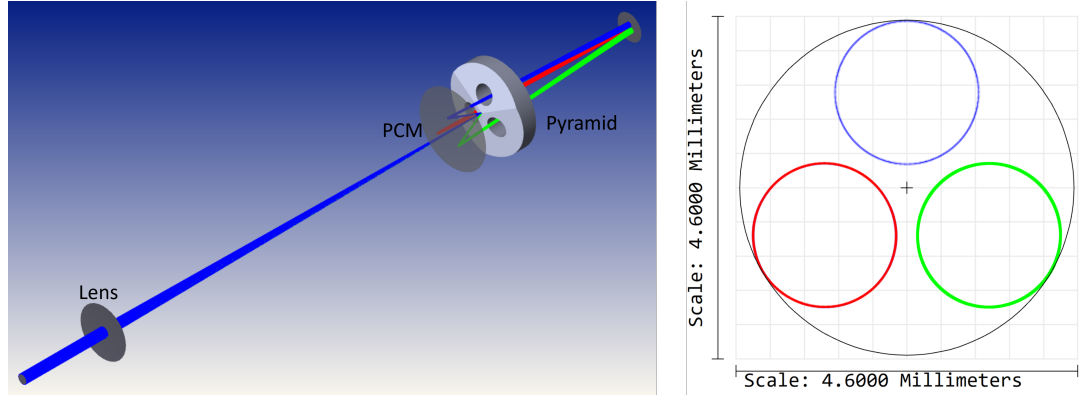


Figure 3.3: (Left) Isometric view of the second-generation 3RPWFS and its resulting pupil footprint. (Right) Resulting pupil footprint on the detector plane, showing the relative positions of the three pupils (red, green, and blue) corresponding to the three pupil images. The compact pupil spacing enabled by the PCM geometry results in a reduced overall footprint diameter of approximately 4.5 mm, and pupil diameter of 2.25 mm.

3.2 Lab Demonstration

3.2.1 Optical Setup

A laboratory demonstration of the second-generation 3RPWFS was conducted using the testbed located in the Laboratory for Adaptive Optics (LAO) at the University of California, Santa Cruz. The optical layout of the system is shown in Fig. 3.4, with a top-down view of the assembled hardware shown in Fig. 3.5. The goal of this experiment was to validate the functionality of the redesigned pyramidal concave mirror (PCM) and demonstrate closed-loop wavefront correction using the new architecture.

A Helium-Neon (HeNe) laser serves as the light source and illuminates an ALPAO DM69 DM, which has 69 actuators arranged in a square grid with a clear aperture of approximately 11 mm. The DM is initially set to its factory flat configuration by applying 0 V to all actuators, thereby generating a nominally flat wavefront. This reference configuration is used to acquire baseline pupil images for calibration but is later further flattened.

The beam is then split into two paths. One path leads to a science camera, simulating the telescope focal plane and enabling direct observation of the point spread function (PSF). The other path is directed toward the wavefront sensor (WFS) arm, which includes a PI (Physik Instrumente) modulating mirror and the 3RPWFS assembly.

The modulating mirror is located in a plane conjugate to the pupil to ensure that its angular modulation produces no lateral motion of the pupil images. Immediately

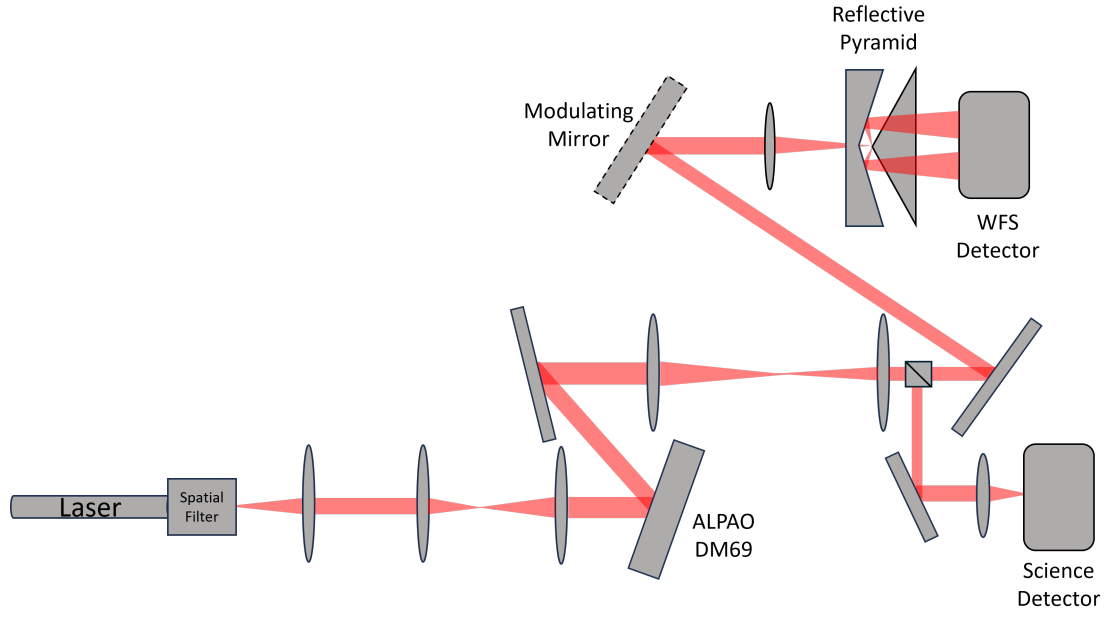


Figure 3.4: Schematic of the AO testbed used to demonstrate the second-generation 3RPWFS. The beam is split between a science focal plane camera and the wavefront sensor arm, which includes a modulating mirror, focusing lens, reflective pyramid, and pyramidal concave mirror (PCM).

downstream, a focusing lens forms an $F/50$ beam that converges onto the apex of the three-sided reflective pyramid. This produces three diverging beams and the PCM is positioned such that it re-images these beams from each pyramid facet and forms three pupil images approximately 70 mm downstream of the apex.

Images of the fabricated PCM and reflective pyramid are shown in Fig. 3.6a and Fig. 3.6b. Both components were precision machined to ensure facet flatness and apex sharpness. Additional microscope images of the pyramid are presented in Fig. 3.7a and

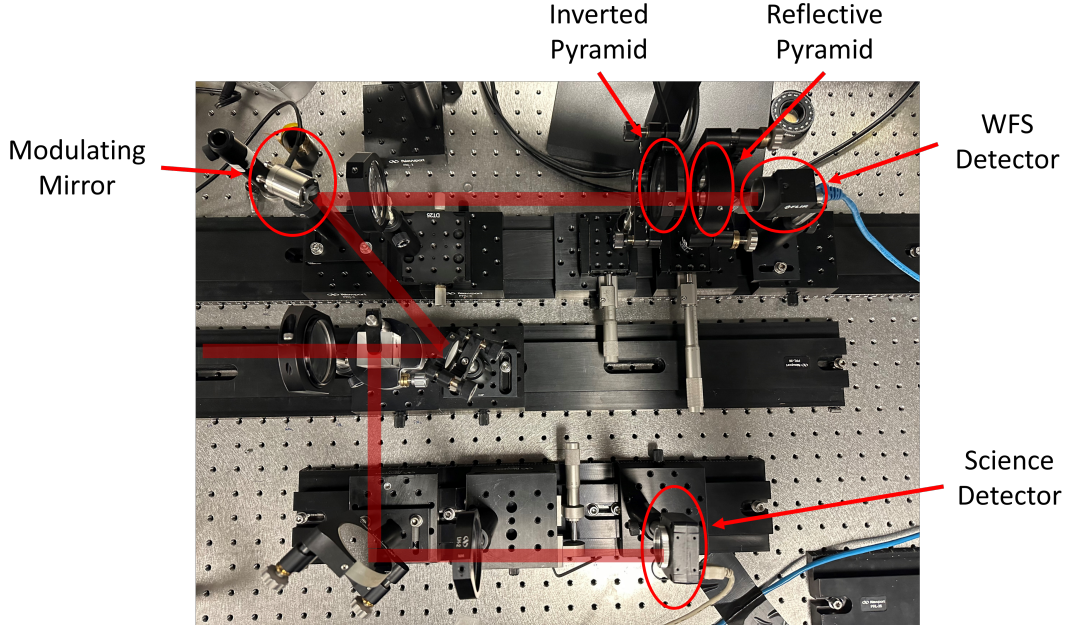


Figure 3.5: Image of the assembled optical setup used in the LAO for the 3RPWFS demonstration.

Fig. 3.7b, highlighting the physical quality of the apex region. The apex imperfection diameter was measured to be less than $10\ \mu\text{m}$, meeting the design requirement for high throughput and minimal diffraction artifacts.

3.2.2 Calibration

To enable wavefront reconstruction, a modal interaction matrix $\mathbf{M}$ is constructed using a standard poke matrix approach. The poke matrix $\mathbf{P}$ is generated by sequentially actuating each element of the DM and recording the corresponding change in the 3RPWFS pupil images. Each actuator is poked with a small amplitude to avoid

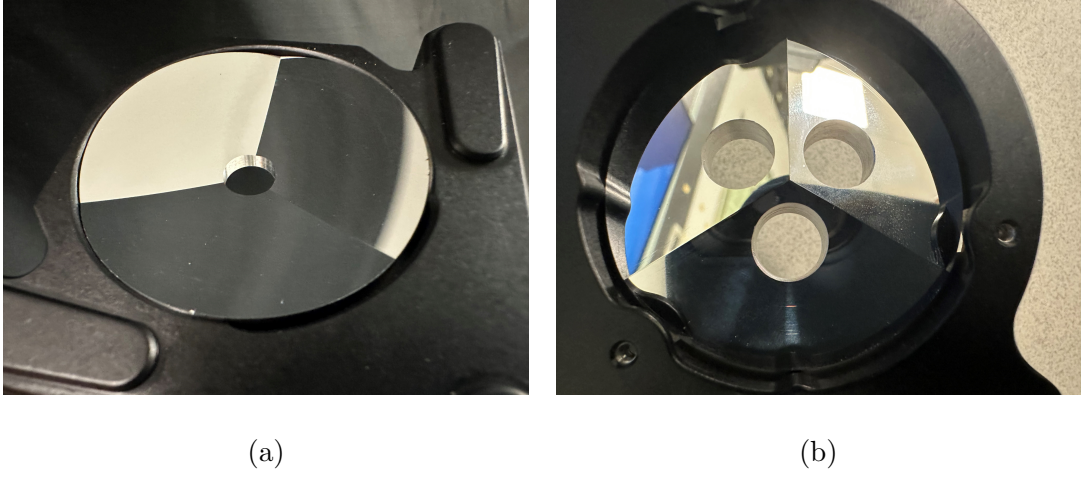


Figure 3.6: Image of the fabricated optical components: (a) the pyramidal concave mirror (PCM), and (b) the three-sided reflective pyramid.

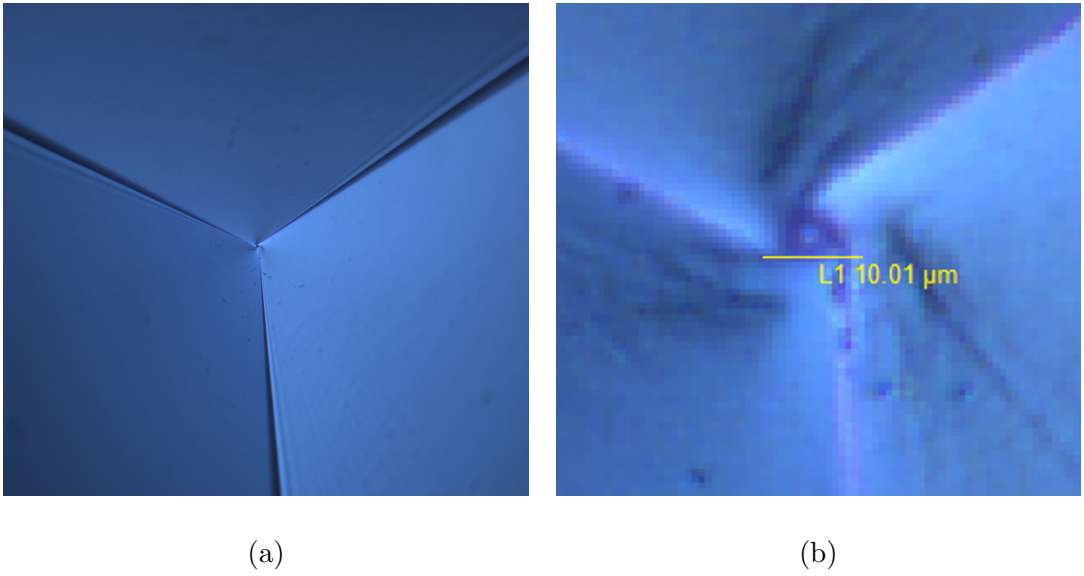


Figure 3.7: Microscope images of the reflective pyramid: (a) a lower magnification view showing surface ridges, and (b) a close-up of the apex region. The measured apex imperfection is less than $10\text{ }\mu\text{m}$, within design tolerance.

nonlinear effects, and the intensity change across the pupils is measured to form a response vector. These vectors are assembled column-wise to form $\mathbf{P}$.

