Flight Integral Field Spectrograph (IFS) Optical design for WFIRST Coronagraphic Exoplanet Demonstration

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IFS for WFIRST Coronagraph Instrument

- IFS is selected as the exoplanet spectrometer for the following reasons:
  - An IFS obtains the entire exoplanet spectrum simultaneously.
    - Compared to filter wheel,
      - Saves observation time
      - All measurements happened at exactly same time.
  - Wavefront sensing process more efficient in broadband light
- Phase A IFS optical design is based on the prototype “PISCES”
  - Primary Design Changes
    - The spectral resolving power has changed from R = 70 to R = 50
    - The spatial sampling has changed from 3 sampling per λ/D to 2 sampling per λ/D
    - Optics re-arranged to mitigate fluorescence from cosmic rays

Phase A IFS Requirement

- The resolving power has reduced to R=50
- Bandwidth for all three bands has ben kept the same at 18%
  - The best shape for lenslet is hexagon to provide most efficient detector pixel usage
  - However, it is preferred to accommodate ~20% bandwidth for a potential Starshade

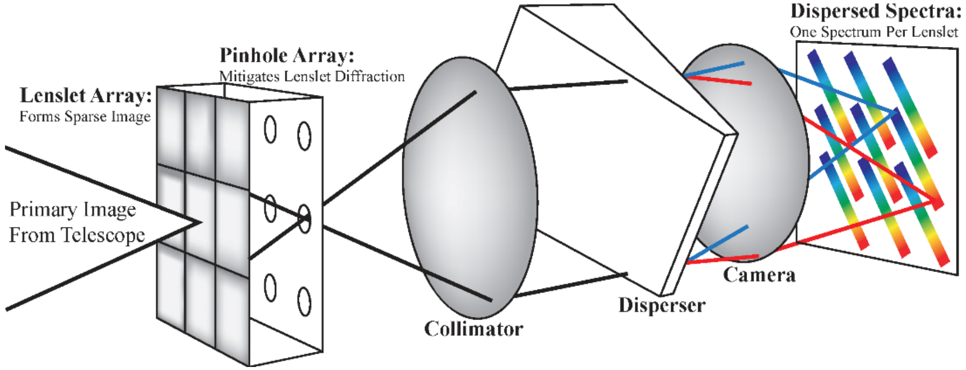
Phase A IFS Specifications			
Central wavelength (nm)	660.0	770.0	890.0
λmin (nm)	600	700	810
λmax (nm)	720	840	970
# of dispersed pixels	18	18	18
Lenslet pitch (μm)	174	174	174
sampling at λ_c	2	2.33	2.7
Spectral resolving power	50	50	50

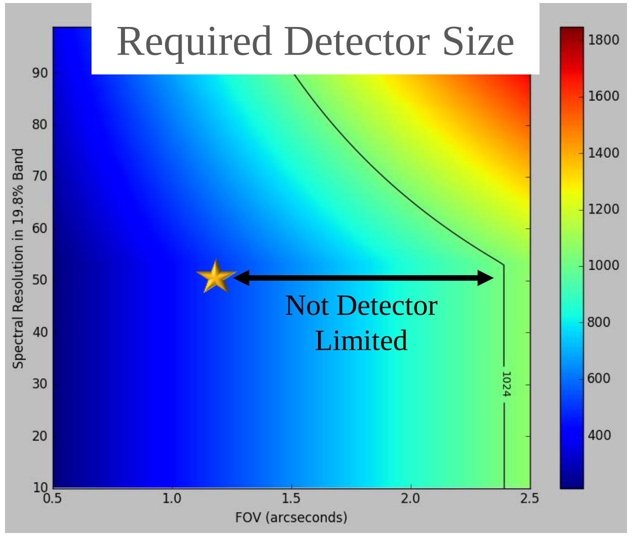
PISCES IFS Specifications			
Central wavelength (nm)	660.0	770.0	890.0
λmin (nm)	600	700	810
λmax (nm)	720	840	970
# of dispersed pixels	26	26	26
Lenslet pitch (μm)	174	174	174
sampling at λ_c	3	3.5	4.0
Spectral resolving power	70	70	70

Trade-off #1: telecentric vs. non-telecentric IFS Relay

- The first optical group to be designed is a relay optics. Its function is to adjust the plate scale so that the Point Spread Function (PSF) on lenslet array meets Nyquist sampling requirement.
- Baseline requirement is Nyquist sampling at λ = 660nm
- Exploring Nyquist sampling at λ = 660nm for better integration times
  - The f/# is calculated at 530 to match the lenslet size
  - The coronagraph provides a collimated incident beam to IFS with a diameter of 5mm
  - Therefore, the effective focal length of relay needs to be >2700mm.
- Telecentric:
  - The main advantage is that the spectrometer design can be fixed if relay needs to be modified.
  - However, telecentric design requires the Lyot stop needs to be in the front focal plane, which is >2700mm away from relay.
  - Not enough space to implement it with the allocated space for IFS.
- Non-telecentric
  - Can be much more compact and fit the allocated space.
  - The possibility of major changes after the IFS design completed is small
  - Non-telecentric is selected as PhaseA relay.

