National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE) Spectrometer

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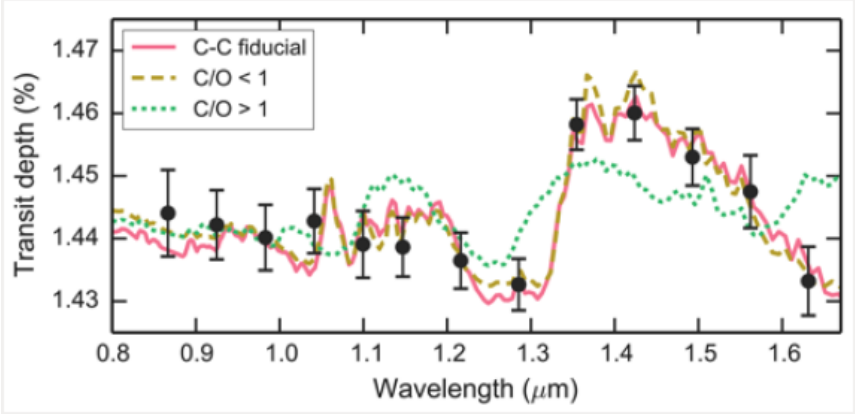
Science overview

- There are ~3,500 confirmed planets orbiting stars other than our own (exoplanets), but for most, we know little beyond their mass and orbit period.
- FINESSE will obtain the atmospheric composition measurements of metallicity and carbon-to-oxygen ratio of that are needed to address all future efforts to understand planet origins, for more than 500 exoplanets.
- FINESSE measurements will determine planetary energy budgets, the role of aerosols in establishing the atmospheric radiation balance, and the processes that control heat redistribution from the dayside to the nightside.

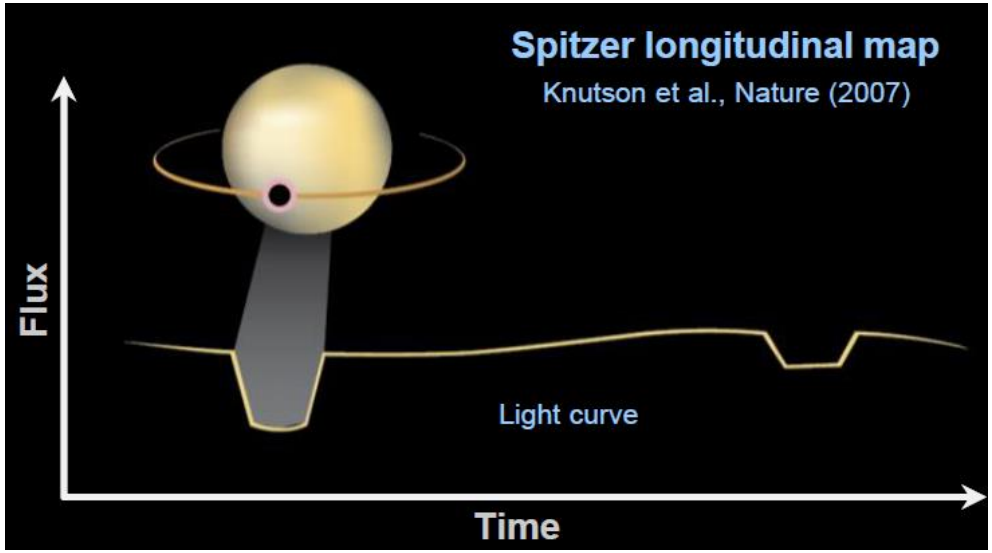
Hubble detection of water

Kreidberg, Bean, Line et al., Astrophysical Journal (2015)



Measurement technique

- During a transit, light from the parent star filters through the planet's atmosphere, encoding molecular features.
- FINESSE obtains a spectrum by measuring how light at each wavelength changes during a transit.

