SCALES Status Report

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ABSTRACT

SCALES (Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy) is the next-generation, diffraction-limited, thermal infrared, fully cryogenic, coronagraphic exoplanet spectrograph and imager for W.M. Keck Observatory. SCALES is fed by the Keck II Adaptive Optics bench. Both modes use common fore-optics to simplify the optical design and have individual detectors, which are JWST flight spares. The imager mode operates from 1 to 5 microns with selectable narrow- and broadband filters over a field of view 12.3 arcseconds on a side, and the integral field spectrograph mode operates from 2 to 5 microns with both low and mid spectral resolutions (R$\sim$ 100 to R$\sim$ 7500) over a field of view 2.15 arcseconds on a side. The diamond-turned aluminum

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optics, most of which are already delivered, with the rest being fabricated, provide low distortion, low wavefront error, and high throughput for all modes. The slicing unit, located behind the lenslet array, allows SCALES to reach heretofore unheard-of spatially-resolved spectral resolution for exoplanet and disc observations from the ground with a coronagraphic integral field spectrograph. The SCALES consortium includes UC Observatories, CalTech, W.M. Keck Observatory, the Indian Institute of Astrophysics, and the University of Durham, with over 40 science team members. We report on the overall design and project status during its ongoing fabrication phase, which started in early 2023.

Keywords: adaptive optics, high-contrast, instrumentation, exoplanets, thermal infrared, integral field spectroscopy, slenslit

1. INTRODUCTION

Adaptive optics and new instrumentation capable of taking full advantage of large-aperture telescopes have allowed astronomers to image $\sim 20-25$ of exoplanets, the brightest and most well-separated from their host stars have been characterized spectroscopically.[1] Purpose-designed integral field spectrographs with coronographic optics (e.g., GPI,[2] SPHERE,[3] and CHARIS[4]) have exploited the difference between exoplanets and speckles to find exoplanets hidden by their host stars' light. These instruments use extreme adaptive optics systems that are designed to deliver excellent wavefront control needed to achieve the high contrast ($\sim 10^6$) to detect an intrinsically faint exoplanet next to its host star. However, two factors have limited this approach: these instruments work at relatively short wavelengths ($1-2.5\mu$m); and are on smaller telescopes.

SCALES (Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy) is a $2-5\mu$m lenslet array integral field spectrograph that will be deployed to the WMKO Observatory's Keck II telescope. SCALES takes advantage of the fact that exoplanets emit most of their radiation at longer wavelengths than other instruments use. It also benefits from being on the Keck II telescope, one of the largest OIR full-sky telescopes available to astronomers.

The SCALES consortium includes astronomers from across the UC system, the California Institute of Technology, the Indian Institute for Astrophysics, University of Durham, NASA, the Institute for Astronomy at U Hawaii, and the U of Arizona. UCSC is the lead institution, but the partnership has taken on key aspects and entire subsystems, such as IIA's leadership on the imaging mode and calibration system. We have also contracted with a private engineering firm, Optomecanique Precision (OMP), to finalize the design and oversee the fabrication of the cryostat and disperser carousel.

SCALES is a lenslet array-based integral field spectrograph (IFS) design, with 6 passbands as shown in Table 1. We have also designed a mid-resolution mode that uses slicing and reimaging optics to geometrically rearrange a rectangular patch of lenslets into a pseudoslit, unlocking much higher spectral resolution across K, L, and M bands. Additionally, the fore-optics are generously oversized to allow for a 12.3×12.3 arcsecond field of view imaging mode. The optical layout is shown in Figure 1.

Table 1. SCALES Top-Level Specifications

	Low-Resolution IFS		**Medium-Resolution IFS**		**Imager**
Wavelength	2.0-2.4μm	R$\sim$150	2.0-2.4μm	R$\sim$6,000	Up to 16 filters spanning 1-5μm
	2.0-4.0μm	R$\sim$50			
	2.0-5.0μm	R$\sim$35	2.9-4.15μm	R$\sim$3,000	
	2.9-4.15μm	R$\sim$80			
	3.1-3.5μm	R$\sim$200	4.5-5.2μm	R$\sim$7,000	
	4.5-5.2μm	R$\sim$200			
Field of View	2.15×2.15"		0.36×0.34"		12.3×12.3"
Spatial Sampling	0.02"		0.02"		0.006"
Coronagraphy	Vector-Vortex		Vector-Vortex		TBD

