Goddard SPACE FLIGHT CENTER

WFIRST Integral Field Spectrograph Design and Operations Concept

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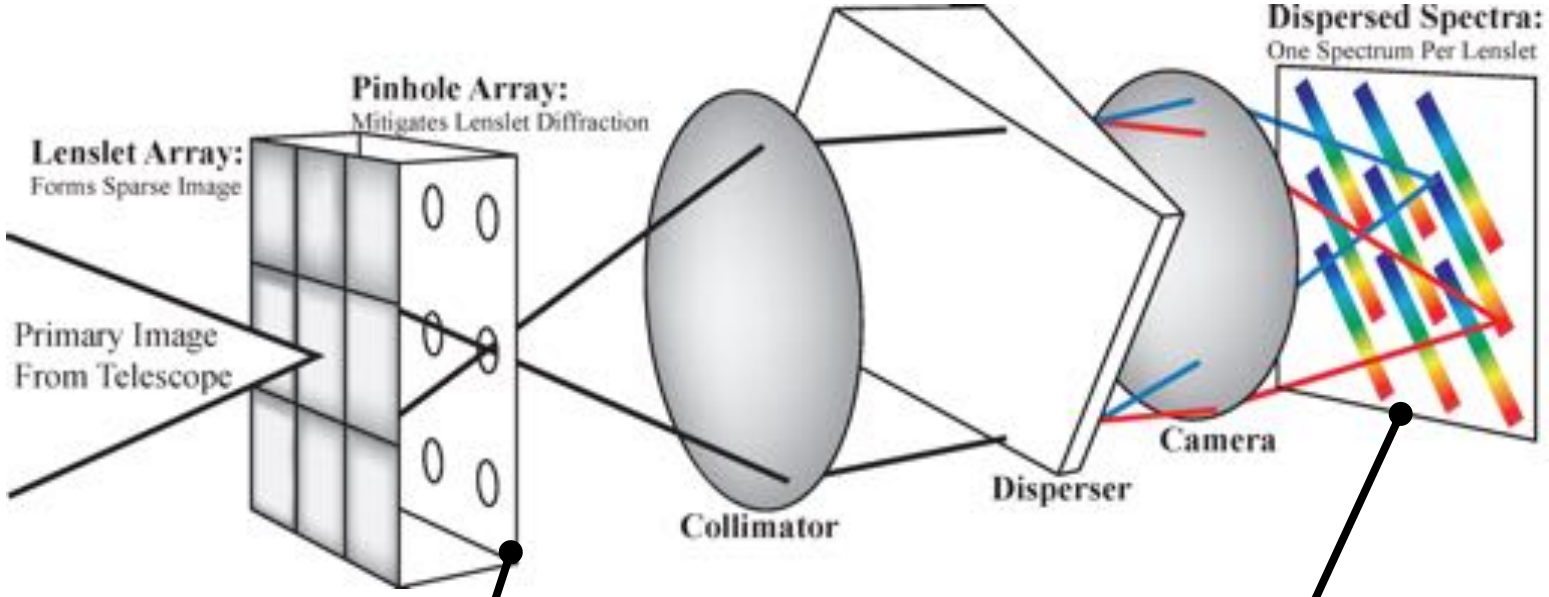
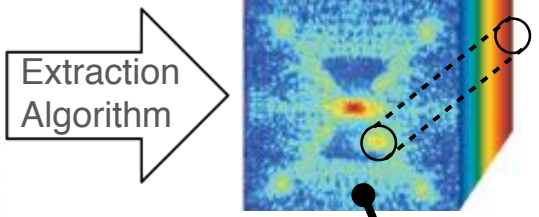
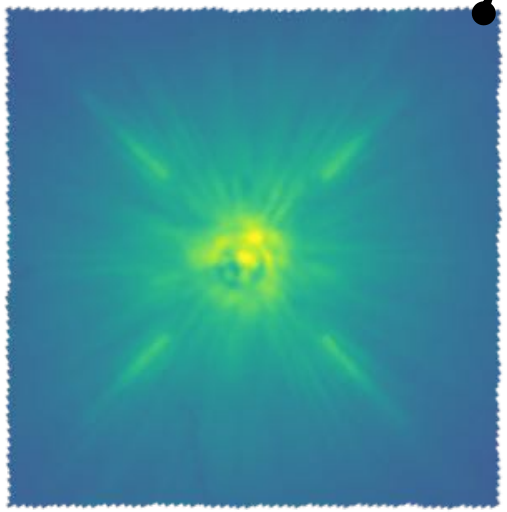
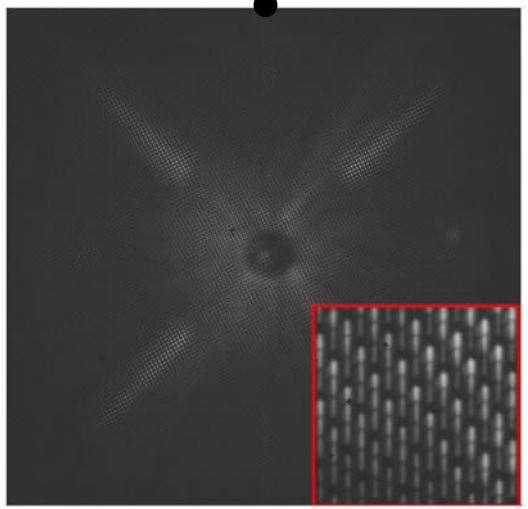
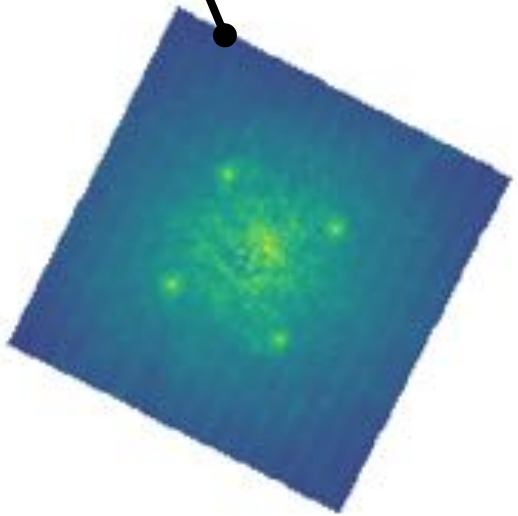
Integral Field Spectroscopy - Concept



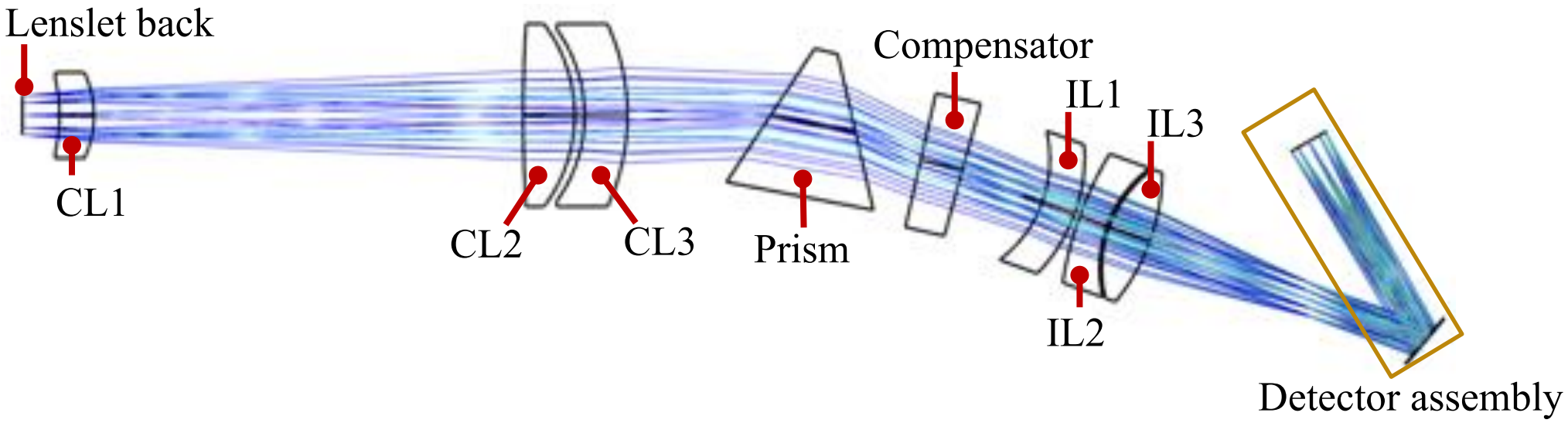








Flight IFS Optics



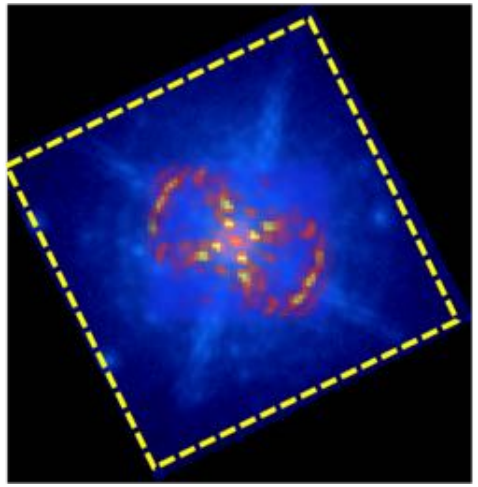
Baseline Filter Bands	Center	Cut-on	Cut-off	Bandwidth %
CGI Band 2 (Shaped Pupil)	660	600	720	18.2
CGI Band 3 (Shaped Pupil)	760	690	830	18.2
Starshade Band 1	728	656	800	20
Starshade Band 2	910	820	1000	20

Phase A IFS Specifications		
	Band 2	Band 3
# of dispersed pixels	18	18
Lenslet pitch (µm)	174	174
sampling at λ_c	2	2.33
Spectral resolving power	50	50

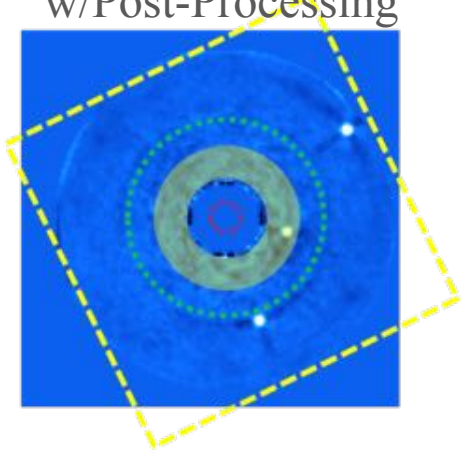
- All lens surfaces are spherical.
- The spectral dispersion is achieved with a prism and a compensator (to flatten the resolving power in defined wavelength range).