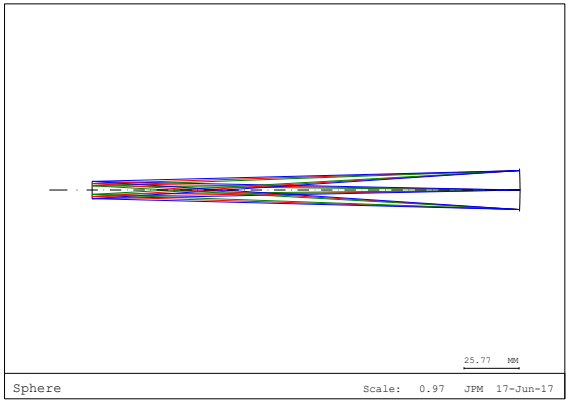


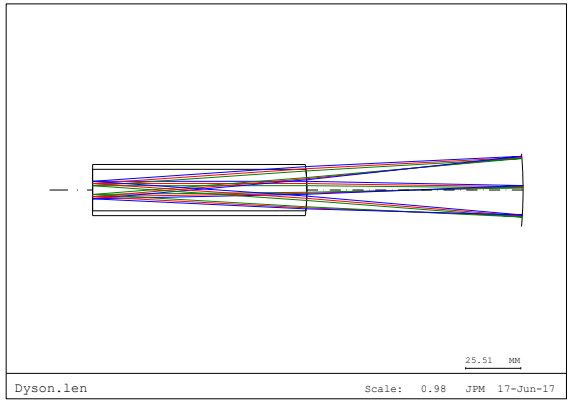
Requirements

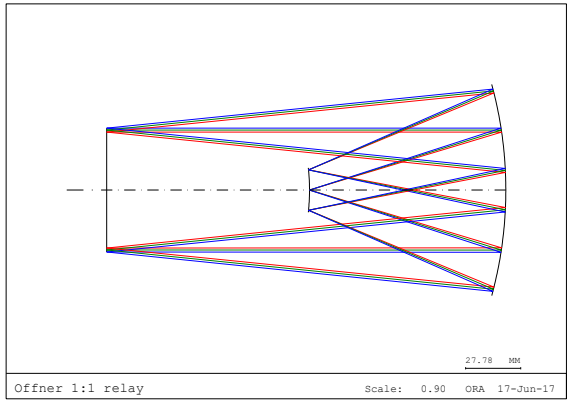
Parameter	Specification	Performance	Comments
1. Spectral a. Wavelengths (µm) b. Resolution (λ/Δλ) c. Dispersion (pixels)	a. 0.45 to 5 b. 80 c. Report	a. Same b. 80 c. 1976	Chose Δλ to correspond to 4 pixels
2. Focal plane a. Number of pixels b. Size (µm)	H2RG 2048 x 2048 18 x 18	Same	
3. F-number	Report	f/12	
4. Field size (arcsec)	20 x 6.5 (two 6.5 arcsec pinholes separated by 7 arcsec)	Same	Pinholes reduce sky background, physical size 893 x 238 µm with 75 cm diameter f/12 telescope
5. Transmission	Report	0.63	Maximize
6. Spectrometer volume (mm)	Report	99 D x 359 L	Smaller is more stable and cheaper

1x concentric relays

- **All spherical surfaces**
- **Free of coma by symmetry**
- **Free of spherical aberration since the surfaces are concentric with the object/image**







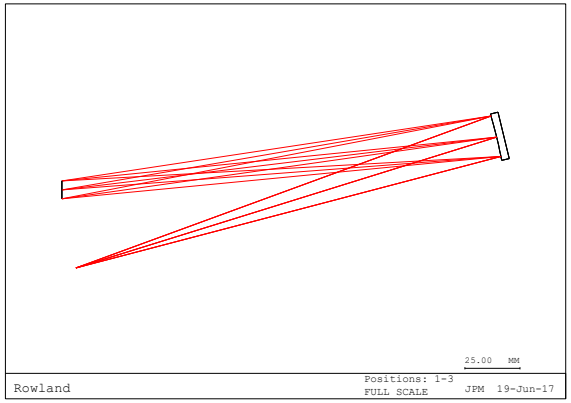
- Sphere
- Limited by astigmatism
- No Petzval correction
- Not telecentric

