

Optical Design of Multi-field Integral Field Unit Spectrograph for the ORCAS Keck Instrument Development II (ORKID II) Instrument

Bert A Pasquale^a, Eliad Peretz^a, Guangjun Gao^a, Peter Kurczynski^a, Victor Chambers^a, Lenward Seals^a, Max Millar-Blanchaer^b, Peter Wizinowich^c, Marc Kassis^c, Peter Plavchan^d, Molly Adams^e

^aNASA/Goddard Space Flight Center, Greenbelt, MD 20771, ^bUniv. of California, Santa Barbara, ^cW. M. Keck Observatory, ^dGeorge Mason Univ., ^eNorthwestern Univ
Bert.Pasquale@nasa.gov, Eliad.Peretz@nasa.gov

ABSTRACT

We have designed an Integral Field Unit for the ORCAS Keck Instrument Development II (ORKID II) Instrument. Building on the success of the ORKID camera which achieved 15.2 msec PSF FWHM visible light imaging, ORKID II will add Integral Field Spectroscopy to analyze Active Galactic Nuclei (AGN), supernovae redshift and brightness, and other observations. Several design options have been explored based on image slicers manufactured by the Canon Corporation's machining process. Field layouts can include up to three disparate spatial sampling, with a lower limit of 6.7 msec. Spectral resolutions are considered from R 100 to R 10,000.

Keywords: Space Instrumentation, Astronomical Optics, Imaging Systems, Telescopes, Dark Energy, Spectroscopy, Systems Engineering, Integrated Modeling UPDATE

1. INTRODUCTION

The use of Integral Field Unit (IFU) optical instrumentation is ubiquitous in both ground and space-based observatories. These are used for astrophysics, heliophysics, earth observations and planetary/solar system science. Because of the complexity of these designs, they are often limited in their capacity and implementation. The emergent technology of precision machined optical components is poised to disrupt traditional thinking in optical design, leading to reduced volume and mass, lower fabrication and integration costs, and increased capabilities. This especially applies to complex structures, such as Integral Field Spectrographs (IFS) which can be comprised of hundreds of mirror faces.

We have worked in concert with the science community and manufacturer to develop buildable opto-mechanical models suitable for large telescopes. These can be ground-based and potentially support future missions including Habitable Worlds Observatory. The design shown in Figure 1 demonstrates the concept for a stand-alone instrument concept for the W.M. Keck Observatory to support the ORCAS¹ (Orbiting Configurable Artificial Star) project. With a 10-m aperture, ORKID II could provide wide-field spectrographic imaging with spatial sampling from 6.7 mas to 26 mas.

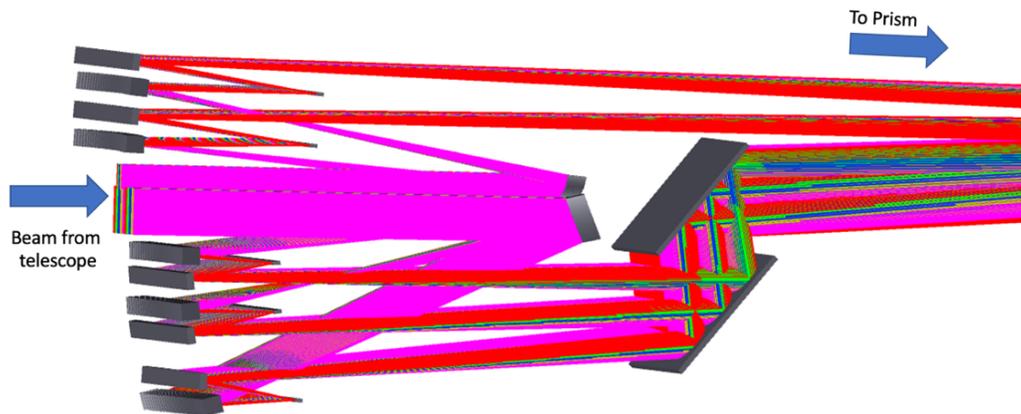


Figure 1. Image Slicer Assembly Optical Path

2. MACHINED OPTICAL COMPONENTS

The Canon Corporation utilizes an optically encoded five-axis milling machine to make precision ruled diffraction grating masters. The specifications for such components are among the most demanding in the manufacturing world. They have expanded the use of this technology to the manufacturing of various optical components, including multi-faceted components machined from a monolithic material.^{2,3,4} These can include image slicers, mirror arrays and freeform diffraction gratings, as shown in Figure 2.