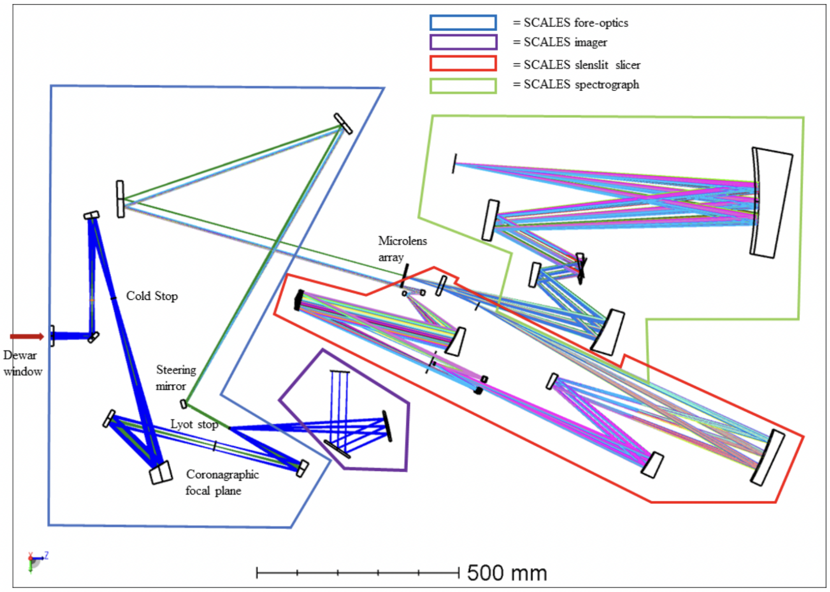

Figure 1. Optical design of SCALES.

The SCALES main science cases are laid out in Sallum, et al 2023,[5] and the optical and opto-mechanical design in Kupke, et al 2022[6] and Skemer, et al 2022.[7] This paper gives a status update for the SCALES instrument. We expect to deliver SCALES to WMKO in Fall 2025 and to be on-sky and available for general use by the 2026A semester.

2. CRYOSTAT, LN2 PRE-COOL SYSTEM, AND BENCH

The SCALES instrument, in spite of being an AO-fed spectrograph, is quite large. The cryostat was delivered to UCSC on June 28, 2024 after integration with the LN2 pre-cool system and bench. Figure 2 shows a few pictures of the delivery and SCALES in the integration facility at UCSC.

The LN2 pre-cool system and bench were integrated into the cryostat in New York in late May before being shipped to UCSC.

2.1 Cryostat

The cryostat is substantially similar to the APOGEE/HPF/NEID design, which uses 304L stainless steel box beams that make up a load ring, with half-cylinder top and bottom lids. The cryostat and bench were fabricated by PulseRay in Beaver Dam, NY, and Cameron Manufacturing & Design in Horseheads, NY. Figure 3 shows a few views of the cryostat at Cameron's facility during integration.

2.2 LN2 Precool System

SCALES has as cold mass of approximately 660 kg, which equates to about 550 MJ of heat energy to extract. The coldheads we will use are 2 CTI-1050 2-stage cryocoolers, which can extract about 130 W of heat with the first stages, meaning it would take about 2 weeks for SCALES to cool to cryogenic temperatures. To speed up the cooldown process, we will use a $\sim$ 100 L LN2 tank that is supported independently of the bench, and connected with engineered copper thermal straps. The LN2 system will cool SCALES in $3-4$ days, at which point the coldheads will be turned on and the LN2 tank evacuated (to minimize convective heating). Figure 4 shows the LN2 tank and the strapping to the bench.

The tank also holds two charcoal-filled getters and two sets of resistor-heater pads to help the warm-up process. The heaters have a maximum input of 940 W, but are only used during warm-up. There are $\sim$ 4 kg of charcoal in the getters, which should be ample for up to 5 years between servicing. The heaters will help drive off captured volatiles in the getters and from the rest of the cryostat before we begin integrating the mechanisms and optics.

Figure 2. SCALES cryostat delivery. *Clockwise from upper left:* SCALES on the truck; SCALES rolling through the shops; SCALES entering the integration cleanroom; fine positioning of the cryostat; SCALES delivery/acceptance team with SCALES. Photo credits: RDS, D. Sanford.

2.3 Optical Bench

The optical bench is an aluminum slab $\sim 1 \times 2$ m^2 and 75 mm thick (see Figure 5). Aluminum was chosen because our mounts, optics, and mechanisms are largely made of the same variety (6061-T6 or T651); this substantially reduces the engineering effort required, as the coefficient of thermal expansion (CTE) is effectively identical for all SCALES components.