CGI IFS Field of View

M5 Globular Cluster



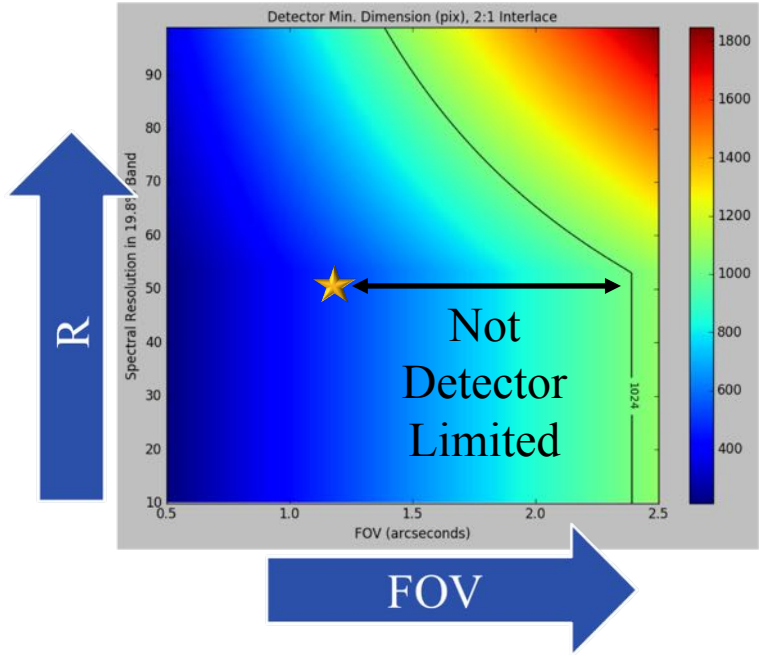
HR8799
w/Post-Processing



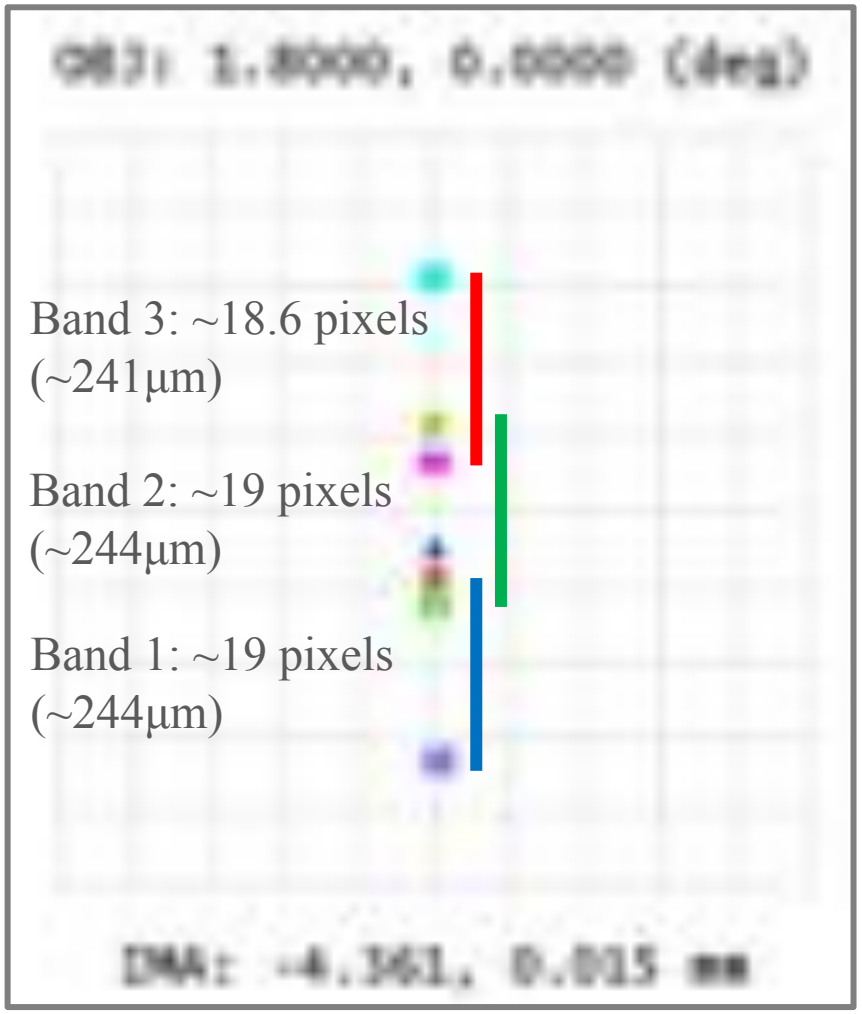
- Detector field of view
- 10 λ/D (~0.5”) Coronagraph outer working angle
- 3 λ/D radial inner working angle
- Angular separation where requirements are set

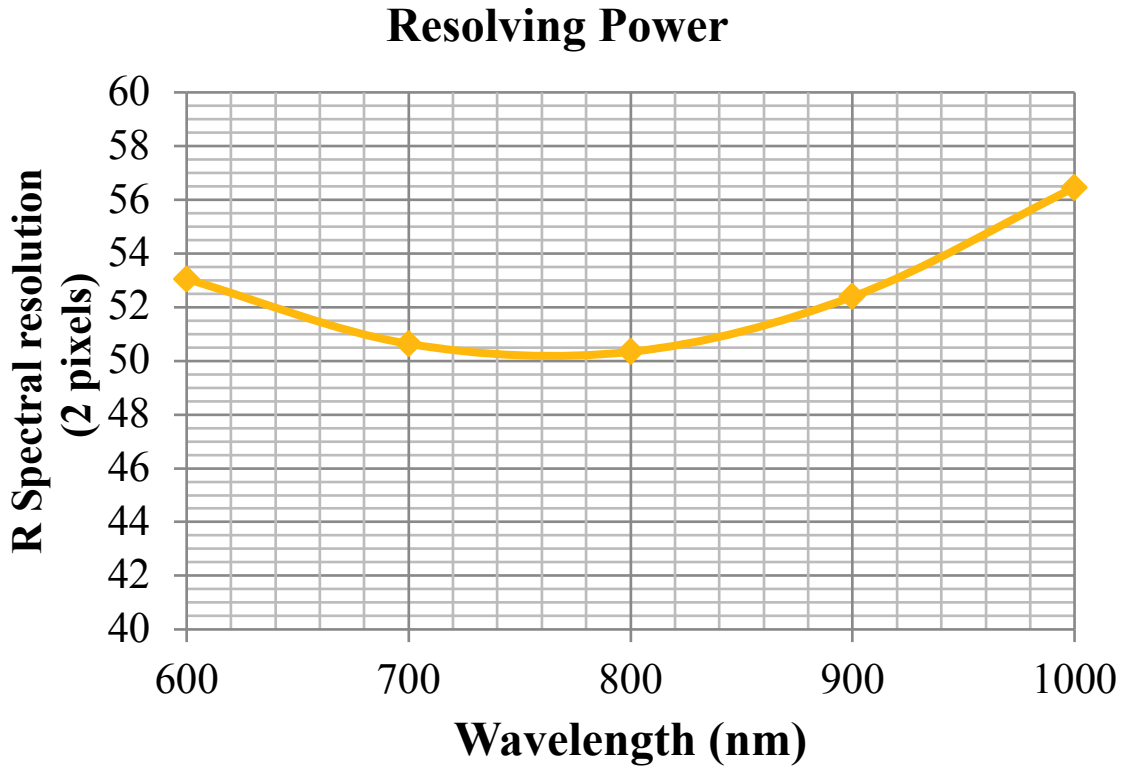
- IFS FOV in CGI is limited by coronagraph
  - 10 λ/D at 660nm
- The designed full FOV is 2.16”,
  - 19 λ/D at 660nm, 16.3 λ/D at 760nm (Radius)
- Larger FOV could be utilized for
  - Potential Starshade
  - Ground-to-Orbit alignment variance