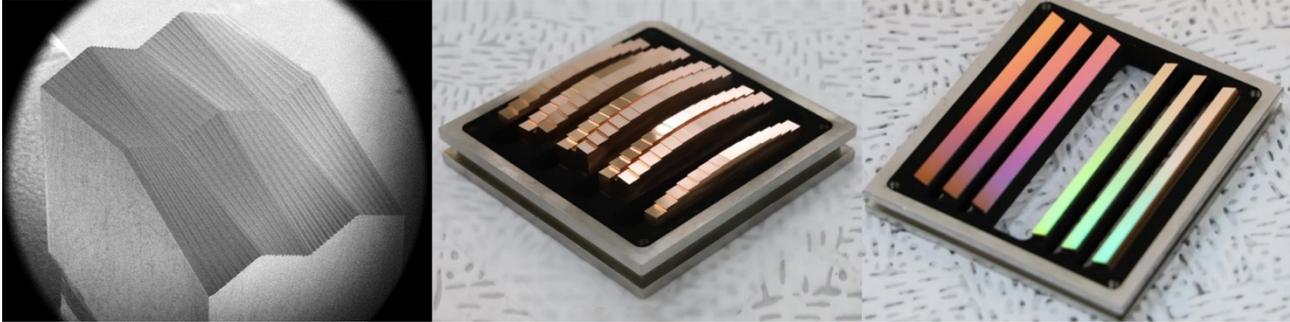


Figure 2. Several Canon machined optical components with multiple optical surfaces on a single substrate. Left: 112-mirror Image Slicer with 36 μ m wide mirrors, middle: Pupil Mirror Array, right: Machined Diffraction Gratings. (Images courtesy Canon Corporation.)

Traditional image slicer fabrication requires meticulous machining of the individual mirrors, an equally meticulous assembly of each piece. This can result in long lead times and high costs. The precision machining of these multi-mirror components is a disruptive technology that potentially reduces both cost and lead time. Mirror-to-mirror tolerances are measured in sub-micron spacings and surface alignments in thousandths of a degree, leading to improved performance error budgets. The substrate's mounting and alignment features also receive the same precision machining. This results in components that can be assembled via mechanical tolerances without additional metrology adjustments during integration and testing (I&T). The resulting cost and schedule savings can be significant, especially for flight projects.

Most significantly, this fabrication technique opens up new possibilities for optical design parameters, especially where volume and mass are constrained. What has been a medium sized optical bench is now potentially viable for a Small Sat or even CubeSat application.

For astronomical and science instruments, there is potential for overall greater performance parameters. This includes wider field coverage with higher sensor density packing, wide bandpass coverage, a full range of spectral resolutions, and variable spatial sampling. The technology is usable from Near-UV (limited only by the current $<10\text{\AA}$ micro-roughness and mirror efficiencies) to Far-IR (100's μm). The machined assembly could be configured for either an integrated spectrograph or forming an external exit pupil optimized for interfacing with an additional spectrographic assembly. This would allow for designs with spectral resolution (R) values from 50-300 to tens of thousands (via prism or grating-based designs).

3. SCIENCE

The science case for IFS instrumentation is wide. Machined optical component optomechanical designs would directly support observatory instrument trade studies. As a strategic long-term plan, by developing these prototype designs now, NASA is essentially getting a start on the design cycles required for flagship missions. For example, a proposed (but unfortunately descope) IFS for the Roman Space Telescope went through several design iterations over several years with the manufacturer before converging on a flight-ready opto-mechanical flight-capable design. It is also essential to advance to unit testing to compare results to other IFS technologies for a given application, such as lenslet-based systems.