To project the actuator responses into a modal basis, a set of 20 Zernike modes is used to define a basis matrix. The modal interaction matrix $\mathbf{M}$ is then calculated from the pseudoinverse of $\mathbf{P}$, allowing each Zernike mode to be expressed as a linear combination of the DM actuator responses. This calibration enables the 3RPWFS to sense arbitrary wavefront aberrations as weighted sums of these modes.

The raw intensity method is used to evaluate the phase response of the system. First, a reference image is obtained by averaging pupil images acquired under a flat DM condition using a modulation radius of $r_M = 8\lambda/D$. This radius is selected to maximize dynamic range and suppress high spatial frequency noise in the reference. Then, for each Zernike mode, the corresponding pupil image is subtracted from the reference to compute a differential response signal. This signal captures the sensor's response to the applied phase mode and forms the basis of the interaction matrix.

To assess the performance of the 3RPWFS testbed, the pupil responses to individual Zernike modes are compared against simulations performed with the HCIPy. Figure 3.8 presents a side-by-side comparison of simulated and measured pupil images. Each column corresponds to a specific Zernike mode applied via the DM. The top row shows HCIPy-generated pupil images assuming ideal optical conditions, while the bottom row displays the corresponding pupil signals measured in the LAO testbed.

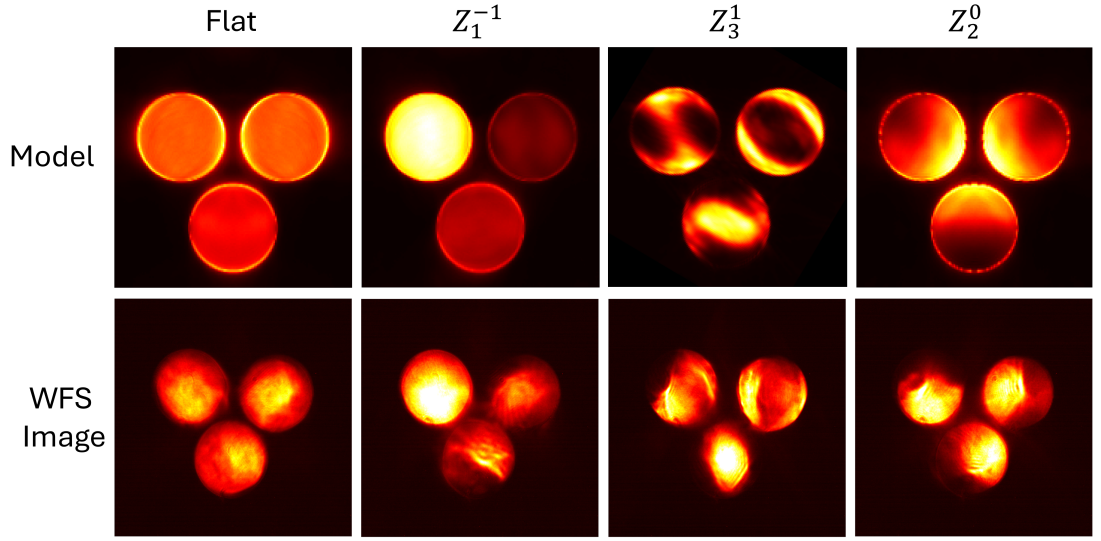


Figure 3.8: Comparison of simulated and measured pupil images for various Zernike modes. (Top) Simulated 3RPWFS pupil images generated using HCIPy. (Bottom) Experimental pupil images obtained from the LAO testbed. Each column corresponds to a single Zernike mode applied to the deformable mirror.

3.2.3 Results

To assess the performance of the second-generation 3RPWFS, we evaluated its modal response, linearity, and closed-loop behavior in a static lab environment. The results are organized into three subsections: qualitative pupil comparison, quantitative linearity and RMS measurements, and closed-loop demonstration.

3.2.3.1 Qualitative Comparison with Simulated Pupils

We induced a series of Zernike modes to compare the 3RPWFS response against HCIPy-modeled pupil images. As shown in Fig. 3.8, the measured pupils match the expected modal patterns reasonably well, especially for low-order aberrations. However, we observe a global spiral-like intensity pattern — most evident in the defocus mode (Z_2^0) — that is not predicted by simulation. This vortex pattern appears consistently in all measured pupils.

Microscope images of the reflective pyramid suggest that this feature may arise from subtle fabrication artifacts on the pyramid surfaces. Figure 3.7a reveals curved shadows along the ridges, and Fig. 3.7b highlights directional surface grooves, both of which indicate a spatially varying surface gradient. These features are consistent with a vortex-like feature and likely introduce the observed intensity redistribution across the pupils.

The observed asymmetry in light distribution across the pupil images is modeled by introducing a global spiral-like surface feature superimposed on an otherwise idealized pyramid optical mask. This spiral pattern qualitatively replicates the structure observed in microscope images of the fabricated reflective pyramid, suggesting that the nonuniform pupil illumination arises from physical imperfections introduced during the manufacturing process. Simulations incorporating this spiral surface deformation produce pupil images that closely resemble those obtained experimentally, lending support to this hypothesis (Fig. 3.9). Thus, the uneven pupil intensities are likely a consequence

of the fabrication method and may require further mitigation in future designs. Despite this behavior, modal signatures remain distinguishable, and interaction matrix calibration is not compromised for the modes tested.

3.2.3.2 Linearity and Wavefront RMS Response

To evaluate the linear response range of the 3RPWFS, we introduced a pure defocus aberration corresponding to the Zernike mode Z_2^0 with varying amplitudes and measured the sensor output using modal decomposition techniques. The x-axis of Fig.3.10a represents the normalized peak phase error of the applied Zernike mode, serving as a proxy for the magnitude of wavefront distortion. The 3RPWFS demonstrates a clear linear response within a bounded range and successfully recovers both positive and negative defocus values, preserving sign sensitivity. Ideally, a linearity curve exhibits symmetric bounds and saturation thresholds about the origin; however, our experimental data reveals an asymmetry. Specifically, the positive linear range ($x \in [0, 0.5]$) is approximately twice as large as the negative range ($x \in [-0.25, 0]$). This asymmetry may originate from nonuniform light distribution across the pupils, likely caused by the spiral-like surface feature introduced during the pyramid fabrication process. The inward radial bias in illumination reduces dynamic range, analogous to the dynamic range loss observed in four-sided PWFSs with roof-like apex defects. Figure3.10b further confirms this behavior, showing the measured wavefront RMS versus the known induced RMS with good monotonicity and a close match to the ideal one-to-one trend.

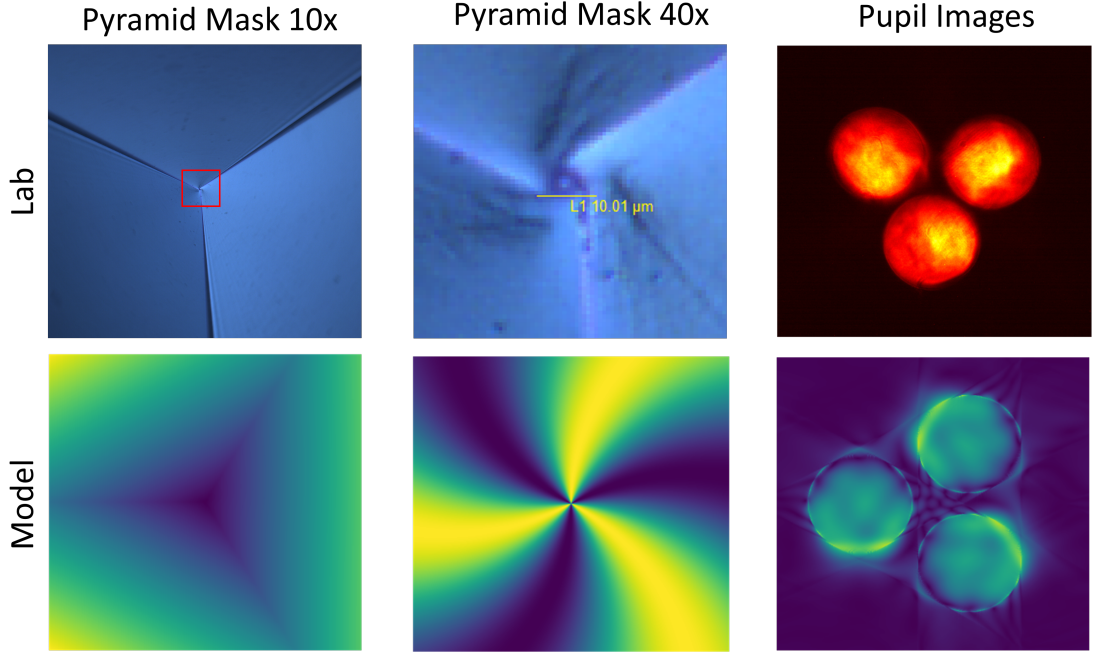


Figure 3.9: Comparison of measured and simulated pupil illumination patterns caused by a spiral-like surface defect on the reflective pyramid apex. (Top row) Lab measurements: (Left) Microscope image showing the macroscopic geometry of the three-sided reflective pyramid. (Middle) Zoomed-in apex view reveals micron-scale ridges and a spiral gradient, consistent with fabrication error. (Right) Pupil images under defocus illumination show asymmetric spiral-like light distribution. (Bottom row) Simulations: (Left) Modeled pyramid shape with superimposed spiral distortion. (Middle) Phase map of the defect. (Right) Simulated pupil images reproduce the asymmetry seen in the lab. The agreement supports the spiral defect as the source of reduced dynamic range.

3.2.3.3 Closed-Loop Operation

We performed closed-loop correction at 100 Hz using three modulation cycles per exposure. The interaction matrix $\mathbf{M}$ was constructed with a modulation radius $r_M = 8\lambda/D$ to desensitize the reference image to small phase errors. After calibration, r_M was decreased to $6\lambda/D$ to improve sensitivity during loop operation—a known property of PWFs that enhances response to low-amplitude aberrations.

A leaky integrator with gain 0.2 was used to close the loop. As shown in Fig. 3.11a and Fig. 3.11b, the point spread function (PSF) was effectively restored and loop stability was maintained. This confirms the sensor’s ability to measure and correct aberrations in the presence of static wavefront error introduced by the DM factory flat.

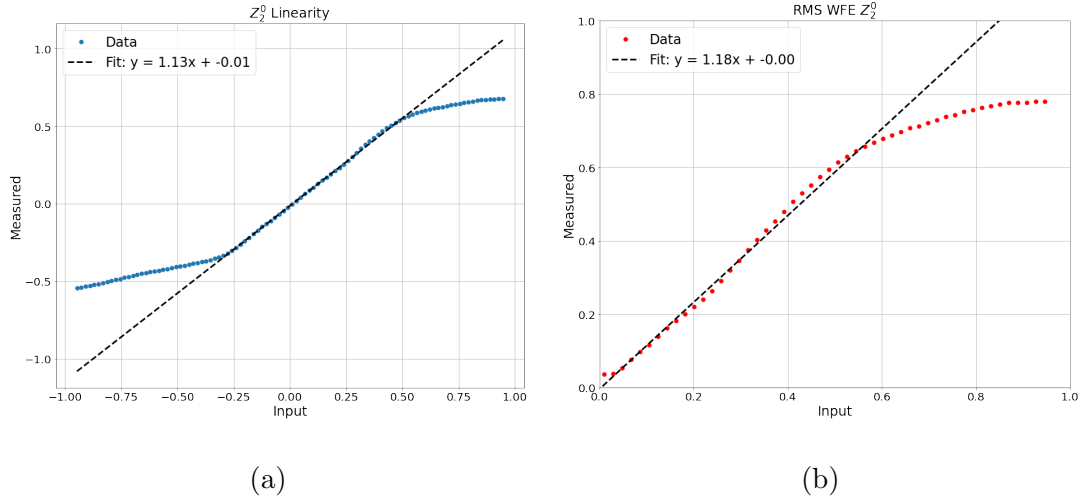


Figure 3.10: (a) Modal amplitude response of the 3RPWFS to varying Z_2^0 inputs. (b) Measured versus induced wavefront RMS.

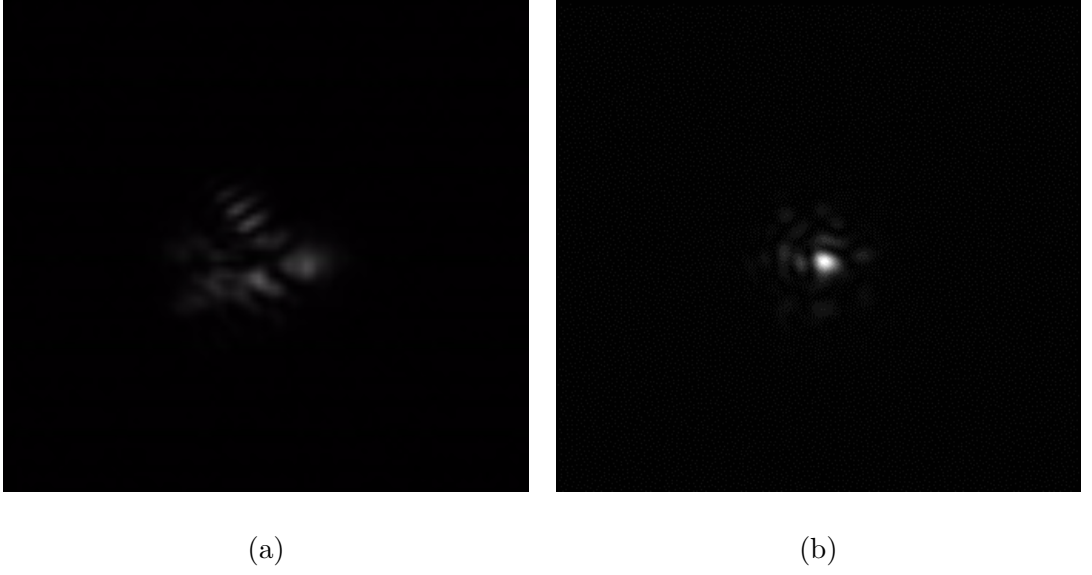


Figure 3.11: (a) PSF prior to correction and (b) PSF after closed-loop AO correction using the 3RPWFS.