Trade-off #2: IFS Selection





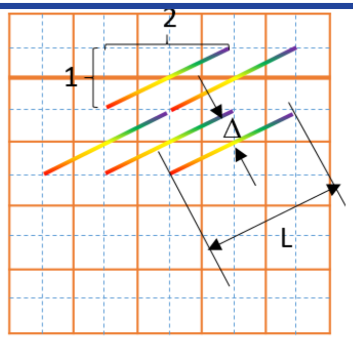
- Three main IFS types:
  - Lenslet array
  - Image slicer
  - Lenslet array + fibers
- Lenslet array based IFS is selected based on the following merits:
  - The lenslet array has a very high transmittance in our wavelength range (600nm – 970nm)
  - Advantage of high throughput, compact, simple, and cost efficiency.
  - After prototype PISCES, we have accumulated all needed techniques and skills: From design, fabrication, integration & test, to data reduction software & data analysis
- The main disadvantage of lenslet based IFS is the low detector pixel efficiency.
  - However, we are dominated by the coronagraph field of view
  - EMCCD for coronagraph has enough pixels. This is not a problem for this application.

Trade-off #3 (1): Lenslet Selection and Design

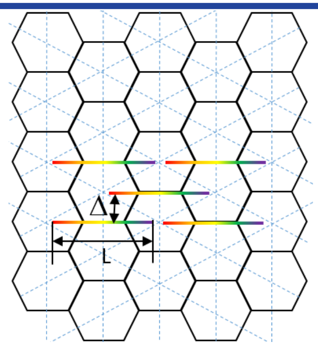
- The main factors that dictates lenslet design and selection:
  - Spectral resolving power R and spectral bandwidth w in %.
  - Half FOV n in λ/D.
  - Assume the # of rows per spectral trace is k to satisfy crosstalk requirement
  - Assume the 2 pixel gap in dispersion direction.
  - We have n spectral samples across the image
- Based on the main factors, the minimum requirement on the total number of pixels on detector is: $k(2wR+4)(4n)^2$
- In the trade-off, we'll discuss how to optimize the lenslet design to approach the required minimum pixel number.

Trade-off #3 (2): Lenslet Selection and Design

- The practical lenslet selection is between square and hexagon shapes.
- For each shape, the constrain is that the interlace has to make all spectral traces have the same gap in cross-dispersion direction. Under the constrain, Δ/L is fixed for each shape with selected interlace.
- Based on R=50, bandwidth at 21%, both shapes have ~same efficiency. Because prototype uses square lenslet and data analysis software exists, square lenslet is selected for PhaseA design.



