Wide Field Instrument

Grism Optical Alignment and Test

August 11, 2019

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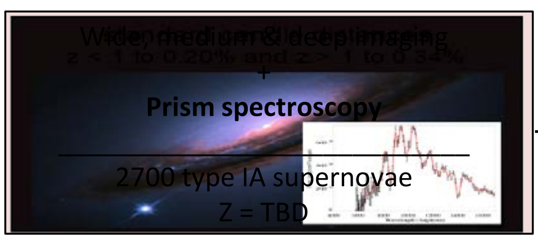
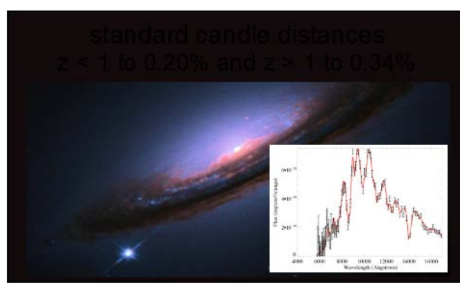
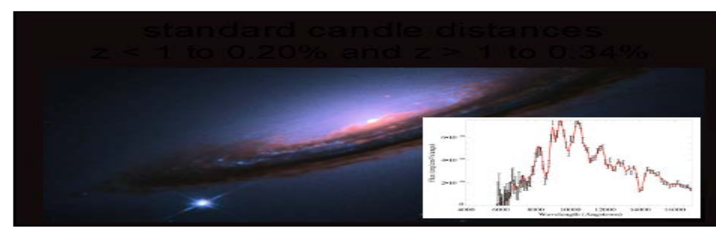
Science Goals & Objectives

WFIRST science objectives related to the Wide Field Instrument:

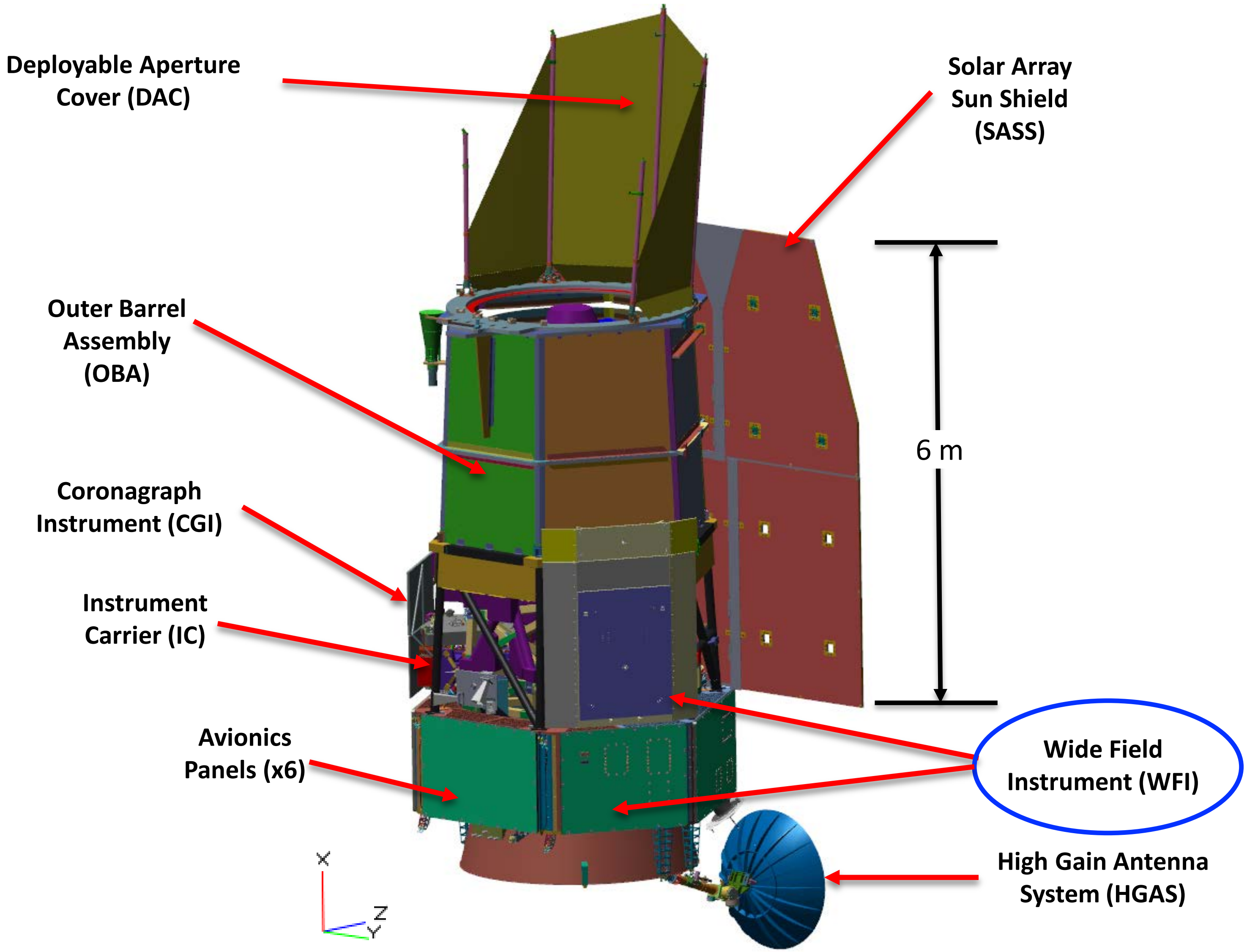
- Study Dark Energy using three techniques
  - Weak gravitational lensing: Requires high quality imaging, to measure subtle correlations in galaxy shapes
  - Baryon Acoustic Oscillations: **Requires wide-area grism spectroscopy, to measure galaxy redshifts** and study large scale galaxy distribution
  - Supernova cosmology: Requires accurate photometry, redshift measurements, and **sensitive prism spectroscopy to classify supernovae** and use them to measure the geometry of the universe.
- Find exoplanets using gravitational microlensing
  - Requires high cadence, accurate photometry in crowded fields.
- Conduct general observer science
  - Primarily levies requirements on operations.
  - Will likely make use of all instrument capabilities.



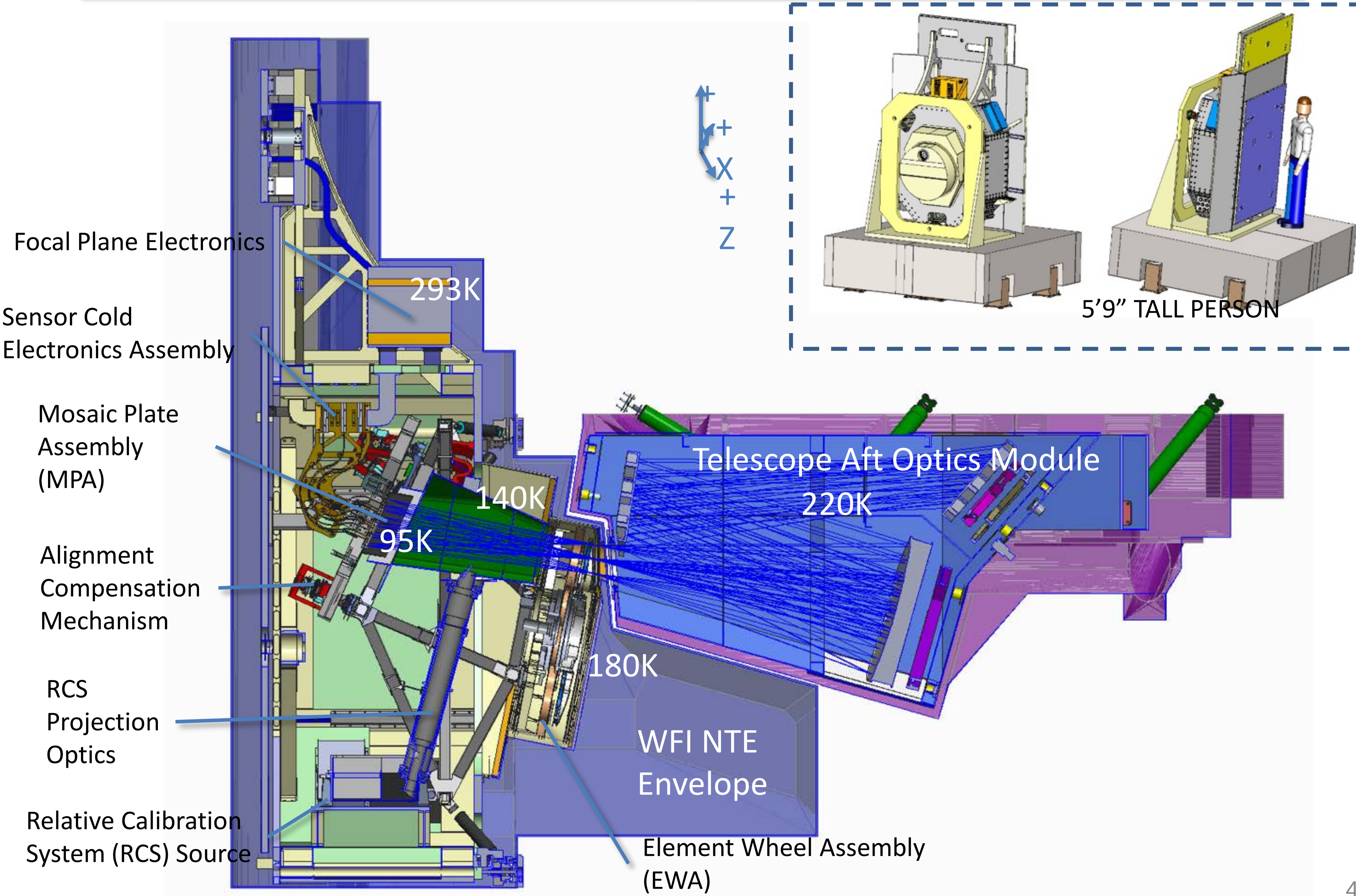




Observatory Overview



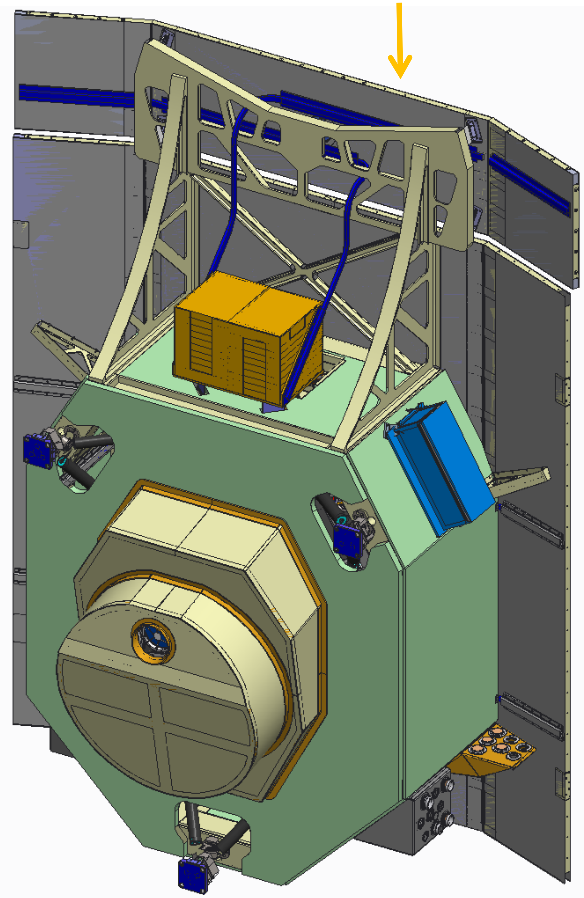
WFI Cold Sensing Module (CSM) Cross Section