3.3 Conclusion

The closed-loop operation of a second-generation three-sided reflective pyramid wavefront sensor (3RPWFS) that incorporates a pyramidal concave mirror (PCM) is demonstrated, enabling a more compact layout and reduced pupil footprint compared to the first-generation system. This revised optical configuration addresses a key limitation in the earlier design by allowing tighter pupil spacing without sacrificing pupil sampling density or increasing overall optical complexity.

During calibration, pupil images revealed an asymmetric, vortex-like intensity pattern across all three pupils, most prominently in the defocus (Z_2^0) mode. Microscope inspection of the reflective pyramid surface revealed spiral-like ridges that produce di-

rectional shading and intensity modulation, consistent with a fabrication artifact. These features were not observed in the prior-generation pyramid used in ShaneAO, suggesting a change in vendor or manufacturing process. To investigate the effect of this surface defect, we performed numerical simulations using an idealized pyramid mask superimposed with a spiral phase perturbation. The resulting pupil images qualitatively reproduce the asymmetry seen in both lab images and microscope views, confirming that the observed structure arises from a physical spiral defect. This artifact reduces the effective dynamic range of the sensor by introducing spatially varying intensity in the reference pupils, thereby distorting the phase-to-intensity mapping fundamental to wavefront sensing.

Despite these artifacts, there is strong qualitative agreement between measured and simulated pupil images across 20 Zernike modes, with no evidence of significant modal degeneracy. The linear response of the 3RPWFS is confirmed by measuring sensor output as a function of induced defocus amplitude (Fig.3.10a). Additionally, the sensor reliably tracks RMS wavefront error across a range of input aberrations and follows a one-to-one WFE estimation (Fig.3.10b). Closed-loop control was successfully demonstrated at 100 Hz using a leaky integrator controller. A factory-flat deformable mirror was used to generate reference pupils, although residual aberrations limited correction fidelity. Inclusion of higher-order Zernike modes in the interaction matrix $\mathbf{M}$ led to unstable loop behavior, suggesting that the sensor may be overly sensitive to high-spatial-frequency components, potentially exacerbated by the spiral defect. Further modeling and experimental validation are required to fully quantify the spiral arti-

fact's impact on sensitivity and linearity. Nonetheless, its absence in previous reflective pyramid designs suggests it is avoidable. Future work will involve interferometric DM flattening, modal gain optimization, and testing under polychromatic conditions in a fully reflective AO relay to assess chromatic robustness.

Part II

Focal Plane Wavefront Sensing

Focal plane wavefront sensing (FPWFS) has emerged as a critical technique in the pursuit of direct imaging of exoplanets, offering unique advantages over traditional pupil plane wavefront sensors. Unlike approaches such as the SHWFSs or PWFSs, which measure phase errors upstream of the focal plane, FPWFS methods directly use intensity measurements in the science image to infer wavefront aberrations. This inherently avoids NCPAs between the wavefront sensor and science beam, a persistent limitation in conventional AO systems. By sensing aberrations where they matter most — at the focal plane — FPWFS provides a more accurate basis for correcting residual starlight and achieving the high contrast ratios required to image faint planetary companions near bright host stars.

The need for FPWFS arises from the fact that AO systems typically rely on wavefront measurements taken several optical elements before the science detector. Even in well-calibrated systems, the presence of optical path differences downstream of the wavefront sensor —especially within coronagraphic instruments — introduces quasi-static aberrations that degrade contrast and limit sensitivity to exoplanets. These aberrations are not sensed by conventional wavefront sensors and can lead to residual speckles that mimic planetary signals. FPWFS addresses this limitation by operating directly in the science image plane, enabling correction of aberrations that are otherwise invisible to upstream sensors.

Another advantage of FPWFS is its compatibility with coronagraphy. Most FPWFS architectures operate simultaneously with a coronagraph, extracting aberration signals from the light that leaks around or through the coronagraphic mask. This

capability makes FPWFS ideal for continuous wavefront correction during science exposures, improving system stability and reducing the need for post-processing algorithms to separate speckles from real astrophysical sources. Because of this, FPWFS plays a central role in the development of next-generation high-contrast instruments for both ground-based observatories and space missions.

Pupil plane WFSs are great first-stage WFSs, correcting for the large amplitude phase errors that would be too difficult to measure with FPWFS. FPWFS can operate under these higher Strehl regimes and leverage interference, phase diversity, or focal plane modulation to encode phase information into measurable intensity changes. These approaches are often well suited to high-Strehl regimes and can be tailored to operate under specific observing conditions. Moreover, because the entire pupil contributes coherently to each point in the focal plane, FPWFS can in principle achieve higher sensitivity than some pupil plane WFSs.

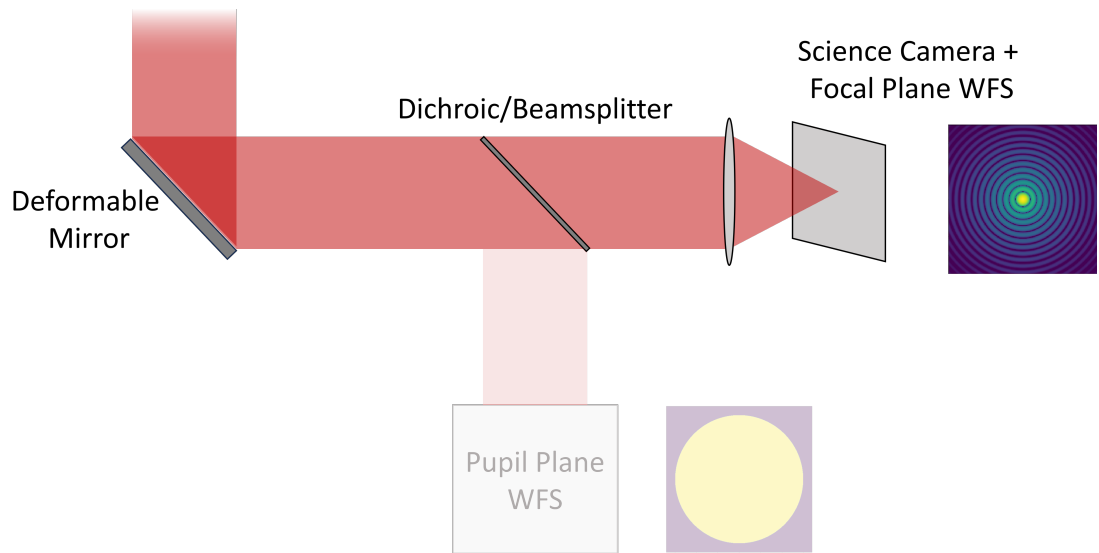


Figure 3.12: Optical layout of a focal-plane wavefront sensor (FPWFS) system. In this configuration, wavefront sensing is performed directly at the science focal plane, ensuring that all measured aberrations are common-path. This eliminates non-common path errors and allows precise correction of residual wavefront errors that affect the final science image.

Chapter 4

Extending Spectral Bandpass for the Self-Coherent Camera Using Wynne Correctors

4.1 Overview of REDWOODS

High-contrast exoplanet imaging remains fundamentally limited by speckle noise and the performance of AO systems. These limitations are particularly severe near the diffraction limit, where residual wavefront errors give rise to quasi-static speckles that degrade contrast and can mimic planetary signals. To address this challenge and demonstrate next-generation AO technologies for high-contrast imaging, we are developing REDWOODS — Real-time Exoplanet Direct imaging via Wavefront control Of Optical Defects at Shane. REDWOODS is a collaborative project between Lawrence Livermore National Laboratory (LLNL) and the University of California, Santa Cruz

(UCSC), designed as an engineering demonstration platform at the 3-meter Shane Telescope at Lick Observatory.

REDWOODS upgrades the existing ShaneAO system with a deployable bench that implements two new second-stage wavefront sensing modes: (1) a high-speed infrared focal plane wavefront sensor based on the Self-Coherent Camera (SCC), and (2) a broadband reflective pyramid wavefront sensor (RPWFS). These modes are enabled by new optics but share the existing ShaneAO woofer and tweeter deformable mirrors (DMs). Rather than relying on dedicated DMs for each WFS channel, REDWOODS uses a real-time software framework to fuse measurements from the new sensors with the existing SHWFS to enable multi-WFS single conjugate AO — a configuration that, to our knowledge, has not yet been demonstrated on-sky (Fig.4.1 and 4.2).

A major design goal of REDWOODS is to support high-contrast AO correction in the near-infrared science band. The SCC mode enables focal plane wavefront control directly on the science detector, eliminating NPCAs that limit conventional upstream WFSs. This approach is particularly beneficial for stabilizing speckles during coronagraphic exposures and improving raw contrast without relying heavily on post-processing. To extend the spectral bandwidth of the SCC mode beyond its intrinsic chromatic limitations, REDWOODS includes an optional Wynne corrector that enables operation across up to 20% bandwidths. Meanwhile, the 3RPWFS mode provides pupil plane wavefront sensing from Z to H band, offering more than a threefold sensitivity improvement over current NIR PWFS implementations.

REDWOODS is designed not only as a testbed for future science instruments,

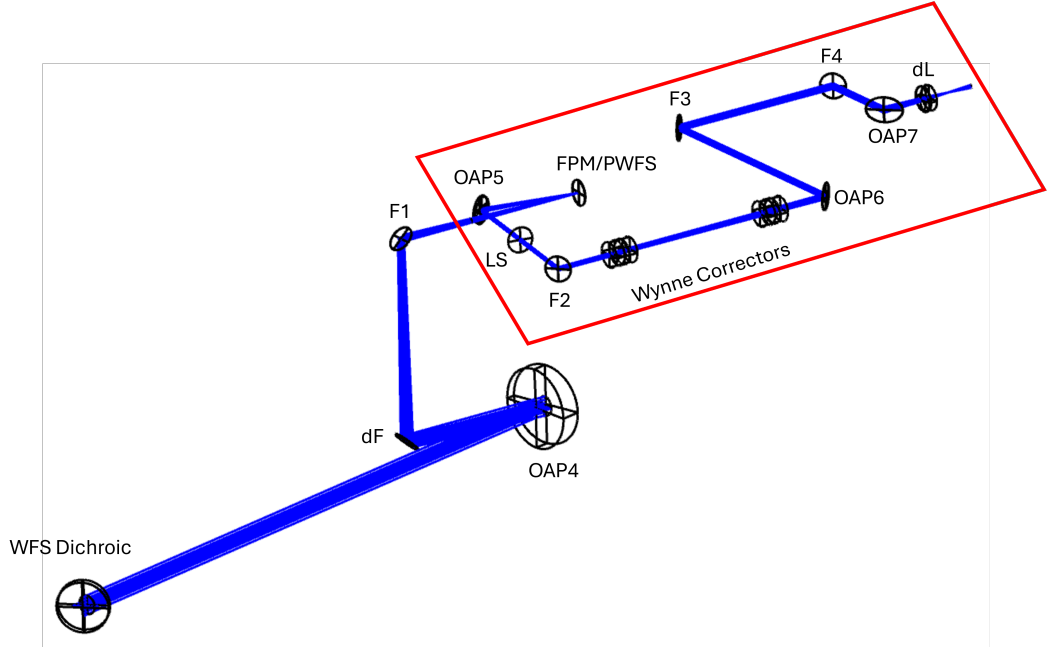


Figure 4.1: Optical layout of the REDWOODS instrument designed for the Shane Telescope. A pickoff mirror sends light to the periscope bench enclosed in the red region. The beam follows a series fold mirrors F_n and off-axis parabolic mirrors (OAP_n), which focus the light onto focal plane mask (FPM) and 3RPWFS for the focal and pupil plane modes respectively. The Lyot stop (LS) is positioned conjugate to the telescope pupil. To switch between focal and pupil plane WFS modes, deployable optics are used and are denoted with prefix d , The Wynne correctors are deployed with the SCC mode and are used to mitigate chromatic effects and preserve fringe contrast across the 0.95–1.25 μm bandpass.

but also as a risk-reduction pathfinder for large observatories such as Keck and the future Thirty Meter Telescope (TMT). The instrument's design and implementation

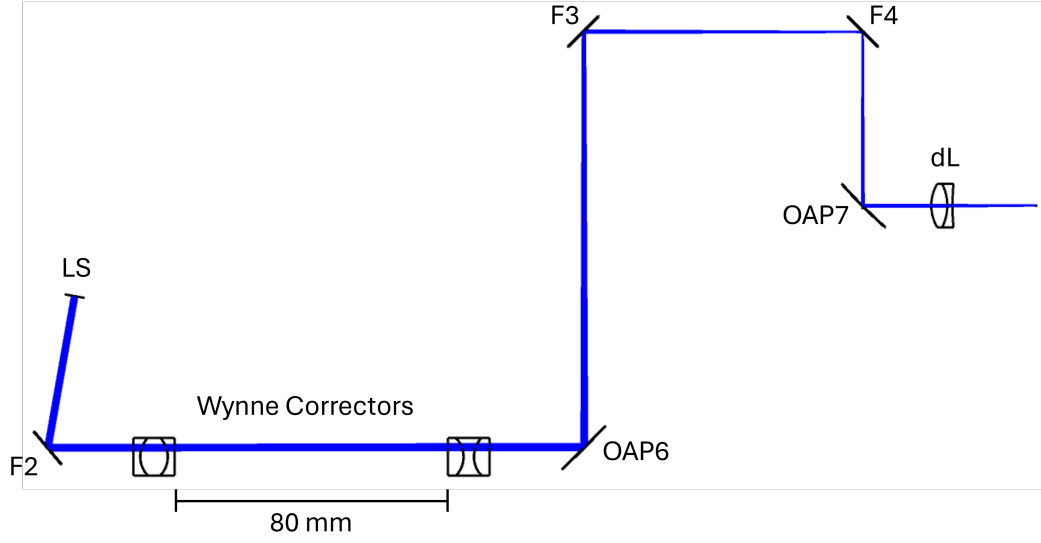


Figure 4.2: Close-up view of the periscope bench and the beam path downstream of the Lyot stop (LS). The Wynne corrector elements are decentered to align the off-axis pinhole with the optical axis, as discussed in the following section. Off-axis parabolas (OAP6 and OAP7) demagnify the pupil, and a deployable doublet lens (dL) focuses the broadband beam onto the detector with a $f/\#_w(\lambda_c) = 78$. This configuration enables chromatically corrected spectropolarimetric imaging across the 0.95–1.25 μm band.

follow recommendations to mature and de-risk key AO technologies. By validating dual-WFS AO, real-time software control, and broadband wavefront sensing techniques, REDWOODS helps bridge the $100\times$ contrast gap identified in the 2020 Decadal Survey as critical for habitable zone exoplanet imaging with ELTs.