Required Detector Size

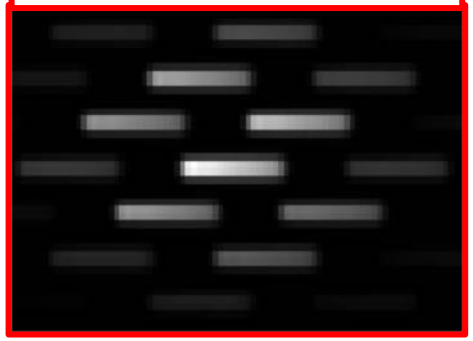


IFS Design Performance: Spectral resolution





Visualization of Spectra on Detector

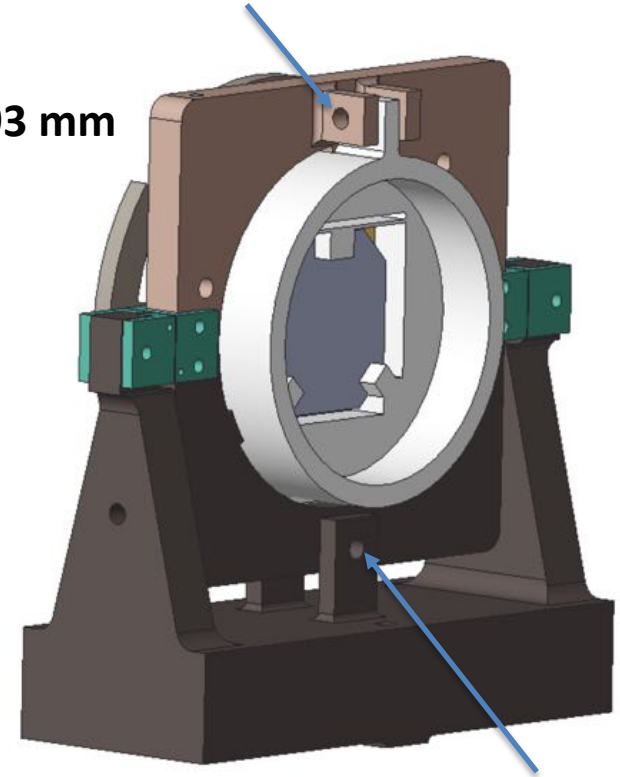


Mounting and Alignment

Lenslet Array Mount

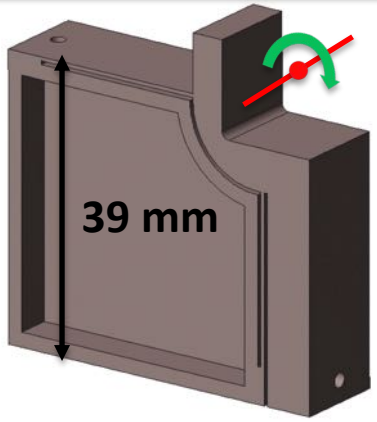
Clocking adjustment mechanism

93 mm



Tip adjustment mechanism

Relay Mirror Mounts

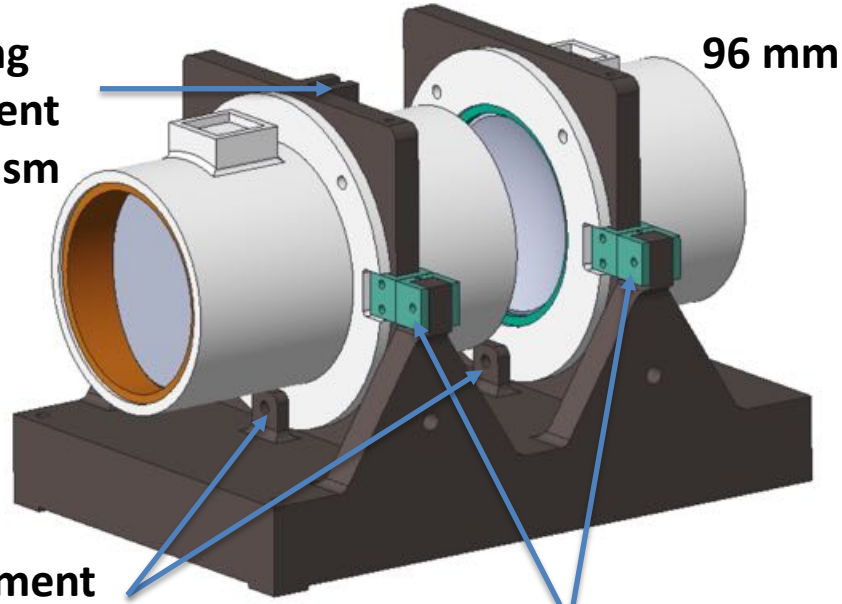


1 rotational DOF around center point of mirror

Lens and Prism Groups

Clocking adjustment mechanism

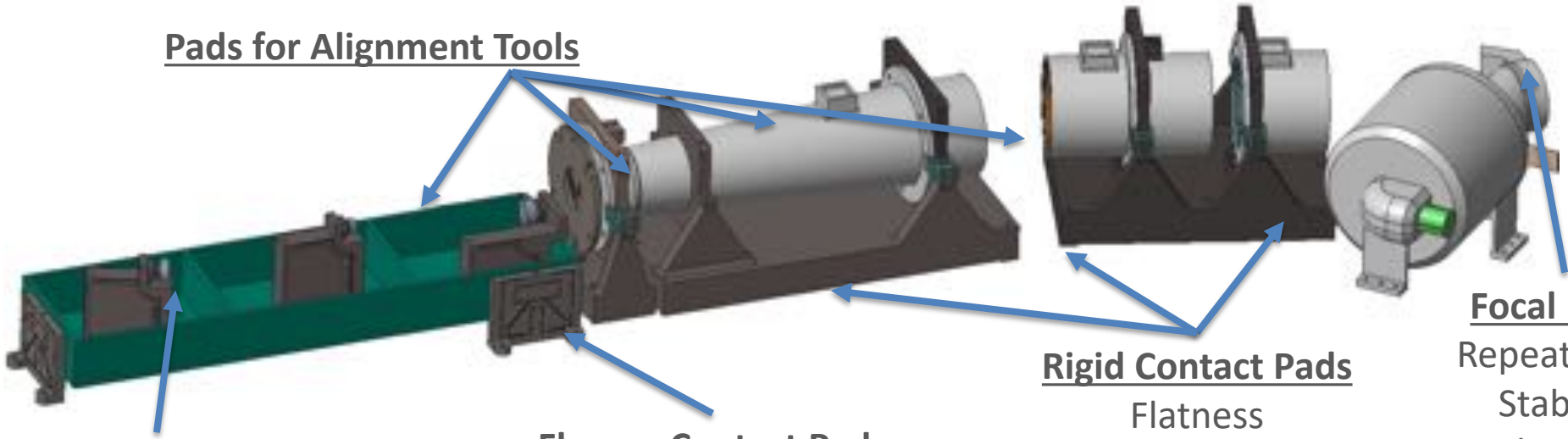
96 mm



Tip adjustment mechanisms

Flex Pivots

Interfaces



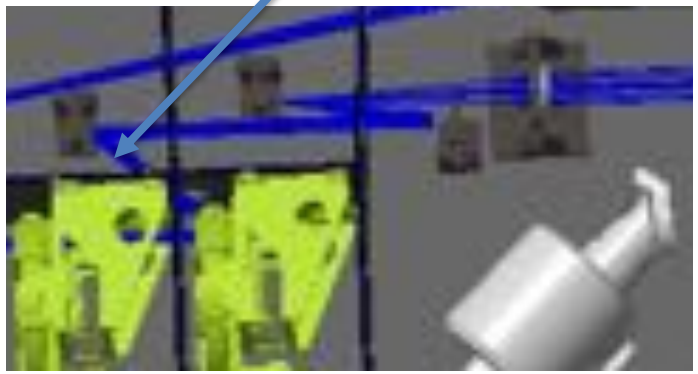
Pads for Alignment Tools

Input Collimated Beam
Stability
Repeatability

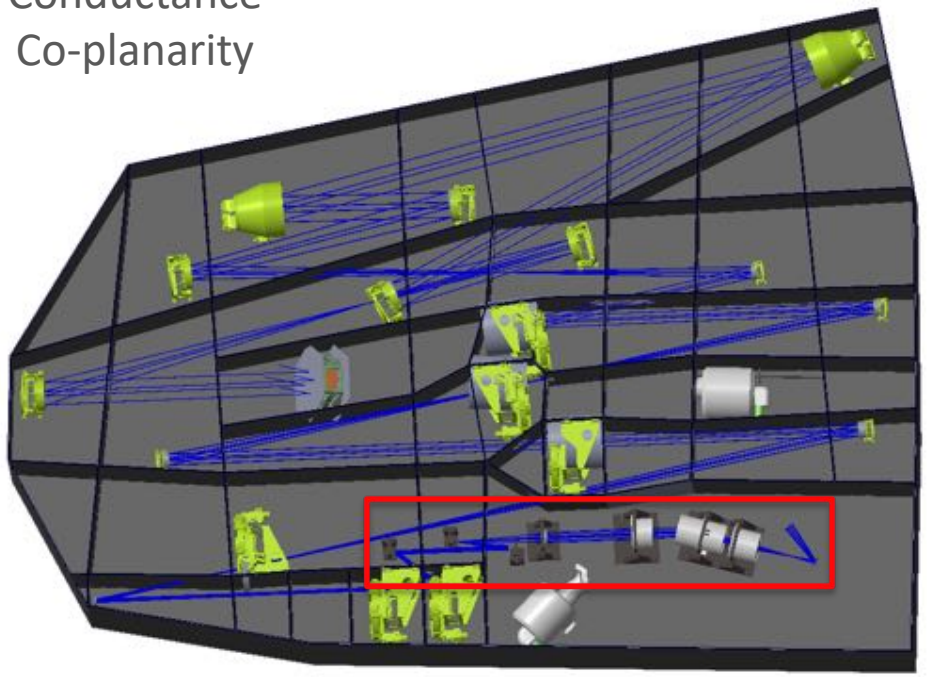
Flexure Contact Pads
Flatness
Conductance
Co-planarity

Rigid Contact Pads
Flatness
Conductance
Co-planarity

Focal Plane
Repeatability
Stability
Flatness

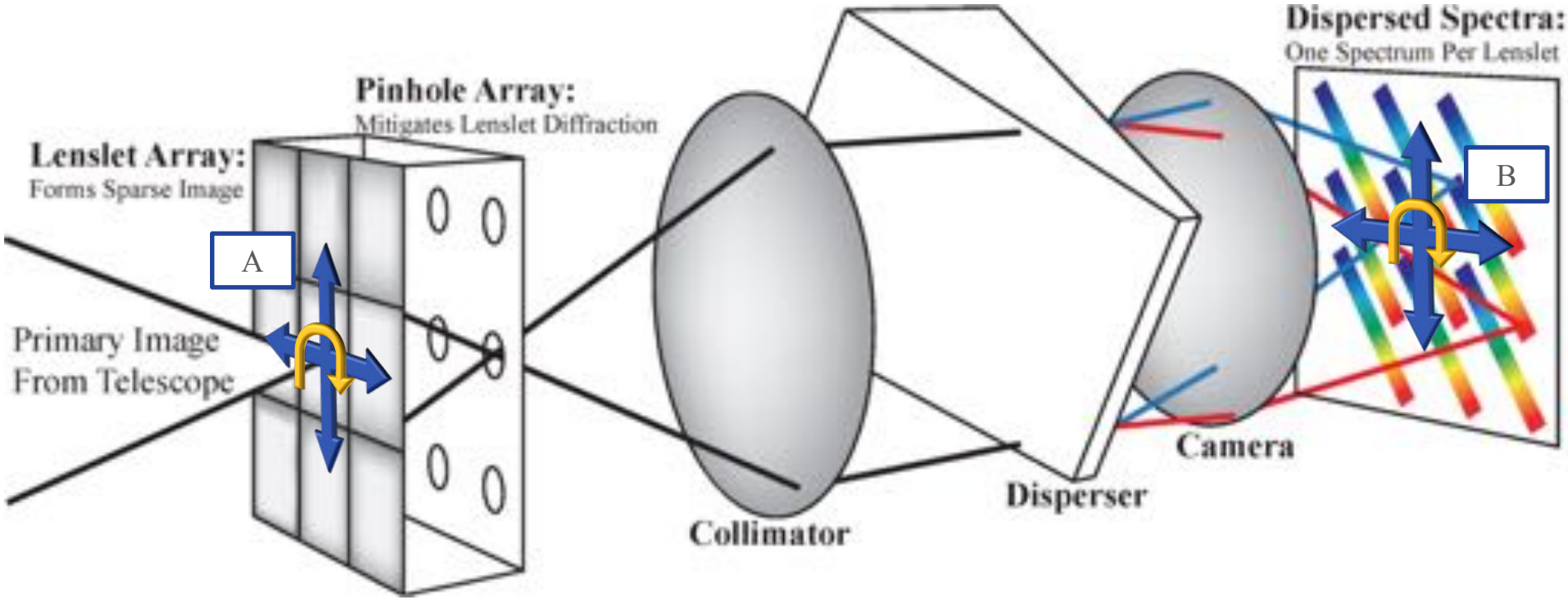


CGI
Carbon Fiber Bench with metal threaded pads



Basic operations Driving the on-orbit stability requirements

- Exposure Time: Period of a single exposure in a long co-added frame sequence (~100 seconds)
- Observation Time: Period between opportunities to recalibrate the IFS (~10-100 hours)
- These periods drive stability requirements on:
  A. The stellar point spread function (PSF) on the lenslet array
  B. The lenslet PSFs (PSFlet) reimaged on the detector



L5 IFS Requirements

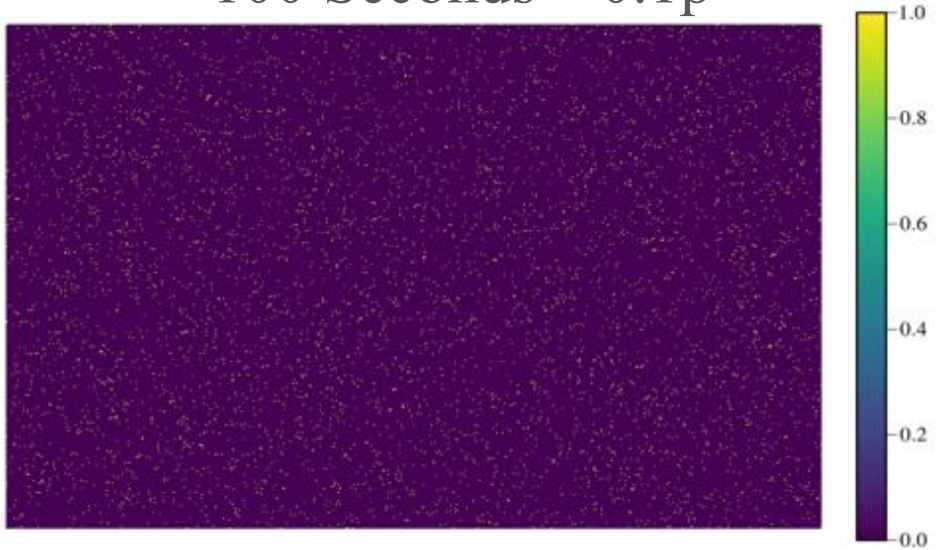
Rqmt #	Requirement Title	Requirement Description	K/D	Requirement	CBE	Margin	CBE Source	Verification Method
597508	Image Jitter Stability	The PSF shall move on the lenslet array by less than 0.5 lenslets at the Nyquist sampled wavelength in the worst-case jitter environment of a CGI observation.	K,D	0.5		Compliance under review	Compliance under review	Test
597509	Image Thermal Stability	The PSF shall move on the lenslet array by less than 1.0 lenslet in the thermal environment of a worst case slew between CGI reference and target stars.	K,D	1	0.71	29%	IFS Thermal	Test
597510	PSFlet Jitter stability	The lenslet PSF positions shall move on the detector by less than 7 microns in the spectral direction and no more than 7 microns in the cross-spectral direction in the worst-case jitter environment of a CGI observation.	K,D	7		Compliance under review	Compliance under review	Test
597511	PSFlet Thermal stability	The lenslet PSF positions shall move on the detector by less than 7 (TBD) microns in the spectral direction and no more than 7 (TBD) microns in the cross-spectral direction from the thermal change from the worst case slew between CGI reference and target stars.	K,D	7		Compliance under review	Compliance under review	Test
597512	PSFlet Focus	The final image plane fous shall deviate by less than ± 38um (TBR) from the as-aligned position for all operating environments of CGI.	D	38		Compliance under review	Compliance under review	Test
597521	Lenslet Sampling	The lenslet sampling of the incident PSF shall be 0.5 λ/D per lenslet at 660nm for the F-number defined by the full telescope pupil.	K	0.5	0.5	NA	design	Test
597522	PSFlet Sampling	The detector sampling of the lenslet PSF (PSFlet) shall be 0.5 λ/D per pixel at 660nm for the lenslet F-number.		0.5	0.5	NA	design	Test
597523	Dispersion Variance	The spectral resolution shall be R50 +10/-0 from 600-1000 nm.		50 +10/-0	50.3—56.4	1%	Zemax	Test
597524	Material Proximity	The optical path from the last refractive element surface shall be >150 mm (TBR) away from the focal plane array.		150 mm	183 mm	22%	CREO	Test