Up to 26% bandpass



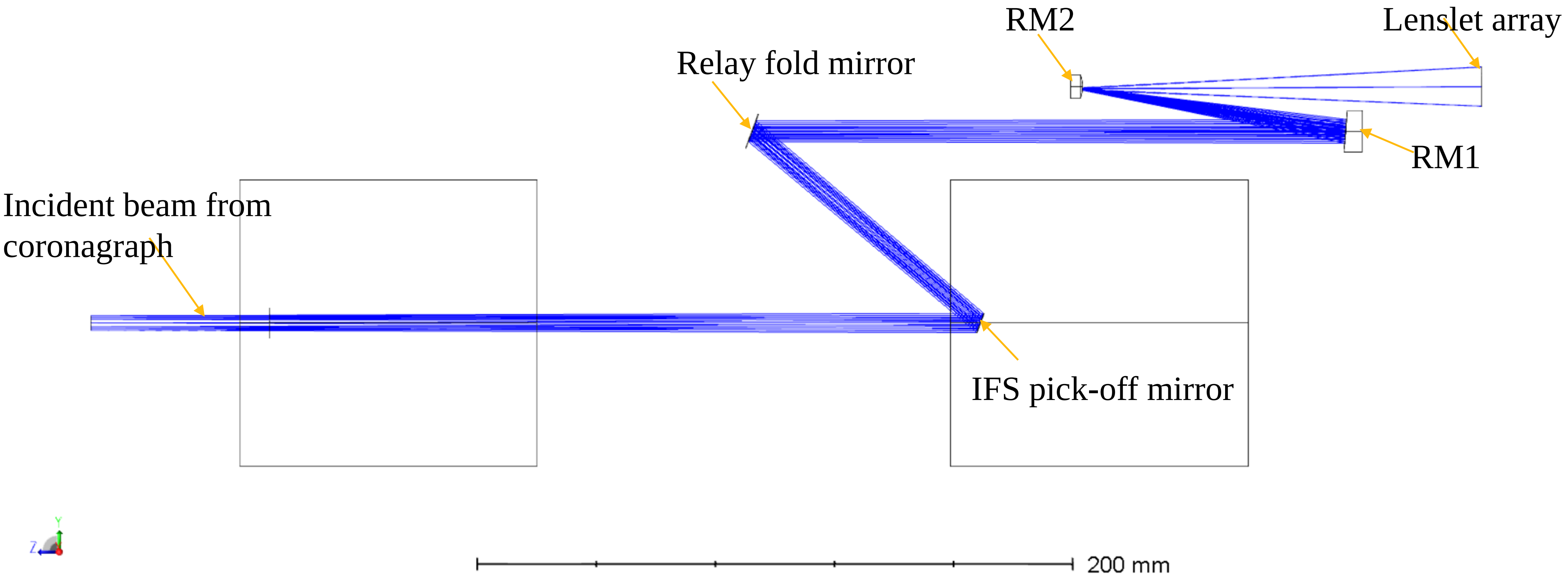
Better detector efficiency for R50x18%

IFS Optical Specification

Relay and lenslet array Specifications	
Wavelength range (nm)	600 - 970
Effective focal length (mm)	2636
f/#	527
FOV	1.08” (λ/D = 19, 16.3, and 14.1 at 660nm, 770nm and 890nm)
Lenslet shape	Square with 174 µm pitch
# of lenslets	120 x 120
Lenslet array size (mm)	22 x 22 (Physical size)

IFS Specifications	
Wavelength range (nm)	600 - 970
Magnification	1:1
f/#	8 (side to side)
Spectral resolution	R = 50 ±5
Spatial resolution	RMS spot diameter < 13µm
Object size (mm)	13 x 13
Detector	EMCCD, 1024 x 1024 with 13 µm pitch

