

Performance analysis of SCALES final optical design: End to End Modeling

Arun Surya^a, Renate Kupke^b, Deno. Stelter^b, Phil Hinz^b, Stephanie Sallum^c, Amirul Hasan^a, Andrew Skemer^b, Sivarani Thirupathi^a, Ravinder Banyal^a, Athira Unni^c

^a Indian Institute of Astrophysics, Bengaluru, India

^b University of California Santa Cruz, Santa Cruz, CA, USA

^c University of California Irvine, Irvine, CA, USA

ABSTRACT

The SCALES instrument is a high-contrast imager and integral field spectrograph that operates in the infrared wavelength and is intended to be utilized behind W.M. Keck Observatory's adaptive optics system. The instrument operates over a broad wavelength range from 1.0 to 5.0 μm . The instrument includes a microlens array-based integral field spectrograph that is used with slicer optics and allows for low ($R \sim 35 - 250$) and moderate ($R \sim 2000 - 6500$) spectral resolution spectroscopy. We have implemented end-to-end modeling of the SCALES instrument optics using both geometric optics and physical optics. This analysis has been useful to understand the spectral formats, spectral resolution, and point spread functions. We have also modeled the geometric PSF from lenslets and combined it with the diffraction effects to model the crosstalk between the closely spaced lenslet spectra. The psf modeling are being integrated with the SCALES simulator to simulate realistic data products that are being used to develop the SCALES data pipeline.

Keywords: infrared:imaging, data:simulator, instrumentation: mid-infrared, spectroscopy

1. INTRODUCTION

Slicer Combined with Array of Lenslets for Exoplanets Spectroscopy (SCALES),¹⁻³ is a coronagraphic imager and integral field spectrograph that works in the mid-infrared wavelengths [1-5 microns] being developed for W.M. Keck Observatory. SCALES mainly aims to study cold self luminous exoplanets that can be directly imaged using coronagraphic techniques in mid-infrared. SCALES also allows for a new mode of using lenslet based integral field spectroscopy at higher resolution by using a slicer in combination with the lenslet.^{4,5} The top level specifications of SCALES are shown in Table 1. The optical design of SCALES is detailed in Kupke et al (2022).⁶ The optical layout is shown in Figure 1. In this paper we will discuss the performance analysis of SCALES final optical design for the integral field spectrograph using end to end analysis using Zemax based ray tracing and physical optics propagation.