- Dyson, 1959
- Limited by astigmatism
- No color correction

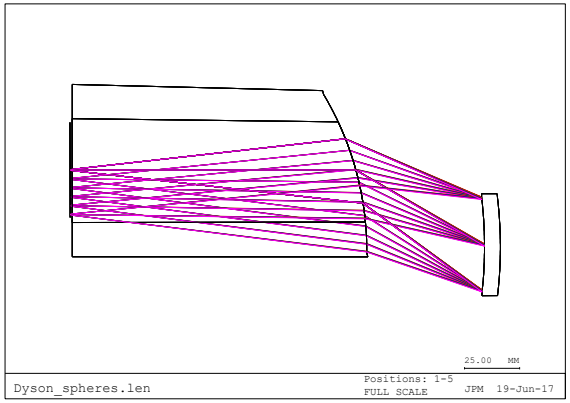
- Offner, 1977
- Limited by astigmatism

1x grating spectrometers

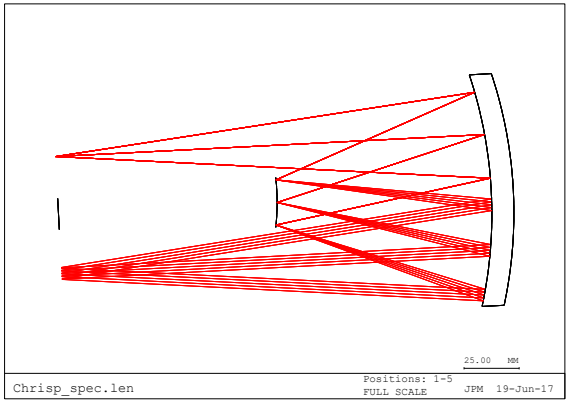
- Adding a grating to the stop turns the relay into a spectrometer
- All spherical surfaces



Rowland, 1882



Mertz, 1977

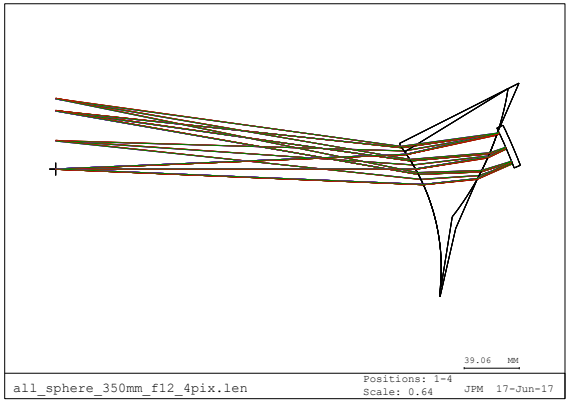


Chrisp, 1996

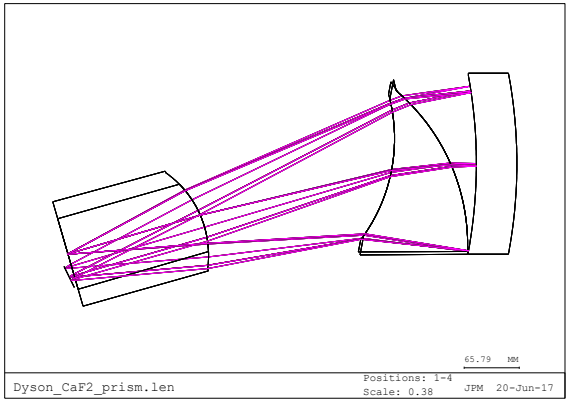
With FINESSE spanning over a factor of 10 in wavelength, the grating efficiency would be less than 0.3. We need a better solution.

1x prism spectrometers

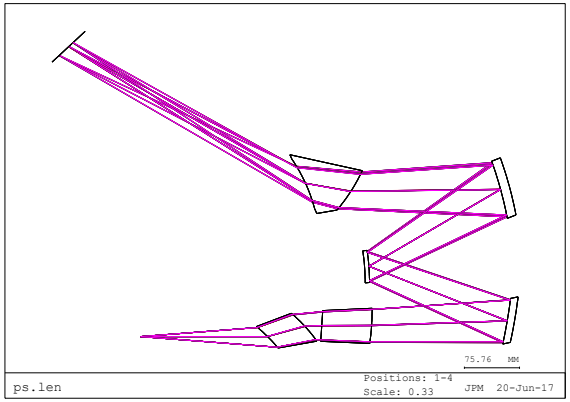
- **Prism spectrometers are more efficient than grating spectrometers**
- **All spherical surfaces**