This chapter focuses on one component of REDWOODS: the design, modeling, and initial laboratory validation of a Wynne corrector to mitigate chromatic fringe

smearing in the SCC mode.

4.2 Self-Coherent Camera Wavefront Sensor and Chromatic Limitations

The Self-Coherent Camera (SCC) is a focal plane wavefront sensing technique designed to estimate and correct residual aberrations directly at the science focal plane. This is particularly valuable in high-contrast imaging systems, where quasi-static speckles generated downstream of traditional wavefront sensors limit the ability to detect faint companions near bright stars.

The core principle of the SCC is to encode phase aberrations into spatial interference fringes within the science image. This is accomplished by introducing a coherent reference beam from a sub-aperture—typically a small pinhole in the Lyot stop plane—that samples starlight rejected by the coronagraph. This off-axis reference interferes with residual starlight that leaks through the coronagraphic mask, producing fringes across the speckle field in the focal plane. These fringes modulate the speckles with a known spatial frequency, enabling estimation of the complex electric field via post-processing.

Mathematically, the image intensity at the science focal plane is given by:

$$I = I_S + I_P + I_R + 2\sqrt{I_S I_R}M \quad (4.1)$$

where I_S is the unfringed stellar speckle, I_P is the infringed planet, I_R is the reference pinhole PSF, and M is the fringe variable. The cross term encodes the phase information

through its interference with the known reference, allowing reconstruction of the residual stellar electric field from a single image.

One of the SCC's main advantages is that it does not require phase diversity or modulation; phase retrieval is performed directly from a single science image, preserving temporal information and observing efficiency. This makes the SCC particularly attractive for real-time correction of quasi-static aberrations in extreme adaptive optics (ExAO) systems, where long integration times and high stability are required.

Despite these advantages, the SCC is fundamentally limited by chromatic effects. The fringe spacing is inversely proportional to wavelength, and in broadband light, each wavelength produces a slightly different interference pattern. The resulting superposition of fringes with varying spatial frequencies causes fringe smearing, reducing visibility and degrading the phase reconstruction accuracy. For a monochromatic central wavelength λ_c , the fringe spacing is determined by the physical offset d between the reference pinhole and the main pupil in the Lyot stop. Over a bandwidth $\Delta\lambda$, the spatial coherence of the interference pattern drops due to this wavelength dependence.

The degradation in fringe visibility V scales approximately as:

$$V \propto \text{sinc} \left(\pi \cdot \frac{d \cdot \Delta\lambda}{\lambda_c^2} \right), \quad (4.2)$$

indicating that larger pinhole separations or broader bandwidths lead to stronger attenuation of the interference signal. In practice, this restricts the SCC to narrowband operation, typically with fractional bandwidths below $\sim 3\text{--}5\%$, depending on the system geometry and required fringe contrast.

This chromatic limitation significantly constrains the use of SCC in broadband science applications, such as spectral differential imaging or near-infrared exoplanet detection. To address this challenge, REDWOODS incorporates a Wynne corrector — an optical system designed to compensate for the wavelength-dependent fringe scaling — thereby enabling fringe-stable operation across bandwidths up to 20%. The next section introduces the principles of the Wynne corrector and its integration into the REDWOODS SCC optical path.

REFERENCES NOT INLCUED YET

4.3 Wynne Corrector and Its Application to the Self-Coherent Camera

One of the primary limitations of FPWFSs, such as the Self-Coherent Camera (SCC), is their sensitivity to chromatic effects. The interference patterns encoded in the science focal plane scale with wavelength, and broadband operation causes these spatial fringes to smear and lose contrast. To overcome this limitation, Wynne proposed an achromatizing optical system designed to equalize the angular scale of diffraction-limited features across a broad bandpass (Fig.4.3b) [43]. This system, now known as the Wynne corrector, provides a wavelength-dependent angular magnification that compensates for the natural chromatic scaling of both the PSF and fringe structure.

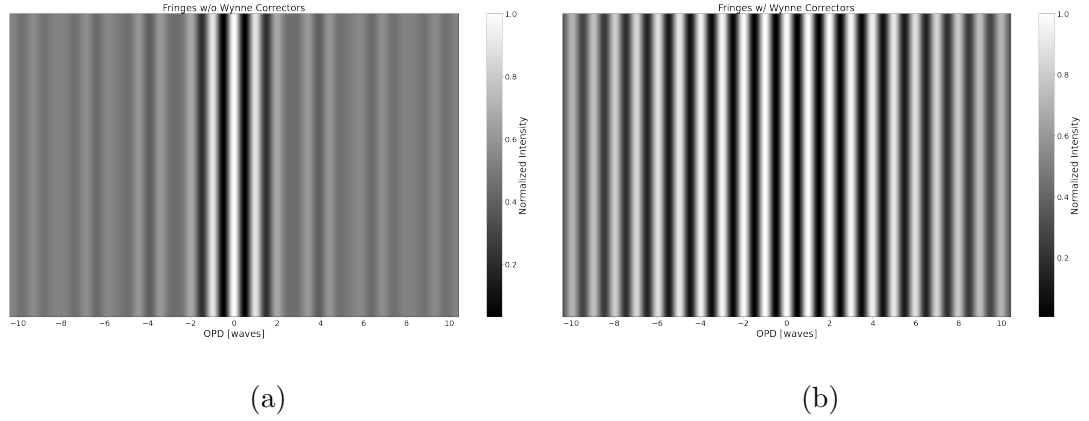


Figure 4.3: Comparison of fringe visibility across a 40% spectral bandpass centered at 480 nm, without (left) and with (right) Wynne correctors. In the absence of correction, chromatic dispersion causes significant fringe smearing, reducing fringe contrast. The Wynne correctors compensate for the wavelength-dependent PSF scale, restoring higher fringe visibility across the full bandpass.

4.3.1 Principle of the Wynne Corrector

In a diffraction-limited optical system, the angular extent of the Airy pattern - and by extension, the speckle field - increases proportionally with wavelength. Specifically, the angular radius of the first null in the PSF is:

$$\alpha(\lambda) = \frac{1.22\lambda}{D}, \quad (4.3)$$

where λ is the wavelength and D is the telescope aperture diameter. This chromatic scaling causes the speckle pattern to broaden radially in broadband systems, degrading both fringe contrast and phase retrieval performance in focal-plane wavefront sensing techniques like the SCC.

To address this issue, the Wynne corrector introduces a wavelength-dependent angular magnification $M(\lambda)$ that scales inversely with wavelength:

$$M(\lambda) \propto \frac{1}{\lambda}, \quad (4.4)$$

so that the effective angular extent of the speckle field becomes:

$$\theta_{\text{eff}}(\lambda) = M(\lambda) \cdot \theta_{\text{PSF}}(\lambda) \approx \text{const.} \quad (4.5)$$

In this way, both the PSF and the spatial interference fringes introduced by the SCC remain fixed in angular scale across the bandpass. This chromatic magnification mitigates fringe blurring, preserving fringe visibility and enabling robust electric field estimation.

The Wynne corrector typically consists of two or more chromatic lens elements - such as doublets or triplets - made from glasses with complementary dispersion properties. The key design principle is to select glasses whose refractive indices cross at a central wavelength λ_c , resulting in the desired angular magnification behavior. The ideal index relationship is:

$$\begin{cases} n_1(\lambda) > n_2(\lambda), & \text{for } \lambda < \lambda_c \\ n_1(\lambda_c) = n_2(\lambda_c), & \text{at } \lambda = \lambda_c \\ n_1(\lambda) < n_2(\lambda), & \text{for } \lambda > \lambda_c \end{cases} \quad (4.6)$$

This crossing behavior causes the net optical power of the system to transition from positive to negative as a function of wavelength. Because the angular magnification is directly tied to this total power, it enables the corrector to compress or expand the PSF angular extent such that it remains fixed across the band.

This behavior can be visualized as a chromatic analog to a Galilean telescope: the beam is effectively expanded at short wavelengths and compressed at long wavelengths, anchoring the PSF width to its size at λ_c . The angular scaling is driven by the wavelength-dependent power of the lens surfaces, which can be approximated by:

$$\phi(\lambda) = \frac{1}{f(\lambda)} = \frac{n'(\lambda) - n(\lambda)}{R}, \quad (4.7)$$

where n and n' are the refractive indices on either side of a curved surface of radius R . If the index difference follows the crossing behavior in Eq. 4.6, then the surface power changes sign across λ_c :

$$\begin{cases} \phi > 0, & \text{for } \lambda < \lambda_c \\ \phi = 0, & \text{at } \lambda = \lambda_c \\ \phi < 0, & \text{for } \lambda > \lambda_c \end{cases} \quad (4.8)$$

Maximizing the magnitude of the index difference $\Delta n(\lambda)$ on either side of λ_c enhances the chromatic scaling while minimizing the separation between lens groups in the optical train.

4.3.2 Application to the Self-Coherent Camera

By implementing a Wynne corrector upstream of the SCC, the chromatic angular magnification introduced by the corrector effectively rescales the speckle field and fringe structure to a fixed angular scale. This stabilization ensures that both the diffraction-limited PSF and the SCC fringe pattern remain coherent across a broad spectral range, increasing fringe visibility and phase retrieval accuracy. The net result

is a higher SNR and improved wavefront sensing performance in broadband light.

Although the Wynne corrector does not eliminate all chromatic aberrations, it significantly reduces wavelength-dependent smearing of focal plane structures. The degree of improvement depends on the dispersive properties of the selected glass materials and the system’s tolerance to residual chromatic deviations.

In the REDWOODS implementation, the SCC is designed to create a dark hole region with an outer working angle (OWA) of $10\lambda/D$, and fringe smearing must be limited to less than one fringe over this range. To quantify this requirement, we define a fringe stability constraint:

$$\Delta r_s(\lambda) \equiv |r_s(\lambda) - r_c| < \frac{1}{30}r_c, \quad (4.9)$$

where r_c is the reference fringe spacing at λ_c , and the factor $1/30$ represents the maximum allowable radial shift corresponding to one fringe over the $10\lambda/D$ dark hole (i.e., $\Delta r_s < \lambda/D$ over $10\lambda/D \Rightarrow \text{max drift} = 1/30$ of r_c). This constraint sets a design target for chromatic dispersion suppression in the Wynne corrector and informs the choice of lens materials and spacing tolerances.

4.4 Visible Wynne Corrector

To evaluate the feasibility of chromatic correction for broadband SCC applications, we first developed and tested a pair of Wynne correctors designed to operate in the visible spectral range. The glass substrates that exhibit the desired chromatic magnification behavior are identified by calculating their wavelength-dependent refractive

index $n(\lambda)$ using the Sellmeier dispersion formula (valid for λ in microns):

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (4.10)$$

where B and C are empirical coefficients specific to the glass substrate. Using Eq. 4.10, we searched commercial glass catalogs for substrates that meet the index-crossing criteria for chromatic scaling.

A pair of Wynne correctors were designed, and the resulting optical layout is shown in Fig. 4.4. The optical elements consist of cemented triplet lenses made from H-LAK51A and H-ZF10 glass substrates, both of which exhibit the same refractive index at 480 nm, as illustrated in Fig. 4.5. A 2.6 mm Lyot stop generates a collimated beam, which is subsequently transformed into an $F/78$ beam using an off-axis parabolic mirror (OAP). The resulting spot dispersion and wavefront root-mean-squared (RMS) values are shown in Fig. 4.6a (spot size vs. wavelength) and Fig. 4.6b (RMS wavefront error across bandpass).