Science use cases include including supernovae, Active Galactic Nuclei (AGN), supernovae redshift and brightness, gravitational events, Gamma Ray Bursts, Tidal Disruption Events, transient atmospheres, and direct exosystem imaging. Solar system & Planetary science can study Earth trojan asteroids, diagnostic absorption features and terrestrial body surfaces. By providing spectral information over its entire FOV, an IFS uniquely enables analysis of cloud compositions, atmospheres, terrestrial surfaces, and comet comae.

4. DESIGN METHOD

In this design, we converged on a layout which meet the manufacturer's fabrication parameters. The design can now be adapted to other platforms. The overall optical design can be used for Ground or Space-based telescopes, matching the input beam to the required angular resolution of the system.

4.1 Input Fields

The input beam for this design can be as fast as $f/160$, with up to 2x anamorphic compression in the X-axis ($f/80$). The Image slicer mirror widths vary from 100 to 400 μm across three fields: Fine, Coarse and Very Coarse. (Figure 3)

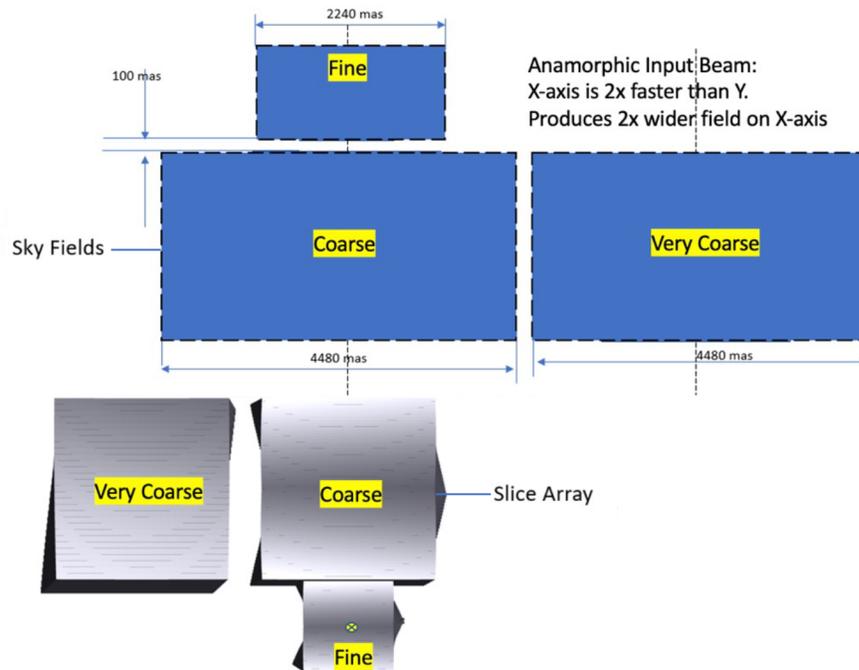


Figure 3. Image Slicer and Layout (bottom) and field projection (top). Note the anamorphic field accommodation.

4.2 Image Slicer Assembly

The Image Slicer Assembly (ISA) is comprised of three main components: The Image Slicer Mirrors array, the Pupil Mirror array, and the Pseudo-Slit Mirror array.

Slicer Mirrors

In this incarnation, the Image Slicer Mirrors are arranged in three adjacent fields with three sampling widths per mirror. The Fine and Coarse fields are aligned on the optical axis and Y meridian for symmetry. The Very Coarse field is displaced along the X-axis. The Fine and Coarse slicers are each made of 58 mirrors with a 58:1 aspect ratio. The Very Coarse slicer consists of 29 mirrors with a 1:29 aspect ratio.