Fery, 1911



Lobb, 1997

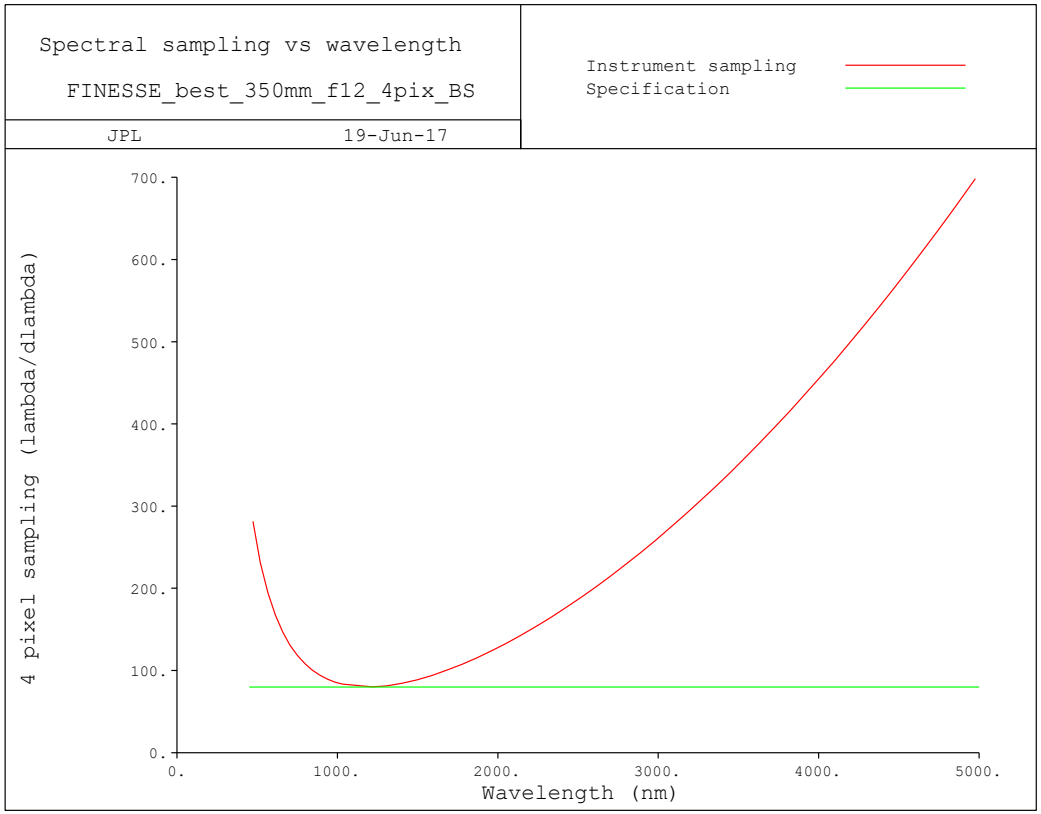


Lobb, 1997

We'll start with the simplest, highest througput configuration.

Design approach

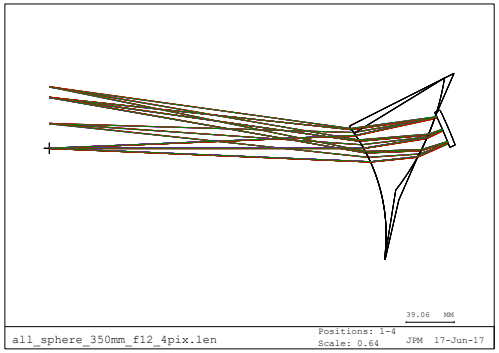
- Use CaF2 to cover 0.45 – 5 µm for FINESSE
- Keep it slow to minimize fabrication sensitivity and size
- Maximize the dispersion, which maximizes the FWHM margin available for the meeting R=80 specification