The optical system is optimized by scaling the $F/\#$ within the spectral range to match the PSF width at $\lambda_0 = 480$ nm. Subsequently, optical aberrations were minimized, making the wavefront error a critical performance metric. Without addressing these chromatic aberrations, the $F/\#$ may be correct, but the resulting PSF could be too aberrated to be functional. Within a 36% bandpass, the spot dispersion remains below $2 \mu\text{m}$, exceeding the initial system requirements. Table 4.1 summarizes the system performance, indicating that the system is diffraction-limited with a 20% bandpass and incurs a maximum wavefront error of 0.1 waves within a 36% bandpass.

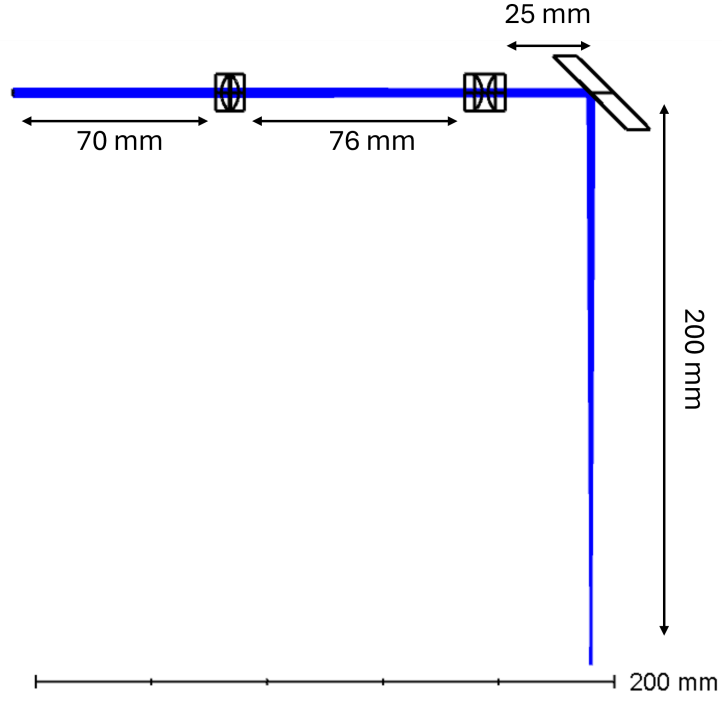


Figure 4.4: Zemax optical design of a pair of visible Wynne correctors illustrating the layout for testbed characterization.

To validate the modeled performance and evaluate chromatic behavior under realistic test conditions, we implemented the Wynne corrector system in the High Contrast Testbed (HCT) at Lawrence Livermore National Laboratory (LLNL). The optical setup was first aligned such that the main pupil was positioned on-axis, placing the pinhole used for the SCC fringe generation off-axis. Under this configuration, the resulting PSF closely matched Zemax predictions, confirming that the Wynne corrector preserved PSF scale and minimized chromatic dispersion for the on-axis pupil. However, due to field-dependent aberrations inherent in the Wynne corrector design, the off-axis

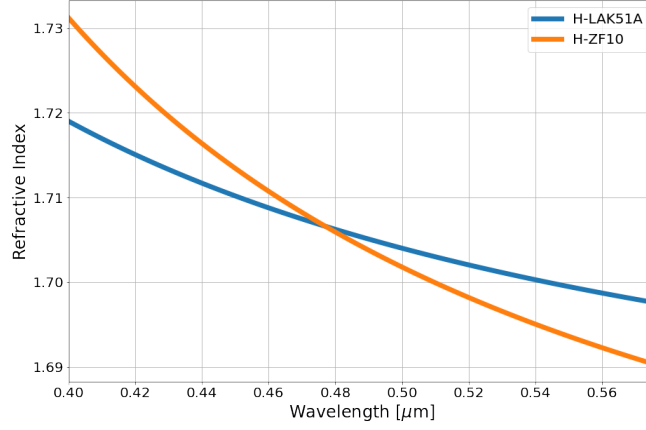


Figure 4.5: Refractive indices for H-LAK51A and H-ZF10 as a function of wavelength. The central wavelength $\lambda_0 = 480$ nm is shown as the intersection between the two functions.

pinhole experienced notable optical distortion, resulting in an aberrated reference PSF that degraded fringe visibility and SCC performance.

To mitigate this, the Wynne correctors were physically decentered such that the reference pinhole was aligned with the optical axis. In this configuration, the SCC produced higher-contrast fringes and operated effectively, despite the main pupil being shifted off-axis and subject to moderate aberrations. The resulting performance trade-off was a threefold increase in PSF spot dispersion and chromatic color spread that was approximately twice the diffraction limit. These metrics are quantified in Fig. 4.8a and Fig. 4.8b. Chromatic focal shift, shown in Fig. 4.10, confirms that longitudinal dispersion remained within tolerances for SCC operation.

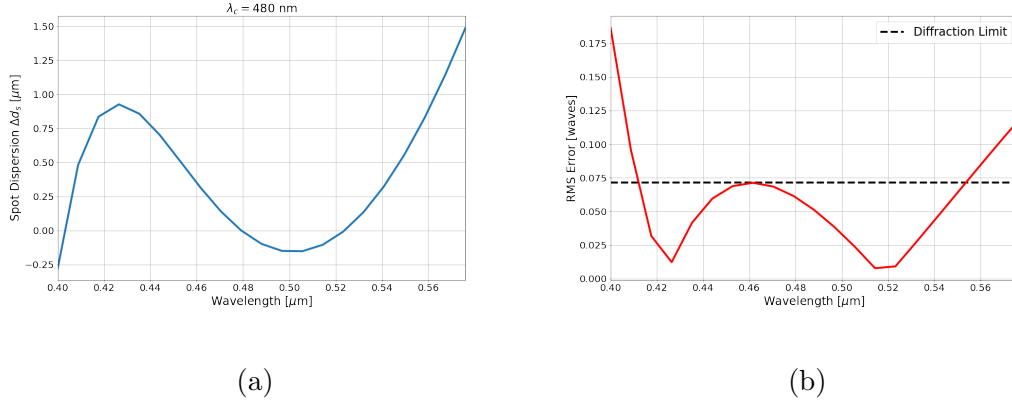


Figure 4.6: **Visible Wynne Corrector:** (a) The peak-to-valley spot dispersion is the difference between the PSF widths at the upper and lower band edges. (b) RMS wavefront error compared to the diffraction limit (dashed line).

Despite not fully achieving the original chromatic performance goals, the system demonstrates robust SCC functionality across the 400–576 nm bandpass. This performance is notable given the residual WFE introduced by chromatic focal shift. A key factor mitigating this error is the careful alignment of the Wynne corrector and pinhole along a common optical axis. In SCC systems, the on-axis pupil—attenuated by the coronagraphic Lyot stop—is significantly dimmer than the off-axis reference beam, making the quality of the reference beam essential. If the pinhole is decentered, off-axis aberrations are introduced, contaminating the reference beam and degrading fringe contrast. By maintaining strict on-axis alignment, the system suppresses these aberrations, preserving the spatial coherence necessary for effective SCC phase retrieval. These results highlight both the limitations and resilience of Wynne-corrected SCC architectures and inform the optical trade-offs needed when adapting such designs to

Table 4.1: Summary of Wynne corrector optical performance metrics in Zemax simulations.

Bandwidth	20%	36%
Spot Dispersion [μm]	1.07	1.76
Wavefront Error [waves]	0.05 ± 0.02	0.06 ± 0.04

longer wavelengths in instruments like REDWOODS.

4.5 NIR Wynne Corrector

Similarly to the visible Wynne correctors’ design process, a pair of near-infrared glass substrates that satisfy the conditions in Eq. 4.6 and Eq. 4.7 must be identified. For REDWOODS, the selected NIR detector has a quantum efficiency QE exceeding 75% at 975 nm, which defines the lower bound of the target spectral bandpass. To ensure this QE threshold is maintained across the entire band, we center the design at $\lambda_c = 1.078 \mu\text{m}$, yielding a 20% bandpass of approximately 975–1200 nm.

The S-NPH7 and S-LAH96 glasses satisfy the chromatic index-crossing conditions with $\lambda_c \approx 1.05 \mu\text{m}$, as shown in Fig. 4.7. Although suitable, the index difference (Δn_λ) is smaller in the NIR than in the visible, leading to a more constrained achromatic compensation and thus limiting the achievable bandwidth.

Due to physical space constraints, limited to ~ 160 mm between Wynne correctors, small Δn_λ requires the surfaces to have increased optical power ϕ_λ to achieve the necessary chromatic scaling. This leads to tighter surface curvatures and greater lens

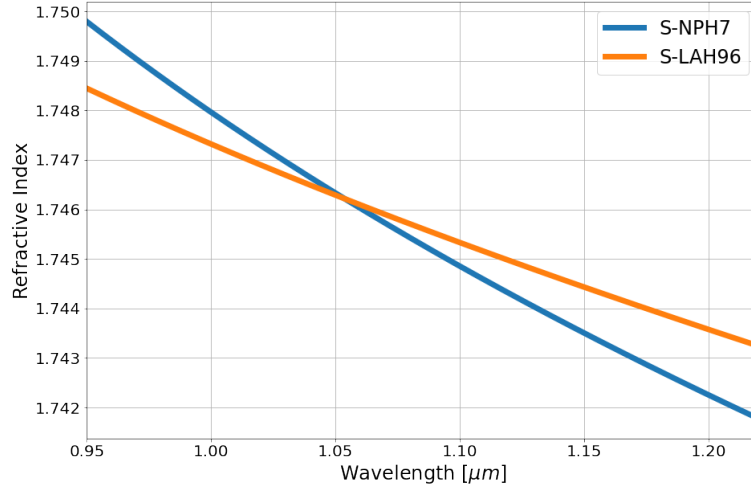


Figure 4.7: Refractive indices for S-NPH7 and S-LAH96 as a function of wavelength. The central wavelength $\lambda_c = 1.05 \mu\text{m}$ is shown as the intersection of the two dispersion curves.

thickness to maintain realistic sag profiles. More critically, stronger curvatures amplify sensitivity to decentration and off-axis aberrations.

Drawing from experience with the visible Wynne correctors in Sec. 4.4, we adopt a relaxed dispersion requirement of $\Delta r_s < \frac{1}{10}r_c$. That earlier system showed robust fringe visibility even with spot dispersions nearly 3x above nominal tolerances, justifying the same relaxation here. Likewise, lateral color tolerances are scaled by a factor of 2.

The REDWOODS beam is focused using a deployable 30 mm EFFL doublet lens, producing an $F/78$ beam onto the C-RED2 detector. The spot dispersion Δr_s meets the relaxed performance requirement across $\lambda \in [0.95, 1.25] \mu\text{m}$, and the

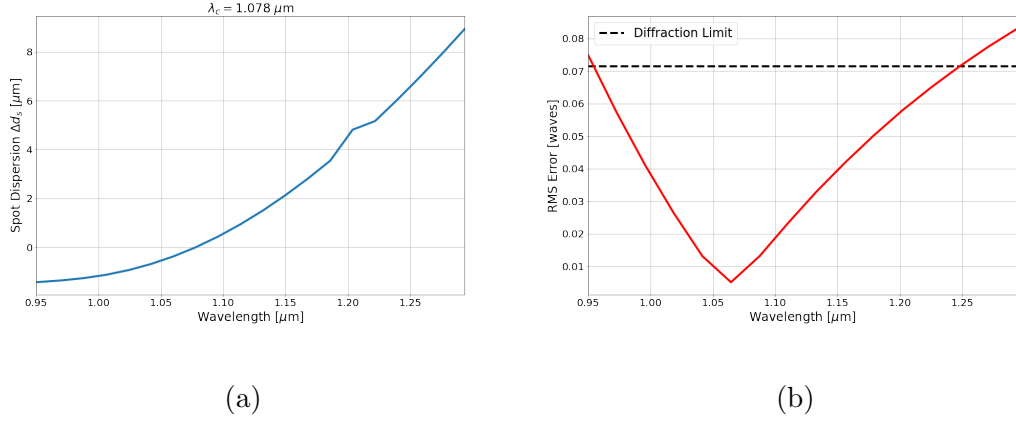


Figure 4.8: **Near-Infrared Wynne Corrector:** (a) The peak-to-valley spot dispersion is the difference between the PSF widths at the upper and lower band edges. (b) RMS wavefront error compared to the diffraction limit (dashed line).

RMS wavefront error remains well below the diffraction-limited threshold (Fig. 4.8a and Fig. 4.8b).

The Wynne corrector pair is physically spaced by 80 mm and will share a deployable OTA downstream of the Lyot stop. The OTA will be laterally decentered by 2.66 mm to align concentrically with the off-axis pinhole in the Lyot stop. Fig.4.9 illustrates the resulting lateral chromatic shear, which remains within tolerable bounds for SCC functionality.

Longitudinal chromatic focal shift also remains within diffraction blur size across the full bandpass (Fig.4.10). Together, these results confirm that the NIR Wynne corrector design preserves the essential PSF and fringe characteristics needed for broad-band SCC operation in REDWOODS.