Once the telescope image is relayed to the image slicer mirrors, each one acts both as an independent slit and optically reimaging the telescope exit pupil to an aligned array of Pupil Mirrors. To do this, each mirror has a cylindrically figured optical surface. Note that the machining process does not place a practical limitation on each surface being cut from the same base optical master. The Fine and Coarse slicers both create two rows of 29 Pupil Images, while the Very Coarse slicer creates a single row, for five rows total, as was shown in Figure 1.

Pupil Mirrors

The Pupil Mirrors are situated in a row aligned orthogonally to the Slicer Mirror stack. Each mirror is an independent anamorphic aspheric freeform surface. The role of the Pupil Mirror is to relay the image of each slice on the stack of slices to a single end-to-end row of images (a “pseudo-slit”) that can be spectrographically dispersed in the orthogonal axis. To do this, the distance needs to be proportional to the reduced magnification. Because the Coarse and Very Coarse slices are double the physical size of the Fine slices, the magnification ratio is also doubled to create pseudo-slits of the same size.

Pseudo-Slit Mirrors

When the slices are re-imaged by the five Pupil Mirror arrays to five output Pseudo-Slits, each slit image lands on an independent Pseudo Slit Mirror (PSM). The role of the PSMs is to re-image the pupils to a common exit pupil for the Image Slicer Assembly. All slices from all pseudo-slits can be projected to a common exit pupil for spectrographic dispersion. The exit pupil can be real or virtual (e.g., a telecentric output). In our example shown here, the exit pupil is real and (Fig 3) the slits are dispersed by $R_{\min}=100$ prisms onto a single 4k x 4k sensor with an 80% fill factor.

4.3 Spectrograph

The modular design of the concept allows for updating the instrument for various observing campaigns. In our example layout, we used a dual fused silica prism design for dispersion with a minimum $R_{\min}=100$ from 0.34 – 1.7 μm . We found it possible to meet our imaging criteria with a dual prism and dual freeform optical surface focus mirrors. (Figure 4).

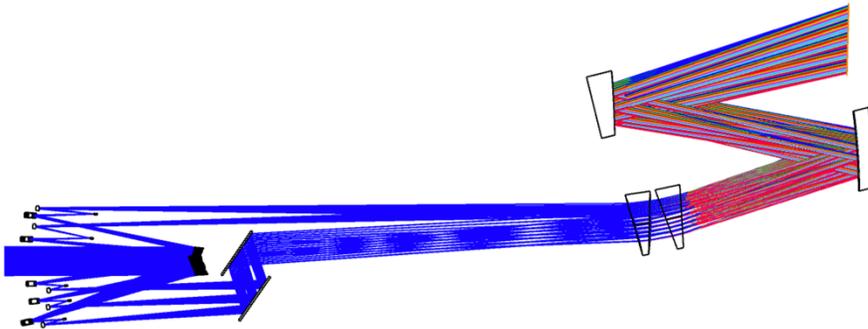


Figure 4. ISA and conceptual spectrograph layout using dual prisms and dual freeform focus mirrors.

4.4 Focal Plane Layout

The spectrums of the five pseudo-slits are laid out on the 4k x 4k (10 μm pixel) sensor as shown in Figure 5. Approximately 83% of the sensor is used. The packing density can be adjusted for various configurations of field and spectral coverage.

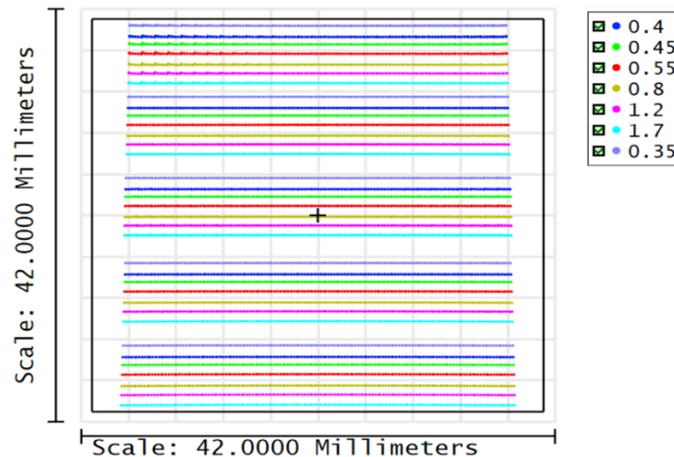


Figure 5. Image Slicer and Field Layout.

