Measured performance of diamond-turned optics for the SCALES high-contrast imager

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High-contrast imaging instruments are strongly limited in their performance by wavefront error, with contributions from uncorrected atmospheric turbulence and optics downstream of AO correction. Single-point diamond turning allows for high-precision optics to be manufactured for use in astronomical instrumentation, presenting a cheaper and more versatile alternative to conventional glass polishing. This paper presents measurements of wavefront error power spectral densities for diamond-turned aluminum optics the Slicer Combined with an Array of Lenslets for Exoplanet Spectroscopy (SCALES) instrument, a 2-5 micron coronagraphic integral field spectrograph and imager under construction for Keck Observatory. Wavefront error measurements for these optics are used to simulate SCALES' final contrast performance, and demonstrate that SCALES' contrast is not limited by the wavefront error introduced by its internal optics.

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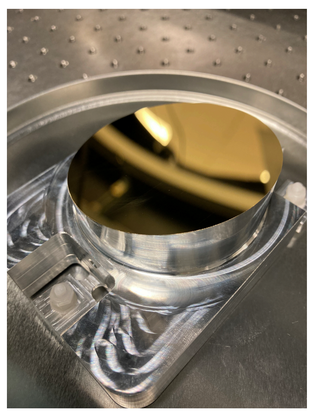
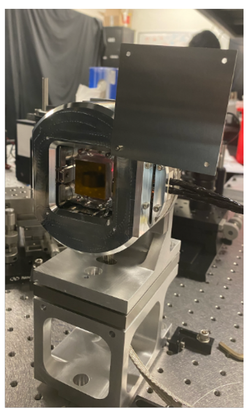
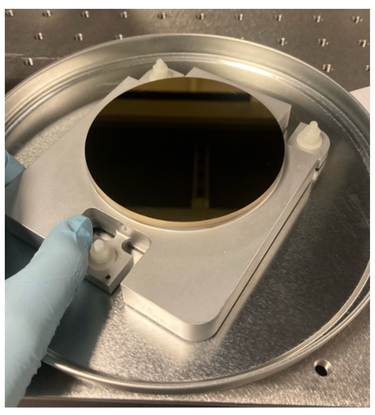
Ask me about **UC Union Busting** and aggressive policing at UC Santa Cruz







Wavefront error across spatial frequencies shapes instrument performance.

- Wavefront error (WFE) at different spatial frequencies has different effects on point spread function (PSF):
  - Low-spatial frequency error (i.e. surface form, e.g. low-order Zernike terms) reshapes core of PSF
  - Mid-spatial frequency error scatters light into the wings of the PSF
  - High-spatial frequency error (i.e. surface roughness) scatters light out of the PSF
- Speckles introduced by WFE can look indistinguishable from exoplanets!

	Form error (Low spatial frequency WFE)	Surface roughness (High spatial frequency WFE)
FM1	*9.3 nm RMS*	2.2 nm RMS
FM2	*14.9 nm RMS*	1.8 nm RMS
FM3	*9.4 nm RMS*	2.3 nm RMS
FM4	*24.0 nm RMS*	2.2 nm RMS
FM5	*12.8 nm RMS*	2.3 nm RMS
OAP1.1	5.2 nm RMS	2.5 nm RMS
OAP1.2	*20.2 nm RMS*	3.0 nm RMS
OAE	9.1 nm RMS	2.7 nm RMS

Table 1: All WFE measurements of the SCALES foreoptics. LSWFE values in italics are taken over 85% of the mechanical aperture; otherwise, value is for an aperture sized to the SCALES beam footprint.