The bench is supported by 3 titanium bipods, which satisfy 3 requirements: 1) they must support the bench both in warm and cold temperatures (the bench shrinks by $\sim$ 0.4% in all linear dimensions), necessitating they flex to compensate; 2) they must minimize the heat transfer from the room-temperature cryostat to the cryogenic-temperature bench (a $\sim$ 200 K temperature difference); and 3) they must survive any shocks due to an earthquake in California (where SCALES is being integrated) and at the summit of Maunakea, or shocks during shipping. Figure 5 shows the bipods before integration.

3. OPTICS

The SCALES optical design is detailed in Kupke, et al 2022[6] and is shown in Figure 1. There are four optical subsystems: fore-optics, imager, spectrograph, and slenslit. The design utilizes a largely homologous construction technique: aside from the entrance window, coronagraphic substrate, lenslet array, prisms, filters, and detectors, the entire optical train is made of gold-coated RSA 6061-T6 diamond-turned aluminum mirrors. RSA aluminum from RSP Technologies is chemically identical to regular 6061-T6, but has a much finer microscopic grain structure. This makes the surface finish achievable through diamond-turning to $\sim 2 - 3$ nm RMS, suitable for diffraction-limited astronomical instruments.

3.1 Mirrors

The SCALES fore-optics, imager, and spectrograph mirrors are being fabricated by Son-X based in Aachen, Germany. The fore-optics and imager mirrors are delivered and undergoing testing (Kain, et al, this proceedings, Paper 13096-260). Mounts for the fore-optics have been fabricated and the design is described in Rodriguez, et al, this proceedings, Paper 13096-265.

The spectrograph optics are currently being fabricated. The remaining optical subsystem is the reimaging

Figure 3. SCALES cryostat at Cameron MD. Top: The cryostat in protective plastic wrap. Bottom left: The top (foreground) and bottom (background) lids. Bottom right: The load ring on its jack stands. Photo credit: B. Blank (PulseRay), RDS.

and slicing optics of the slenslit,[8] which will be fabricated by the University of Durham's Centre for Advanced Instrumentation. The slenslit is currently in the pre-manufacturing phase and is slated for delivery in late summer 2025.

3.2 Filters

The two IFS modes use the same filters, which were fabricated by Asahi Spectra, and delivered to UCSC in early 2024. We have 2 sets of 6 filters each for the 6 low-resolution mode, 3 of which are also used for the mid-resolution mode. Figure 7 shows one set of the filters in aluminum cells used for a cryogenic survivability test, which all passed.

We have ordered a set of 25 mm diameter, 5 mm thickness imaging filters, and they are currently being fabricated. The expected throughput of the SCALES imaging filter is $\sim 95\%$ across all bandpasses, with very good out-of-band rejection, particularly on the $3 - 5\mu$m wavelengths. We looked at the previous 15 years of NIRC2 filter usage to make our list of desired filters.

3.3 Dispersers

The 6 prisms used for the low-resolution mode are being fabricated out of sapphire ($3.1 - 3.5\mu$m), silicon ($2.9 - 4.15\mu$m), CaF2 (all other bandpasses) by Optimax, with scheduled delivery in early Fall 2024.

Figure 4. The SCALES LN2 tank. *Clockwise from upper left:* The LN2 tank from the rear left; it is supported by G10 bipods to the load ring. The lead author filling the getters with charcoal using a precision leveling device. A test-fit of the LN2 tank to the load ring. A detail shot of the copper strapping: the gold-plated bar bolted to the LN2 tank is a fixed copper cooling strap, and the flexible copper cooling strap (not gold-plated) is bolted to it and the bench. M. Gonzales (co-author) checking the wiring of the heater pads and temperature sensors on the LN2 tank and under-bench volume. A detail shot of the heater pads; in between the two pads is a thermal switch that will interrupt the circuit to prevent runaway heating. Photo credit: RDS, B. Blank (PulseRay).

Figure 5. The SCALES bench. *Left*: The underside of SCALES with its temperature sensors. *Middle*: The three titanium bipods and pins that support the bench. *Right*: Test-fitting the bench to the load ring. Photo credits: M. Gonzales, RDS.

The gratings for the mid-resolution mode have been completed by Optimetrix. The substrate is Zerodur with a thick gold coating that is directly ruled (e.g., these are not replica gratings). Earlier we were sent samples of Zerodur substrates with grating lines ruled onto them, and we ran them through several cryogenic cooldowns with no ill effects.