5. SPECTROGRAPH PERFORMANCE

The final IFS performance was evaluated for various parameters of image quality and spectral resolution. The spectral resolution based on ray-trace separation for every two pixels in the Y-axis are shown in Figure 6. The RMS Spot size is shown in Figure 7. For reference, note that the pixel size is $10\ \mu\text{m}$.

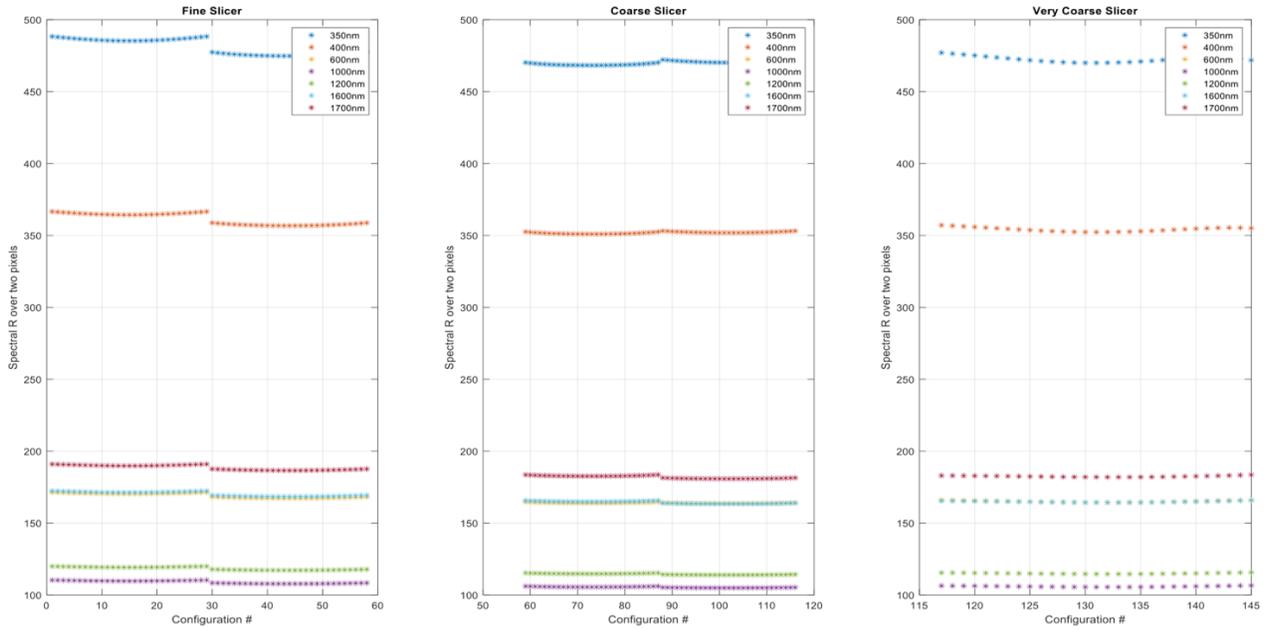


Figure 6. Spectral Resolution (Pixel Pairs).