Table 1. SCALES specifications

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

E-mail: A.S.: arun.surya@iiap.res.in

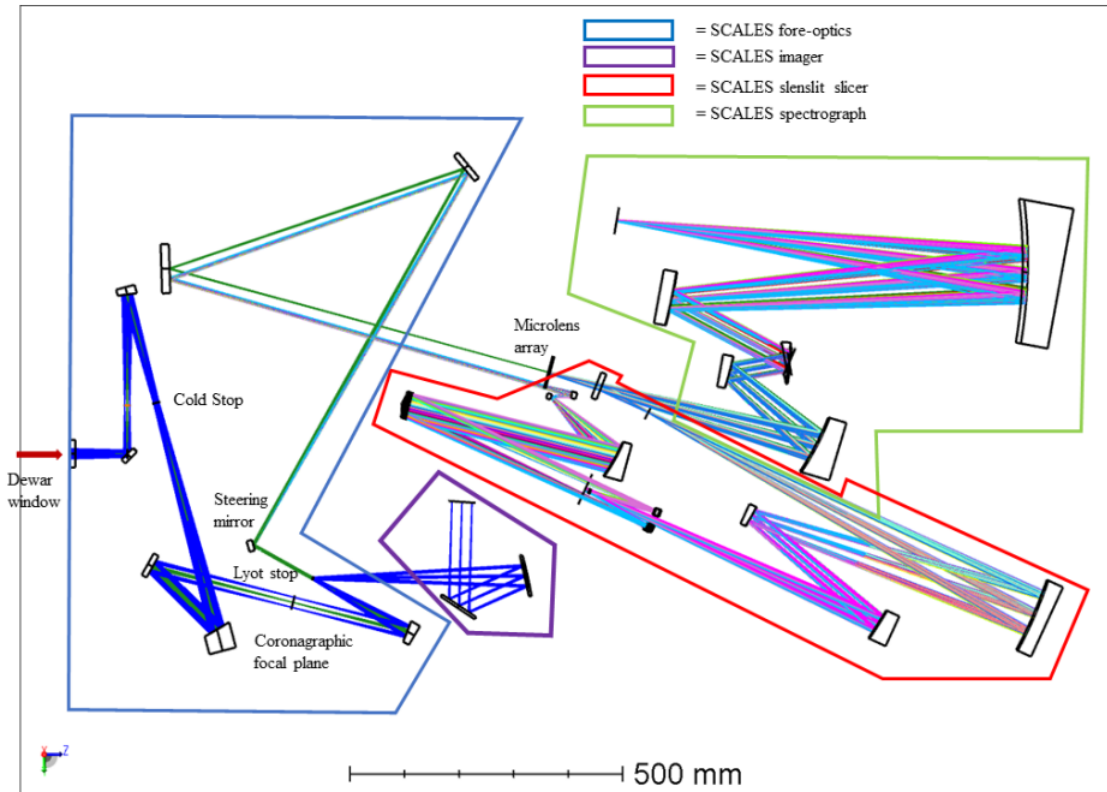


Figure 1. Optical layout of the SCALES instrument. The fore-optics, imager, low and medium resolution spectrograph are shown.

For a realistic end to end modeling we have done two levels of analysis using Zemax on optical design of SCALES.

- Spectrograph only Model : This analysis starts from the micro pupil plane imaged by the lenslet array. Ray tracing using Zemax is used to map the traces of the lenslet spectra in the detector.
- Full integrated End-to-End Mode: The full fore-optics including adaptive optics and telescope surfaces are included in the tracing. This analysis is also used to understand the point spread function (PSF) shape which is a combination of geometric and diffraction effects.

2. SPECTRAL LAYOUT AND SPACING

For spectrograph-only model we start with the plane of micro pupil images as imaged by the lenslet. The micro-pupils are the object plane to the spectrograph which are dispersed by the spectrograph with different filter and prism/grating combinations. The field points corresponding to the center of micro-pupil images created by each of the lenslet are mapped and used for tracing the spectra for each mode. The field point map for the low resolution mode and the slenslet mid-resolution mode is shown in Figure 2. Zemax macro scripts are used to measure the spot patterns on the detector for all the field points with a good sampling of the wavelength dispersion. The centroid information is used to map the spectra on the detector.

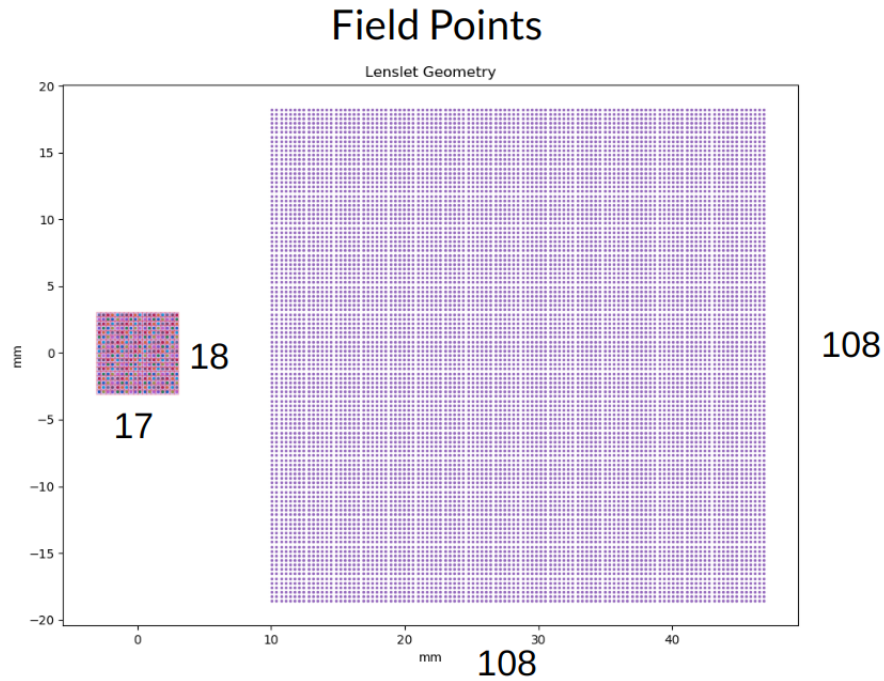


Figure 2. The field points at the lenslet plane showing the positions of the low resolution lenslet and the part of the lenslet for the mid-res slenslit mode. The coordinate system in this case is centered around the 18×17 mid-res lenslet center.