We will use a flat mirror for aligning our disperser mechanism. This mirror will be gold-coated, and as it is not meant to be used for observing, the surface quality is not particularly important and will be a catalog item.

For flatfielding our detector, we will use a gold-coated diffuser, which spreads the light from each lenslet across a broad swath of the detector. When combined with the monochromator, we will be able to calibrate the linespread function at the detector.

3.4 Calibration system

The calibration system uses a light source, a monochromator, a fiber link to the telescope simulator, and the telescope simulator. The light source and monochromator have been purchased, and the fiber (a 4-meter-long

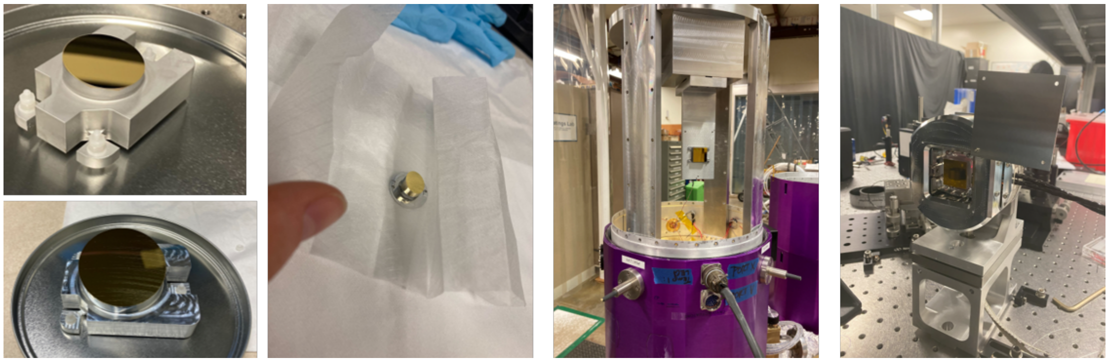

Figure 6. Fore-optics mirrors. Top left: OAP2; bottom left: Imager OAH. Left center: Imaging channel flat mirror (to be installed in the pupil plane Lyot mechanism). Right center: Testing the tip-tilt stage mirror (fold mirror 3). Right: Tip-tilt mechanism undergoing warm testing. Photo credits: I. Kain

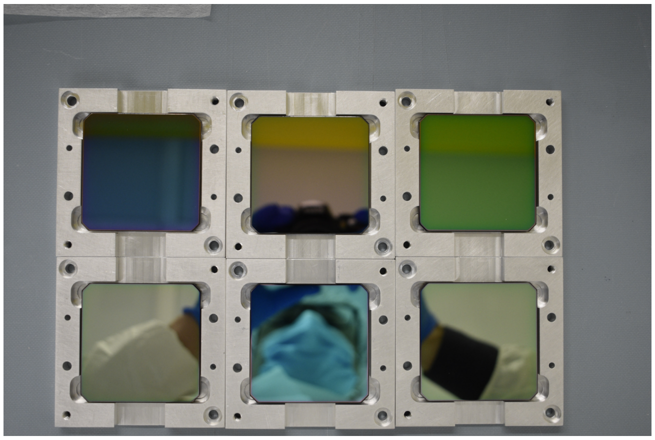

Figure 7. Filters in their cells for cryogenic survival test. Photo credit: A. Skemer.

run to maximize throughput at the longer wavelengths) is on order. The telescope simulator optical design is being performed by IIA; WMKO will dothe mechanical design and integrate it onto the AO bench with the delivery of SCALES.

4. MECHANISMS

SCALES has 9 cryogenic mechanisms. Here, we describe their current status in the order in which photons encounter them.

4.1 Cold stop rotator

IIA is building the cold stop rotator mechanism. It is similar to the cold stop rotator the HARMONI ELT instrument[9] and uses an encoder to servo the mask to the desired azimuth. The SCALES cold stop masks are described in.[10] The cold stop mechanism, shown in Figure 8, is undergoing warm testing at IIA, and will be tested cold before being shipped to UCSC for integration to SCALES.

The cold stop of SCALES will be fixed for IFS observations (e.g., pupil tracking mode), and will rotate to match the field rotation for the imaging mode. The pupil plane masks in the Lyot mechanism (see §4.4) will be carefully aligned to the cold stop plane such that masks overlap without causing further vignetting.