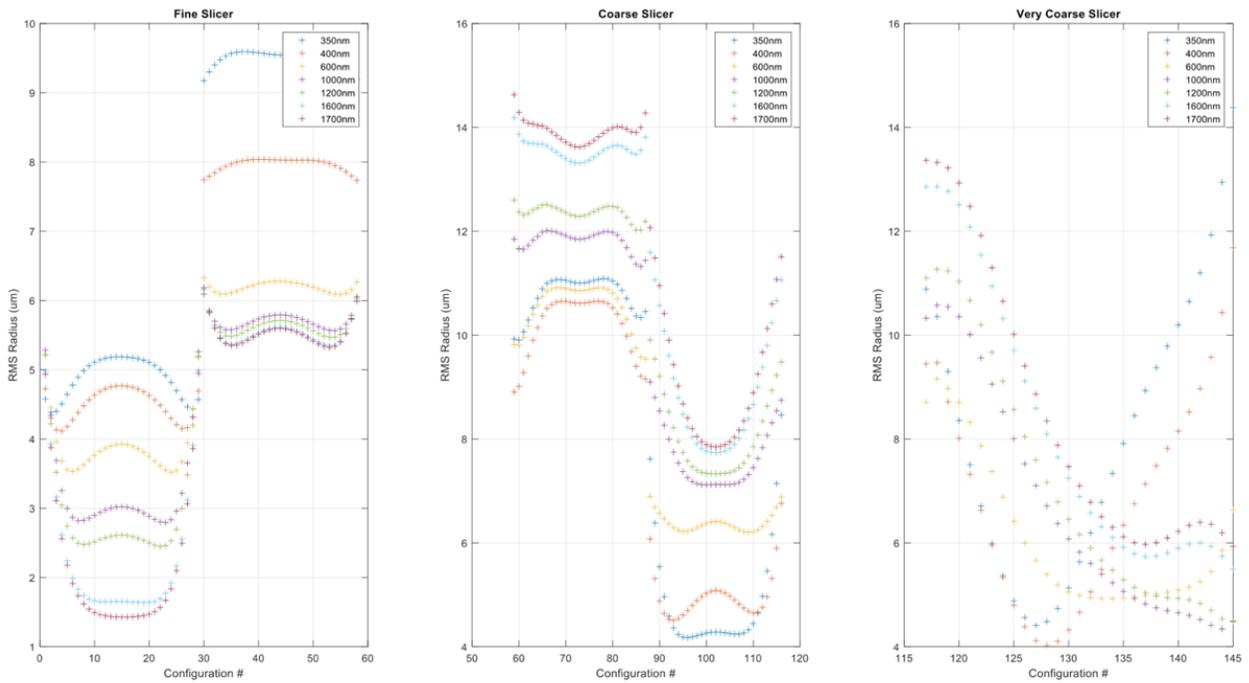


Figure 7. RMS Spot Size.

The final plot (Figure 8) shows the scale of the original image slicer width as imaged onto the sensor in numbers of pixels. This is convolved with the spot size to deliver the final spectrographic performance.