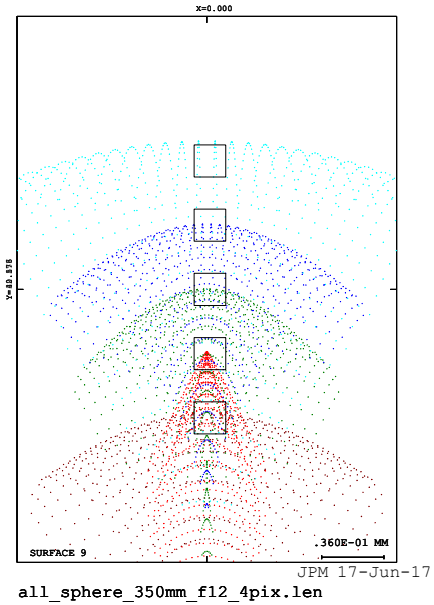
Layouts and spot diagrams

- Warren showed an aplanatic prism could be used to correct spherical, coma, and astigmatism of the prism, but astigmatism of the mirror is not corrected
- Use a free-form mirror to correct the astigmatism

All spherical

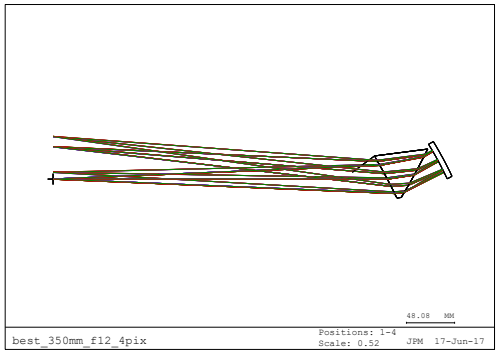


350 mm

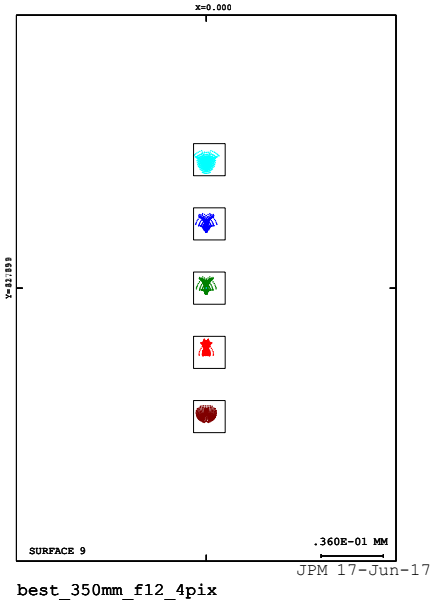


< 169 µm rms

Free-form Mirror



350 mm



< 12 µm rms

Error Budget

- **Tolerances are not scary**

FINESSE FWHM ERROR BUDGET
CENTER FIELD POINT
Linewidths at 1.179 µm

Telescope		
Mean	2.6	pix
2Sigma	0.800	pix

On Axis		
2.2 to	**3.8**	**pix**
mean	**3**	
2sigma	**0.8**	**pix**
Spectrometer		
Mean	0.4	pix
2Sigma	0.144	pix
Beamsplitter		
	0.040	pix
Fabrication	0.040	pix
S1 Power	0.013	
0.5	fr	
S1 Irregularit	0.006	
0.25	fr	
S2 Power	0.018	
0.5	fr	
S2 Irregularit	0.009	
0.25	fr	
Thickness	0.024	
0.025	mm	
TIR	0.020	
0.005	mm	
Alignment	0.006	pix
Z Decenter	0.000	
0.25	mm	
XY Tilt	0.006	
0.4	mrad	

Goal	**2 to 4**	**pix**
Reserve	**0.2**	**pix**
Integration	0.026	pix
Z Decenter	0.026	
0.025	mm	
XY Tilt	0.005	
1	mrad	
CaF2 prism		
	0.016	pix
Fabrication	0.011	pix
S1 Radius	0.006	
1.5	fr	
S1 Irregularit	0.007	
0.5	fr	
S2 Radius	0.001	
0.528	mm	
S2 Irregularit	0.003	
0.5	fr	
Thickness	0.001	
0.075	mm	
TIR	0.004	
0.011	mm	
Alignment	0.012	pix
XY Decenter	0.004	
0.05	mm	
Z Decenter	0.006	
0.075	mm	
XY Tilt	0.009	
0.3	mrad	