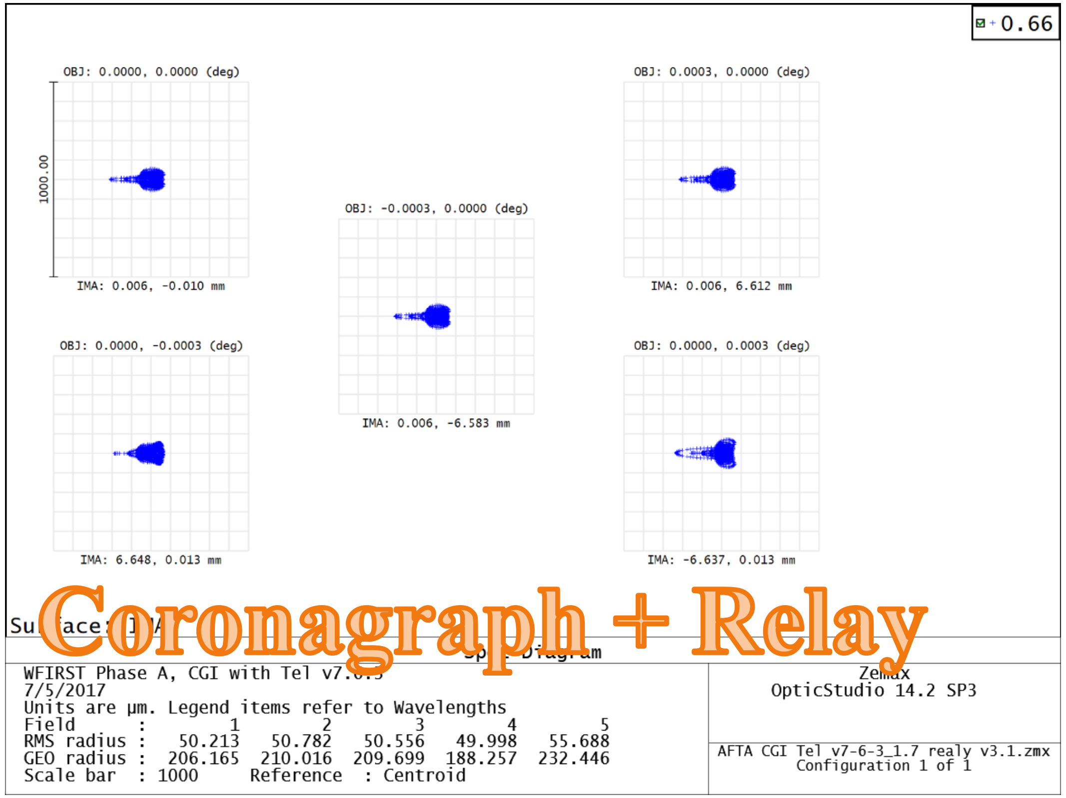
IFS Relay Design

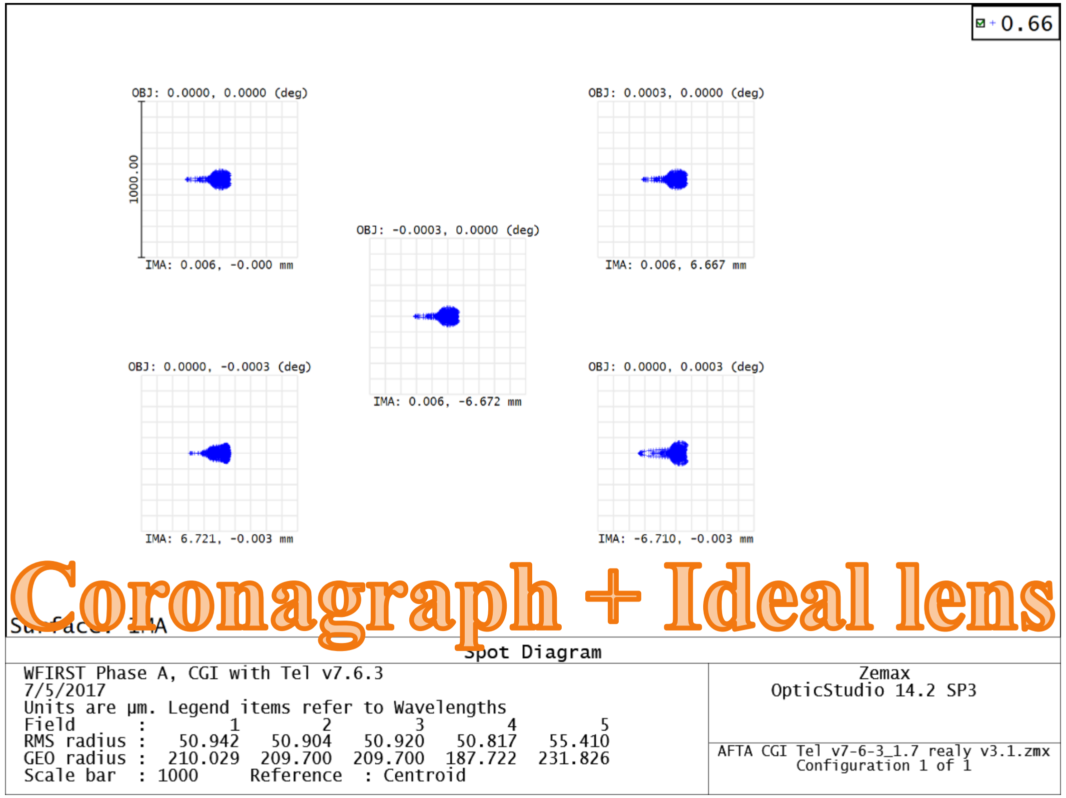


- Based on the trade #1, the relay is designed as an off-axis Cassegrain telescope

IFS Relay Elements and Performance

	Radius of curvature (mm)	Conic constant
RM1	187.716 (concave)	-1
RM2	10.019 (convex)	-1.1442

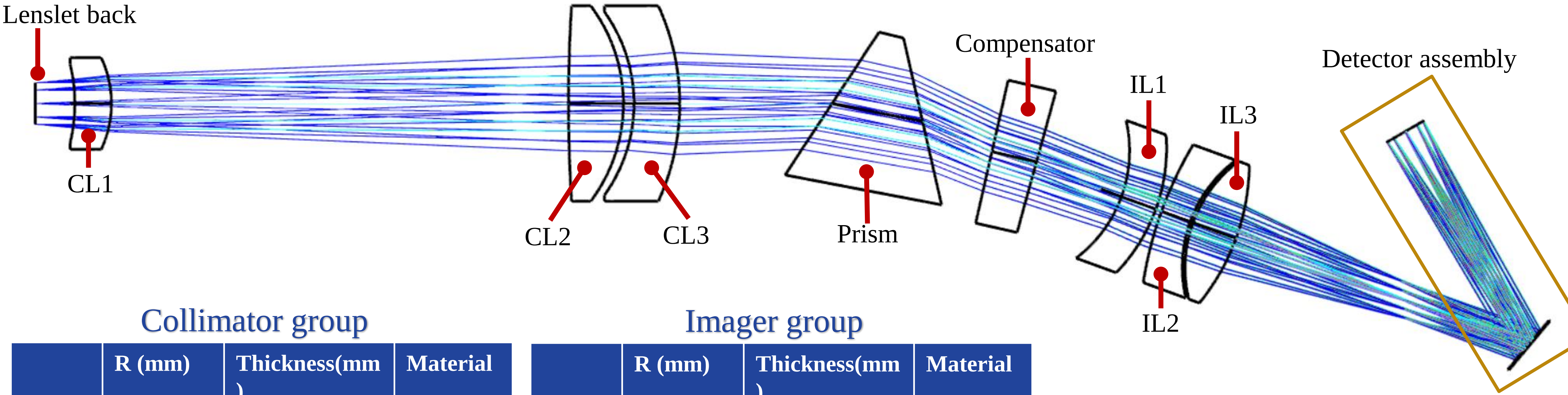




- The spot size is large, but still diffraction limited due to huge f/527 beam.
- Comparing to ideal lens shows the residual aberration is from upstream coronagraph optics