The spectral layouts for all the prism and grating modes were produced and analysed for:

- Missing / partially missing spectra from different lenslets.
- Distance from adjacent spectra defined as the perpendicular distance to adjacent spectra from spectra centroid.
- Dispersion solution at the detector

This information is useful for the raw data simulator and to check the resolution achieved in different modes. An example of prism spectra layout for the L band filter is shown in Figure 3.

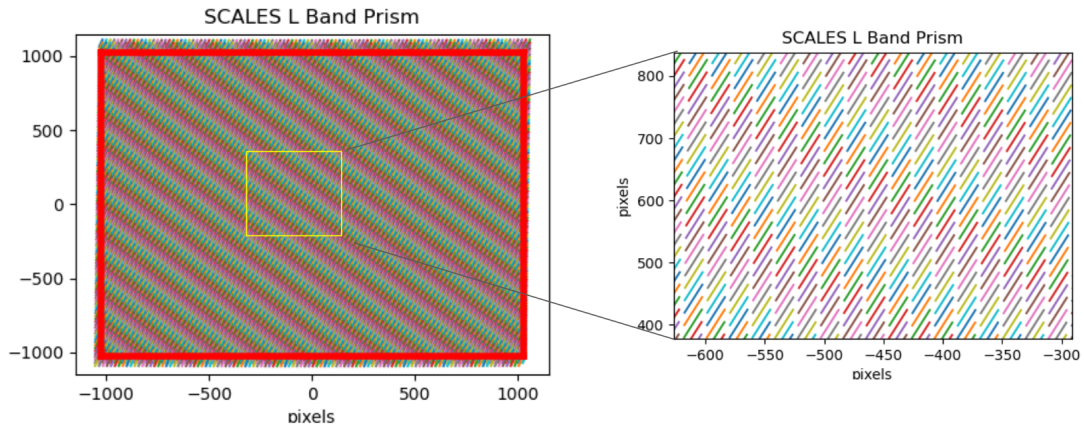


Figure 3. Spectral layout for the L-band low-resolution mode of the SCALES spectrograph. Different colors are used to represent different lenslet spectra.

The mid-resolution slenslit mode has 18×17 lenslet array reshaped as a pseudoslit using a slicer. The spectral format for this mode is shown in Figures 4. We also used the maps of spectral distance with adjacent spectra for all the lenslets to optimize the slicer. This information is crucial in adjusting the slices to place the slenslit spectra optimally. Having adequate spacing between the spectra helps to avoid crosstalk. The distance map of the adopted slenslit design is shown in Figure 5. One other important aspect of the spectral layout modeling effort is also to map the lenslet spectra that are partially falling out from the detector. This determines the effective field of view limited by the dispersion at detector. Example of these maps for L-band prism mode are shown in Figure 6.