During integration, we will use this rotator to block half the pupil with a Hartmann mask. This makes the cold stop rotator a selectable Hartmann mask, allowing us to measure the tip, tilt, and focus of each detector in one mechanism.

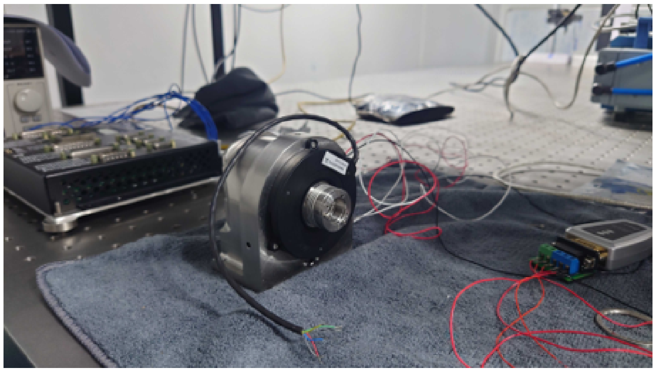

Figure 8. The cold stop rotator at IIA undergoing warm validation testing. Photo credit: M. Gonzales

4.2 Imager filter wheel

This mechanism is used for the imaging mode, and has unfilled slots used for the IFS modes. It supports up to 17 filters, as described in §3. One of the positions will be a 'dark' to help identify light leaks. IIA is also building this mechanism, which will undergo warm and cold verification testing at IIA before being shipped to UCSC.

4.3 Focal plane coronagraph slide

The focal plane coronagraph slide[11] is a linear mechanism that will have an open (or retracted) position, a half-field position, a pupil imaging lens, and up to 4 positions for focal plane coronagraphic masks. This mechanism was built at UCSC and will undergo its final set of cold testing before being integrated into SCALES.

4.4 Pupil plane Lyot wheel

SCALES is a variant of the Lyot coronagraph design and like most coronagraphic mechanisms has both focal plane and pupil plane masks, held in two separate mechanisms. Thus, the coronagraph slide and Lyot mechanism work together to suppress starlight. The Lyot mechanism has 16 positions, 3 of which are devoted to the imaging arm. We have a 'dark' position at this location to help identify light leaks during integration.

The imaging arm requires a reflection at the Lyot plane for space constraint and minimizing the number of cryogenic mechanism reasons. We also have designed a pupil imaging mode so that we can align the telescope pupil to that of SCALES. A simple lens at the focal plane coronagraph slide is reimaged onto a lightly-powered mirror at the Lyot mechanism, which illuminates the imaging detector with an image of the telescope pupil. The imaging optics are quite small (an OD of 10 mm), and one is shown in Figure 6.

The Lyot mechanism has been assembled and is undergoing cold testing at UCSC in preparation for integration this Fall.

4.5 Tip-tilt mirror

In order to switch between the low- and mid-resolution modes, we need to steer the beam onto our mid-res lenslet patch. We use a Physikalishe Instrument (PI) two-axis piezo-electric cryogenic steering mirror for this. The PI tip-tilt stage has undergone warm testing in the lab, and will undergo cold testing in late July. The stage is shown in Figure 6.

4.6 Lenslet array field of view selector

As part of the switch between low- and mid-resolution modes, we use a simple rotary stage carrying a mask that blocks the mode not in use. We also can block the full lenslet array to help identify light leaks. This mechanism primarily holds the lenslet array in the proper location both at warm and cold temperatures, and is one of the few instances we have in SCALES where differential CTE effects matter. Delivery to UCSC is expected this Fall, where warm and cold verification will take place before it is installed in SCALES.

4.7 Mode selector

The mode selector is a turntable-style mechanism designed to either 1) let the low-resolution mode beams pass while blocking the mid-resolution mode beams; and 2) block the low-resolution mode beams when using the mid-resolution mode. It also carries a focal plane mask at the location of the mid-resolution pseudoslit, and the return fold mirror (which sends the pseudoslit into the spectrograph). As with the lenslet array mechanism, delivery to UCSC is expected in August, where warm and cold verification will take place before it is installed in SCALES.

4.8 Disperser carousel

The disperser carousel is being fabricated by OMP in Quebec City and will be integrated for warm testing before being shipped to UCSC. It has 12 positions. The carousel will be integrated with its prism and grating cells at UCSC, and the dispersers, alignment flat mirror, and diffuser will be co-aligned there. There is one extra position (possibly two if one removes the fold mirror), and we plan on having a ’dark’ position. The disperser dark is a 5-sided open box coated in Vantablack or similar absorptive material. Other possible uses would be a high-resolution grating combined with a narrowband filter in the IFS filter wheel, which could give a spectral resolution as high as 25,000 (Martinez, et al, this proceedings, Paper 13096-266).