Trade-off #4: Spectrometer: Refractive vs. Reflective

Refractive Design



Collimator group

	R (mm)	Thickness(mm)	Material
CL1 s1	-53.948	12.0	CaF2
CL1 s2	-35.245		
CL2 s1	511.953	18.0	L-FPL51
CL2 s2	-53.069		
CL3 s1	-51.187	15.0	S-LAH79
CL3 s2	-76.331		

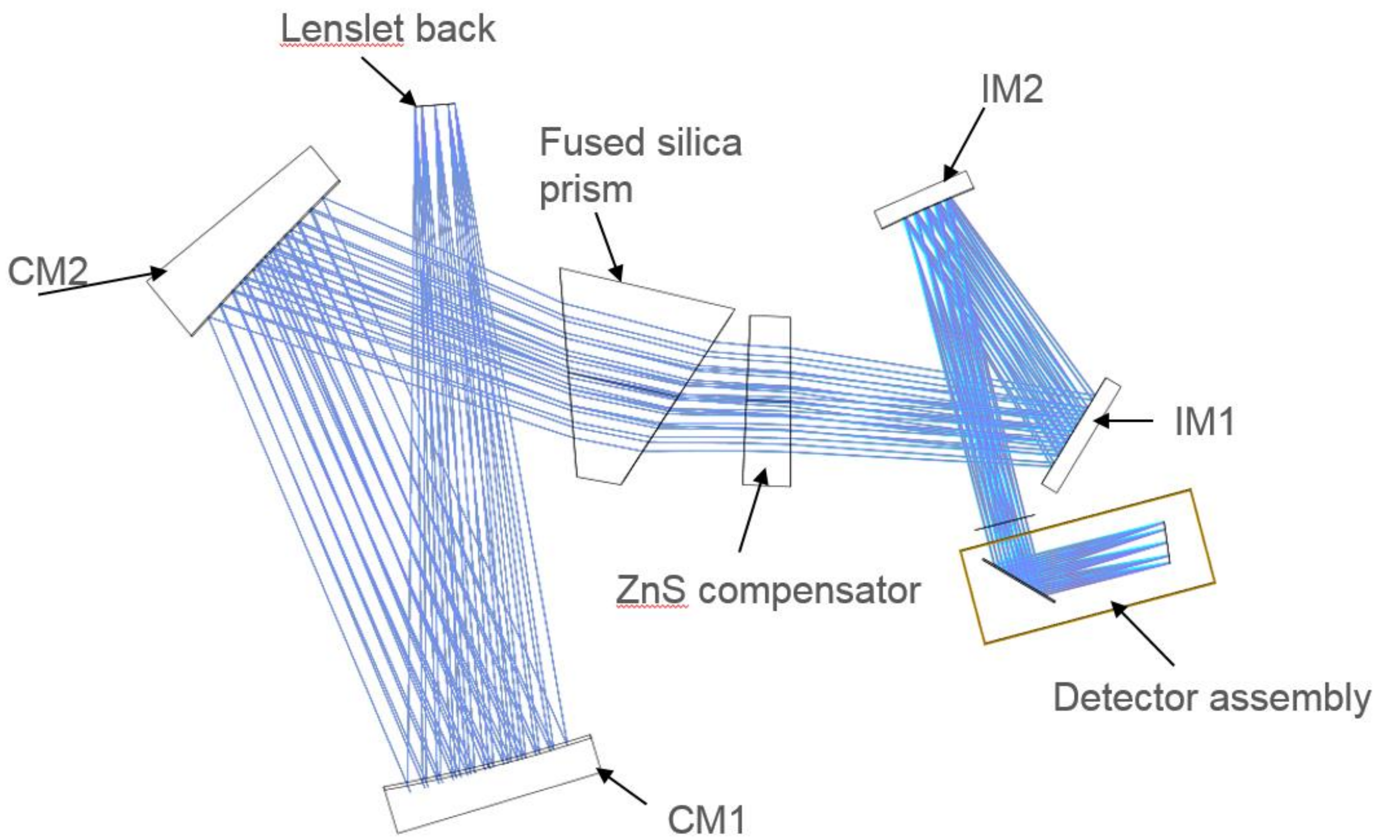
Imager group

	R (mm)	Thickness(mm)	Material
IL1 s1	-44.031	12.0	S-FSL5
IL1 s2	-58.737		
IL2 s1	125.255	10.0	L-BAL43
IL2 s2	43.463		
IL3 s1	43.422	15.0	CaF2
IL3 s2	-72.638		