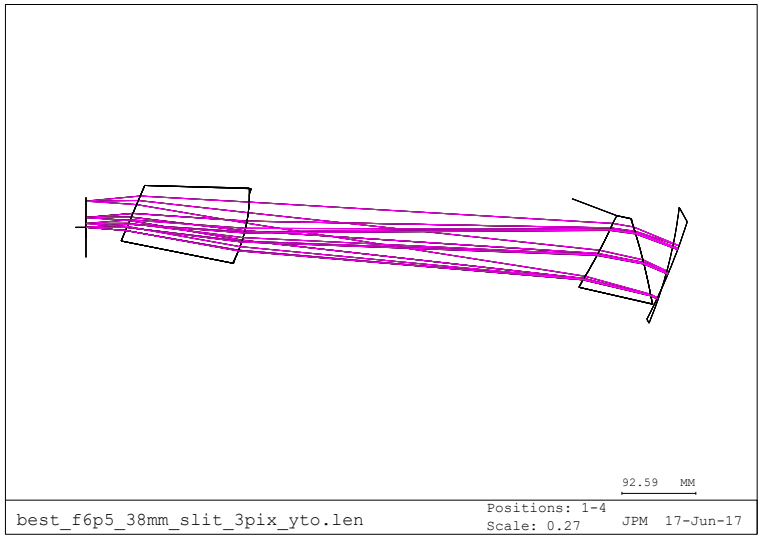
Mirror		
	0.052	pix
Fabrication	0.044	pix
Power	0.042	
3	fr	
S2 Irregularit	0.012	
1	fr	
Alignment	0.028	pix
Z Decenter	0.028	
0.46	mrad	

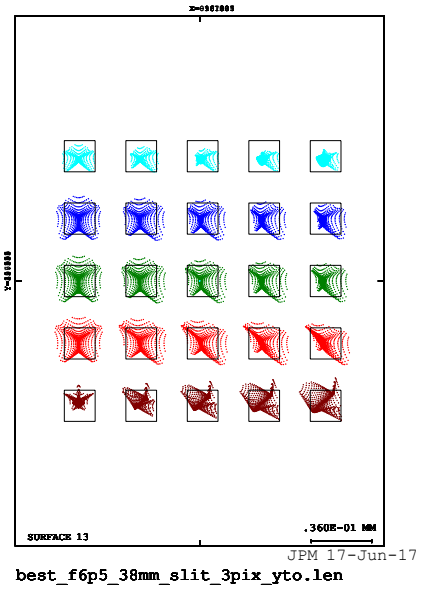
Adjustment Precision		
	0.078	pix
CaF2	0.064	pix
XY Decenter	0.064	
0.015	mm	
Mirror	0.028	pix
Z Decenter	0.028	
0.0125	mm	
Detector	0.035	pix
Z Decenter	0.026	
0.025	mm	
XY Tilt	0.023	
0.7	mrad	

Environment		
	0.10	pix
	0.10	pix
Thermal	0.10	
5	K	
Refr Index	0.008	
0.0005		
Abbe #	0.001	
0.005		

Imaging Prism Spectrometers

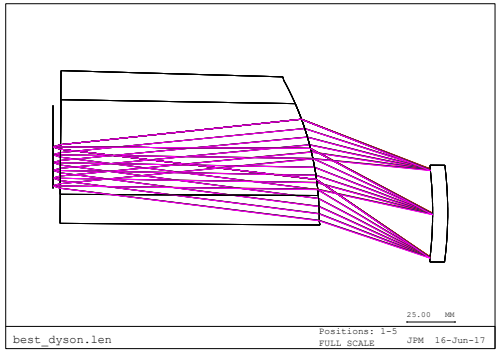
- Dyson spectrometers can work at faster speeds than Offners, but have the disadvantage of a large (heavy) element
- Surprising performance can be obtained by using two thin elements with spherical surfaces and a free-form mirror to balance the on-axis astigmatism
- "Field prism" controls distortion
- Example at f/6.5 and a 38 mm slit
  - Spots < 15 µm rms
  - Smile < 0.4 µm
  - Keystone < 0.6 µm