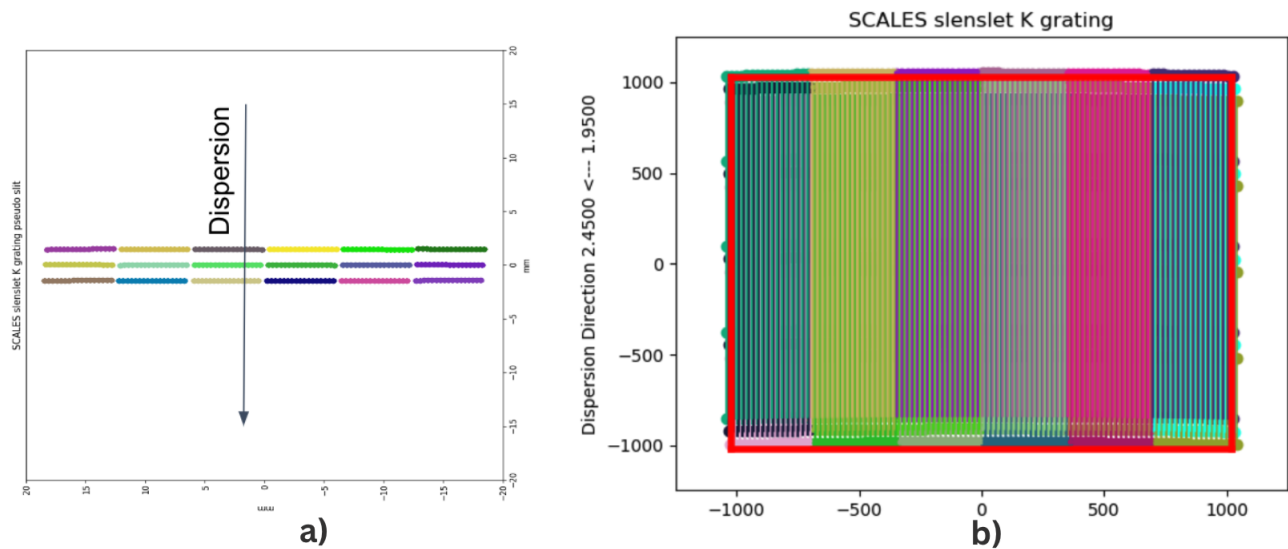


Figure 4. Spectral layout for the K-band mid-res mode of the SCALES Slenslit spectroscopic mode. a) The reformatted 17×18 micropupil pseudoslit is shown. b) The dispersed spectral layout in K-Band with different colors are used to represent the spectra of the columns of lenslets.

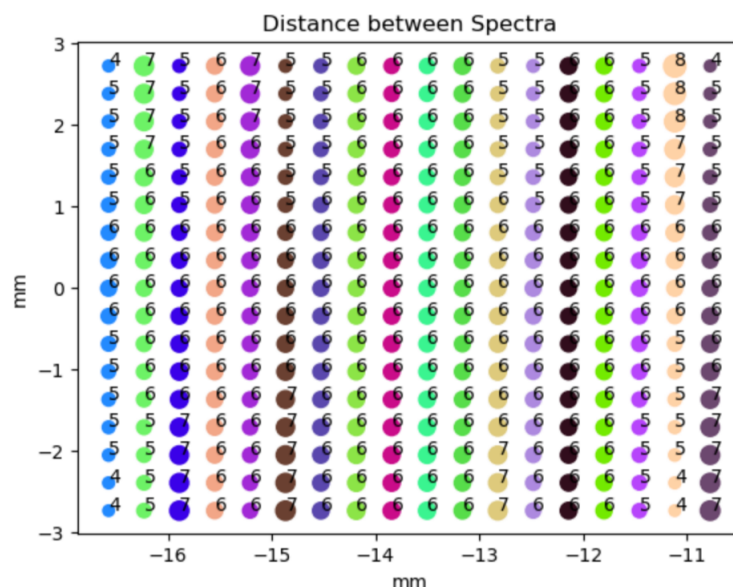


Figure 5. The spectral separation map of the slenslit K band mode showing the distance of each lenslet spectra from the nearest lenslet spectra. The numbers represent the distance to nearest spectra in pixels. The colors represent the different slice groups.

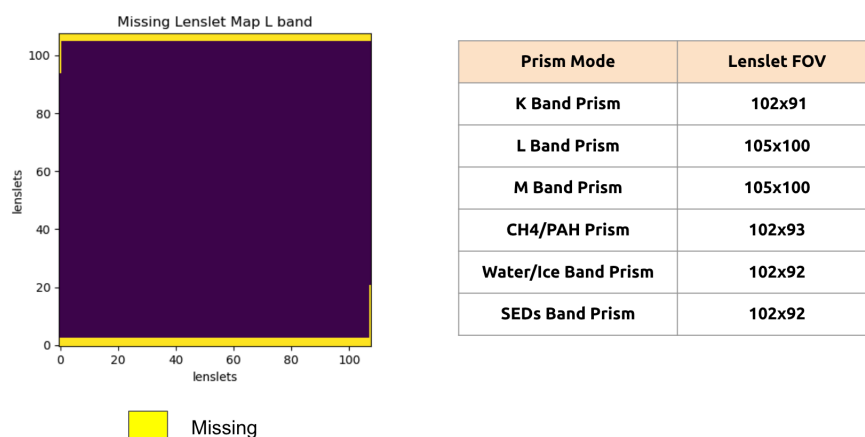


Figure 6. The map of missing spectra corresponding to different lenslets in L-band prism mode. The yellow color implies the spectra are partially or completely falling off of the detector. The lenslet fov available for different SCALES spectrograph filters are also shown.