Prism & compensator

	Apex angle (°)	Material
Prism	46.3	F-SILICA
Compensator	2.61	ZnS

Trade-off #4: Spectrometer: Refractive vs. Reflective



Collimator

	R (mm)	C. C.	2nd	4th
CM1	550.669 (concave)	0.3266		
CM2	563.075 (concave)		-4.1527E-4	-1.7731E-9

Imager

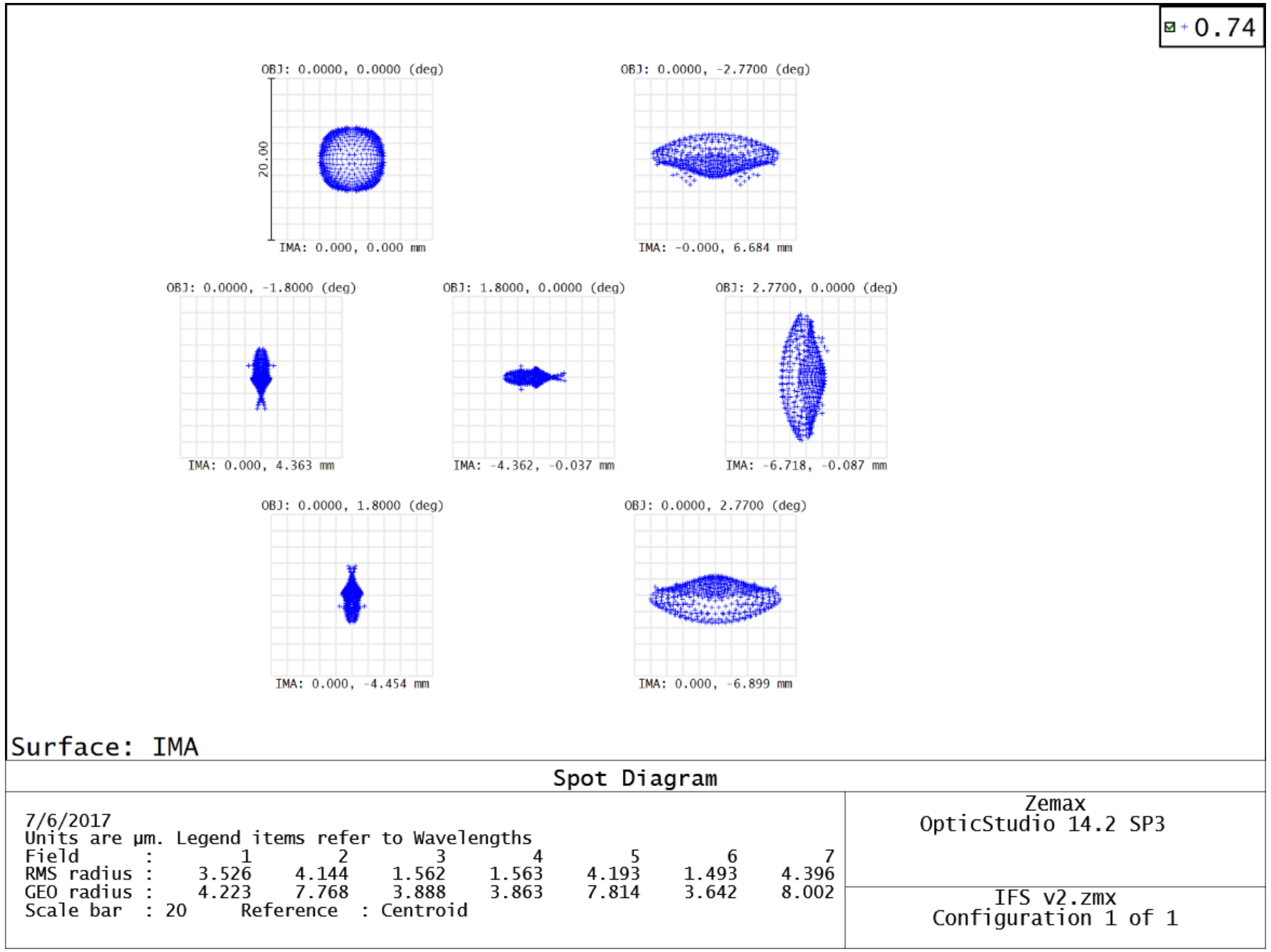
	R (mm)	C. C.	2nd	4th
IM1	225.492 (concave)		2.2091E-3	1.7897E-8
IM2	449.087 (concave)	2.8638		