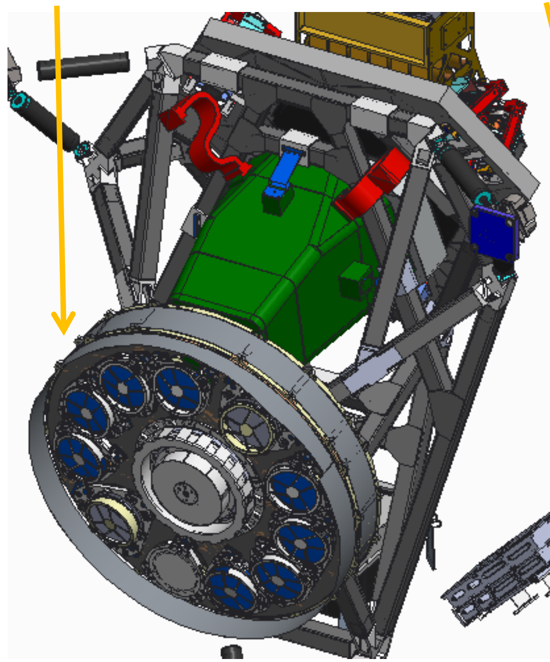


Location of Grism & Prism

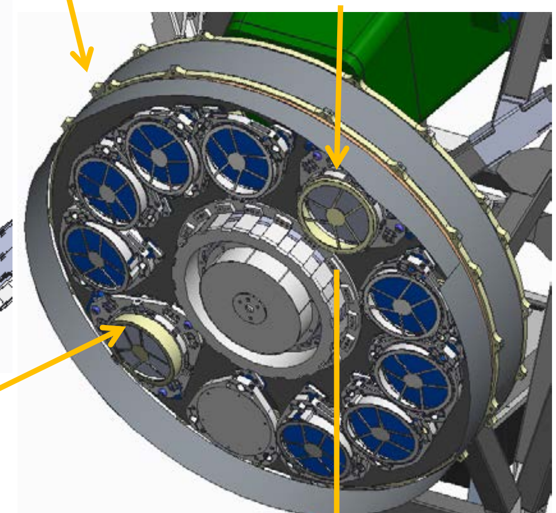
Element Wheel (filters, Grism, Prism, dark)

Wide Field Instrument

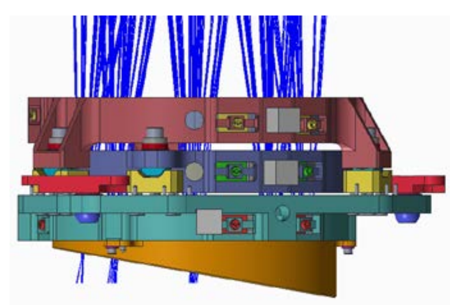




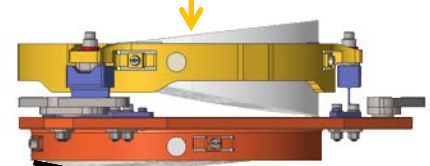
Prism Assembly



Grism Assembly



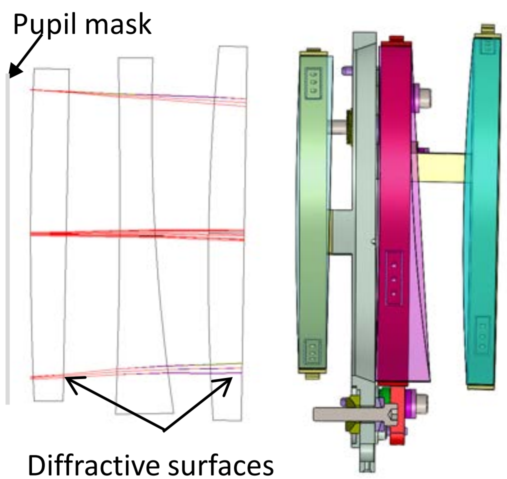
Prism Assembly



Pupil Mask

Grism Design Evolution

2014-2019
Prototype (PT)



Prototype
(all AR coated):

Pupil mask.

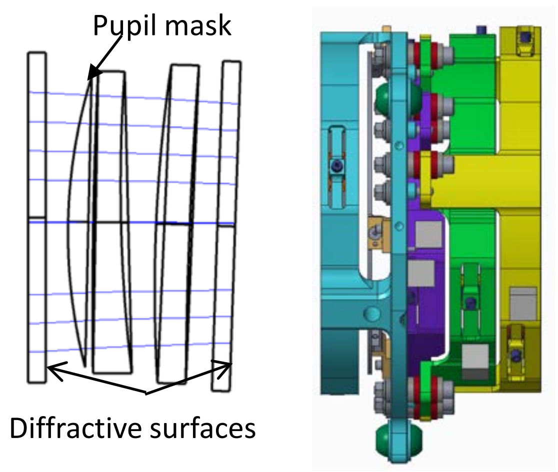
Element 1: S1 is sphere, and S2 is a diffractive on a flat.

Element 2: Both S1 and S2 are spheres.

Element 3: S1 is sphere, and S2 is a diffractive on a flat (adhesive-free-bonded).

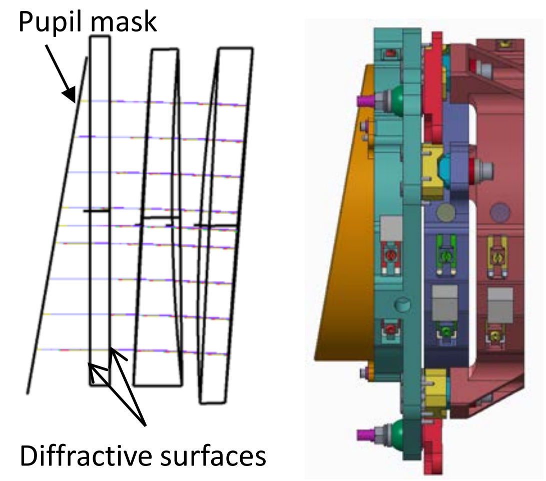
2018-2020
EDU and ETU
(SRR Design)

EDU (all AR coated): Element 1: Plane- parallel -plane, S2 is a diffractive on a flat. Pupil mask. Element 2: Both S1 and S2 are spheres. Element 3: Both S1 and S2 are spheres. Element 4: Plane- parallel -plane, S2 is a diffractive on a flat.	ETU (E1, E3, E4 are AR coated, E2 is band-pass and out of band blockage coated): Element 1: same as EDU. Pupil mask. Element 2: same as EDU. Element 3: same as EDU. Element 4: same as EDU



Completed EDU build

2020-2021
Flight (FM)



Flight
(E1, E3 are AR coated, E2 is band-pass and out of band blockage coated):

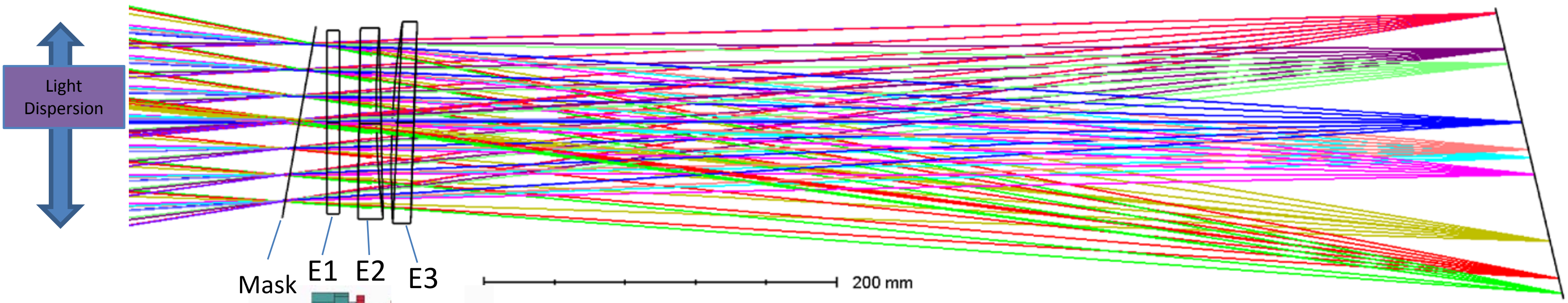
Pupil mask.

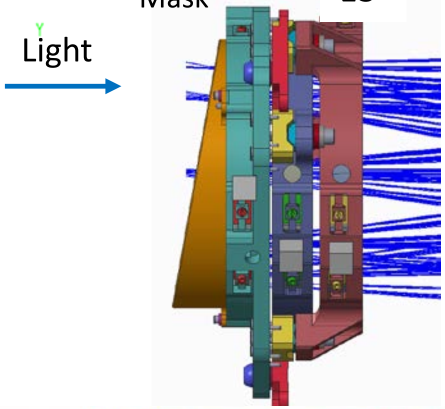
Element 1: Plane- parallel -plane, S1 and S2 have a diffractive on each surface.

Element 2: Both S1 and S2 are spheres.

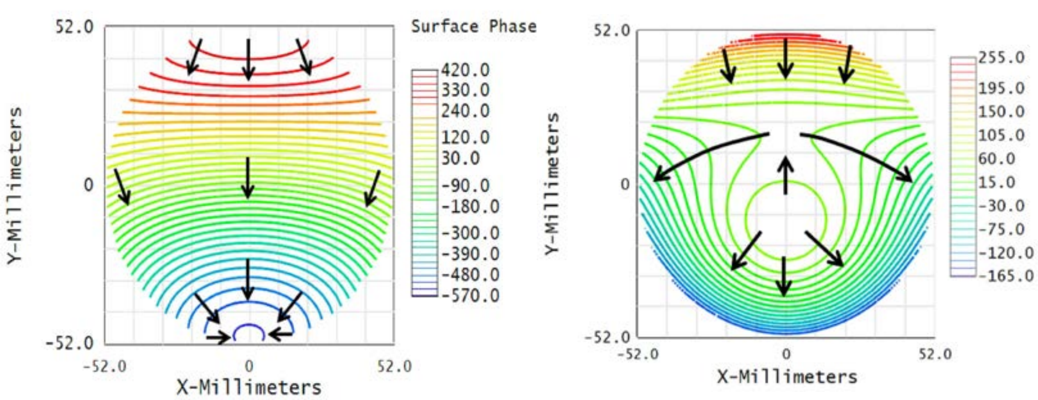
Element 3: Both S1 and S2 are spheres.