L5 IFS Requirements

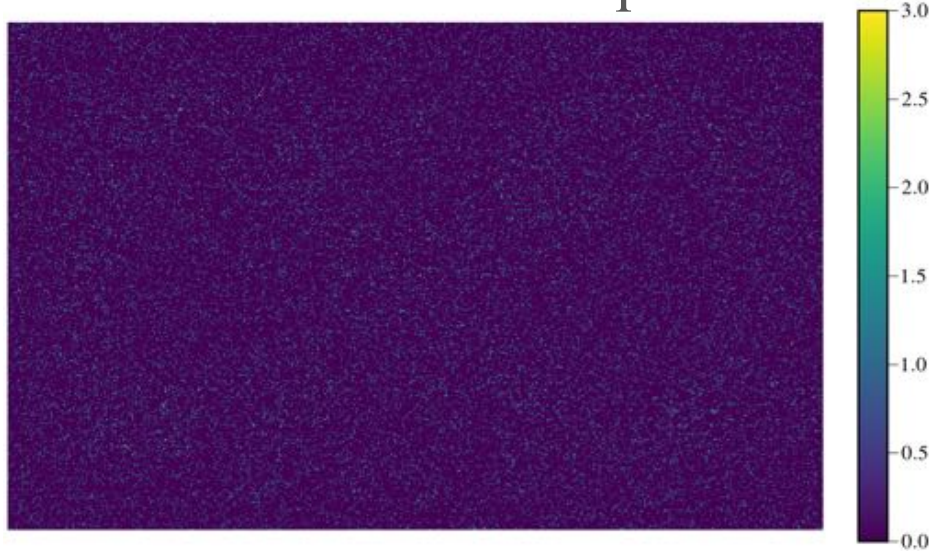
Rqmt #	Requirement Title	Requirement Description	K/D	Requirement	CBE	Margin	CBE Source	Verification Method
678051	IFS Transmittance	The transmittance of the IFS from the input pupil to the final focal plane shall be >60% from 600 nm to 1000 nm including diffractive losses from the lenslet PSF outside of the core.		60	70	15%	Uncertainty estimate	Test
678052	IFS Alignment	PSF alignment shall deviate < ±10 lenslets from initial alignment to on-orbit.		± 10	± 10	0	Compliance under review	Test
678053	Starshade Science Filters	The IFS shall support an instantaneous bandpass of 20% for starshade accommodation.	K, D	20%	25.9%	NA	Designed filter band	Test
678054	Coronagraph Filter Bands	The IFS shall have an instantaneous bandpass of 18% for the coronagraph observations.	K	18%	25.9%	NA	Designed filter band	Test
678055	Total Wavelength Range	CGI shall include an Integral Field Spectrograph (IFS) that operates across the wavelength range from 600-1000 nm.		600-1000	590-1025	NA	Zemax	Test
678056	Wavelength Accuracy	CGI IFS data shall have absolute wavelength accuracy of <= 2 nm in filter 3 spectral band.	D	2 nm	0.69 nm	65%	Centroid Models	Test
678057	IFS Radial FOV	CGI IFS channel shall have a field of view with radius >= 0.75 arcsec on the sky, without vignetting.		0.75”	1.08”	44%	Zemax/Python Models	Test
678058	IFS Angular Sampling	CGI in IFS mode shall have lenslet angular sampling = 29 +/-0.1 mas (126 nrad) on the sky.		29 ± 1 mas	29.1 mas	3%	CBE Telescope D	Test
678059	IFS Crosstalk	The ensquared energy of lenslet PSFs within the required FOV shall be >95% within a 5x5 pixel area at TBD nm.		95%	~96.5%	1.5%	Compliance Under Review	Test