3. END TO END ANALYSIS

Full end-to-end analysis uses the complete optical design including telescope, adaptive optics surfaces and fore-optics together with the spectrograph for complete ray tracing. We start with mapping sky field points to the center of each lenslet. These field points are used for simulating the spectral layout of the spectrograph. The map of the lenslet centers to the sky are shown in Figure 7 with arrows pointing to the distortion at the lenslet plane.. A histogram of the distortion at the lenslet plane is shown in Figure 8. These maps are used to create the field points in the sky that are traced to the detector through the end to end optics. We use Zemax macros to trace subfields that fall in the same lenslet and compute the image at the detector. These more densely sampled sub-lenslet field points are used to compute the micro pupil image spots in the detector. A sample of different spots across the detector are shown in Figure 9. The end to end rms spot radius for the whole field of view of the low resolution mode is shown in Figure 10.

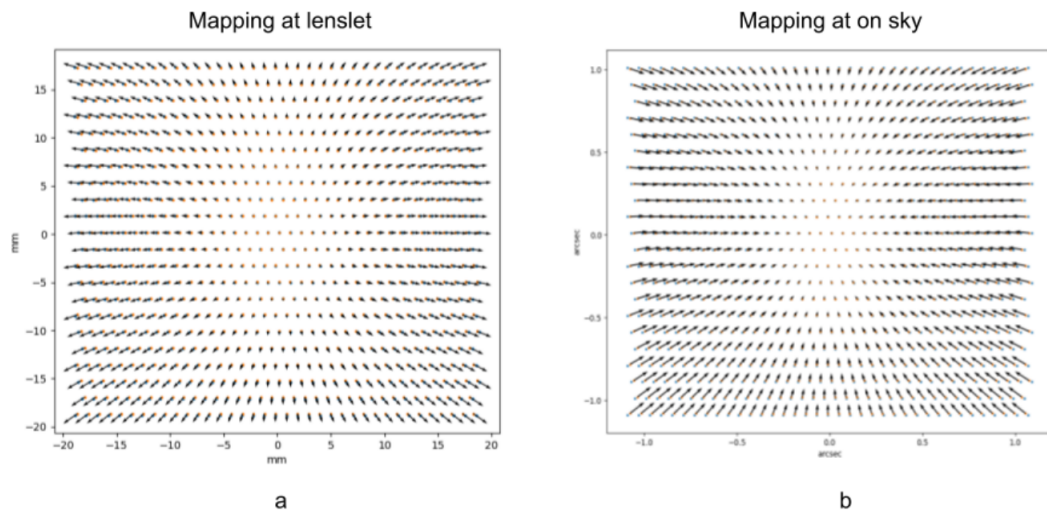


Figure 7. Distortion Map at the lenslet plane. The points from the lenslet centers are traced back to the sky and shifts from the ideal grid points are shown in arrows with scaling. Similar method is used to map ideal grid points in sky to lenslet plane. a. is in lenslet plane and b. is in sky plane.

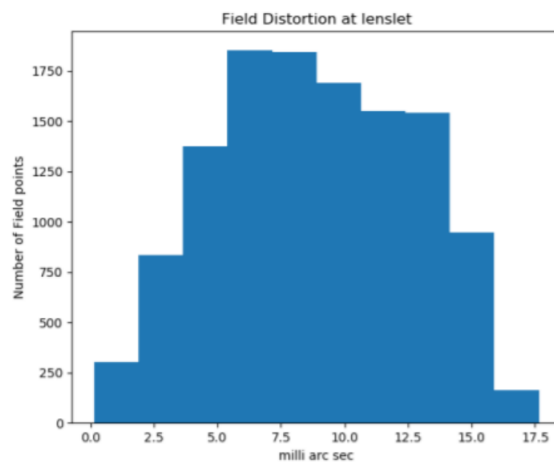


Figure 8. Histogram of the deviation at the sky plane from the ideal grid points (separation of 20 mas between points). The distortion effects seem to be within the size of the lenslet.