GRISM Raytrace & Wavefront Map

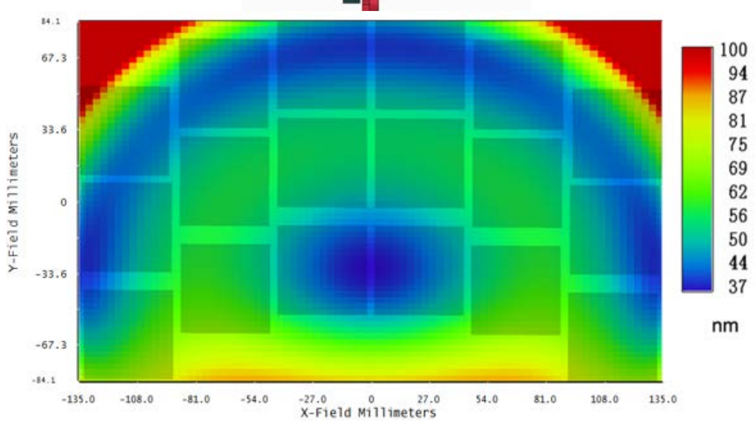




- All fused silica elements
- E1 is a plane parallel plate with diffraction patterns etched on both the front and back surfaces



- E2 is a wedged, meniscus lens with Bandpass and Out of Band Blocking coatings on both sides
- E3 is an AR coated wedged, meniscus lens
- Obscured mask to block thermal emissions from telescope

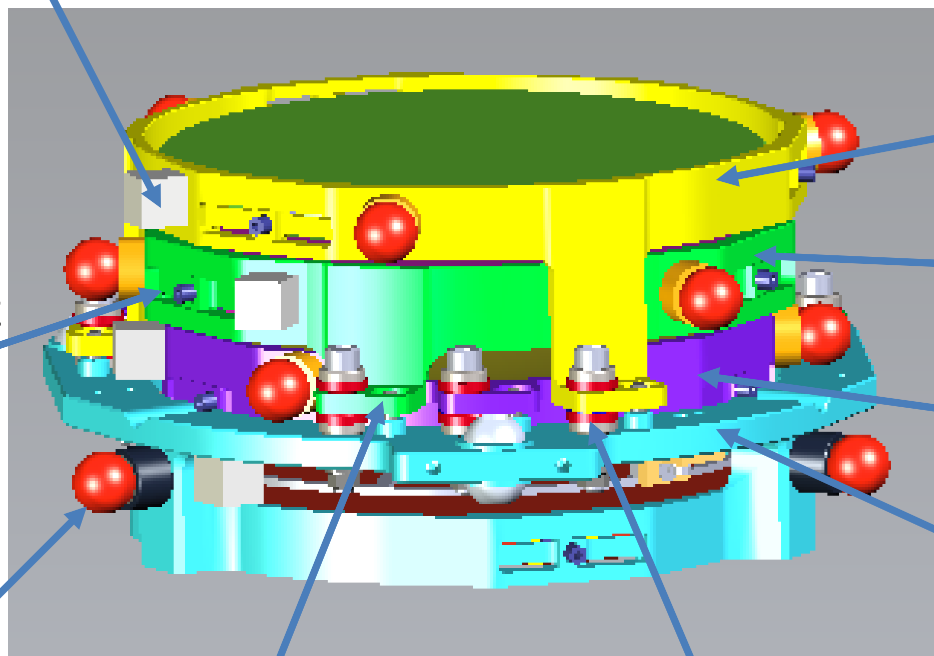


WSM Grism Design Residual (nm RMS) at 1.55um

4 Element EDU Grism Assembly

Alignment Cubes

Cell to Element Bond Flexures



Element 4 in cell

Element 3 Cell

Element 2 Cell

Grism Deck and Element 1 Mount

Laser Tracker/Radar SMR or Balls

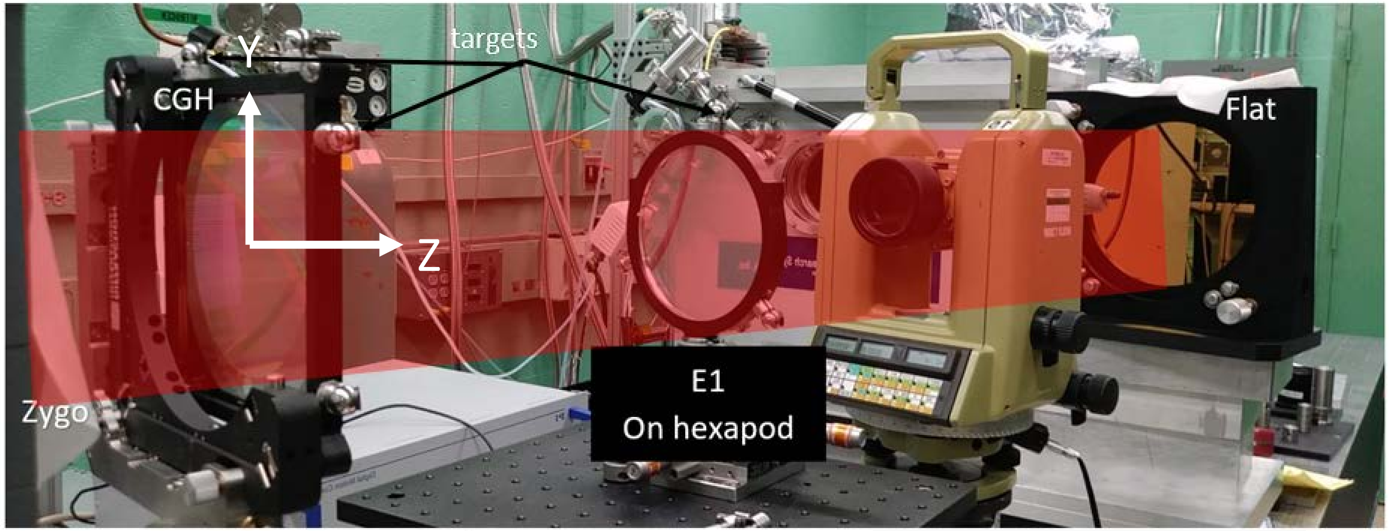
Alignment Pins Bushings (3 eache)

Spherical washers and shims for post assembly alignment (3 each)

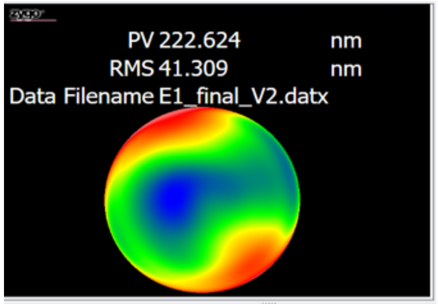
Grism Element Characterization and Assembly Alignment

- Grism Element Characterization
  - Grism Elements were optically characterized using a Computer Generated Hologram (CGH) null
  - Each Element and CGH has integral references to allow deterministic alignment and assembly alignment
    - E1 and E4 are flats which allow direct viewing of normal; each have center and clocking fiducials to enable both CGH and Assembly alignment
    - E2 and E3 have integral flats at 90 degrees related to optical axis and center and clocking fiducials to aid alignment
  - Elements were aligned to nominal position relative to interferometer and CGH and then interferograms acquired
- Grism Assembly Alignment
  - Grism assembly coordinate system was established on deck
  - Elements were aligned one by one to deck in 6 DOF using hexapod to place them before installing cells over them and bonding them to cells
  - Order of assembly was E2, E3, E4 with E1 last as it was bonded to deck
  - Theodolites were used to used to set tip/tilt
  - Micro Vu optical CMM was used to set clocking, despace and decenter
  - Cells have bushings that allow repeatable placement to deck

Grism EDU E1 CGH Testing Summary



E1 Zernike Fit (RMS normalized)	
WFE RMS	41nm
ZFR 4 (power)	26nm
ZFR 5 (ast X)	-17nm
ZFR 6 (ast Y)	-21nm
ZFR 7 (coma X)	-9nm
ZFR 8 (Coma Y)	2nm
ZFR 9 (spherical)	-3nm



E1 minus background (high frequency) minus CGH, minus flat.

The center of the CGH was set as the origin and the spacing between the origin and the center fiducial of E1 was 300mm. E1 was tilted wrt the grism optical axis. The E1 surface was measured directly to set the designed tilt angle.

Grism EDU E2 Inspection and Characterization

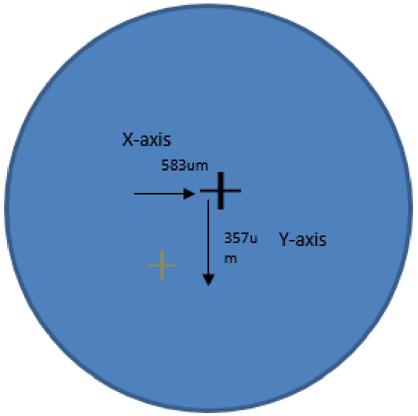
Upon receipt of E2 from the manufacturer (Optimax), it was:

1) Inspected under a microscope to verify requirements. It was found that the center crosshair was not properly placed and the offset had to be measured to account for during alignment.

2) Placed in its GSE Lollipop mount (LPM) and characterized under the micro-vu (establish a relationship between fiducials 12'oclock, 6o'clock, 9 o'clock and center fiducials) and hemispherical targets (on LPM). E2 CGH was also measured with micro-vu. The center fiducial of E2 represented the origin itself.

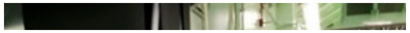
3) E2 was measured with CGH following the CGH testing procedure.

4) Once E2 was fully characterized it would proceed with mechanical bonding. E2 was bonded so that it would have a specific angle wrt the normal of E1.