Impact of Instability: Low Flux Regime

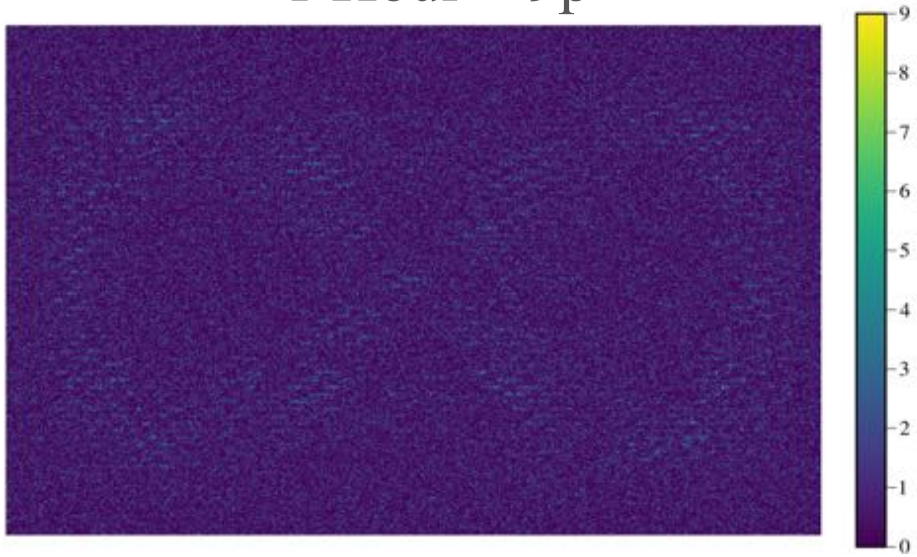
100 Seconds – 0.1p



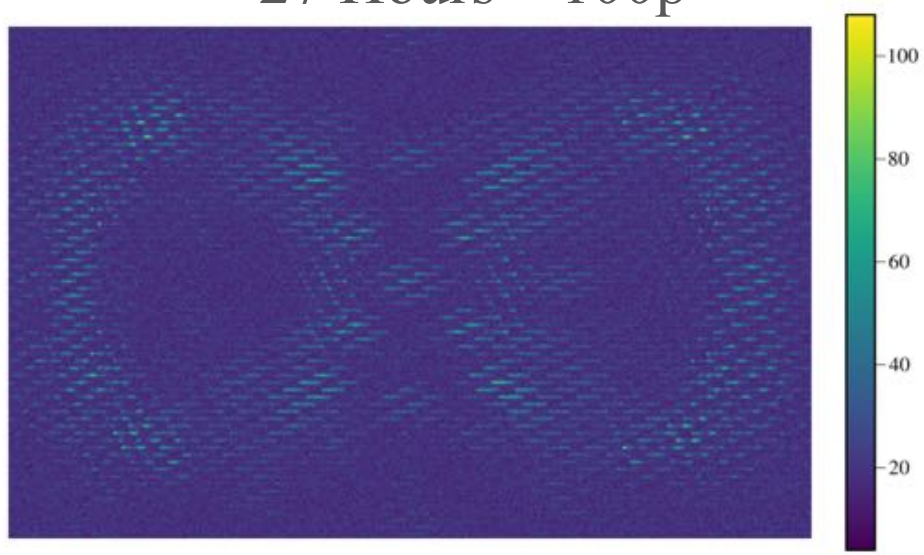
10 Minutes – 3p



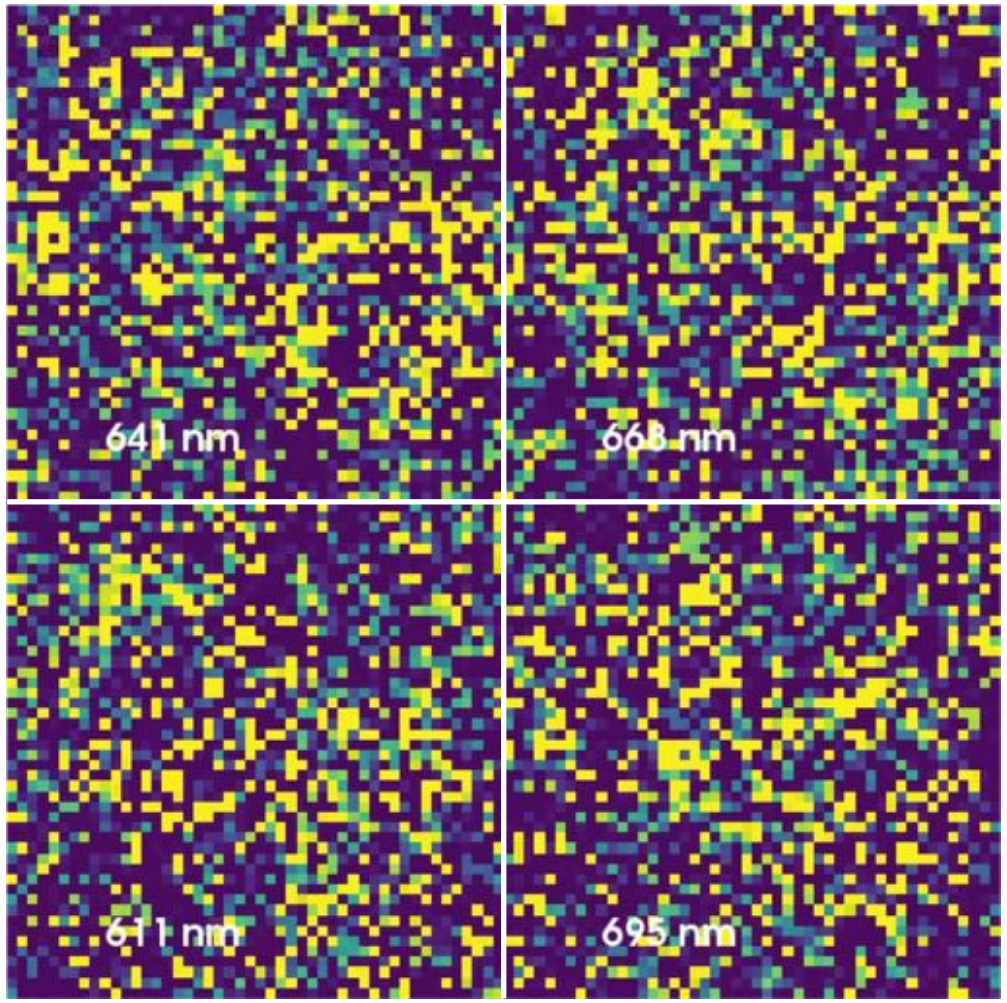
1 Hour – 9p

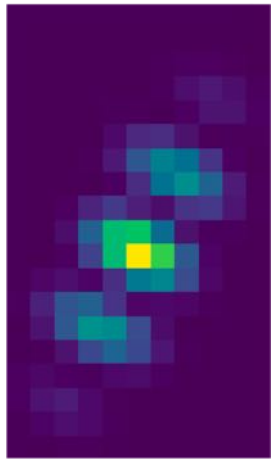


27 Hours – 100p



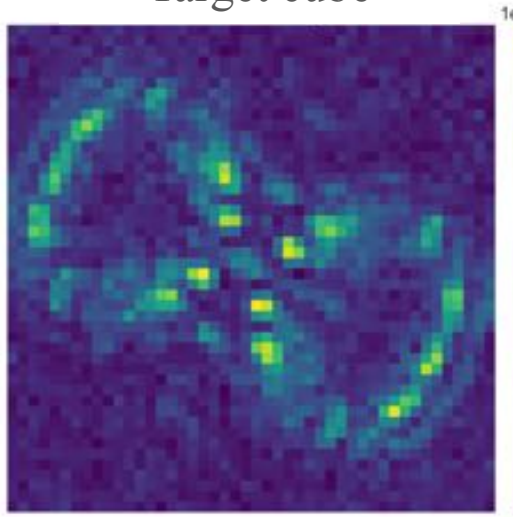
Noisy IFS extracted cube slices



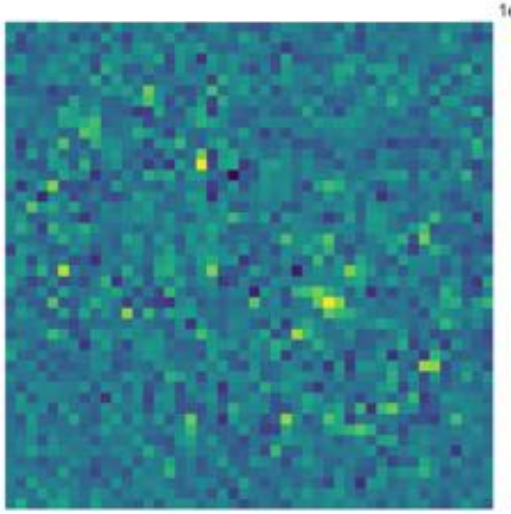


Off-axis PSF used for matched filter

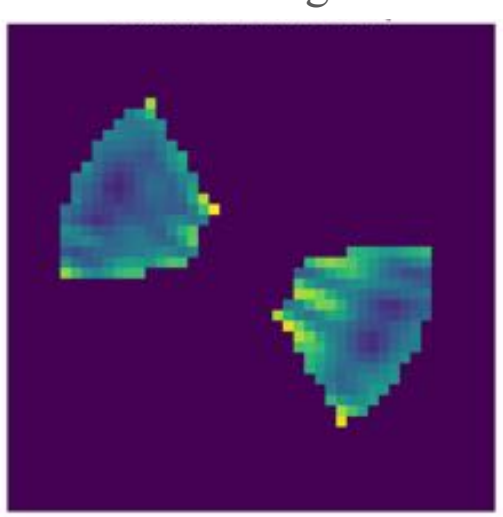
Target cube



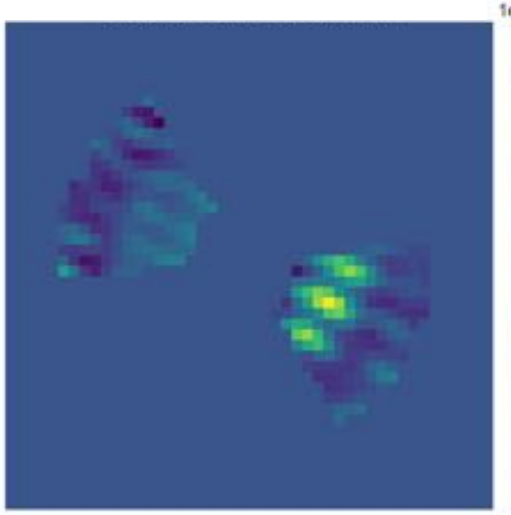
Subtract reference



Convolved target cube

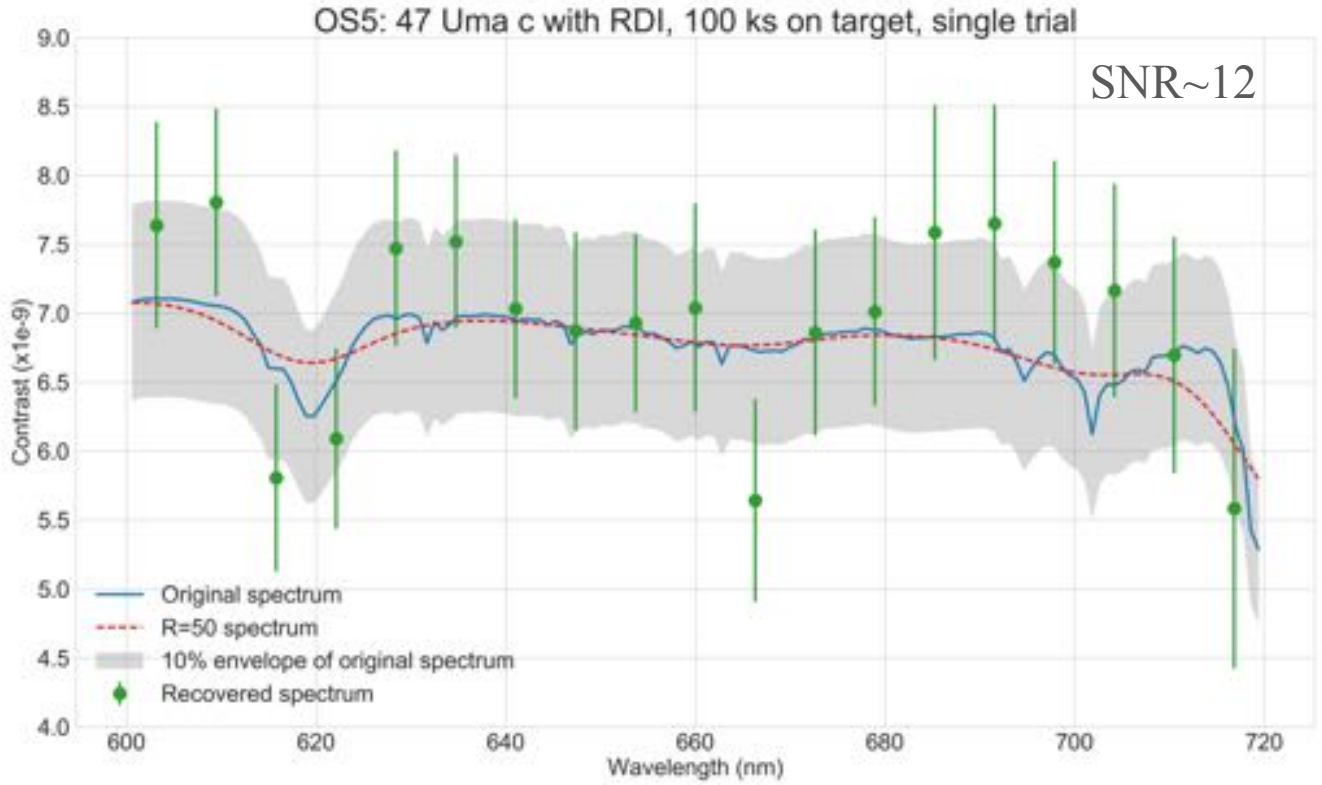


Convolved subtracted

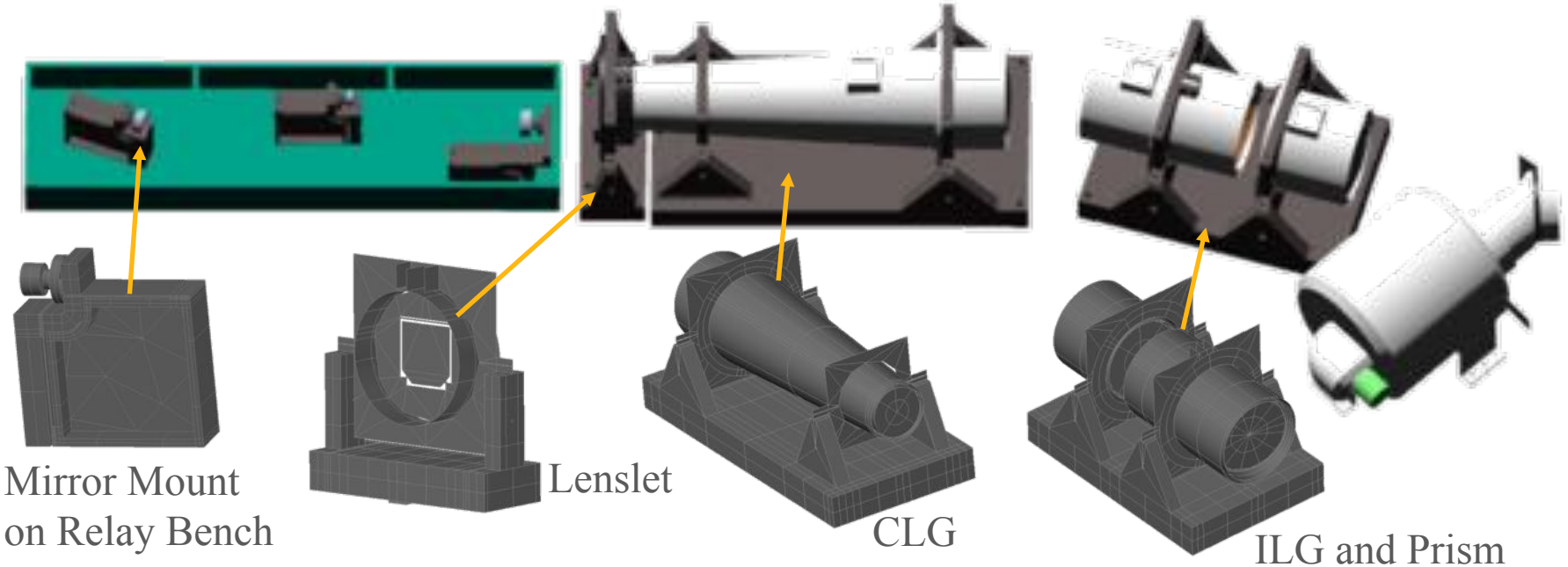


WFIRST observing scenarios

- 30ks (8h) on reference star Beta Uma
- 100ks (27h) on target star 47 Uma, with companion RV planet 47 Uma c
- Implement reference differential imaging (RDI)



Thermal Models and CAD

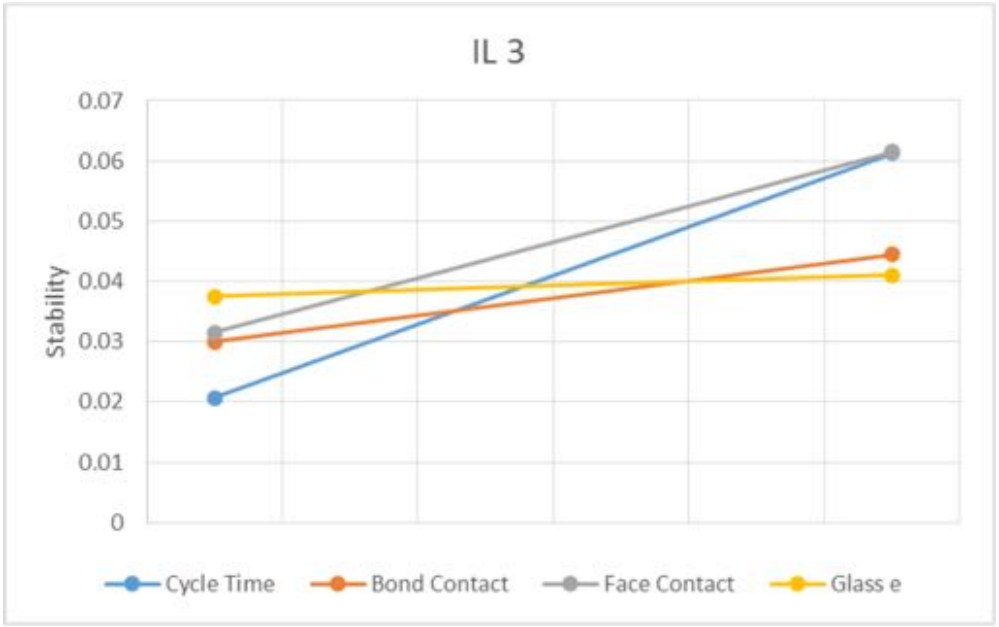


Mirror Mount on Relay Bench

Lenslet

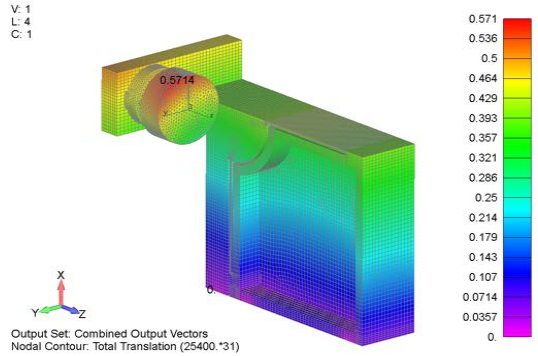
CLG

ILG and Prism



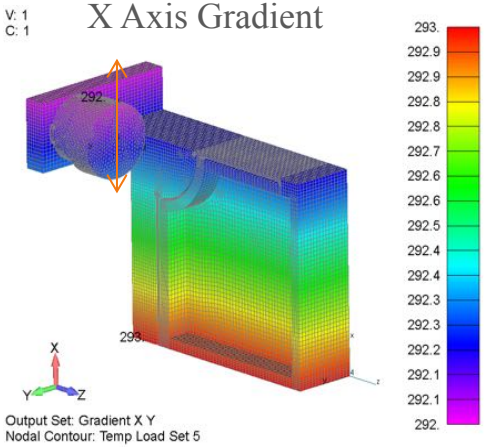
Representative Thermal Distortions

- Bulk 1 K
- X Axis Gradient
- Y Axis Gradient



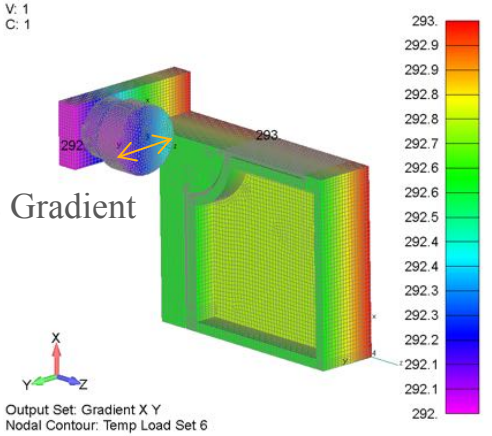
Translation from Bulk 1K(µm)