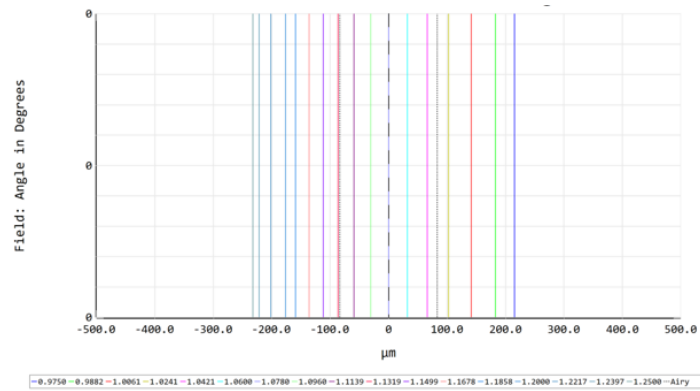


Figure 4.9: Lateral chromatic color induced by Wynne corrector decentration.

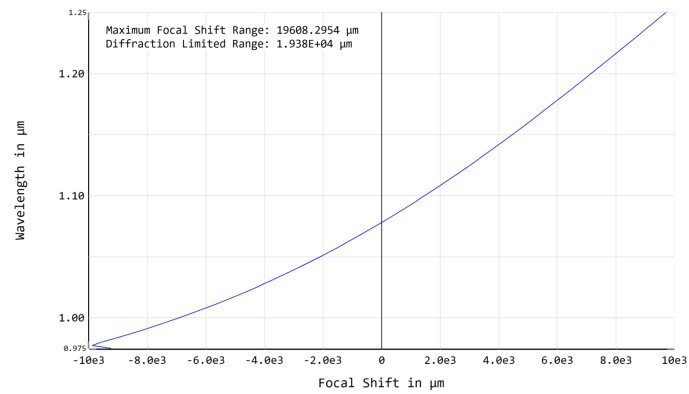


Figure 4.10: Chromatic focal shift induced by Wynne corrector decentration.

Table 4.2: Summary of NIR Wynne Corrector Performance Metrics

Central Wavelength λ_c	1.078 μm
Operating Bandpass	0.95–1.25 μm
Spot Dispersion Δr_s	<3.4 μm
RMS Wavefront Error	<0.1 waves
Lateral Chromatic Shear	< $2 \times$ diffraction limit
Longitudinal Focal Shift	≈ 1 diffraction blur size
WC Separation	80 mm
WC Decenter	2.66 mm

4.6 Conclusion

This chapter presents the design, modeling, and initial validation of Wynne correctors to extend the broadband performance of the SCC wavefront sensor for use in high-contrast imaging systems. Chromatic smearing of interference fringes poses a fundamental challenge for SCC-based focal plane wavefront sensing, limiting its application to narrowband observations. The Wynne corrector concept, which introduces a wavelength-dependent angular magnification to maintain a constant PSF scale across the bandpass, offers a promising solution to this limitation.

The chromatic limitations inherent to SCC wavefront sensing and the principle of operation behind Wynne correctors were reviewed. An analytical framework was provided to show how pairs of glasses with crossing refractive indices can be configured to maintain fringe visibility by minimizing spot dispersion and lateral/longitudinal chromatic aberration. This approach was demonstrated through the design and Zemax modeling of Wynne correctors in both the visible and near-infrared spectral regimes.

In the visible, a suitable glass pair (H-LAK51A and H-ZF10) is identified, with an index crossing at 480 nm, achieving diffraction-limited performance over a 20% bandwidth and functional performance over a 36% band. A prototype implementation was tested on the High Contrast Testbed (HCT) at LLNL, where performance tradeoffs between on-axis and off-axis pupil alignment were explored. By centering the pinhole rather than the main pupil, the system achieved improved fringe contrast despite modest degradation in PSF quality — demonstrating the operational flexibility of Wynne-corrected SCCs.

We then extended this approach to the NIR regime in support of REDWOODS, targeting a 0.95–1.25 μm bandpass compatible with the system’s detector quantum efficiency. The selected glass pair (S-NPH7 and S-LAH96) provides an index crossing near 1.05 μm . Optical modeling shows that the system meets relaxed functional requirements for spot dispersion and wavefront error across the desired band, with tolerance to small amounts of decentering and longitudinal shift. The design is compact enough to fit within REDWOODS’s optomechanical constraints, and experimental validation is planned for future commissioning phases.

Overall, this work demonstrates that Wynne correctors provide a viable pathway to enable polychromatic SCC wavefront sensing and extend its application to science cases requiring broader spectral coverage. These developments lay the groundwork for future broadband SCC demonstrations on-sky with REDWOODS, and ultimately contribute to the advancement of focal plane wavefront sensing techniques critical to direct imaging of exoplanets with current and next-generation telescopes.

Part III

Protoplanetary Disks and the Snow Line

Chapter 5

Spectropolarimetry with SCALES

5.1 Introduction

Protoplanetary disks are essential laboratories for studying the early stages of planet formation, containing the dust, gas, and ices that seed planetary cores and atmospheres. Observations in the 2–4 μm spectral range are particularly valuable, as they probe both thermal emission from warm circumstellar material and vibrational features of molecular ices. In this band, the 3 μm absorption feature associated with water ice is a key diagnostic of the snow line — the location where water transitions from gas to solid — offering insight into the volatile content of forming planets.

Because light scattered off disk dust becomes polarized while direct stellar emission remains largely unpolarized, polarimetric techniques offer enhanced contrast for detecting faint disk structures. When combined with spectroscopy, spectropolarimetry enables spatially and spectrally resolved measurements of polarized light, providing

sensitivity to disk geometry, grain composition, and the spatial distribution of ices. These measurements are particularly effective in inclined systems, where the scattering geometry yields strong polarization signatures across the bandpass.

This chapter presents the design and implementation of a reflective dispersive Wollaston prism for the SCALES instrument at the Keck Observatory, enabling near-infrared spectropolarimetry from 2–4 μm . The system is optimized to capture spatially resolved, orthogonally polarized spectra across this band, targeting features such as the 3 μm ice band with sufficient spectral resolution and instrumental stability. These capabilities support the broader goal of constraining the dust and ice content of protoplanetary disks and enhancing our understanding of planet formation conditions.

5.2 Polarization of the 3 μm Water Ice Feature

Water ice exhibits a prominent spectral feature near 3 μm , attributed to the O–H vibrations of ice molecules. This absorption feature is commonly detected in the outer regions of protoplanetary disks where temperatures are low enough for water to freeze onto dust grains. Although typically studied in total intensity through extinction or scattering, this feature also produces a distinctive signal in polarized light that can be exploited with spectropolarimetry (Fig.5.1).

The polarization behavior of the 3 μm ice feature is sensitive to both grain size and ice abundance. Micron-sized icy grains, in particular, produce an enhanced degree of linear polarization across the band compared to adjacent wavelengths. This excess

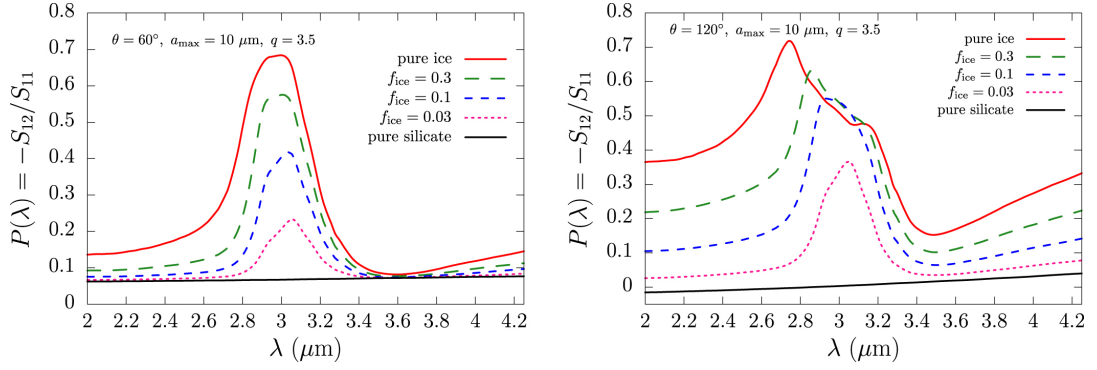


Figure 5.1: Modeled degree of polarization $P(\lambda) = -S_{12}/S_{11}$ as a function of wavelength for various water ice volume fractions f_{ice} , adapted from Tazaki et al. (2021). Each panel corresponds to a different scattering angle: $\theta = 60^\circ$ (left) and $\theta = 120^\circ$ (right), with a maximum grain size of $a_{\text{max}} = 10 \mu\text{m}$ and a power-law index $q = 3.5$. The prominent polarization peak near $3 \mu\text{m}$ corresponds to the water ice absorption feature, with polarization strength increasing with ice abundance. Pure silicate grains exhibit low polarization across the band and highlights the sensitivity of the $3 \mu\text{m}$ feature to water ice content in spectropolarimetric observations of protoplanetary disks (Figure Credit: [5]).

arises because absorption by ice suppresses internal scattering and enhances surface reflection, which is preferentially polarized (Fig.5.2) [5].

Radiative transfer simulations of the outer disk of HD 142527 have confirmed that such polarization enhancements at $3 \mu\text{m}$ are observable in disk-scattered light and are strongest when the grains are $\gtrsim 0.5 \mu\text{m}$ in size and moderately ice-rich (e.g., $f_{\text{ice}} \sim 0.03\text{--}0.1$). For these grains, the polarization fraction is enhanced by up to 15% across the

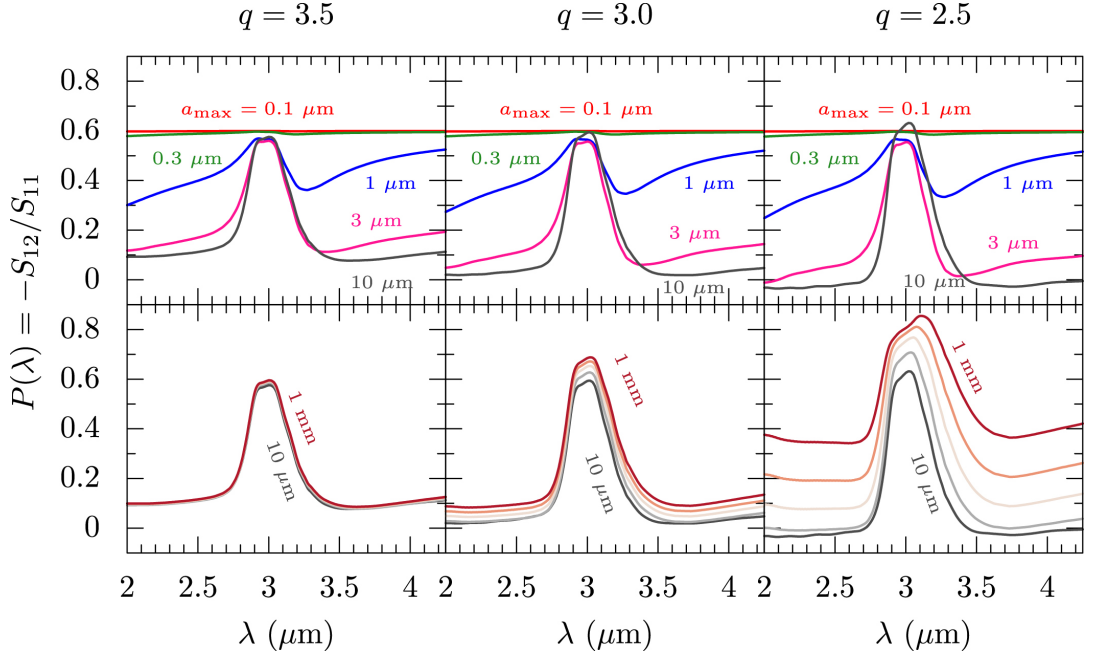


Figure 5.2: Scattering polarization spectra at ($\theta = 60^\circ$) for varying maximum grain sizes (a_{max}) and size distribution slopes (q), assuming an ice abundance of ($f_{ice} = 0.3$) and a minimum grain size of $0.005 \mu\text{m}$. Top panels show results for submicron to $10 \mu\text{m}$ grains, while bottom panels explore polarization for larger grains up to 1 mm . From left to right, the power-law index decreases from ($q = 3.5$) to ($q = 2.5$) (Figure Credit: [5]).

feature relative to the continuum. This polarization enhancement is observable in both the fractional polarization spectrum and the polarized intensity spectrum, depending on the scattering geometry and the viewing angle of the disk.

In the reflection regime—where light is dominated by surface scattering—the polarization excess is especially pronounced. This condition is typically met when grains

are large (a few microns) and the absorption optical depth becomes significant near the ice band center. As such, detection of this polarization feature is a robust tracer of large icy grains and can help constrain both the spatial distribution and vertical mixing processes in disks.

These theoretical and observational results strongly support the feasibility of detecting the 3 μm polarization feature in protoplanetary disks using a low-resolution spectropolarimeter. This motivates the design and implementation of a Wollaston-based spectropolarimetric mode within the 2–4 μm bandpass, where polarized scattering features and key molecular absorption bands — such as the 3.1 μm water ice feature — coincide. To effectively characterize this signal, the instrument must meet several observational and optical design requirements: (1) full coverage of the 2–4 μm band to enable continuum measurements on either side of the absorption feature; (2) a spectral resolving power of $R \gtrsim 5$ to resolve the feature’s width; (3) polarimetric modulation capability to disentangle intrinsic polarization signals from instrumental effects; (4) a single optical element that both disperses light and separates orthogonal linear polarization states; (5) optical quality sufficient to preserve image fidelity and spectral resolution across the full bandpass; and (6) compatibility with the existing SCALES optical footprint to ensure seamless integration. These combined requirements directly inform the use of a reflective dispersive Wollaston prism in a compact double-pass architecture.