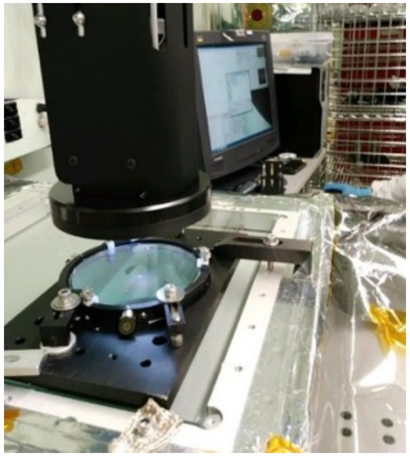


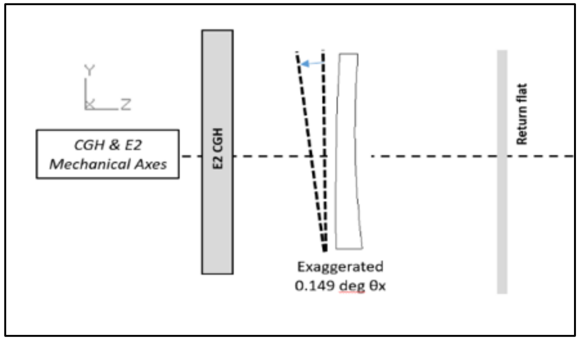
Inscribed center crosshair fiducial

Actual E2 center from circumference diameter (measured to be 111.935um)



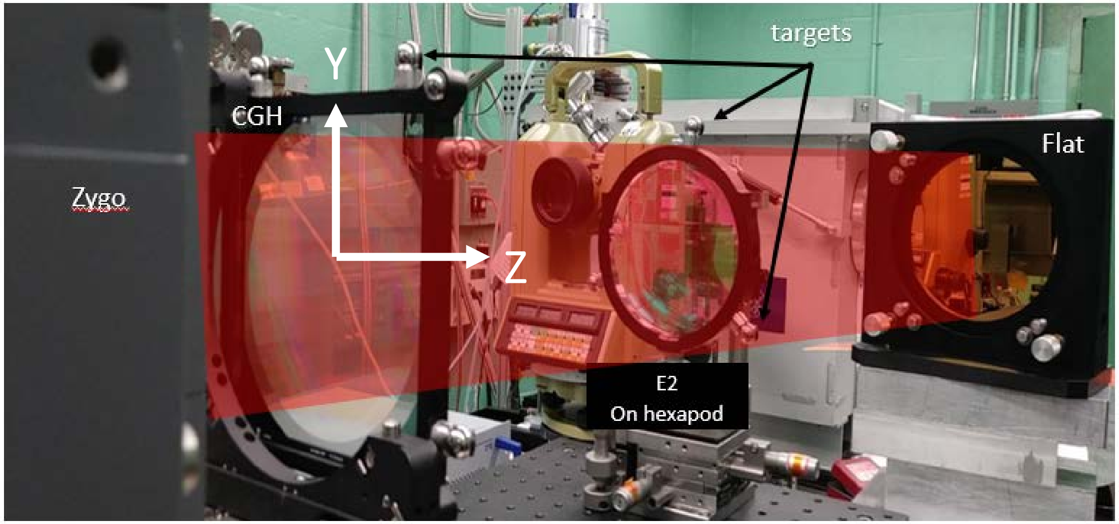
E2micro-vu characterization



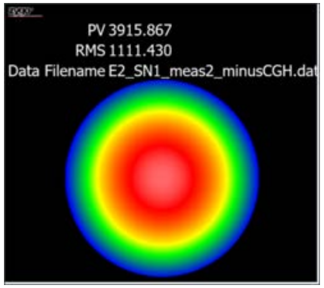


E2-CGH test setup, E2 tilted forward wrt CGH.

Grism EDU E2 CGH Testing Summary



E2 SN1 Zernike Fringe Fit (RMS normalized)	
WFE RMS	1111nm
ZFR 4 (power)	-1114nm
ZFR 5 (ast X)	-21nm
ZFR 6 (ast Y)	-11nm
ZFR 7 (coma X)	6nm
ZFR 8 (Coma Y)	-1nm
ZFR 9 (spherical)	-2nm



E2 minus background (high frequency) minus CGH, minus flat.

The center of the CGH was set as the origin and the spacing between the origin and the center fiducial of E2 was 300mm. E2 was tilted wrt the grism optical axis. The E2 integral flats were used to measure the designed tilt angle for the CGH test.

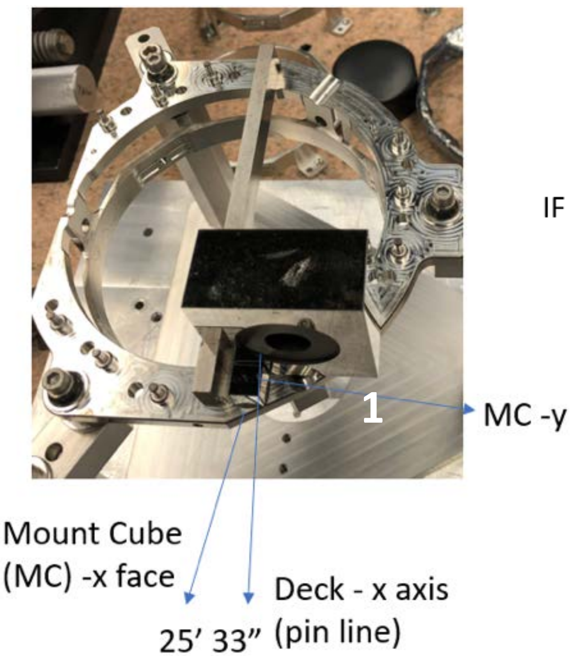
Grism EDU E2 CGH Testing Results Discussion

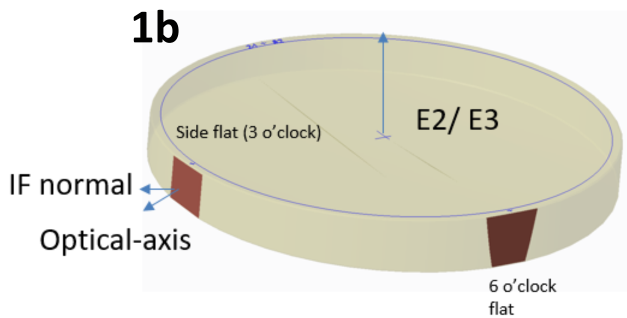
- Power was much higher than expected
  - All elements were manufactured from Suprasil 3001 (flight material) which is different than Fused Silica 7979, for which the CGH was designed and fabricated for.
  - E2 and E3 had opposite power which allowed successful nulling at the grism assembly level.
  - E1 and E4 also had smaller but opposite power which also nulled.
  - Flight CGHs will be designed to null Suprasil 3001 elements.

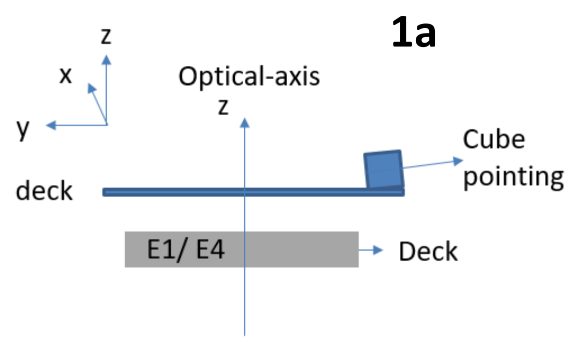
Building the Grism EDU

Grism EDU Alignment Steps

1) The deck cube was used as the base reference for alignment. Therefore the deck cube was measured wrt the large mount cube and the offset was added to all additional cell cubes pointing.
2) Once each element was on the hexapod they were measured with the micro-vu (for xyz and clocking) and theodolite for tip/tilt.
   a) For E1 and E4 the optical surface was measured directly (using a relay) wrt the deck cube.
   b) For E2 and E3 the side integral flats were measured wrt the deck cube. Since these had been measured since they were mounted on their LPM the pointing between the side flat and the grism optical axis was already known.
3) Each step taken for aligning the individual grism elements was listed in the “Grism Assembly and Alignment Procedure”.

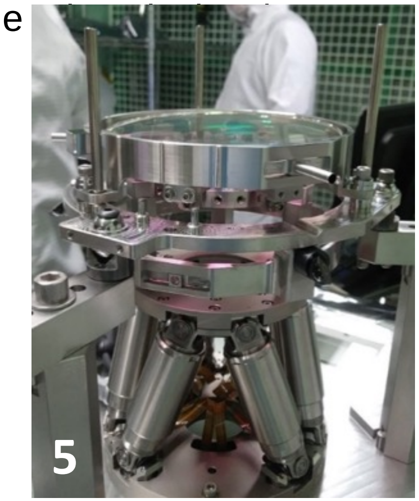


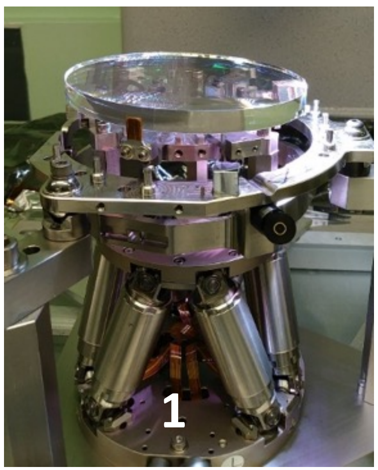


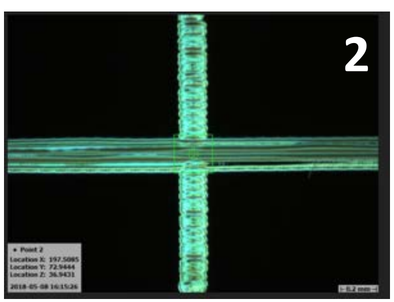


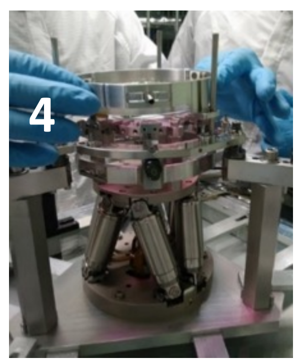
Grism EDU E2 Alignment and Bonding

1. Place E2 on hexapod without deck on the grappler.
2. Using the micro-vu, look for the center (adjust for measured offset) and edge fiducials to set XYZ placement and clocking.
3. Using the side integral flats measure tip/tilt (using theodolites). Relative to the
4. Slide E2 cell over E2 and verify E2 did not move with Micro-vu.
5. Bolt E2 cell onto deck.
6. Inject epoxy and let cure for five days.