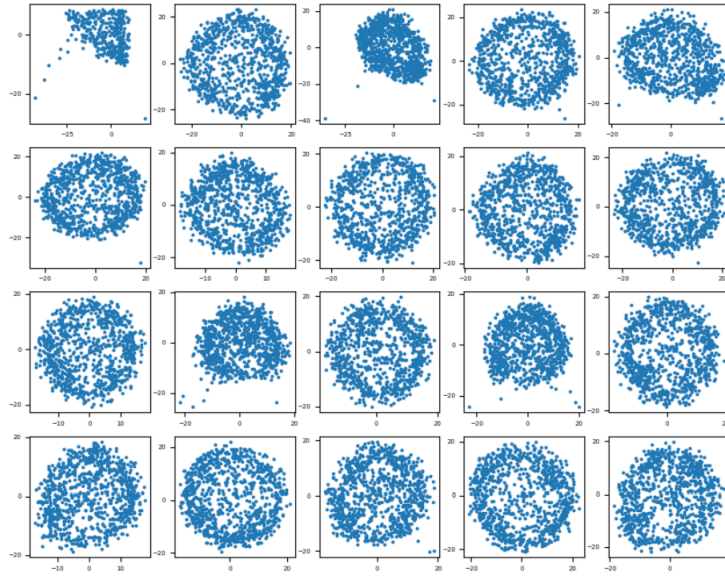


Figure 9. The plot shows the spots diagram for sample of lenslets in 2.2 micron in K band prism mode. Full field within a single lenslet are used for the ray trace. The box labels are in microns.

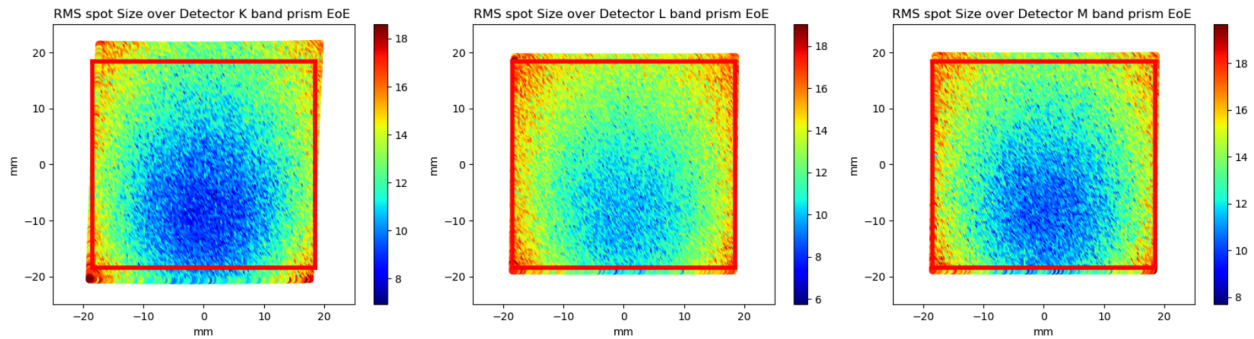


Figure 10. The full field end to end spot radius diagram for the K , L and M bands in low-resolution mode at the central wavelengths. The spot radius is in microns. The red box is the detector outline.

4. SPECTRAL RESOLUTION WITH THE OPTICAL DESIGN

One of the important aspects of lenslet spectrographs with tightly spaced spectra is the modeling of the spectrograph PSF and the understanding of cross-talk. Such modeling is important to develop the deconvolution algorithms used for retrieving the spectral cube from the raw data. We modeled the spectrograph PSF using physical optics propagation and geometric end-to-end tracing. This PSF information is used to compute the spectral resolution with different filters of the SCALES spectrograph. The spectral resolution with the SCALES spectrograph for different filter bands is shown in Figure 11.