4.9 IFS filter wheel

IIA is constructing the IFS filter wheel and will undergo warm testing before being shipped to UCSC for cryogenic testing and integration. It is a 2 wheel mechanism with 5 slots per wheel. Currently we have a complement of 6 filters and a total of 7 available positions (1 spot in each wheel is reserved as an open, plus a blank-off for a dark), and as noted in the disperser carousel section, that gives us room for future upgrades.

4.10 Entrance window environmental shutter

While not a cryogenic mechanism, SCALES does use a Uniblitz DSS 35B shutter to protect the entrance window. This shutter is not involved in determining the start or stop of exposures and is meant to keep the entrance window protected from dust or other contaminants when not in use.

5. DETECTORS, ELECTRONICS, AND SOFTWARE

5.1 Detectors

UCLA is handling the detector package work (mechanical, electrical, and software). The software work is described in this Proceedings (Banac, et al SPIE Paper 13096-263). The detector mechanical packages are shown in Figure 9.

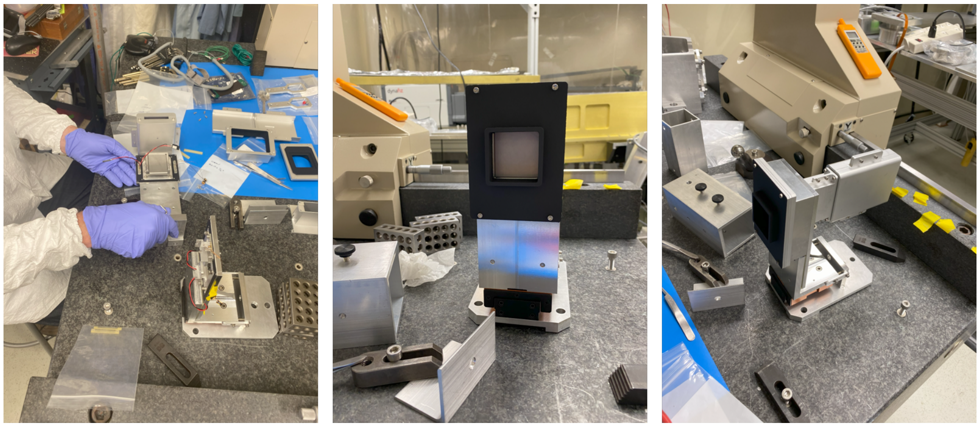

Figure 9. Detector package integration using a molybdenim dummy block at UCLA. Photo credit: A. Skemer.

The detectors were integrated in early July at UCLA and will undergo verification at cryogenic temperatures this summer. Delivery to UCSC for integration into SCALES is expected by the end of August.

5.2 Electronics

The electronics have been developed during the final design phase. The focal plane coronagraph slide was built partway into the preliminary design phase as a learning experience, and to force the electronics and software engineers to work with SCALES hardware without a foreshortened timeline. This has been quite useful, and resulted in a largely modular approach to our mechanism electronics and software control.

Cabling interior to the cryostat has been defined, and the full build-out of cabling is scheduled to match the integration rate of the cryo-mechanisms. Exterior cabling has also been defined, and we are seeking quotes from manufacturers.

The electronics enclosure is slated to be inherited from the NIRC2 instrument, which has recently upgraded its readout electronics from transputers to ASICs and FPGAs. Once received from WMKO, we will populate the electronics enclosure with the SCALES electronics.

5.3 Software

The low-level SCALES software is being developed as we test our mechanisms. The software follows previous Keck instruments and keyword/value pairs are tracked using the Keck Task Language (KTL[12]) standards. The high-level SCALES software will be built out as we continue integrating SCALES, and will follow the excellent example of the Keck Planet Finder[13] (KPF) software.

6. WORK AT WMKO

Some modifications to the AO enclosure and Naysmith platform are needed before SCALES arrives. For example, the light source and monochromator will be stationed below the Naysmith platform to both reduce the footprint of SCALES inside the AO enclosure and to keep the heat generated by the light source have a minimum impact on the AO enclosure temperature. One of the more dramatic modifications is widening the door; SCALES' coldhead slightly protrudes beyond the edge of one side of the current door footprint. The current plan is to cut a profile into the wall that allows SCALES to pass by unimpeded without having to rebuild the wall and door.