X Axis Gradient



Component	Material	Young's Modulus (psi)	Poisson 's Ratio	Density (lb/in^3)	Fty (psi)	Ftu (psi)	Ref. Source
Flexure	Ti6AL4V	16e6	0.31	0.16	120000	130000	MMPDS-06
Relay Mirror 1	AL6061-T6	10e6	0.33	0.098	35000	42000	MMPDS-06
Mirror-Pad Bond	RTV 566	500	0.498	0.050	---	470 Lap Shear	Momentive Data Sheet

Y Axis Gradient



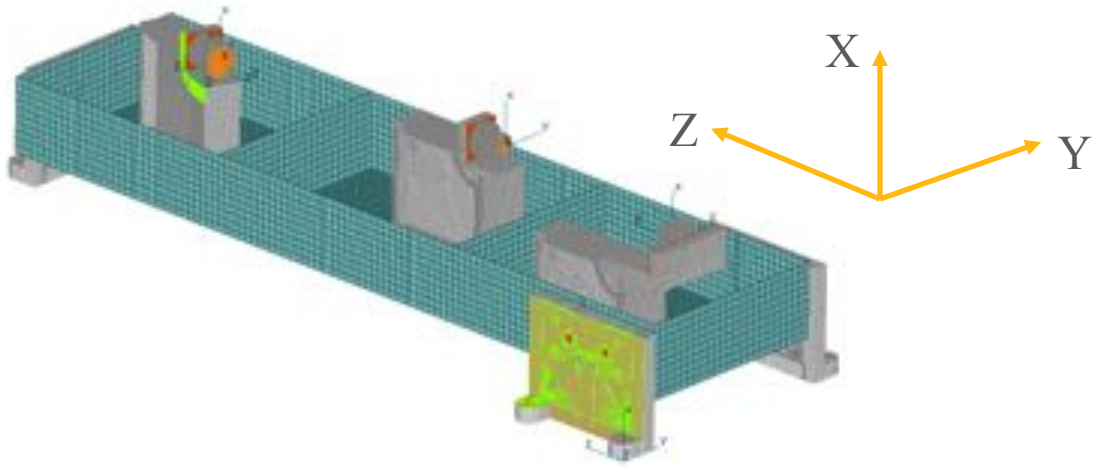
Thermal Distortion Scalable to Component Sensitivities

Load Case	dX (Microns)	dY (Microns)	dZ (Microns)	Rot X (µradians)	Rot Y (µradians)	Rot Z (µradians)
Bulk 1 K	-0.3161	-0.1311	-0.1307	0.00123	-3.91541	-0.00002
X Axis Gradient 1 K	-0.1110	-0.1316	-0.1248	0.00116	2.47650	-3.22293
Y Axis Gradient 1 K	-0.2659	0.1875	-0.1674	-8.03040	-0.95162	11.12000

Net Stability Requirement: XY < 2 µm, Rot XY< 4.85 µrad, Rot z < 24.2 µrad

Mirror Bench Thermal Distortion Sensitivities

- Evaluated 1K Gradient Cases
- Tabulate RM motions individually

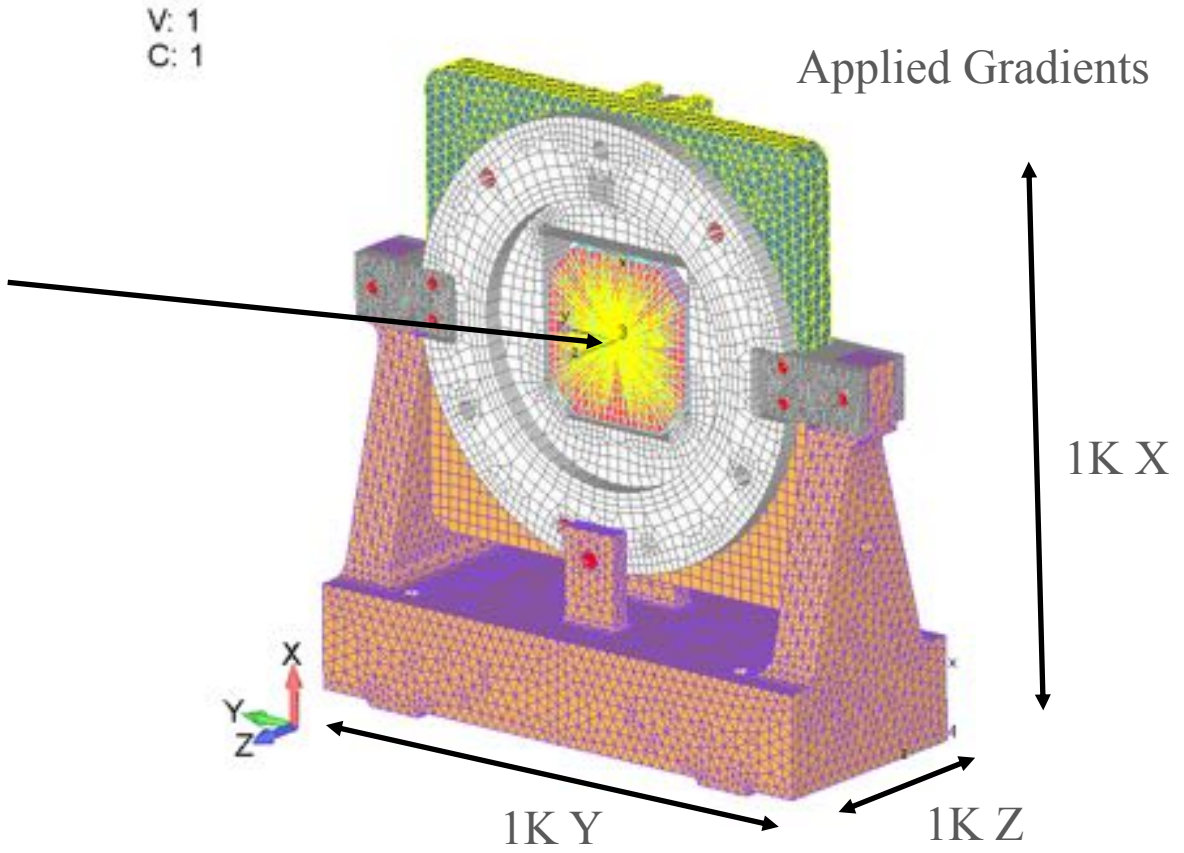


Mirror Motions Scalable to Compare to Optical Budget

Mirror #	Load Case	dX (Microns)	dY (Microns)	dZ (Microns)	Rot X (µradians)	Rot Y (µradians)	Rot Z (µradians)
RM1	1 K Gradient X	-0.2061	0.0567	-0.5223	0.16999	10.17690	1.23261
RM2	1 K Gradient X	-0.2856	-0.1281	-0.1919	-0.16495	2.44286	-2.02090
RM3	1 K Gradient X	-0.1795	-0.0086	0.4072	-0.03465	-4.18329	-0.68637
RM1	1 K Gradient Y	-0.2796	-0.2401	-0.4029	4.66725	4.94459	-5.95018
RM2	1 K Gradient Y	-0.2844	0.2301	-0.0812	-3.43374	-1.11560	6.82510
RM3	1 K Gradient Y	-0.3729	0.3175	0.2923	3.45862	-2.83431	6.29561
RM1	1 K Gradient Z	-0.4957	0.0890	-0.5380	-0.12895	6.01204	2.04585
RM2	1 K Gradient Z	-0.0539	-0.0032	0.0973	0.46723	-2.64542	0.18308
RM3	1 K Gradient Z	-0.2307	-0.0137	0.2804	-0.03465	-4.18329	-0.68637

Net Stability Requirement: XY < 2 µm, Rot XY< 4.85 µrad, Rot z < 24.2 µrad

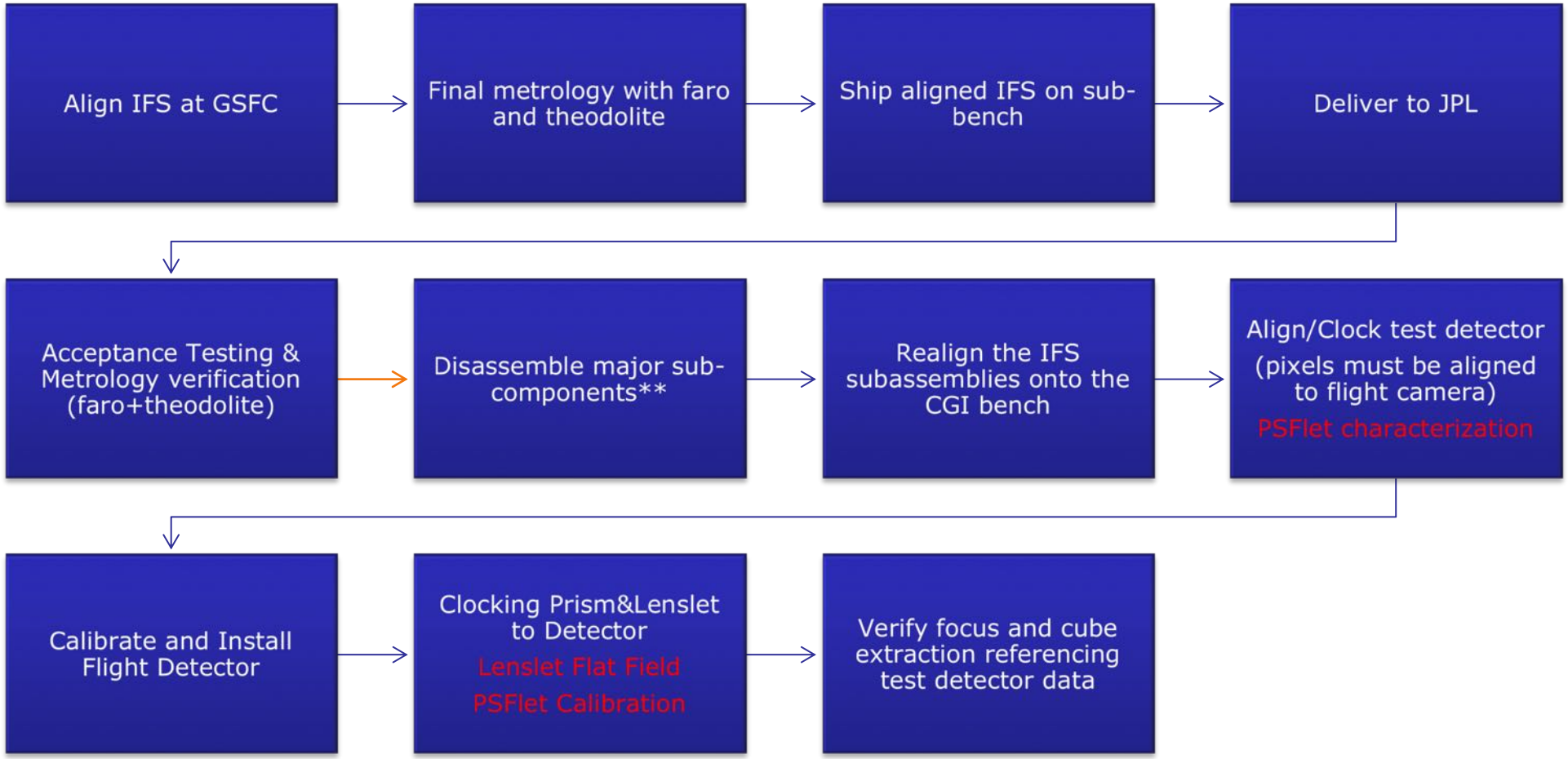
Lenslet Array Gradients



Component	Load Case	dX (Microns)	dY (Microns)	dZ (Microns)	Rot X (µradians)	Rot Y (µradians)	Rot Z (µradians)
FuSi Array	1 K Gradient X	0.2494	-0.0006	-0.0627	-0.01575	0.56269	0.00308
FuSi Array	1 K Gradient Y	0.2979	-0.1874	-0.0370	-0.12833	0.07701	-2.78676
FuSi Array	1 K Gradient Z	0.3395	-0.0006	-0.0627	0.08048	4.41279	-0.00777