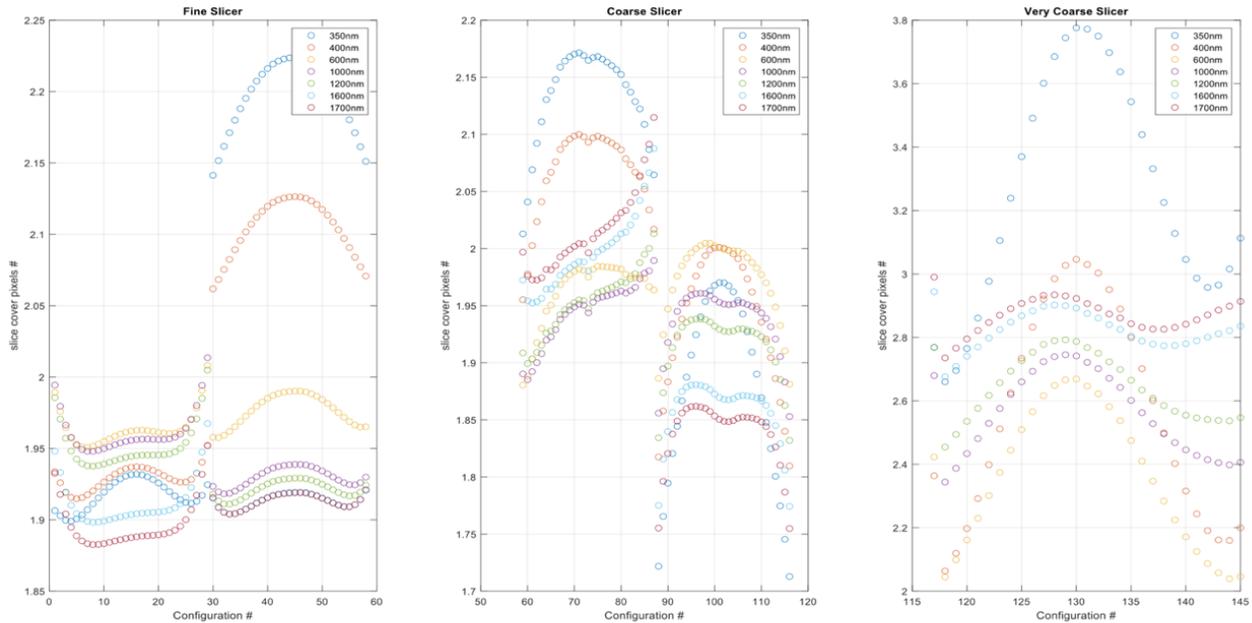


Figure 8. Y-Axis slit magnification.

6. SUMMARY AND CURRENT EFFORTS

The use of machined Image Slicer Assemblies is a proven technology that can be expanded on for use in all areas of spectrophotometric imaging. We have a well-defined path forward to build and utilize a new class of Integral Field Spectrographs based on machined optical components. This will continue to be developed for ground- and space-based instrumentation. Future work will include detailed tolerancing of fabrication and alignment parameters and stray light modeling once final mechanical parameters are defined.

The technology maturation roadmap includes risk reduction and improving the performance of existing Integral Field Spectrographs. In consultation with the science community, we will continue to model designs that cover a range of performance parameters applicable to astrophysics, planetary science, but could be used for a wide range of applications. Follow-on proposals will plan for the prototyping of one or more units. These would undergo optical characterization and environmental testing for TRL advancement.

7. ACKNOWLEDGEMENTS

We sincerely acknowledge that this study is the product of a well-coordinated and growing team. This includes the ORCAS Formulation Science Working Group, team co-members of many disciplines, contractors, and project leadership and support staff. Other ORCAS/ORKID II team members include (alphabetical): Kayla Carmical, Jason Chin, Imke de Pater, Jules Fowler, Étienne Gauvin, Luke Gers, Jack Grossman, Shui Hung Kwok, Rebecca Jensen-Clem, Peter Kurczynski, Eric L. Nielsen, Andrew Lewis, Scott Lilley, Eduardo Marin, John Mather, John O'Meara, Vivian Palmer, Sam Ragland, Steph Sallum, Shobita Satyapal, Brett Smith, Jean Thomas Landry and Ed Wetherell.

This work was funded by the National Aeronautics and Space Administration (NASA.)

8. REFERENCES

- [1] ORCAS Project Page, <https://asd.gsfc.nasa.gov/orcas>
- [2] Ultra-compact machined slicer IFU, *Takashi Sukegawa, Haosheng Lin, Morgan Bonnet* Proceedings Volume 12777, International Conference on Space Optics — ICSO 2022; 127773V (2023) <https://doi.org/10.1117/12.2690568>
- [3] MISI-36: Machined image slicer integral field units for the Diffraction-Limited Near-IR Spectropolarimeter, (*Haosheng Lin, Takashi Sukegawa, Morgan B. Bonnet, Yukinobu Okura, Tomonao Nakayasu, Yukimasa Suyama*, Proceedings Volume 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V; 1218828 (2022) <https://doi.org/10.1117/12.2629979>
- [4] The innovative capabilities of machined free-form mirror for IFU (Integral Field Unit), *Takashi Sukegawa, Yukinobu Okura, Masatsugu Koyama, Tomonao Nakayasu, Yukimasa Suyama*, Proceedings Volume 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V; 121880R (2022) <https://doi.org/10.1117/12.2629081>