Prism & compensator

	Apex angle (°)	Material
Prism	37.71	F_SILICA
Compensator	2.57	ZnS

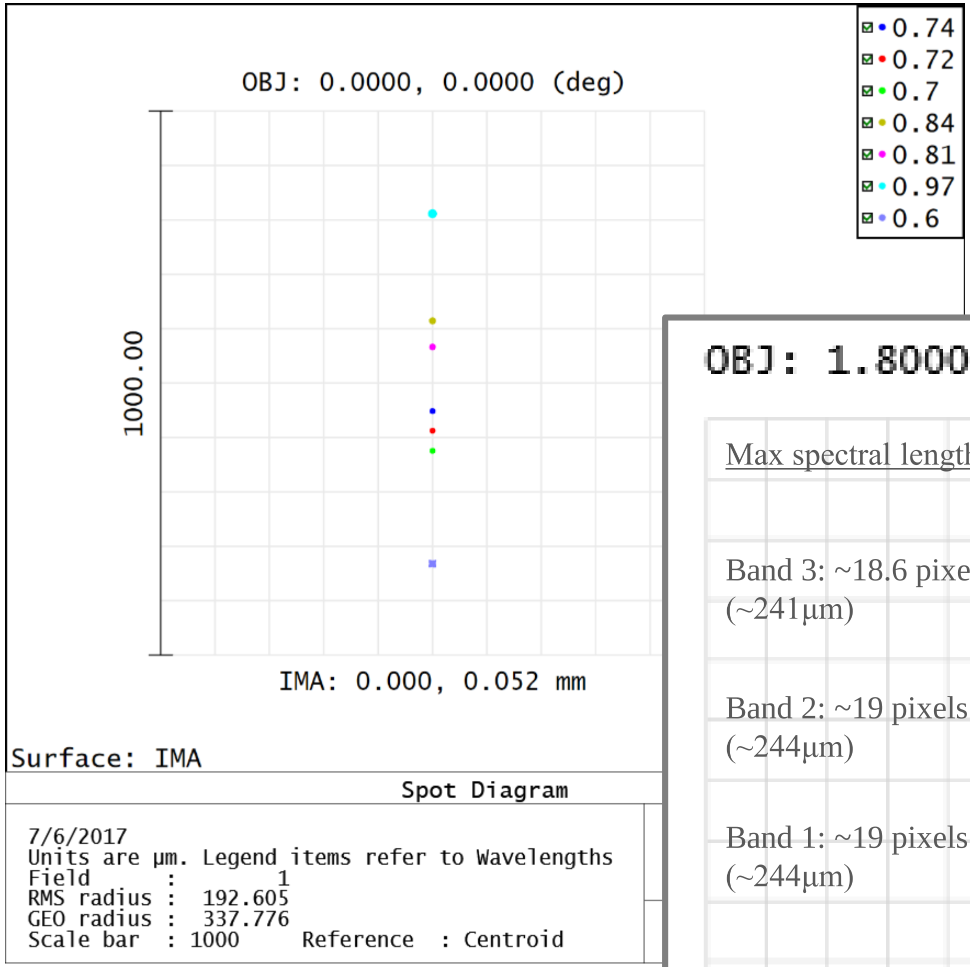
Trade-off #4: Spectrometer: Refractive vs. Reflective

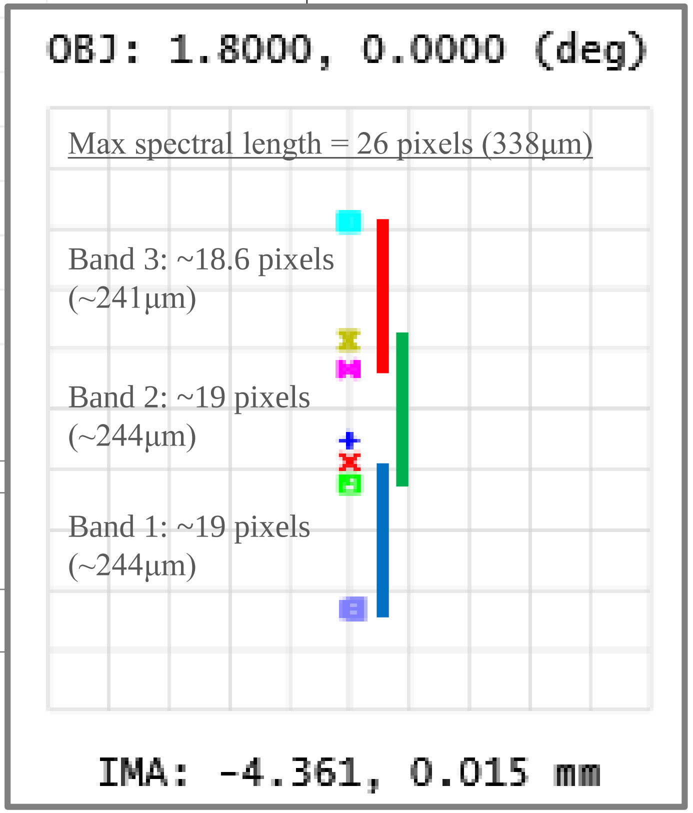
- Both refractive and reflective designs have1:1 magnification between object (lenslet array focal plane) and image (CCD chip).
- From performance point of view, both designs can achieve similar performance on throughput, spectral resolution and spatial resolution
- From packaging perspective, refractive design can be easily fit into the space allocated to IFS.
- From cost perspective, reflective design is more costly due to all elements in collimator and imager are off-axis aspheric mirrors. They are more expensive to make, test, and align.
- From schedule perspective, prototype PISCES is refractive. We have all information needed for vendors, materials, and test and integration equipment, which provides us better schedule control.
  - However in either case, designing for flight will reduce this difference
- Refractive spectrometer is selected as a baseline for Phase A IFS.