5.3 SCALES Instrument Overview and Science Capabilities

The Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy (SCALES) is a diffraction-limited, infrared integral field spectrograph (IFS) designed for use at the Keck Observatory. Operating from 2–5 μm , SCALES extends high-contrast imaging into the mid-infrared, targeting a spectral regime where cold, self-luminous exoplanets emit most strongly. These longer wavelengths enable the detection and characterization of older and lower-mass planets that are otherwise inaccessible to near-infrared instruments like GPI or SPHERE.

SCALES integrates AO and coronagraphy to suppress starlight and deliver high contrast ratios ($\sim 10^6$) at small angular separations. The instrument includes both low- and medium-resolution modes ($R \sim 100\text{--}2000$), optimized for key molecular bands such as H_2O , CO , CH_4 , NH_3 , and PH_3 . These bands are essential for atmospheric retrievals of exoplanets and brown dwarfs, and they overlap with the Gaia-discovered population of long-period gas giants — many of which will be prime targets for SCALES.

In addition to exoplanet characterization, SCALES is equipped to study a broad range of astrophysical environments. It enables detection of accreting protoplanets through hydrogen emission lines, spectral mapping of polycyclic aromatic hydrocarbons (PAHs), and absorption features from silicates and ices in circumstellar disks. SCALES also supports transient Solar System science, such as volcanic activity monitoring on Io or thermal mapping of comets.

SCALES includes a mode selection wheel that accommodates interchangeable optical elements, such as a prism or polarimetric optical element (Fig.5.3 and 5.4)[6, 7]. This architecture allows the integration of a reflective dispersive Wollaston prism to enable spectropolarimetry. Combined with AO and coronagraphy, this mode allows simultaneous acquisition of orthogonal polarization spectra across the 2–4 μm range, targeting features like the 3 μm water ice band. These data provide powerful constraints on grain composition and disk structure, enabling spatially resolved studies of the snow line and dust evolution in planet-forming regions.

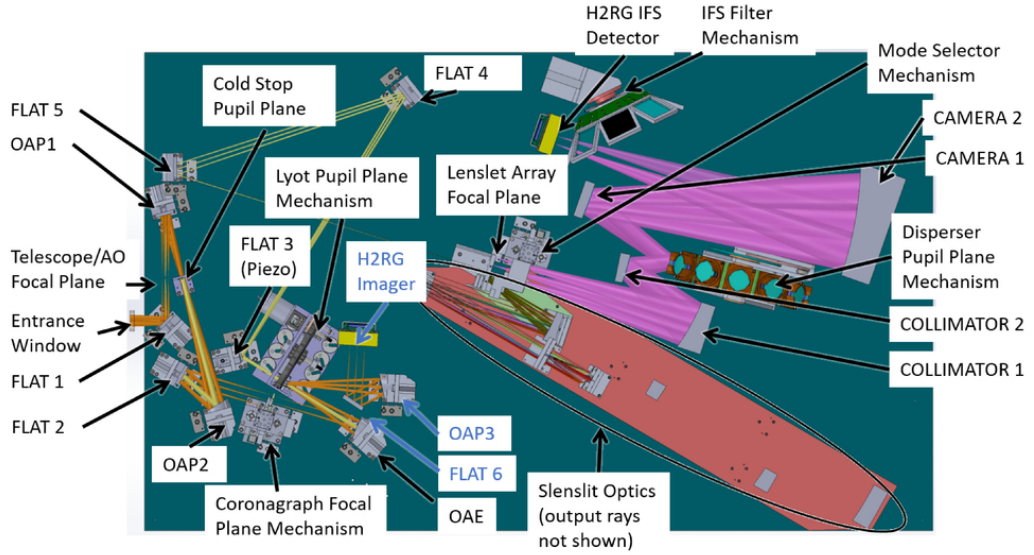


Figure 5.3: Labeled optomechanical CAD model of the SCALES instrument. The green footprint measures 1.15 m by 1.9 m and supports the full infrared optical path, including pupil mechanisms, coronagraph components, and IFS optics (Figure Credit: [6]).

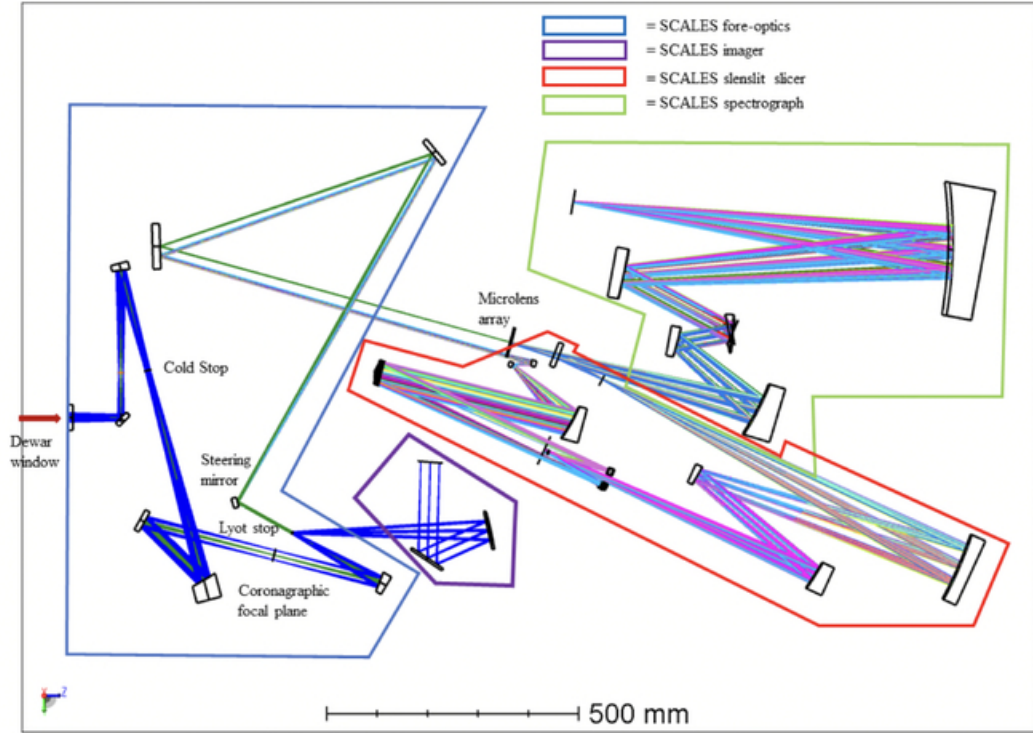


Figure 5.4: Optical layout of the SCALES instrument. Light from the Keck AO system enters through the dewar window (left) and passes through the foreoptics module (blue), which houses the cold stop, coronagraph, and IFS optics. A deployable mirror in the Lyot stop mechanism redirects light to the imaging channel (purple). The IFS operates in two modes: a low-resolution mode using a 108×108 lenslet array feeding the spectrograph (green), and a medium-resolution mode where the slenslit (red) 17×18 lenslet produces micro-pupils (Figure Credit: [7]).

5.4 Dispersive Wollaston Prism Design

To enable spectropolarimetric observations with SCALES, we developed a custom reflective dispersive Wollaston prism that splits incoming light into orthogonal linear polarization states while simultaneously dispersing it spectrally across the 2–4 μm band. This design is tailored for SCALES’ low-resolution mode and leverages the instrument’s reflective optical layout through a compact double-pass configuration (Fig. 5.5). To fully characterize the polarization state of the incoming light and recover the complete Stokes vector, a polarization modulator is required. A rotating half-wave plate placed upstream—ideally near the telescope focal plane—modulates the incident polarization state, enabling differential measurements that disentangle true astrophysical polarization signals from instrumental polarization and allow accurate reconstruction of linear Stokes parameters.

The prism consists of two birefringent wedges made of magnesium fluoride (MgF_2), arranged in a traditional Wollaston configuration with crossed optical axes. Yttrium Orthovanadate (YVO_4) was also investigated as a potential glass substrate for fabrication; however, it is absorptive within the spectral bandpass of interest and its high refractivity makes it a difficult substrate to design around SCALES. Although MgF_2 ’s polarization beam deviation has a stronger wavelength dependence, it is a feature when implementing a dispersive Wollaston prism.

The wedge angle α_w and prism apex angle α_p are tuned to produce angular separation between the ordinary and extraordinary rays, while also providing modest

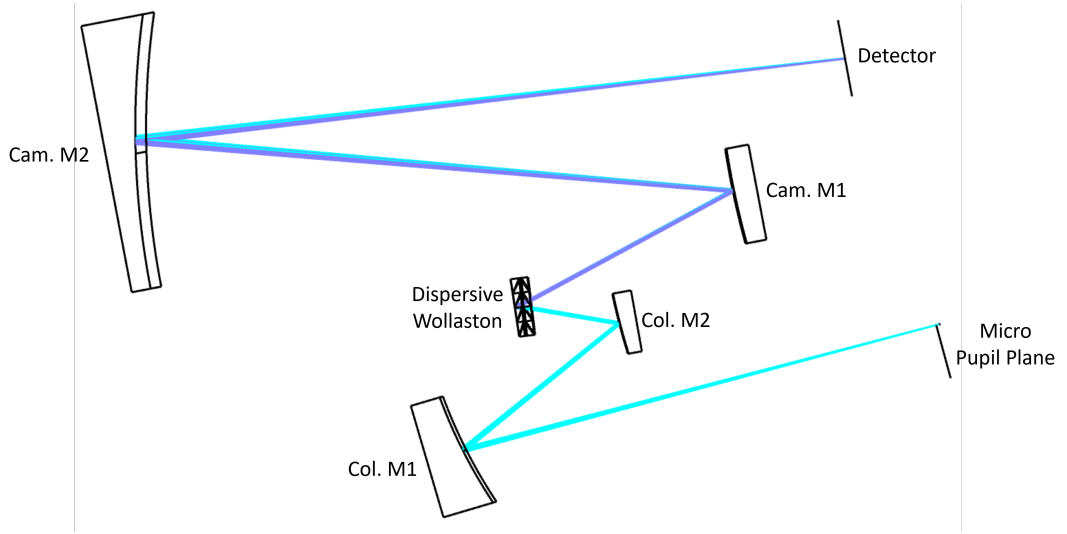


Figure 5.5: Zemax layout of the SCALES spectropolarimetric mode featuring a dispersive Wollaston prism. The prism splits the incoming beam into ordinary (blue) and extraordinary (purple) rays, which are then reimaged onto the detector through a series of reflective optics. This configuration enables simultaneous observation of orthogonally polarized spectra across the 2–4 μm bandpass.

spectral dispersion. The wedge geometry enhances the angular deviation, making it suitable for resolving the o- and e-rays on the detector.

A key design feature is the reflective configuration: the back face of the prism is coated with a broadband reflective layer, allowing the beam to reflect and retrace its path through the prism. This double-pass geometry doubles the optical path and increases the effective separation and dispersion of the polarized spectra while maintaining alignment with the rest of the instrument’s reflective optics. It also simplifies optomechanical integration within the limited space of the SCALES prism wheel.

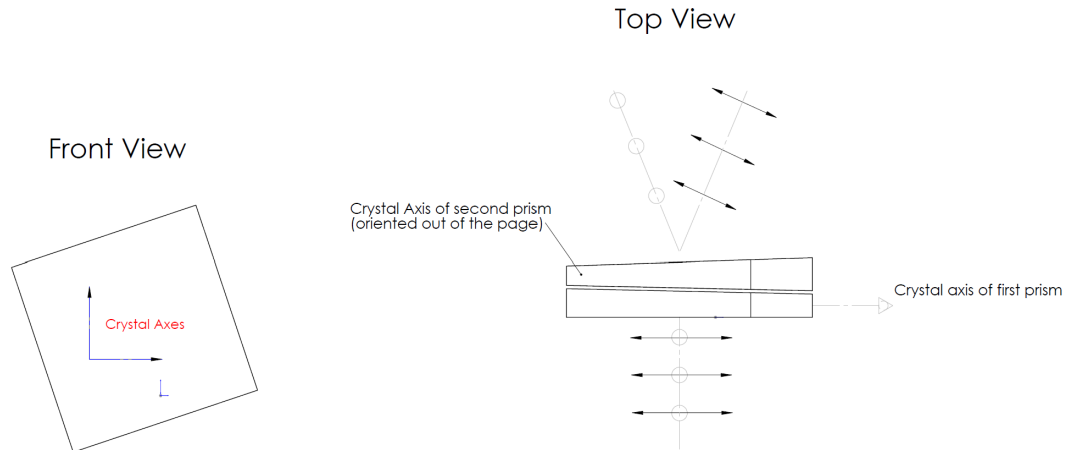


Figure 5.6: Drawing of the dispersive Wollaston prism used in the SCALES spectropolarimetric mode. The drawing illustrates the transmissive light path where ordinary and extraordinary rays are angularly separated by the birefringent prism pair. In the final design, the rear surface of the second prism is coated with a reflective layer to enable a double-pass configuration. The two MgF_2 prisms are separated by an air gap and are not cemented.