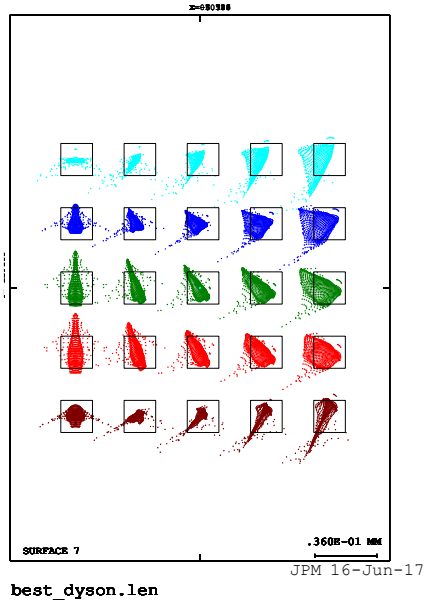


Imaging Grating Spectrometers

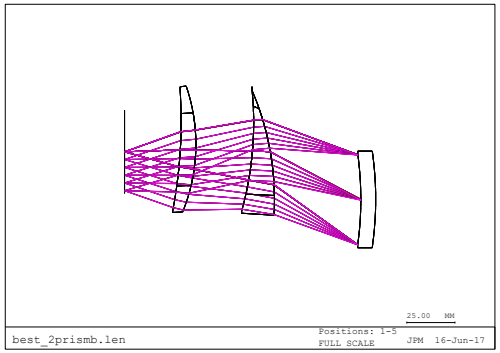
- The same aberration balancing that was used with the 2-element prism spectrometer can be used in a grating spectrometer.
- This is especially valuable in the far-IR. The concentric spherical surface in the Dyson images the telecentric input onto the stop, so the Dyson block takes up a greater proportion of the total length as the index increases. We can achieve better results with 2 thin elements
- Example f/1.5 with CdTe covering 11.8-15.4 µm with a 15 mm slit
- Both designs use a free-form mirror