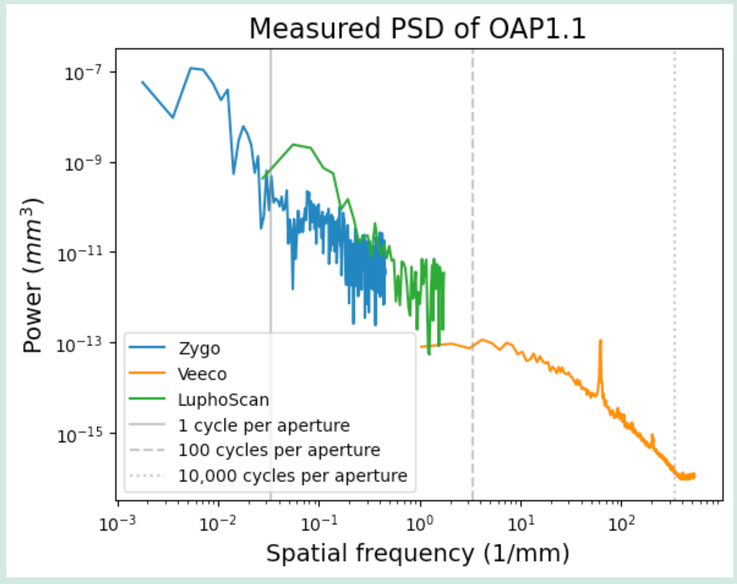


Figure 1: Measured power spectral density (PSD) of one of SCALES' foreoptics. The RMS wavefront error for a given range of spatial frequencies (Table 1) is the integral of the PSD.

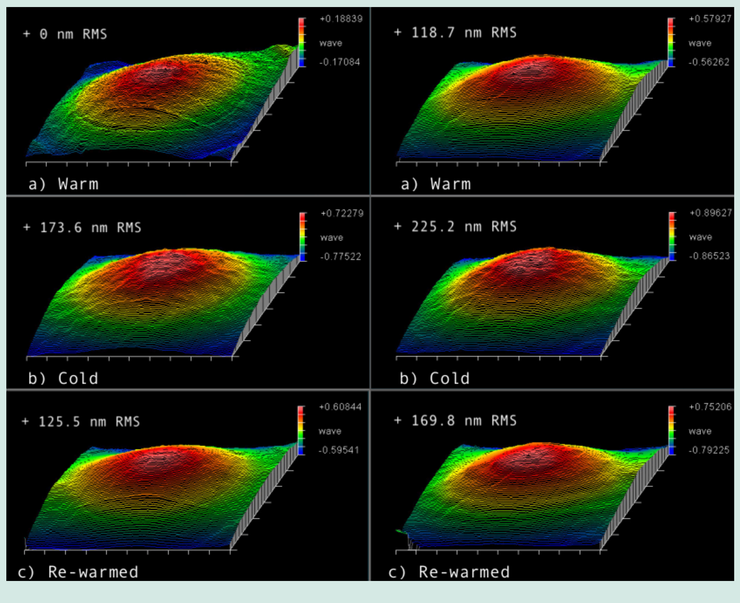


Figure 2: Surface form measurements of a rejected optic throughout a thermal stability test, before (top row), during (center), and after (bottom) cryocycling in a liquid nitrogen dewar. The left column shows progression through the first cryocycle, and the right column shows a second cryocycle. This optic had an RSA 443 substrate, which showed unacceptable plastic deformation between cooldowns, and has been remade with Al 6061.

SCALES' optical quality is not the limiting factor in contrast performance.

- An end-to-end physical optics propagation simulation of SCALES was developed using `poppy`
- This model includes WFE measurements from SCALES optics, uncorrected residuals from the current Keck AO system, and the projected uncorrected residuals from the proposed Keck AO upgrade, HAKA
- Comparative contrast curves (Fig. 4) show that SCALES' contrast is limited by performance of the Keck AO system.