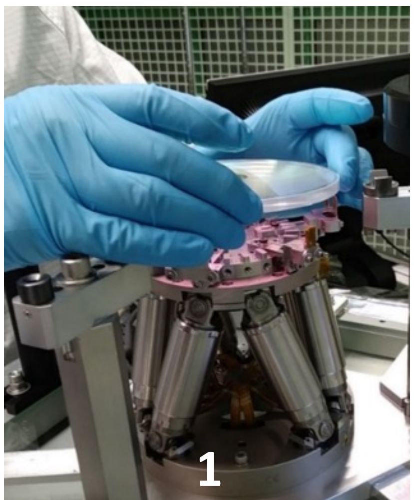


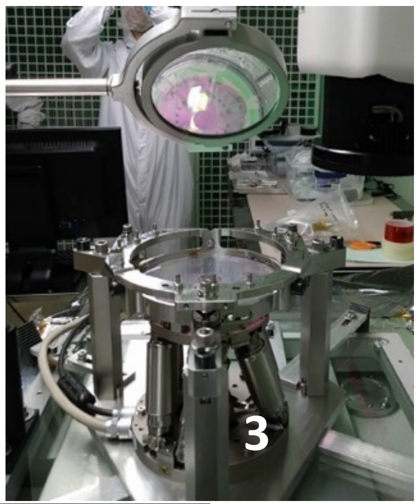


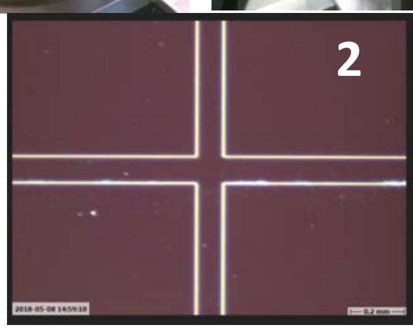


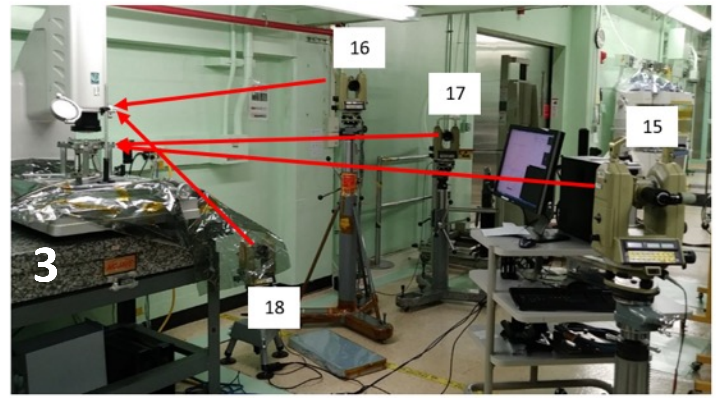
Grism EDU E1 Alignment and Bonding

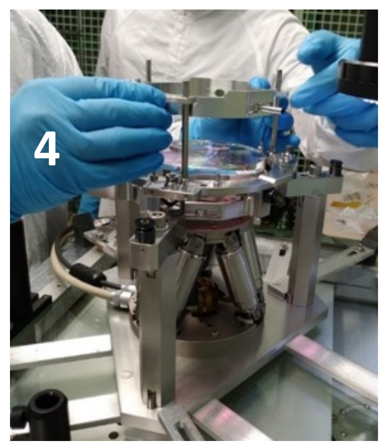
1. Place E1 on hexapod without deck on the grappler.
2. Using the micro-vu, look for the center and edge fiducials to set XYZ placement and clocking.
3. Add a relay mirror over E1 to measure tip/tilt (using theodolites). Relative to the grism optical axis.
4. Slide cell over it and verify E1 did not move with Micro-vu.
5. Inject epoxy and let cure for five days.

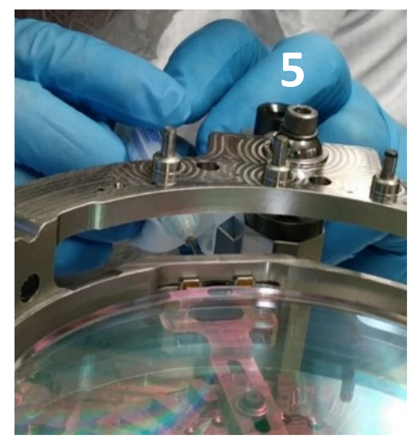










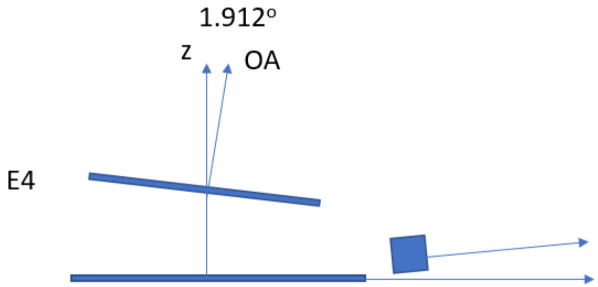


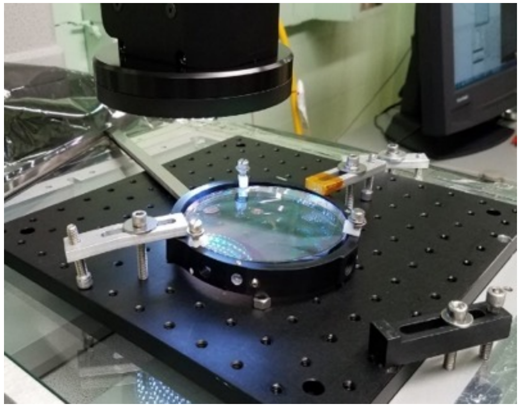
Grism EDU E3 and E4

Grism elements E3 and E4 were inspected, mounted, aligned and bonded following the same process as E2 and E1 followed respectively.

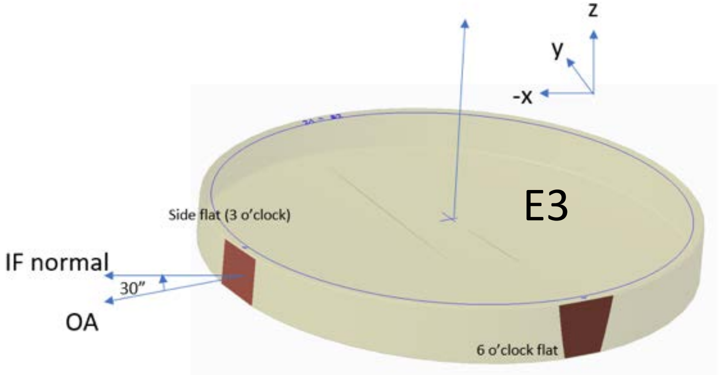
For E4 its surface was measured with the relay to set that angle wrt the deck cube.

For E3 the tilt angle was set by measuring the side integral flats wrt the deck cube.





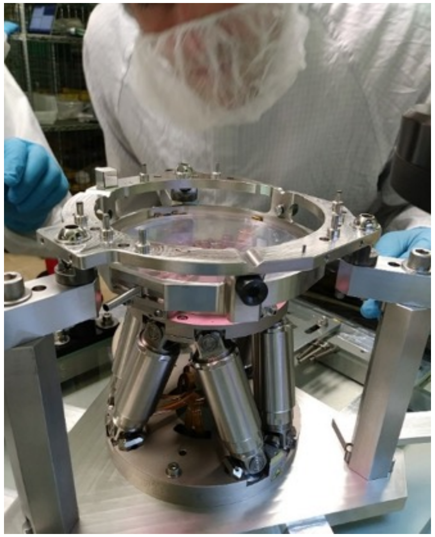
E3 micro-vu characterization



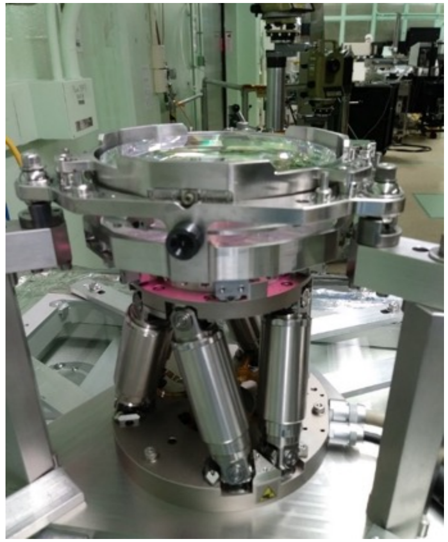
Building the Grism EDU

Grism EDU Assembly Stack-up

E1 in deck

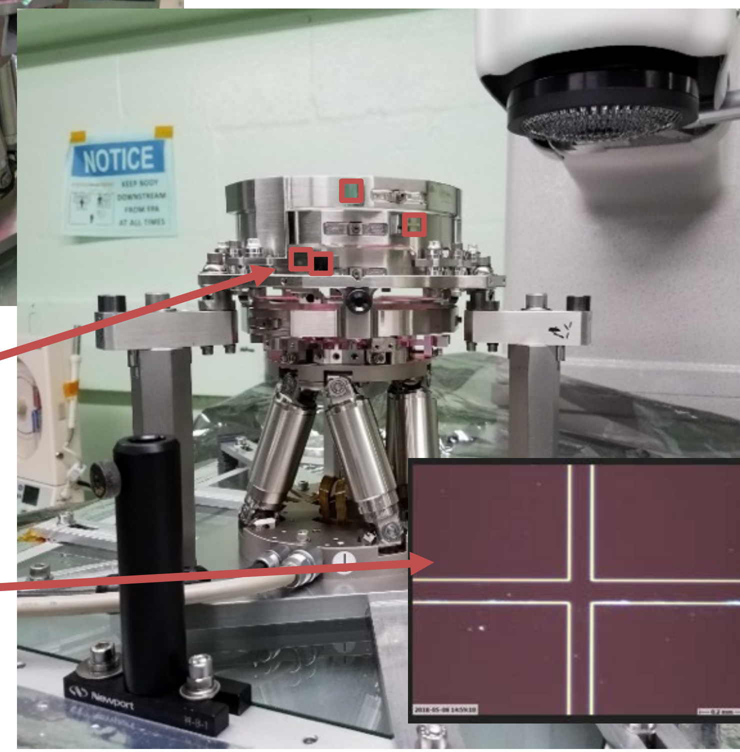


E1 + E2 in deck



E1 + E2 + E3 in deck

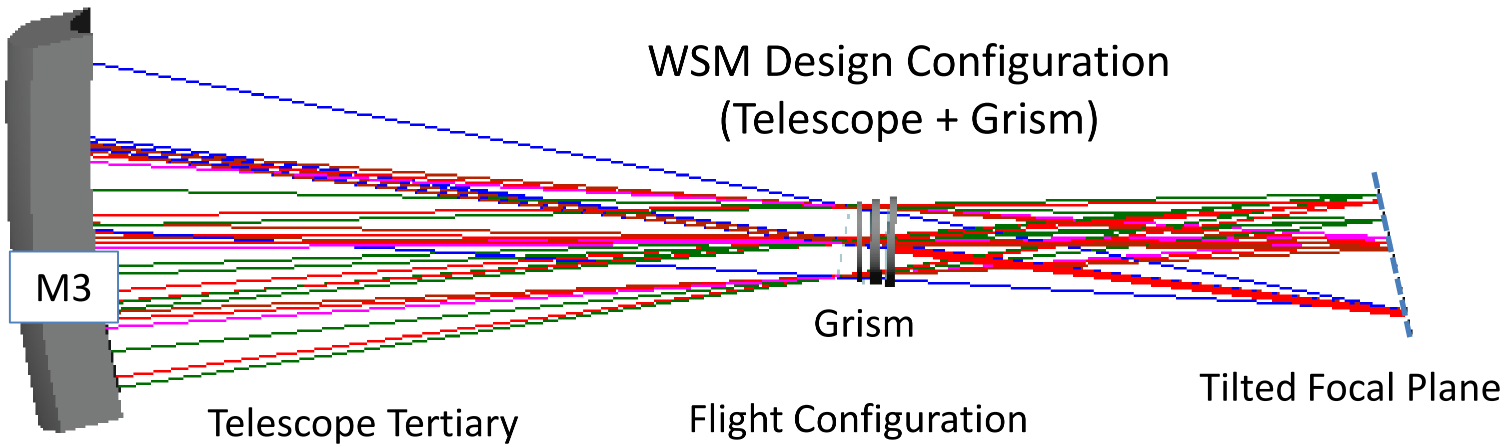
E1 + E2 + E3 + E4 in deck



Using:

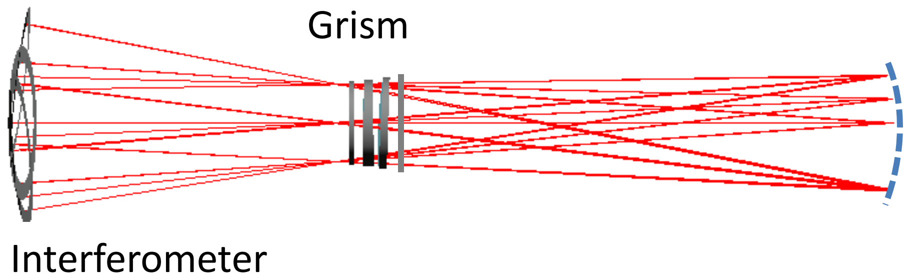
1) Theodolites: shooting cell cubes
2) Micro-Vu non-contact multisensor measurement system: center and edge crosshair fiducials

Grism Test Configuration is Not the Same as WSM Design Configuration



Grism Test Configuration

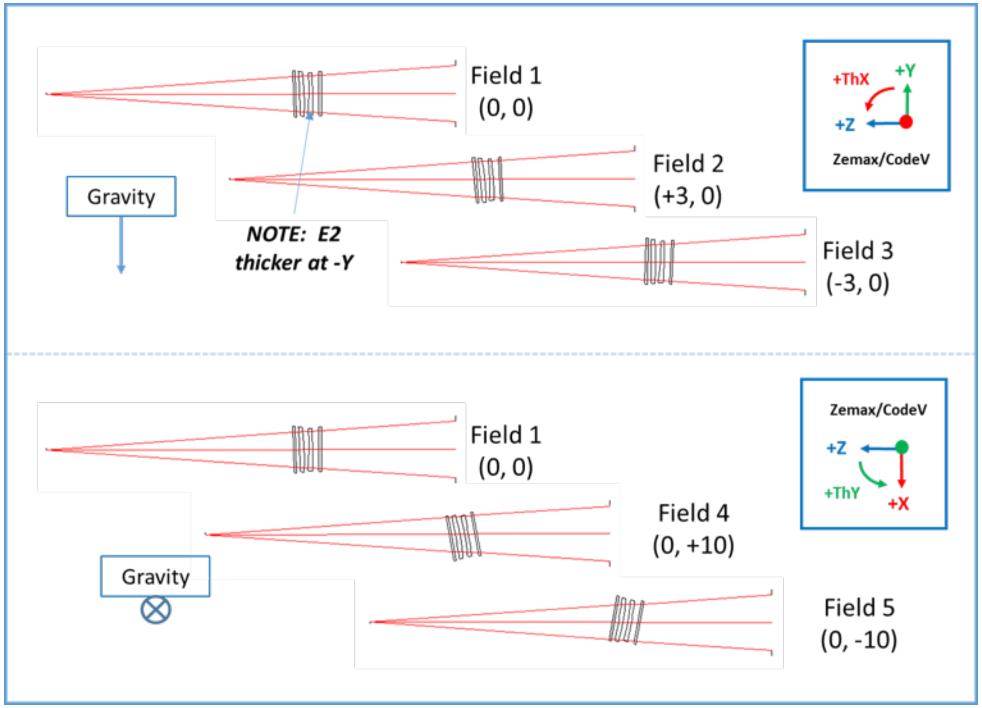
Rotates about a point and traces out a curved focal surface. Interferometer modeled as 1090mm EFL transmission sphere, 150mm diameter, F/7.27

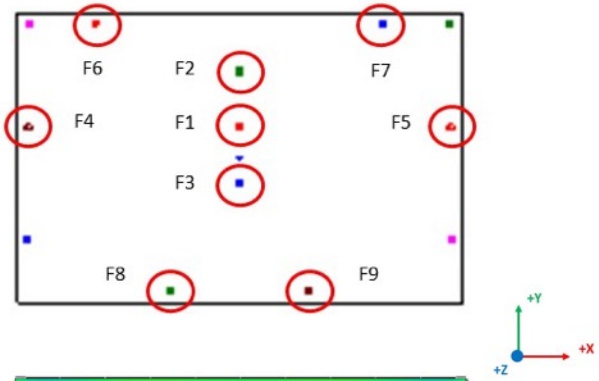


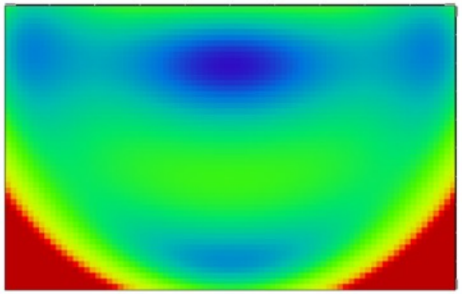
This brings into question whether alignment in the Test Configuration will adequately ensure performance at the Payload level

Monte Carlo analysis will provide answers

Grism EDU WFE and Confocality Sensitivity Analysis







Test Field Angles	Field 1 (On-Axis)	Field 2 (Back)	Field 3 (Forward)	Field 4 (CCW)	Field 5 (CW)	Field 6	Field 7	Field 8	Field 9
ThX (deg)	0	+3	-3	0	0	+5	+5	-7	-7
ThY (deg)	0	0	0	+10	-10	+7	-7	+3	-3

Grism EDU WFE and Confocality Sensitivity Analysis

Zernike Term	Residual (nmRMS)	E2 Field F1 (0, 0) *(nm-RMS per MM or nm-RMS per DEG)*					
		dX	dY	dZ	dThX	dThY	dThZ
Focus	*0.0*	0	-4	385	28	-4	0
X-Astig	*11.8*	0	-2	6	138	-4	0
Y-Astig	*0.0*	-1	0	0	0	-136	-4
X-Coma	*0.0*	0	0	0	0	58	2
Y-Coma	*2.6*	0	1	5	54	0	0
Spherical	*-2.4*	0	-1	-1	2	0	0

E2 Selected as compensator

X astigmatism corrected with rotations about y
Y astigmatism corrected with rotations about x

First, align On-Axis using the 6DOF sensitivities for F1 (above)

Then, balance Astigmatism terms for the edge fields F4 & F5 (right)

Finally, correct Focus over the full Focal Plane (dZ above)

Zernike Term	E2 Field F4 (0, +10, CCW) *(nm-RMS per DEG)*			E2 Field F5 (0, -10, CW) *(nm-RMS per DEG)*		
	Residual	dThX	dThY	***Residual***	dThX	dThY
Focus	*0.0*	32	-983	*0.0*	32	972
X-Astig	*-11.2*	141	-833	*-11.2*	141	823
Y-Astig	*-9.7*	-809	-134	*9.7*	809	-133
X-Coma	*-34.9*	0	62	*34.9*	0	62
Y-Coma	*7.8*	55	1	*7.8*	55	-1
Spherical	*-2.3*	2	1	*-2.3*	2	-1

Grism EDU Alignment Tolerances

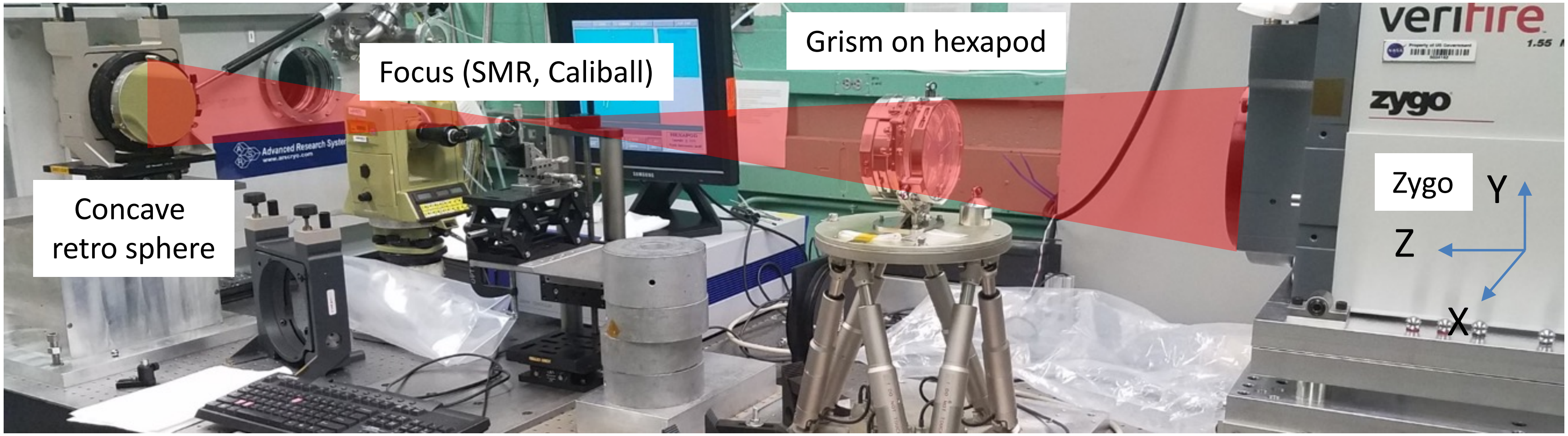
Tol	PARAMETER	ALIGNMENT			
#		resolution	(units)	resolution	(units)
700	Decentering, Horiz. (u-axis)	0.100	mm		
701	Decentering, Vertical (w-axis)	0.100	mm		
702	Focus (v-axis)	0.050	mm		
703	Tilt, Horizontal (u-axis)	*0.014*	*deg*	*0.250*	*mrad*
704	Tilt, Vertical (w-axis)	*0.014*	*deg*	*0.250*	*mrad*
705	Tilt, axial (clocking,v-axis)	*0.029*	*deg*	*0.500*	*mrad*

Alignment was achieved for each element with the following caveats:
1. E2 fiducial was found not to be at geometrical center of optic
2. Tip/tilt capability of shimming was close to tolerance

Improvements for Flight:
1. Better knowledge of fiducials at vendor
2. Better tip/tilt capability with upgraded interface

Grism EDU WFE and Confocality Test Configuration

Ambient Grism EDU layout in lab 6 on hexapod



Hardware used:
Zygo, hexapod, SMR on XYZ stage, concave retro on tip/tilt stage, theodolite to measure grism, laser tracker to measure SMR.