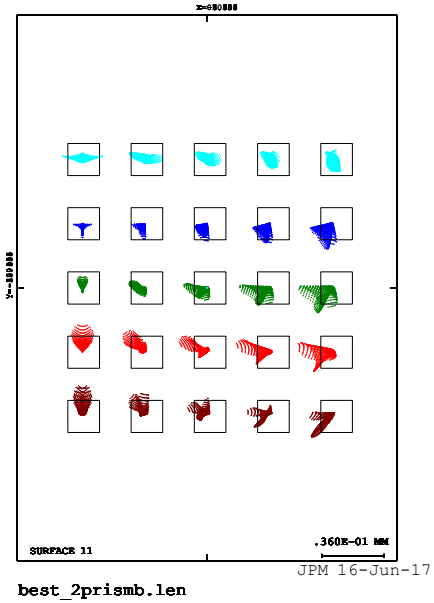
200 mm



< 20 µm rms



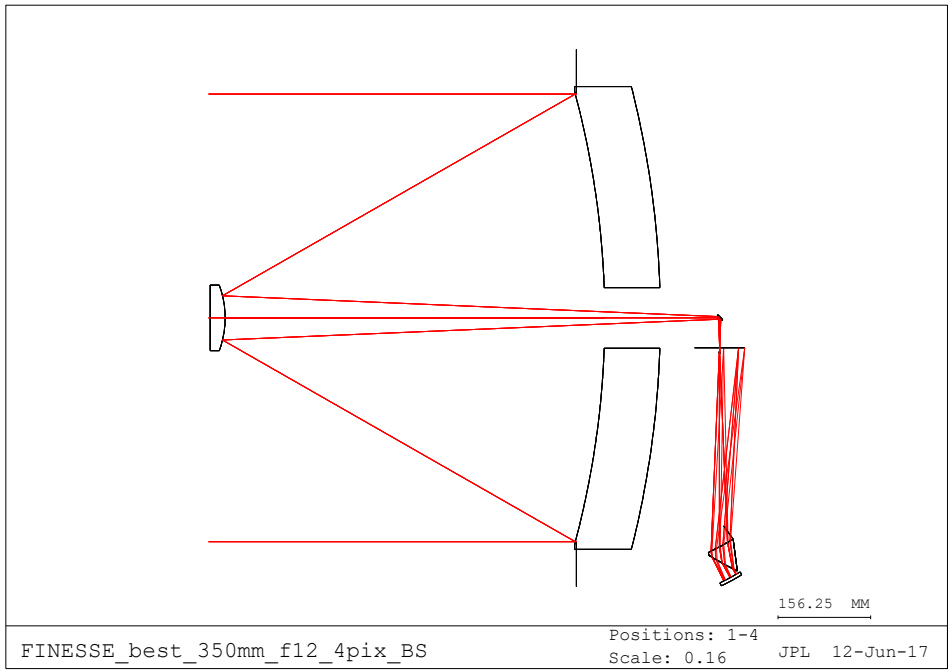
125 mm

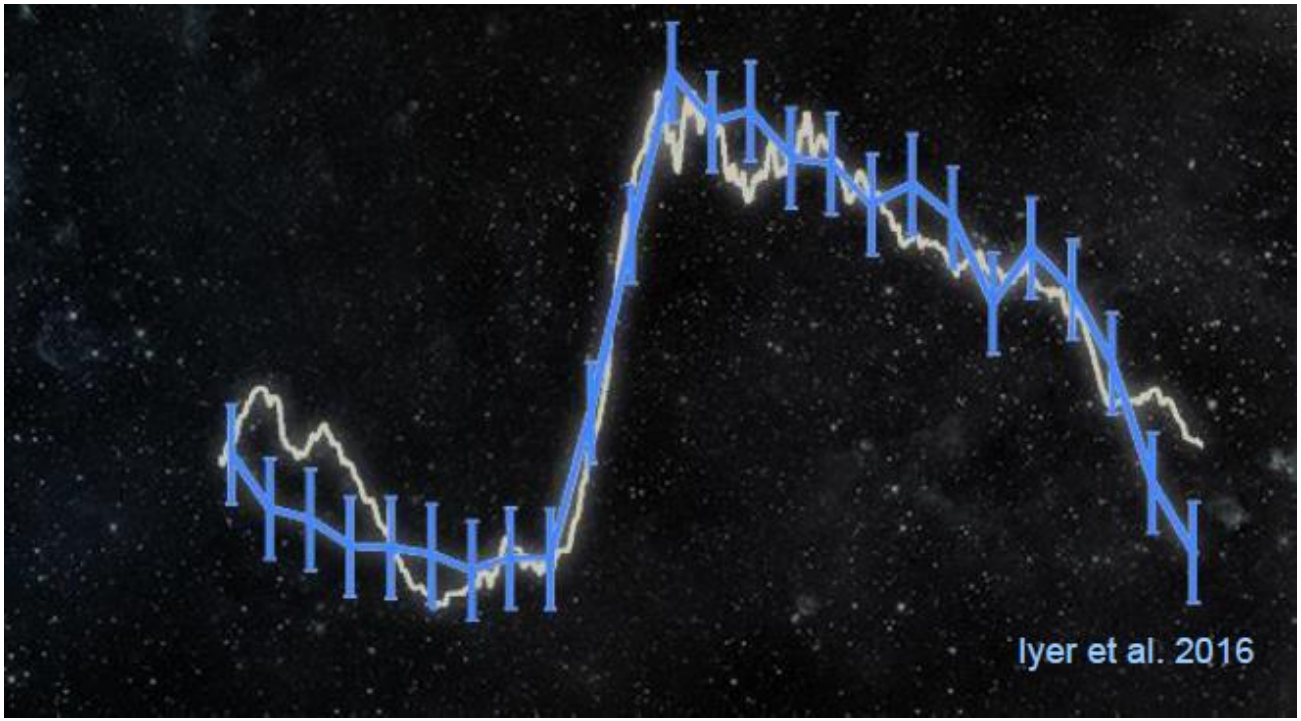


< 12 µm rms

Conclusions

- 1x relays provide an excellent basis for both grating and prism based spectrometers
- Replacing the spherical mirror with a free-form mirror simplifies removal of on-axis astigmatism, which improves performance and/or reduces size
- Useful performance can be obtained with two tilted and decentered elements and a free-form mirror



Acknowledgements

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