Other modifications are more typical: more communications lines, helium line rerouting, and electrical power will be supplied to the 'pedastal' where all connections to SCALES inside the AO enclosure are made.

7. CONCLUSION

We have presented an update to the SCALES instrument, which we expect to deploy to WMKO in the late Fall 2025. Integration and testing is underway at UCSC and its partner institutions, with full integration scheduled to be finished in early Fall 2025.

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REFERENCES

[1] Currie, T., Biller, B., Lagrange, A., Marois, C., Guyon, O., Nielsen, E. L., Bonnefoy, M., and De Rosa, R. J., "Direct Imaging and Spectroscopy of Extrasolar Planets," in [*Protostars and Planets VII*], Inutsuka, S., Aikawa, Y., Muto, T., Tomida, K., and Tamura, M., eds., *Astronomical Society of the Pacific Conference Series* **534**, 799 (July 2023).

[2] Macintosh, B., Graham, J. R., Ingraham, P., Konopacky, Q., Marois, C., Perrin, M., Poyneer, L., Bauman, B., Barman, T., Burrows, A. S., Cardwell, A., Chilcote, J., De Rosa, R. J., Dillon, D., Doyon, R., Dunn, J., Erikson, D., Fitzgerald, M. P., Gavel, D., Goodsell, S., Hartung, M., Hibon, P., Kalas, P., Larkin, J., Maire, J., Marchis, F., Marley, M. S., McBride, J., Millar-Blanchaer, M., Morzinski, K., Norton, A., Oppenheimer, B. R., Palmer, D., Patience, J., Pueyo, L., Rantakyro, F., Sadakuni, N., Saddlemyer, L., Savransky, D., Serio, A., Soummer, R., Sivaramakrishnan, A., Song, I., Thomas, S., Wallace, J. K., Wiktorowicz, S., and Wolff, S., "First light of the Gemini Planet Imager," *Proceedings of the National Academy of Science* **111**, 12661–12666 (Sept. 2014).

[3] Beuzit, J.-L., Feldt, M., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Abe, L., Antichi, J., Baruffolo, A., Baudoz, P., Boccaletti, A., Carbillet, M., Charton, J., Claudi, R., Downing, M., Fabron, C., Feautrier, P., Fedrigo, E., Fusco, T., Gach, J.-L., Gratton, R., Henning, T., Hubin, N., Joos, F., Kasper, M., Langlois, M., Lenzen, R., Moutou, C., Pavlov, A., Petit, C., Pragt, J., Rabou, P., Rigal, F., Roelfsema, R., Rousset, G., Saisse, M., Schmid, H.-M., Stadler, E., Thalmann, C., Turatto, M., Udry, S., Vakili, F., and Waters, R., "SPHERE: a 'Planet Finder' instrument for the VLT," in [*Ground-based and Airborne Instrumentation for Astronomy II*], McLean, I. S. and Casali, M. M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7014**, 701418 (July 2008).

[4] Groff, T. D., Kasdin, N. J., Limbach, M. A., Galvin, M., Carr, M. A., Knapp, G., Brandt, T., Loomis, C., Jarosik, N., Mede, K., McElwain, M. W., Leviton, D. B., Miller, K. H., Quijada, M. A., Guyon, O., Jovanovic, N., Takato, N., and Hayashi, M., "The CHARIS IFS for high contrast imaging at Subaru," in [*Techniques and Instrumentation for Detection of Exoplanets VII*], Shaklan, S., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9605**, 96051C (Sept. 2015).

[5] Sallum, S., Skemer, A., Stelter, D., Banyal, R., Batalha, N., Batalha, N., Blake, G., Brandt, T., Briesemeister, Z., de Kleer, K., de Pater, I., Desai, A., Eisner, J., Fong, W.-f., Greene, T., Honda, M., Jensen-Clem, R., Kain, I., Kilpatrick, C., Kupke, R., Lach, M., Liu, M. C., Macintosh, B., Martinez, R. A., Mawet, D., Miles, B., Morley, C., Powell, D., Sethuram, R., Sheehan, P., Spilker, J., Stone, J., Surya, A., Thirupathi, S., Unni, A., Wagner, K., and Zhou, Y., "The Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy (SCALES): driving science cases and expected outcomes," *arXiv e-prints* , arXiv:2310.07134 (Oct. 2023).