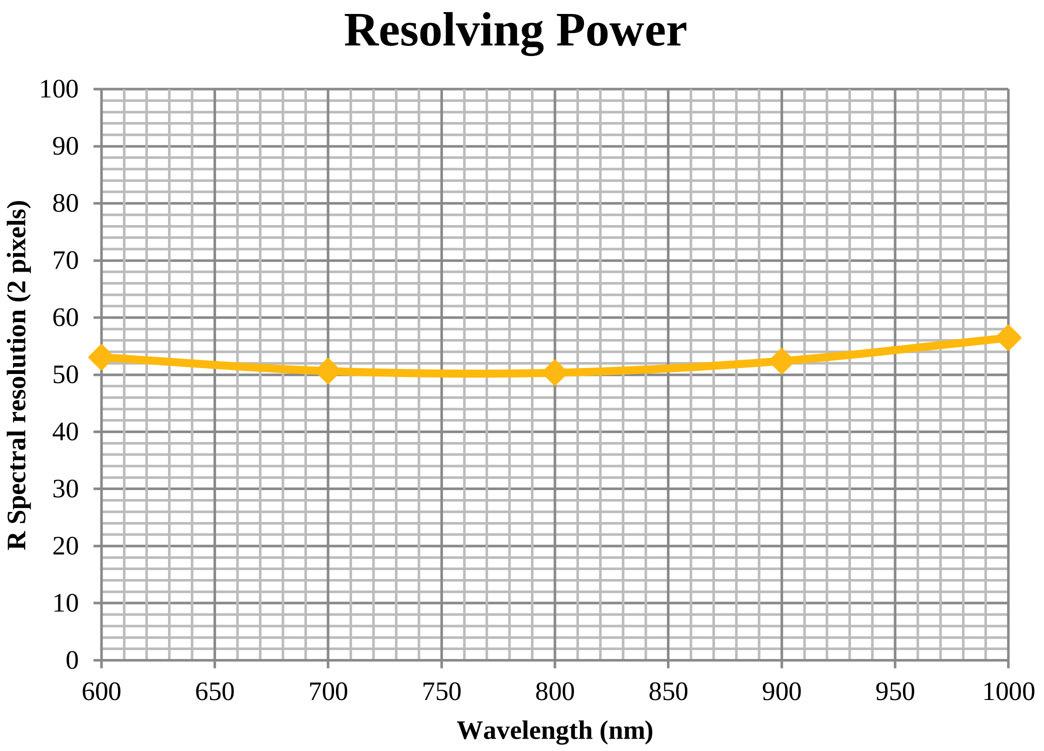


- The spot size from refractive design meets the requirement:
  - RMS PSFlet spot diameter is no more than one detector pixel (13 µm).
- PSFlet size is too small for Nyquist sampling
  - Current plan is to defocus to make it Nyquist.
  - Allows us to trade sampling for signal to noise ratio.

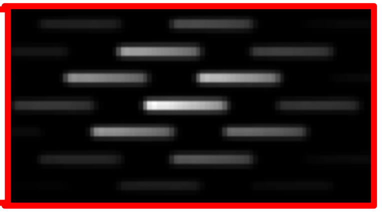
Baseline IFS Design Performance: Spectral resolution







Visualization of Spectra on Detector



Summary and Path Forward

- After a number of trade-offs, Phase A IFS design baseline has been established.
- Baseline design meets the specification derived from Level 3 and 4 requirements.
- General sensitivity and tolerances have been performed to support mechanical design.
- Future work will be concentrated on modifying current design to relax tolerances for some sensitive optical elements.
- Work with potential vendors to use the tolerance aligned to vendor's capability.
- Lenslet array design will start after relay design is frozen, because lenslet array mask is a function of relay telecentricity.