Grism EDU Alignment Optimization Overview

- Goals of Optimization
  - Characterize wavefront error of Grism at select fields
  - Calculate the tip/tilt adjustments of the E2 element which is our selected compensator to minimize wavefront error
  - Adjust the E2 tip/tilt by shimming the element
  - Verify that the non-power wavefront error is minimized
  - Map the focal surface across the Grism field and determine the best global back focal distance
  - Calculate the despace adjustment to E2 required to optimize the back focal distance
  - Shim the E2 element, preserving its tip/tilt to correct the back focal distance
    - Initially we worked to a relaxed requirement of 100 microns because we did not know how much the back focal distance would change after cooldown

Grism EDU Alignment to ZYGO

- Grism Alignment to ZYGO interferometer
  - Install transmission sphere and internally align to interferometer
  - Place caliball at focus of transmission sphere
  - Install transmission flat in interferometer and internally align
  - Align Grism E1 to transmission flat (this aligns grism to on-axis field in tilt)
  - Scan Grism reference tooling balls with laser radar (this defines the 6 DOF alignment of the grism and the test coordinate system in tilt)
  - Project a line from the caliball parallel to the Z axis
  - Adjust the Grism in decenter and despace to be on the Z axis and set the E1 S1 center 731.39 mm from the caliball. This is defines the Grism On-Axis coordinate system.
  - Replace transmission flat with transmission sphere and internally align (alignment has been shown to repeat very well)

Grism EDU WFE and Focal Surface Mapping

- The Grism test configuration is dictated by its large field of view and difficulty in moving the interferometer. Therefore, the grism is adjusted relative to the interferometer using a hexapod.
- Grism wavefront error mapping is done in a double pass configuration with the interferometer beam retro reflecting off of a high quality sphere
- Grism focal surface mapping and is done using a Caliball as the retro reflector
- Alignment to each field
  - The Grism alignment for off-axis fields is set relative to its on-axis alignment to the interferometer (this relationship is transferred to table tie points)
  - For off-axis fields the Grism is adjusted in tip/tilt to the desired field angle and then translated to center the E1 S1 back to where it was on-axis.
  - Once the focus position is determined we remove the Caliball and adjust the high quality convex retro sphere to null power and tilt and acquire interferograms

Grism EDU WFE Optimization

- The Grism opto-mechanical alignment places each element to the allocated 6 degree of freedom tolerances to allow a reasonable starting wavefront error
- Optimization is performed by measuring the initial wavefront error over 5 selected field fields
  - (0 degrees off-axis in elevation, 0 degrees off-axis azimuth) or (0,0), (+3,0), (-3,0), (0,+10), (0,-10)
  - Misalignment manifests itself as wavefront error and is greatest off-axis; therefore we use the (0,+10), (0,-10) field points for initial optimization of non-focus terms
  - Based on sensitivity analyses the most sensitive decoupled motion to perform optimization using the E2 element as compensator is:
    - Elevation (rotation about X) for y astigmatism
    - Azimuth (rotation about Y) for x astigmatism
  - We need only measure at the (0,+10), (0,-10) fields during optimization

Grism EDU WFE Optimization

	WFE nm	WFE nm	WFE nm	WFE nm	WFE nm			
	Grism Delta El,Az (deg) (0, 0)	Grism Delta El,Az (deg) (+3, 0)	Grism Delta El,Az (deg) (-3, 0)	Grism Delta El,Az (deg) (0, +10)	Grism Delta El,Az (deg) (0, -10)	E2 Adj. Delta Az (arc min)	E2 Adj. Delta El (arc min)	
Total WFE								
Initial x ast		**94**	**-35**	-84	97			
y ast		27	-26	138	-167			
Adj1 x ast		127	-44	-82	129	-0.8	-6.6	wrong way
y ast		36	-28	220	-235			
Adj 2 x ast		28		-101	78	0.1	17.8	Right way
y ast		28		-13	-10			774 nm/deg
Adj3 x ast				-188		-6.7	0.7	wrong way
y ast				7				
Adj 4 x ast		32	-13	-35	6	12.0	-1.0	Right way
y ast		**-10**	**18**	-10	-33			890 nm/deg
Total WFE	**37**	**42**	**43**	**72**	**56**			

- Adjustments were initially the the wrong direction due to sign flips in the Grism optical model
- Balancing the x and y astigmatism across the (0,+10), (0,-10) also reduced the other aberrations and demonstrated that E2 was an effective global compensator
- The WFE includes a non-real contribution from spherical aberration that is fit due to the central obscuration. We later determined that using 6th instead of 12th order zernikes reduced this error
- The second stage of optimization required adjustment of E2 in despace to set the grism back focal length across the field

Grism EDU Confocality and Back Focal Length Adjustment

- As described previously, we have to tip/tilt the grism relative to the interferometer to measure wavefront error and back focal distance across the field of view.
- Modeling of the test configuration was performed to determine the nominal back focal length BLF for specific field points relative to the E1 Surface 2 center.
- After non-power wavefront optimization we measured the BFL for each field point and adjusted E2 spacing to correct for the error
- At the time of EDU initial despace adjustments we were still optimizing our alignment process and had not yet discovered that using 12th order Zernike fits was biasing our power measurement. Therefore we have a limited baseline for comparison. (we elected to use 6th order Zernikes instead of annular Zernikes)
- In total E2 was moved 323 microns towards E3; this slightly perturbed tip/tilt as well. The modelled and measured BFL for each field is shown below

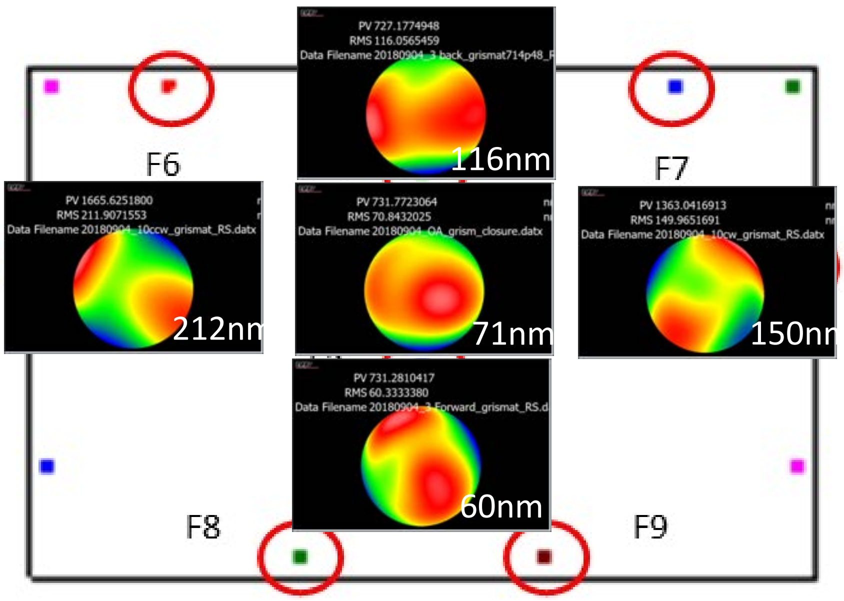
11_06_18	WFE (refocus zygo)	33.5	50.8	32.6	72	57	68.7	60.1	50.5	40.9
E1S1 Frame Measurements		1 (0, 0)	2 (+3, 0)	3 (-3, 0)	4 (0, +10)	5 (0, -10)	6 (+5, +7)	7 (+5, -7)	8 (-7, +3)	9 (-7, -3)
	global nom	731.35	731.23	731.50	731.33	731.33	731.04	731.04	731.71	731.71
No grism	(x with offset)									
0.00	X (mm)	-0.02	0.00	0.01	2.84	-2.86	1.98	-2.00	0.83	-0.86
0.00	Y (mm)	-0.17	-1.06	0.64	-0.34	-0.35	-1.77	-1.73	1.70	1.72
725.04	Z (mm)	724.98	724.78	725.11	724.88	724.85	724.60	724.60	725.33	725.34
6.35		6.35	6.35	6.35	6.35	6.35	6.35	6.35	6.35	6.35
731.39	actual best focus	731.33	731.13	731.46	731.24	731.21	730.96	730.95	731.69	731.69
	Ind field best focus	731.404	731.231	731.56	731.332	731.332	731.035	731.035	731.768	731.768
-0.089	Delta to best focus	-0.072	-0.105	-0.097	-0.092	-0.125	-0.079	-0.080	-0.082	-0.074
bias for avg	**Delta from Model (**	**0.018**	**-0.016**	**-0.007**	**-0.003**	**-0.035**	**0.011**	**0.009**	**0.008**	**0.015**
0.017	average (and devia	-0.08	-0.05	-0.05	-0.06	-0.03	-0.07	-0.07	-0.07	-0.08

Grism EDU Confocality and Back Focal Length Adjustment

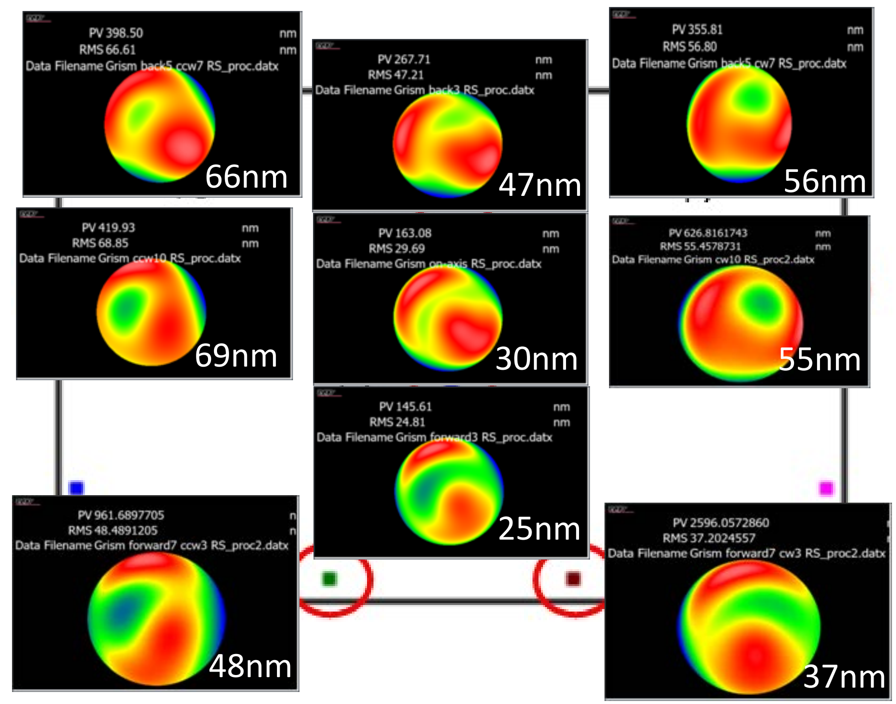
- In summary the Grism offset between the no-Grism focus of the interferometer and the Grism in focus position of the Caliball is 89 microns shorter than the ideal predicted by the model
- The standard deviation of the focus across the field is 17 microns, within the error of the measurement
- We elected to defer further adjustment to remove the residual -89 microns of back focal length error for the following reasons
  - We wanted to test the EDU grism cold to determine if there was a focus shift offset for cold
  - The E2 element was going to be changed out after the cold test and replaced with the ETU E2 element with the flight-like band pass coating; this requires re-optimization of the grism

Grism EDU WFE Improvement

Initial (before aligning)



Final (after aligning)