[6] Kupke, R., Stelter, R. D., Hasan, A., Surya, A., Kain, I., Briesemeister, Z., Li, J., Hinz, P., Skemer, A., Gerard, B., Dillon, D., and Ratliff, C., "SCALES on Keck: optical design," in [*Ground-based and Airborne Instrumentation for Astronomy IX*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12184**, 121844A (Aug. 2022).

[7] Skemer, A. J., Stelter, R. D., Sallum, S., MacDonald, N., Kupke, R., Ratliff, C., Banyal, R., Hasan, A., Varshney, H. M., Surya, A., Prakaesh, A., Thirupathi, S., Sethuram, R., K. V., G., Fitzgerald, M. P., Wang, E., Kassis, M., Absil, O., Alvarez, C., Batalha, N., Boucher, M.-A., Bourgenot, C., Brandt, T., Briesemeister, Z., de Kleer, K., de Pater, I., Deich, W., Divakar, D., Filion, G., Gauvin, É., Gonzales, M., Greene, T., Hinz, P., Jensen-Clem, R., Johnson, C., Kain, I., Kruglikov, G., Lach, M., Landry, J.-T., Li, J., Liu, M. C., Lyke, J., Magnone, K., Marin, E., Martin, E., Martinez, R., Mawet, D., Miles, B., Sandford, D., Sheehan, P., Sohn, J. M., and Stone, J., "Design of SCALES: a 2-5 micron coronagraphic integral field spectrograph for Keck Observatory," in [*Ground-based and Airborne Instrumentation for Astronomy IX*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12184**, 121840I (Aug. 2022).

[8] Stelter, R. D., Skemer, A. J., Kupke, R., Bourgenot, C., Martinez, R. A., and Sallum, S. S., "Weighing exo-atmospheres: a novel mid-resolution spectral mode for SCALES," in [*Ground-based and Airborne Instrumentation for Astronomy IX*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12184**, 1218445 (Aug. 2022).

[9] Gigante, J. V., Hernández, E., Rodríguez-Ramos, L. F., Estévez, C., Moreno, A. F., Garcia-Lorenzo, B., Herreros, J. M., Mediavilla, E., Bryson, I., Clarke, F., and Thatte, N., "Development of cryogenic components based on COTS parts for the HARMONI instrument," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9908**, 99089U (Aug. 2016).

[10] Li, J., Skemer, A., van Kooten, M. A. M., Kupke, R., and MacDonald, N., "Fabrication of pupil masks for a new infrared exoplanet imager at Keck Observatory," in [*Adaptive Optics Systems VIII*], Schreiber, L.,

Schmidt, D., and Vernet, E., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12185**, 121858N (Aug. 2022).

[11] Gonzales, M., Stelter, R. D., Kruglikov, G., Ratliff, C., Deich, W., MacDonald, N., Sallum, S., and Skemer, A., "Cryogenic test results of the SCALES focal plane coronagraph mechanism," in [*Techniques and Instrumentation for Detection of Exoplanets X*], Shaklan, S. B. and Ruane, G. J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11823**, 118231W (Sept. 2021).

[12] Gates, J. and Deich, W., "A multi-threaded approach to using asynchronous C libraries with Java," in [*Software and Cyberinfrastructure for Astronomy III*], Chiozzi, G. and Radziwill, N. M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9152**, 91522Y (July 2014).

[13] Gibson, S. R., Howard, A. W., Rider, K., Roy, A., Edelstein, J., Kassis, M., Grillo, J., Halverson, S., Sirk, M. M., Smith, C., Allen, S., Baker, A., Beichman, C., Berriman, B., Brown, T., Casey, K., Chin, J., Coutts, D., Cowley, D., Deich, W., Feger, T., Fulton, B., Gers, L., Gurevich, Y., Ishikawa, Y., James, E., Jelinsky, S., Kaye, S., Lanclos, K., Li, A., Lilley, S., McCarney, B., Miller, T., Milner, S., O'Hanlon, T. J., Pember, J., Raffanti, M., Rockosi, C., Rubenzahl, R., Rumph, D., Sandford, D., Savage, M., Schwab, C., Seifahrt, A., Shaum, A., Smith, R., Stuermer, J., Thorne, J., Vandenberg, A., Von Boeckmann, T., Wang, C., Wang, Q., Weisfeiler, M., Wilcox, M., Wishnow, E. H., Wizinowich, P., Wold, T., and Wolfenberger, A., "Keck Planet Finder: design updates," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11447**, 1144742 (Dec. 2020).