Assembly and Alignment Plan

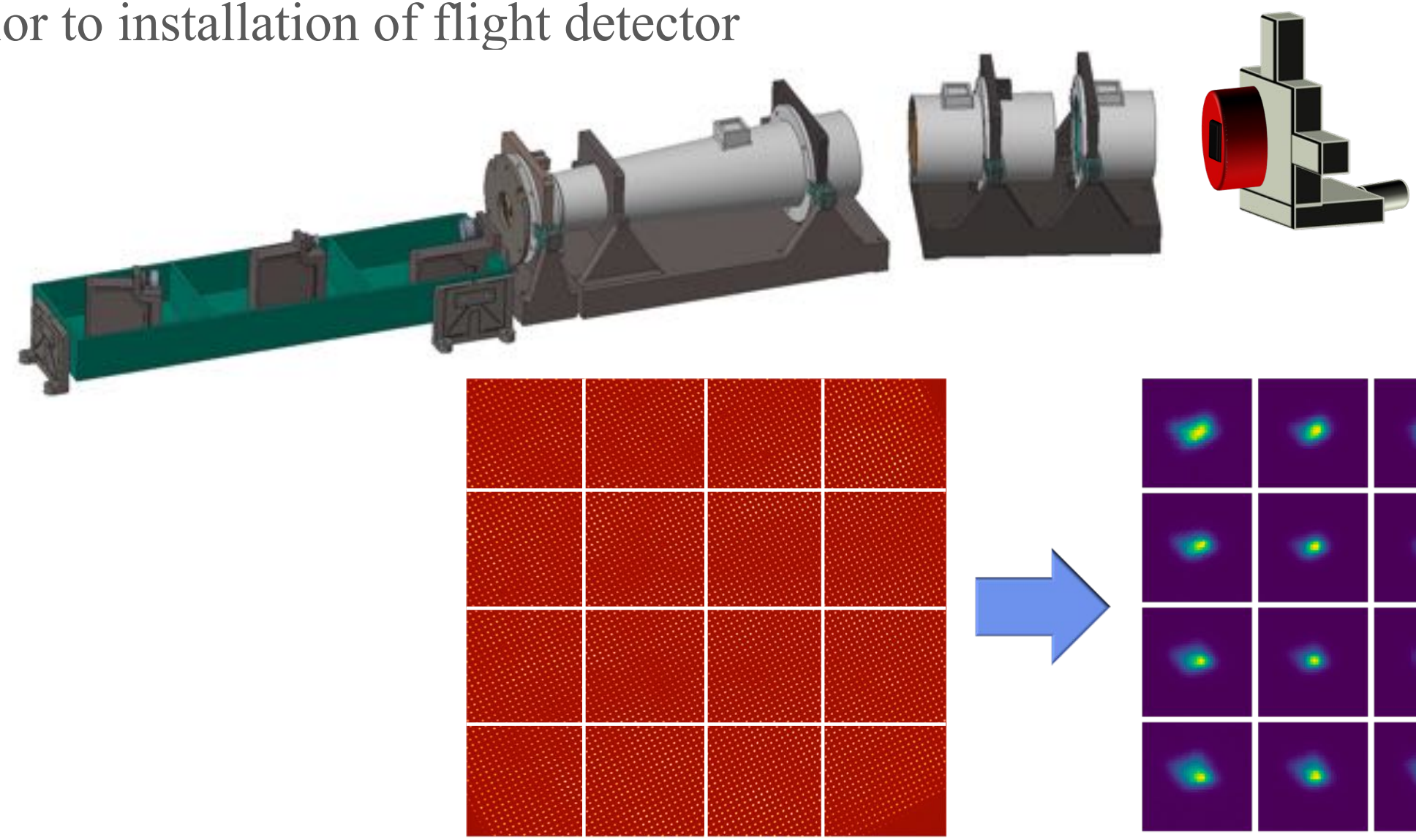
- Relay Mirror Group (RMG)
- Collimating Lens Group (CLG)
- Detector (D)
- Imaging Lens Group (ILG)
- Prism Group (PG)



** Installation of a complete sub-bench is a trade to be undertaken in Phase B

Fine Pitch Characterization Sensor

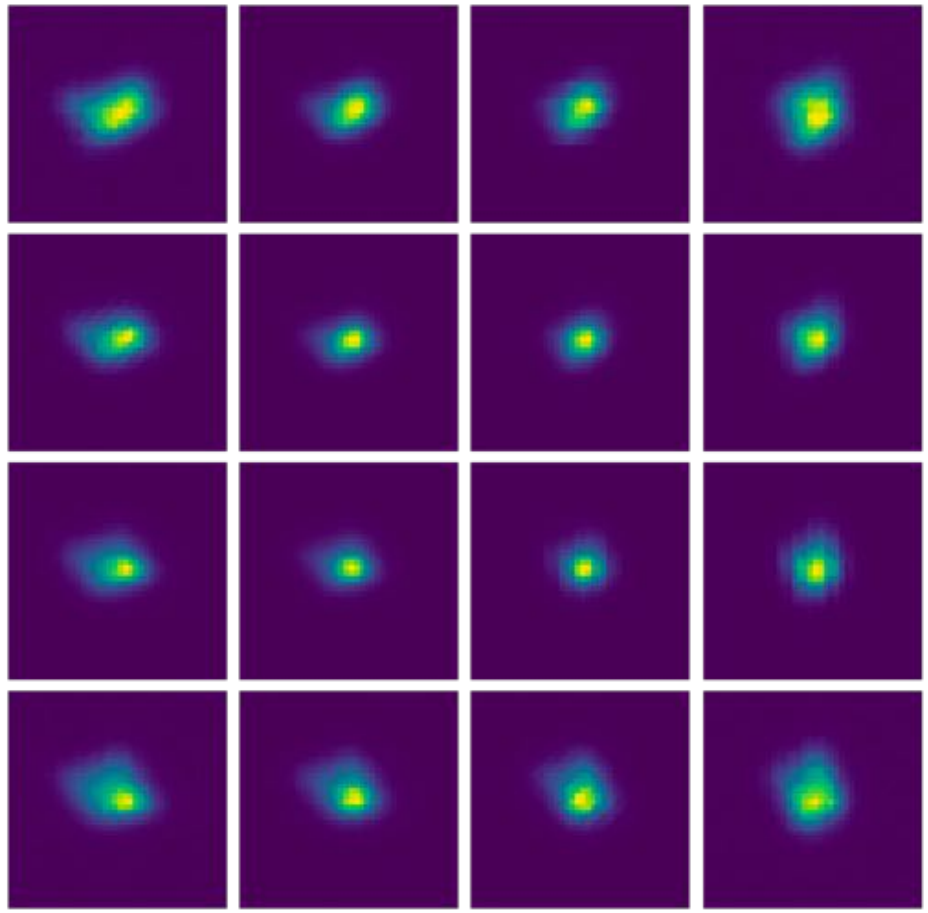
- Fine pitch detector and stage must be used to characterize PSFlets during I&T prior to installation of flight detector



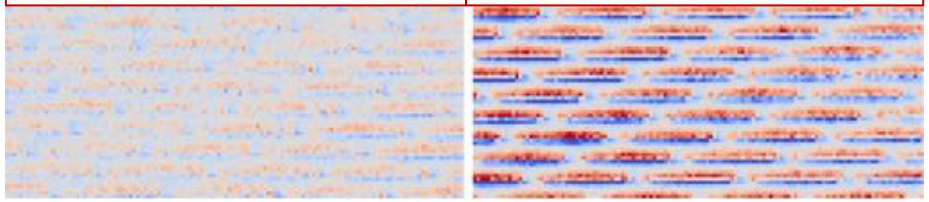
Generating PSFlet Templates and Libraries

- Gather high spatial resolution PSFlet templates with flat field
  - **fine-pitch detector + dithering**
  - Multiple focus positions (6 dimensions of data)
- Enables EM Vibration testing without the detector mounted to the unit
- Enables swap in of flight detector in final I&T
- Mitigates lack of focus mechanism

PSFlets over FOV



Good centroids Low residuals	~0.1 pixel error: Higher residuals



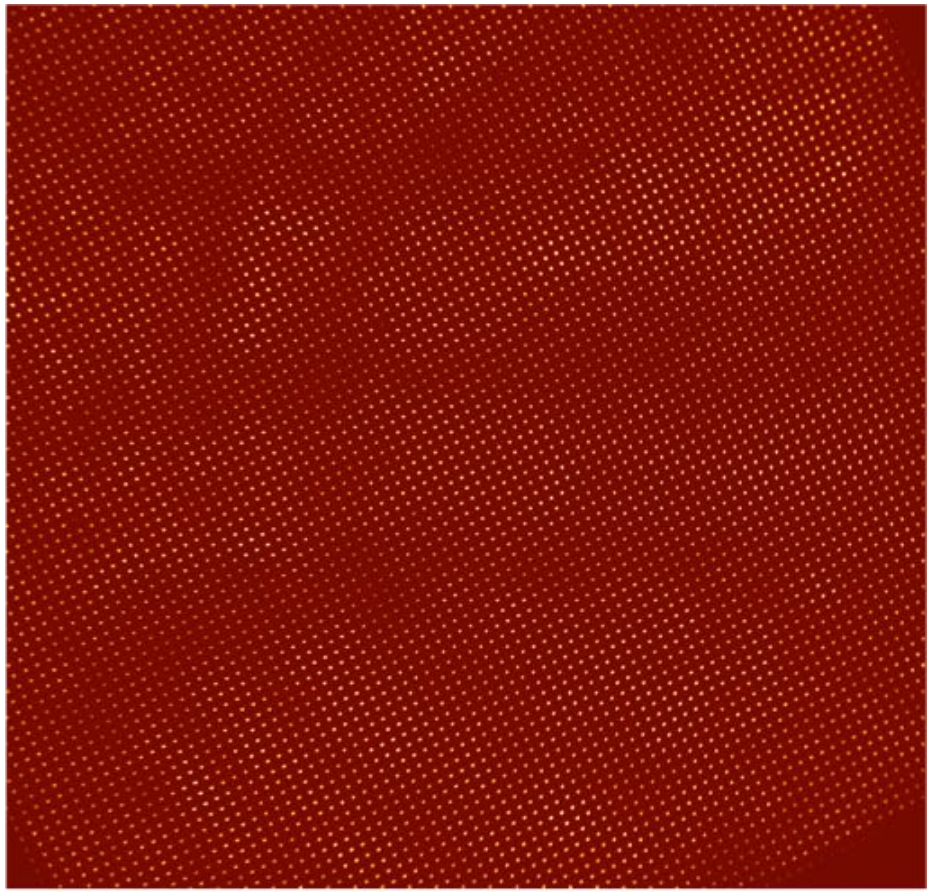
On-orbit Computing Tasks

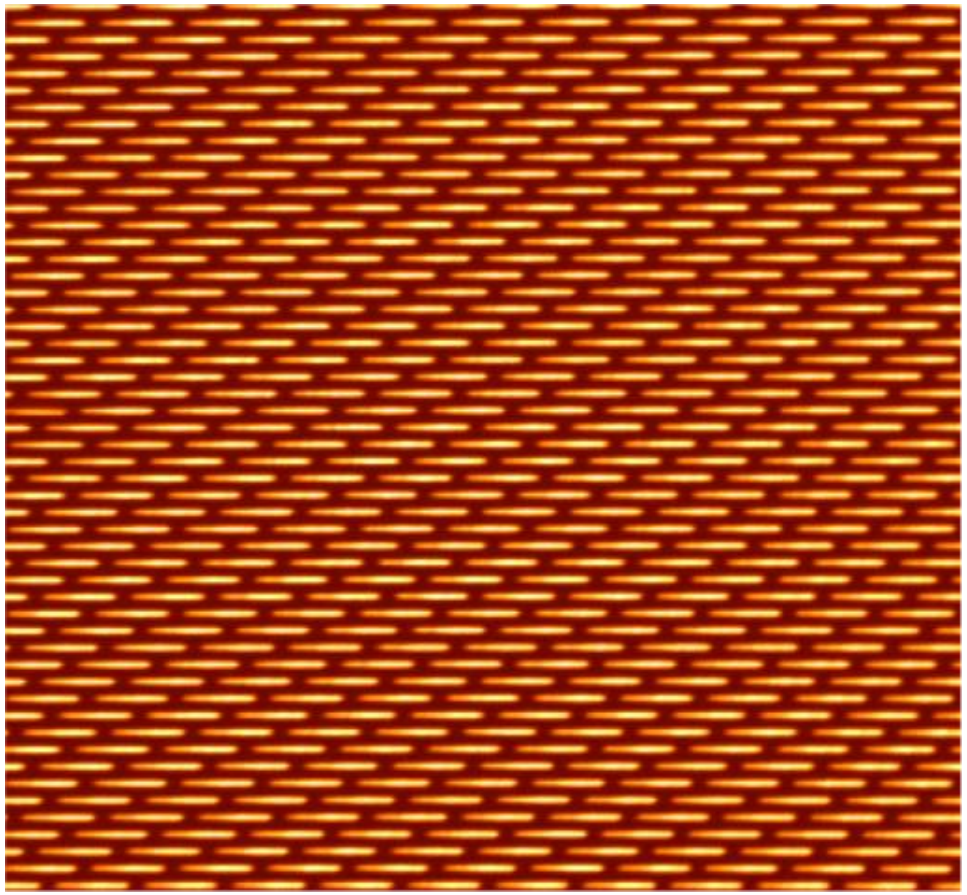
1. Monochromatic update:

Find centroids of PSFLets on grid and find X, Y, theta offsets; fit focus changes if any

2. Extraction:

Extract each microspectrum into cube using Horne extraction



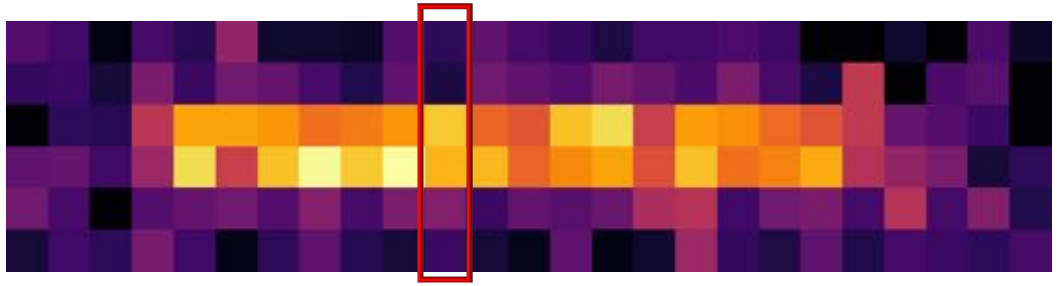


Efficient method for on-orbit extraction

- Science-grade extraction requires a lot of memory and processing
  - Can use a simpler, 1D extraction method (Horne et al. 1986 method)
  - Keep science-grade extraction for ground processing

- **Broadband wavefront control with PISCES has already been achieved successfully in the lab with this simpler algorithm (to 1e-8 contrast)**

- Cons:
  - Less efficient in SNR
  - More covariance

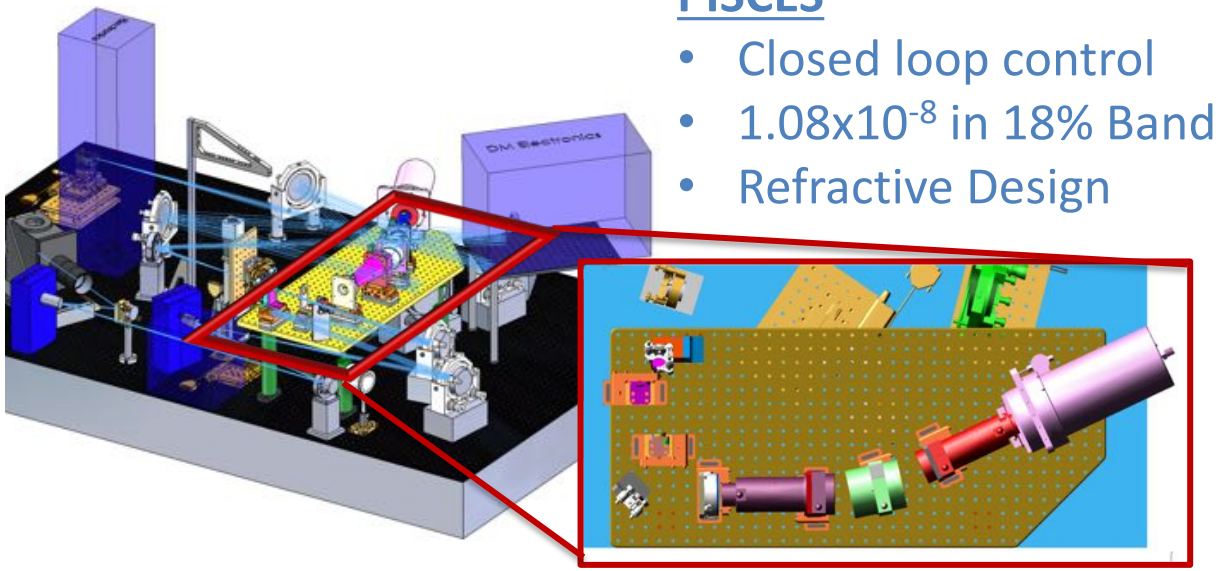


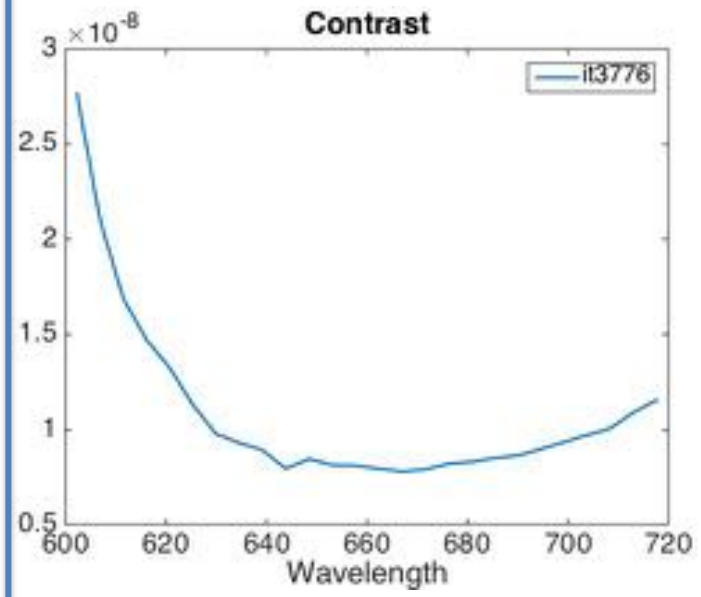
- Pros:
  - Simpler implementation
  - No matrix inversion (only ~1.4 Mflops << CGI needs)
  - More robust against PSFLet shape errors

Key Demonstrations Feeding the CGI IFS

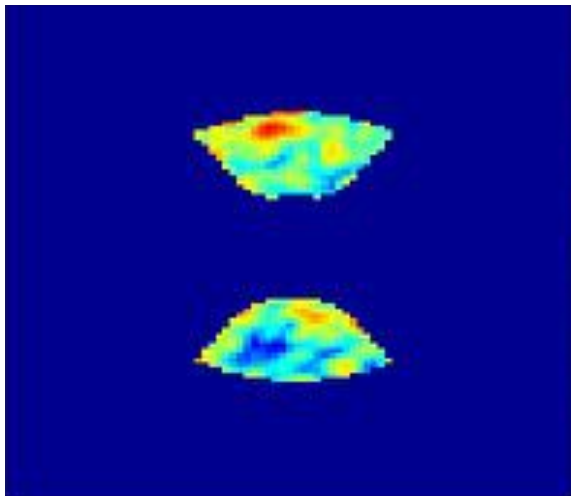
PISCES

- Closed loop control
- 1.08×10^{-8} in 18% Band
- Refractive Design



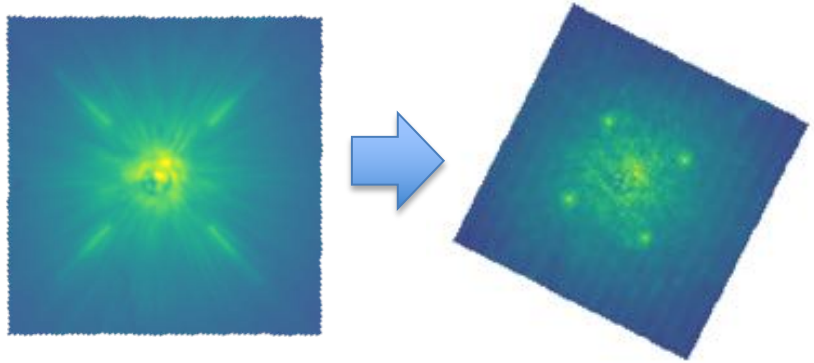


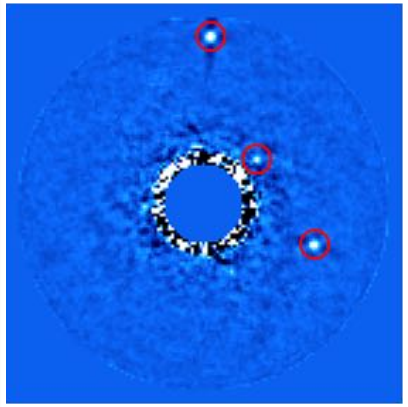
Mean Contrast: 1.08×10^{-8}

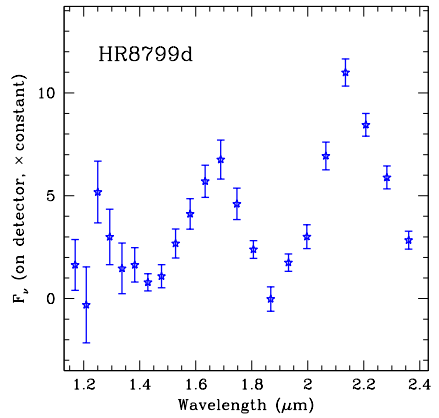


CHARIS

- Data Reduction Pipeline
- Demonstrated baseline operations and calibration procedures on-sky
- Demonstrated science grade data products with the extraction algorithms to be used on WFIRST







CGI IFS Task and Milestone Matrix

FY	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
FY18	Requirements	Requirements	Requirements	Requirements	Requirements SRR/MDR	IFS Peer Review	Requirements KDP-B	CGI SRR Start of Phase B	FLT Model/Analysis	FLT Model/Analysis	FLT Model/Analysis	EM Model/Analysis
FY19	EM DWGs REC:Clean Tent	EM DWGs Lab Setup	EM DWGs Lab Setup	Begin Subs Lab Setup	IFS PDR 18% Milestone Lab Setup	Subs Lab Setup	Subs REC: Masks REC: OAPs Lab Setup	Subs CGIsim	complete subs CGIsim	CGIsim CGI PDR	CGIsim	CGIsim
FY20	REC. EM sub Align EM	Align EM	Align EM MPDR	Air EM KDP-C	Vibe EM	Air EM IFS Redesign	TVAC EM IFS Redesign	Air EM IFS Redesign	Air EM IFS Redesign	DEL: EM IFS Redesign	IFS Redesign	IFS Redesign
FY21	IFS Redesign	IFS CDR FLT subs CGI CDR	FLT subs FLT prep	FLT subs FLT prep	FLT subs FLT prep	Rec: FLT sub, Assemble FLT	Assemble FLT	Test FLT	Test FLT, WFIRST CDR MCDR	Test FLT	Test FLT	FLT PSR, Ship:FLT
FY22	DEL:FLT Inherited Telescope Complete	sup. JPL	CGI SIR Instrument Carrier Delivery to OTA	sup. JPL	sup. JPL	sup. JPL	sup. JPL	sup. JPL	CGI TRR	sup. JPL	sup. JPL Spacecraft I&T	sup. JPL
FY23	sup. JPL	sup. JPL	sup. JPL	sup. JPL	CGI Delivery	sup. GSFC Telescope Delivery	sup. GSFC WFI Delivery	sup. GSFC	sup. GSFC SIR	sup. GSFC SC Delivery	sup. GSFC Payload I&T KDP-D	sup. GSFC
FY24	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC Payload Delivery	sup. GSFC Obs I&T	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC
FY25	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC PSR	sup. GSFC I&T Complete	sup. GSFC	sup. GSFC	sup. GSFC	sup. GSFC KDP-E	sup. GSFC