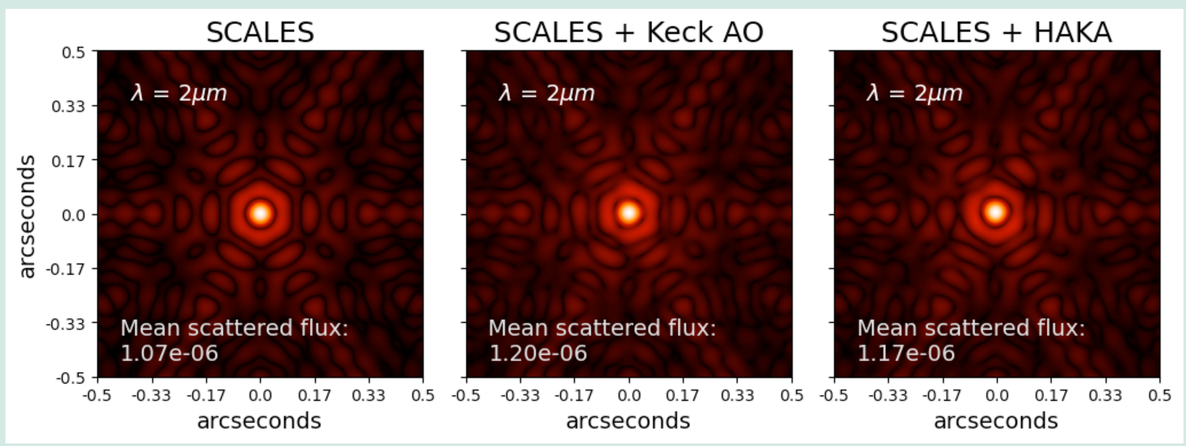


Figure 3: Modeled unsuppressed PSFs for 3 combinations of WFE sources: SCALES' foreoptics only (left), SCALES with uncorrected residuals from the current Keck AO system (center), and SCALES with residuals from HAKA, a future Keck AO upgrade (right). Mean scattered flux is calculated within a 5-10λ/D annulus around the PSF.

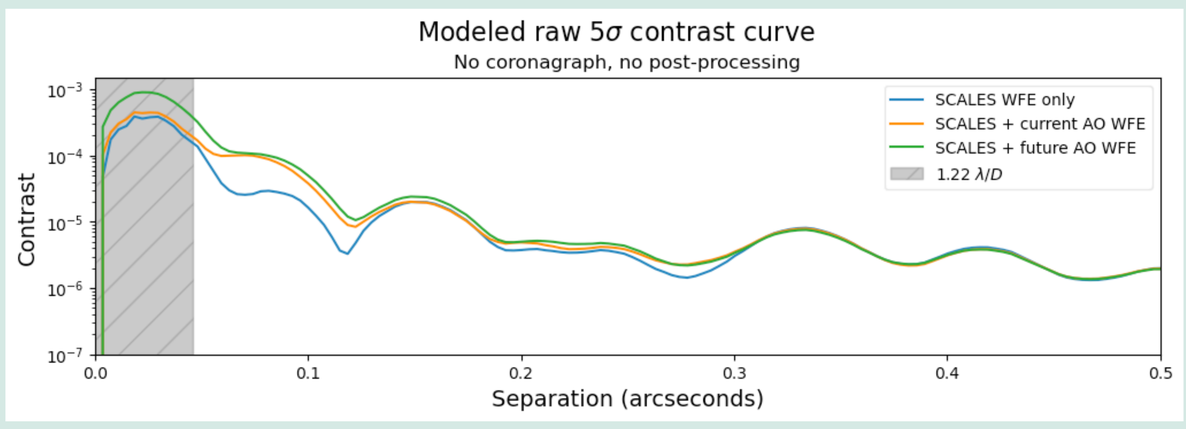


Figure 4: Contrast curves derived from the three PSFs modeled in Fig. 1. These curves are overly optimistic and should be interpreted in comparison with each other — SCALES's contrast is limited by AO performance, not its own optics.

What's next?

- Integration!
- The SCALES cryostat has passed its first empty cooldowns and is en route to UC Santa Cruz
- SCALES is scheduled for delivery to Keck Observatory in **Fall 2025**