The spectral footprint of this design matches that of SCALES' existing low-resolution prism mode. The total spectral extent of each polarization component is 27 pixels, combining to match the 54-pixel length used in standard low-resolution observations. The o- and e-ray spectra are spatially separated along the slit (cross-dispersion) axis. Zemax simulations confirm that the beams remain distinct across the full 2–4 μm bandpass, with sufficient spatial separation to avoid overlap or cross-contamination

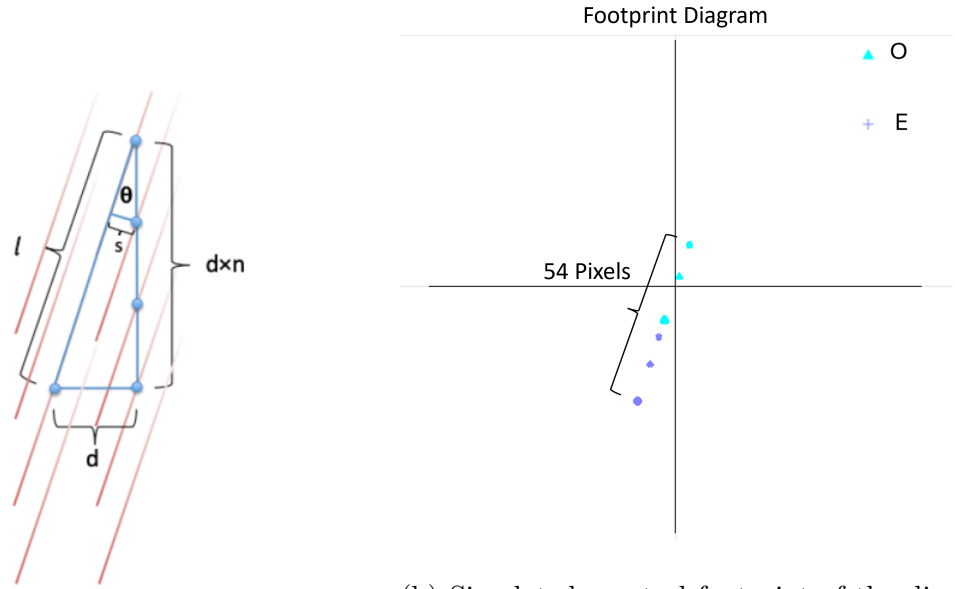
(Fig.5.7a and 5.7b)[7].

Calibration of this spectropolarimetric mode follows procedures common in polarimetry. A rotating modulator, such as a half-wave plate, is used upstream to measure and remove instrumental polarization, enabling accurate extraction of Stokes parameters. Simultaneous acquisition of both polarization components in a single exposure is essential for mitigating the effects of time-variable atmospheric seeing and instrumental drift, and ensures high fidelity in detecting weak polarized features such as the 3 μm ice band.

This implementation enables a compact, stable, and efficient spectropolarimetric mode within SCALES, requiring minimal modification to the instrument’s optical path. It offers a novel tool for characterizing the grain composition and scattering geometry in protoplanetary disks, particularly in systems where polarized scattered light traces structural and compositional features beyond the reach of conventional spectroscopy alone.

5.5 Conclusion and Future Work

The integration of a reflective dispersive Wollaston prism into the SCALES instrument represents a significant advancement in enabling near-infrared spectropolarimetry of protoplanetary disks. Designed to operate across the 2–4 μm band, this mode provides simultaneous measurement of orthogonal polarization spectra in a compact and optically efficient configuration. The design leverages SCALES’s reflective



(b) Simulated spectral footprint of the dis-

(a) Spectra are tilted relative to the detectorpersive Wollaston prism showing ordinary to increase separation in lenslet-based IFSs.and extraordinary rays at 2, 3, and 4 μm .

Figure 5.7: (Left) Spectral tilt improves packing efficiency in IFSs; spacing and length are governed by spaxel pitch d and tilt angle $\theta = \tan^{-1}(1/n)$. (Right) Simulated double-pass Wollaston prism footprint, aligned along spectral length axis, spanning 54 pixels. Based on [7].

architecture and existing prism wheel infrastructure, and matches the low-resolution spectral footprint of the instrument while maintaining spatial separation of polarization components.

Zemax modeling confirms that the dispersive Wollaston prism meets optical performance requirements, providing sufficient angular separation and dispersion for resolving polarization states across the bandpass. The double-pass geometry enhances optical efficiency, and enables alignment within the constrained SCALES spectrograph layout. While the spectral resolution is reduced relative to the standard mode, the gain in polarimetric capability—particularly for tracing faint, extended structures—is a key enabler for new science.

This spectropolarimetric mode is optimized for measuring spatially resolved polarization spectra in circumstellar disks, targeting key features such as the 3 μm water ice band. These measurements can constrain the snow line location, grain growth, and dust composition in planet-forming environments. The system is particularly powerful in edge-on or inclined disks, where scattering geometry induces strong polarization signatures.

Future work includes fabrication of the prism, lab characterization, and integration into the SCALES instrument. Laboratory tests will validate spectral resolution, beam separation, and polarization measurement. A rotating modulator will be used to calibrate and correct instrumental polarization effects. In parallel, simulations of the spectropolarimetric system will be performed to evaluate sensitivity to water ice features, optimize observing strategies, and predict disk signatures under a range of in-

clination and composition scenarios. These efforts will predict the expected performance and potential disk candidates for observation.

This development expands SCALES's scientific capabilities by coupling thermal infrared spectroscopy with polarization sensitivity. It offers a powerful new diagnostic for studying the structure and composition of protoplanetary disks, and contributes to the broader effort to understand the conditions that shape emerging planetary systems.

Part IV

Conclusion

This dissertation presents a series of technology developments aimed at advancing wavefront sensing and spectropolarimetric capabilities for high-contrast astronomical observations. The work spans three main areas: (1) the design and demonstration of a three-sided reflective pyramid wavefront sensor (3RPWFS) for AO, (2) the application of Wynne correctors to broaden the spectral bandwidth of focal-plane wavefront sensing with the Self-Coherent Camera (SCC), and (3) the implementation of a reflective dispersive Wollaston prism for near-infrared spectropolarimetry with the SCALES instrument. Each of these technologies addresses a distinct limitation in existing instrumentation, contributing toward the broader goal of enabling the detection and characterization of exoplanets and planet-forming environments.

The 3RPWFS was developed to offer a compact, achromatic, and reflective alternative to traditional transmissive pyramid wavefront sensors. The first-generation system was designed with ShaneAO constraints in mind, using a novel glass wedge modulator and reflective re-imaging optics to minimize the optical and mechanical footprint. Laboratory testing in the SEAL testbed confirmed accurate detection of low-order aberrations, and closed-loop operation was demonstrated both in the lab and on-sky at Lick Observatory. Subsequent improvements to the design culminated in a second-generation 3RPWFS that incorporated a pyramidal concave mirror (PCM), reducing pupil footprint and enhancing spatial compactness. While microscope inspection revealed fabrication-induced vortex-like illumination features, the sensor maintained linear response across 20 Zernike modes. The demonstrated sensitivity and successful loop closure at 100 Hz validate the 3RPWFS architecture for use in current and future

AO systems, including those with limited optomechanical flexibility or reflective relay designs.

Building on the need for focal plane wavefront sensing in high-contrast systems, the SCC offers a powerful technique for estimating the complex electric field in the coronagraphic focal plane. However, chromatic fringe smearing has historically limited its performance to narrowband observations. This thesis introduced Wynne correctors as a solution to this problem, employing pairs of glass elements with crossing refractive indices to provide wavelength-dependent angular magnification that equalizes PSF scale across the band. Designs were presented for both visible and near-infrared implementations. The visible configuration achieved diffraction-limited performance over a 20% band and was tested in the High Contrast Testbed at LLNL, demonstrating operational flexibility. The NIR implementation, developed for REDWOODS, was designed for 0.95–1.25 μm and met relaxed spot dispersion and wavefront error requirements, even under moderate decentering. These results show that Wynne correctors enable broader band SCC operation, with significant implications for high-contrast imaging missions targeting faint exoplanets.

Finally, a reflective dispersive Wollaston prism was developed for the SCALES instrument to enable spectropolarimetry in the 2–4 μm range. The design splits orthogonal polarization states while matching the low-resolution spectral footprint of the existing prism mode in SCALES. Zemax modeling confirmed the viability of a double-pass geometry using MgF_2 birefringent wedges, which ensures compactness, mechanical stability, and spectral separation across the full bandpass. The prism enables simulta-

neous acquisition of polarized spectra without moving parts, critical for detecting weak features such as the 3 μm water ice band in scattered light from protoplanetary disks. Future work will include fabrication, calibration, and system simulations to predict the sensitivity to disk composition and morphology.

Collectively, the contributions in this dissertation form a collection of technologies that advance the state of wavefront control and polarimetric detection in astronomical instrumentation. The 3RPWFS offers a compact, reflective pupil plane sensor suitable for AO systems constrained by chromatic and spatial limitations. Wynne-corrected SCCs address a key barrier to focal plane wavefront sensing across wide bandpasses, enabling faster correction and/or larger throughput during science observations. The spectropolarimetric mode of SCALES provides a novel window into the composition and structure of planet-forming disks. Together, these developments address key challenges in the path toward directly imaging and characterizing exoplanets and the environments from which they emerge, and lay the groundwork for future deployment in large observatories and space-based missions.

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Appendix A

Poke Matrix and Modal Interaction Matrix

A.1 Poke Matrix: Sensor Response to Actuators

Let there be p DM actuators and n WFS measurements. For each actuator $j \in \{1, \dots, p\}$, we apply a small known displacement δ_j (e.g., 1 radian or 100 nm) and record the resulting WFS response vector $\mathbf{s}_j \in \mathbb{R}^n$. The resulting **poke matrix** is:

$$\mathbf{P} = \begin{bmatrix} | & | & & | \\ \mathbf{s}_1 & \mathbf{s}_2 & \dots & \mathbf{s}_p \\ | & | & & | \end{bmatrix} \in \mathbb{R}^{n \times p} \quad (\text{A.1})$$

Each column represents the WFS signal caused by a unit poke to one actuator.

A.2 Modal Interaction Matrix: Sensor Response to Orthogonal Modes

Let $\Phi \in \mathbb{R}^{q \times m}$ be a matrix whose columns contain m orthogonal modal phase maps (e.g., sampled Zernike modes on a pupil grid of q points). Let $\mathbf{D} \in \mathbb{R}^{q \times p}$ be the DM influence matrix (i.e., how actuators shape the pupil phase).

We want to synthesize each mode ϕ_i by finding actuator weights $\mathbf{c}_i \in \mathbb{R}^p$ such that:

$$\mathbf{D} \cdot \mathbf{c}_i \approx \phi_i \quad \Rightarrow \quad \boxed{\mathbf{c}_i = \mathbf{D}^\dagger \cdot \phi_i} \quad (\text{A.2})$$

This gives the actuator command to approximate mode i . Now apply $\mathbf{c}_i$ to the poke matrix:

$$\mathbf{s}_i = \mathbf{P} \cdot \mathbf{c}_i = \mathbf{P} \cdot \mathbf{D}^\dagger \cdot \phi_i \quad (\text{A.3})$$

Repeat for all m modes and assemble the **modal interaction matrix**:

$$\boxed{\mathbf{M} = \begin{bmatrix} | & | & & | \\ \mathbf{s}_1 & \mathbf{s}_2 & \cdots & \mathbf{s}_m \\ | & | & & | \end{bmatrix} = \mathbf{P} \cdot \mathbf{D}^\dagger \cdot \Phi \in \mathbb{R}^{n \times m}} \quad (\text{A.4})$$

Each column of $\mathbf{M}$ represents the WFS response to a unit-amplitude orthogonal mode.

A.3 Modal Reconstructor

To estimate the modal coefficients $\mathbf{a} \in \mathbb{R}^m$ from a measured WFS signal $\mathbf{s}$, compute the Moore-Penrose pseudoinverse of $\mathbf{M}$:

$$\boxed{\mathbf{R}_{\text{modal}} = \mathbf{M}^\dagger = (\mathbf{M}^\top \mathbf{M})^{-1} \mathbf{M}^\top} \quad (\text{A.5})$$

Then:

$$\boxed{\hat{\mathbf{a}} = \mathbf{R}_{\text{modal}} \cdot \mathbf{s}} \quad (\text{A.6})$$

This gives a modal decomposition of the measured wavefront.

A.4 4. From Modal Reconstruction to DM Commands

To convert modal coefficients to actuator commands:

$$\boxed{\hat{\mathbf{c}} = \mathbf{D}^\dagger \cdot \Phi \cdot \hat{\mathbf{a}}} \quad (\text{A.7})$$

Thus, the full control path is:

$$\boxed{\hat{\mathbf{c}} = \underbrace{\mathbf{D}^\dagger \cdot \Phi \cdot \mathbf{R}_{\text{modal}}}_{\text{Full reconstructor}} \cdot \mathbf{s}} \quad (\text{A.8})$$

A.5 DM Command

$$\boxed{\hat{\mathbf{c}} = \mathbf{R}_{\text{full}} \cdot \mathbf{s} \quad \text{where} \quad \mathbf{R}_{\text{full}} = \mathbf{D}^\dagger \cdot \Phi \cdot (\mathbf{P} \cdot \mathbf{D}^\dagger \cdot \Phi)^\dagger} \quad (\text{A.9})$$

This matrix maps wavefront sensor measurements directly to actuator commands using a modal reconstruction framework.