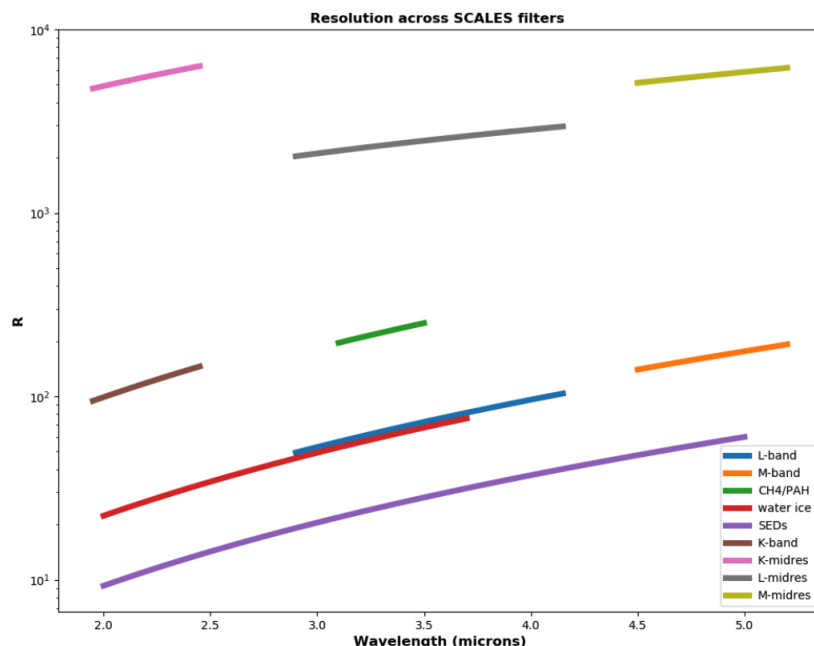


Figure 11. The spectral resolution for different filter bands of SCALES integral field spectrograph plotted as a function of wavelength.

5. SUMMARY

We have reported the performance analysis of SCALES integral field spectrograph using end to end geometric raytracing and physical optics modeling. We have done detailed Zemax based raytracing to analyze spectral layout, spacing, spectrograph point spread functions and distortion effects. End to end analysis offers a unique way to understand spectrograph performance. The analysis data products will be used in the raw data simulator for the development of the SCALES data reduction pipeline.

REFERENCES

- [1] 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).
- [2] Stelter, R. D., Skemer, A. J., Sallum, S., Kupke, R., Hinz, P., Mawet, D., Jensen-Clem, R., Ratliffe, C., MacDonald, N., Deich, W., Kruglikov, G., Kassis, M., Lyke, J., Briesemeister, Z., Miles, B., Gerard, B., Fitzgerald, M., Brandt, T., and Marois, C., “Update on the preliminary design of SCALES: the Santa Cruz Array of Lenslets for Exoplanet Spectroscopy,” in *[Ground-based and Airborne Instrumentation for Astronomy VIII]*, Evans, C. J., Bryant, J. J., and Motohara, K., eds., **11447**, 1144764, International Society for Optics and Photonics, SPIE (2020).
- [3] Banyal, R. K., Hasan, A., Kupke, R., Varshney, H. M., Prakaesh, A., Sivarani, T., Skemer, A. J., MacDonald, N., Sallum, S., Deich, W., Fitzgerald, M. P., Govinda, K. V., Ratliff, C., Sethuram, R., Stelter, D., Surya, A., and Wang, E., “Design of an IR imaging channel for the Keck Observatory SCALES instrument,” in

- [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V*], Navarro, R. and Geyl, R., eds., **12188**, 121881U, International Society for Optics and Photonics, SPIE (2022).
- [4] Stelter, R. D., Skemer, A., and Bourgenot, C., “From colors to chemistry: a combined lenslet/slicer IFS for medium-resolution spectroscopy,” in [*Techniques and Instrumentation for Detection of Exoplanets X*], Shaklan, S. B. and Ruane, G. J., eds., **11823**, 118230E, International Society for Optics and Photonics, SPIE (2021).
- [5] 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., **12184**, 1218445, International Society for Optics and Photonics, SPIE (2022).
- [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).