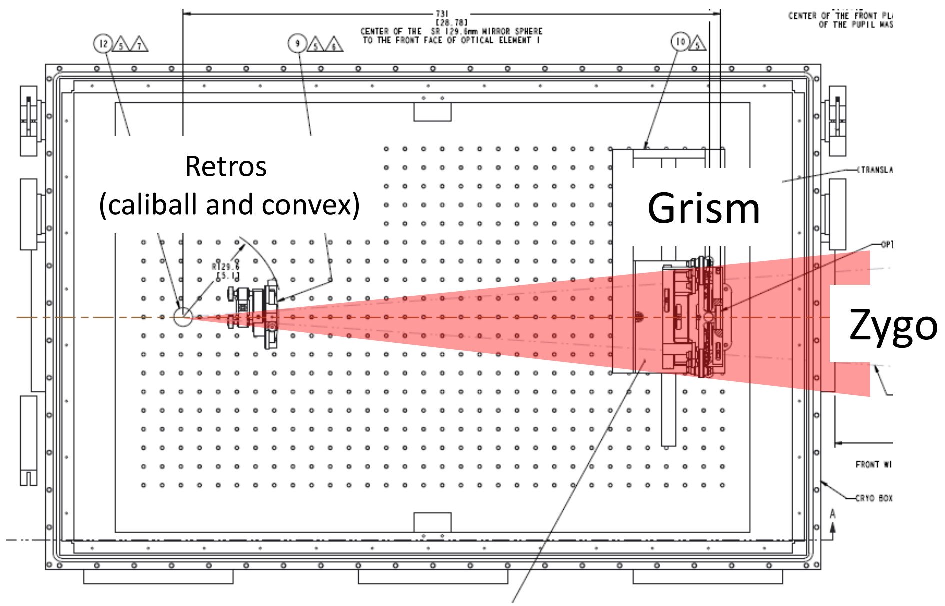


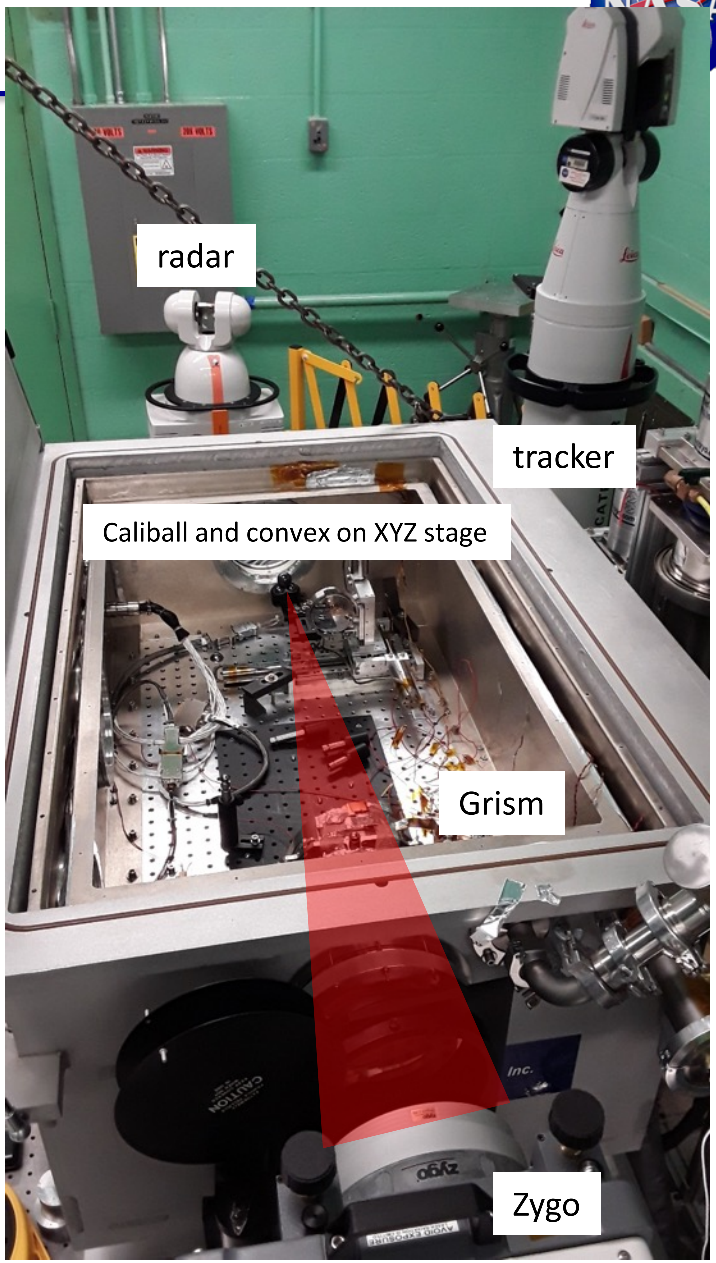
Using Concave retro

EDU Grism Cryogenic Testing

- The Grism minimal operating temperature is 160 Kelvins
- The Grism was mounted on a translation stage in the Cryogenic Distortion Measurement Facility (CDMF) \and configured for testing at cryogenic temperatures.
  - The CDMF has pressure windows and sapphire windows which are thermally sinked to the cold shroud to prevent thermal loading.
  - A convex retrosphere was used to allow the optical cavity to fit in the CDMF; by translating the grism, the WFE of the windows and retrosphere can be subtracted from the test set.
  - The convex retrosphere was mounted onto an x y z translation stage to allow fine alignment to the grism at temperature
  - A caliball was also mounted on the x y z stage to allow realignment to retro off of the caliball for measurements of the back focal length relative to the grism at cold temperature
  - The position of the grism, caliball and convex retrosphere was monitored through out testing with a laser radar viewing them through the back window of the CDMF.

Cryo Grism EDU layout in lab 6 CDMF chamber using convex retro and caliball

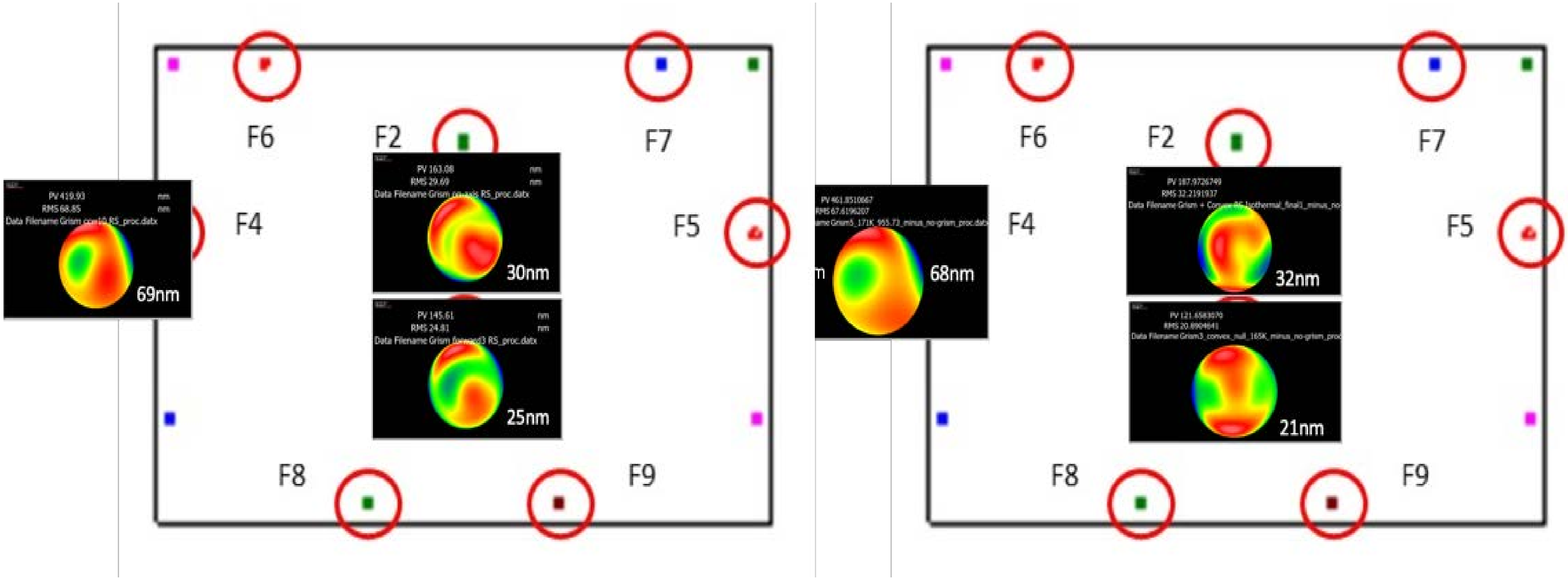




Hardware used:
Zygo, SMRs an TBs on motorized XYZ stage and grism deck, caliball, convex retro (ROC=126mm), motorized XYZ stage, laser tracker and laser radar.

Grism warm and cold WFE at 3 Fields

- Figure 2. Initial and adjusted wavefront error of grism
-



Grism EDU Cryo: Radar-Tracker Correlation

Correlation between laser radar and laser tracker

- On average the tracker and radar match each other within 23 µm
- There were differences in the tracker and radar (through window) absolute measurements due to known phase errors due to windows
- We demonstrated that radar could accurately measure changes in alignment even through the window for displacements larger than seen in test

		Grism displacement (pre-post cryo cycle) [mm]		
		X	Y	Z
3 deg tilt	Tracker	0.033	-0.060	-0.001
	Radar	-0.010	-0.041	-0.028
	Difference	0.042	0.019	0.027
0 deg tilt (1st round)	Tracker	-0.054	-0.125	0.001
	Radar	-0.028	-0.122	0.009
	Difference	0.026	0.003	0.008
0 deg tilt (2nd round)	Tracker	-0.005	-0.072	0.020
	Radar	0.013	-0.109	-0.005
	Difference	0.018	0.037	0.025

Grism EDU Cryo: WFE and BFL Measurements

- The EDU cryogenic test demonstrated that the Grism wavefront error was stable from ambient to cryogenic operating temperature at the 3 selected fields that were measured.
  - Change for Zernike fit data was within the measurement noise
  - Change for subtracted data for the 10 degree off-axis field including unfit Zernikes was 38 nm; we consider this to be a very conservative estimate
- The second parameter measured was Back Focal Length (BFL) at cryogenic operating temperature
  - Only the on-axis field position was configured for this measurement
  - We found that the change in the BFL from ambient to cryogenic operating temperature was close to the noise of the measurement
  - Additional testing of the Cryo BFL will be performed at other field angles

Grism EDU BFL Cryo Change On-Axis

On-Axis				
Ambient Vacuum		x mm	y mm	z mm
Focus (w/ grism)	Caliball	-0.833	-0.529	715.140
Focus (no grism)	Caliball	-0.837	-0.409	715.231
	Delta (mm)	0.004	-0.120	-0.091
Cold Vacuum		x mm	y mm	z mm
Focus (w/ grism)	Caliball	-0.786	-0.501	715.339
Focus (no grism)	Caliball	-0.824	-0.403	715.393
	Delta (mm)	0.038	-0.098	-0.054
			cold - warm	0.037
Post Test Ambient Vacuum		x mm	y mm	z mm
Focus (w/ grism)	Caliball	-0.785	-0.550	715.204
Focus (no grism)	Caliball	-0.845	-0.423	715.267
	Delta (mm)	0.060	-0.128	-0.063
			warm-warm	0.028

Grism focus change was close to the measurement error

Conclusions

- We believe the EDU demonstrates we can deliver a Flight Grism to the required specifications
- The elements can be fabricated to the required tolerances
- The elements can be aligned to an initial starting condition within our capture range
- The elements can be realigned to meet the WFE and BFL tolerances
- The opto-mechanical design is athermal and can meet requirements at cryo operational temperature