Point Source sensitivity, Pupil alignment, Calibration and Control for TMT-NFIRAOS-IRIS

Glen Herriot[1]

Jean-Pierre Véran[1], Ryuji Suzuki[2], Gelys Trancho[3]

[1]National Research Council Canada, [2]NAOJ, [3]TMT

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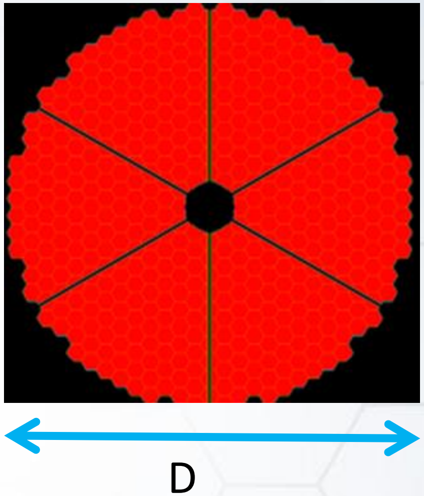
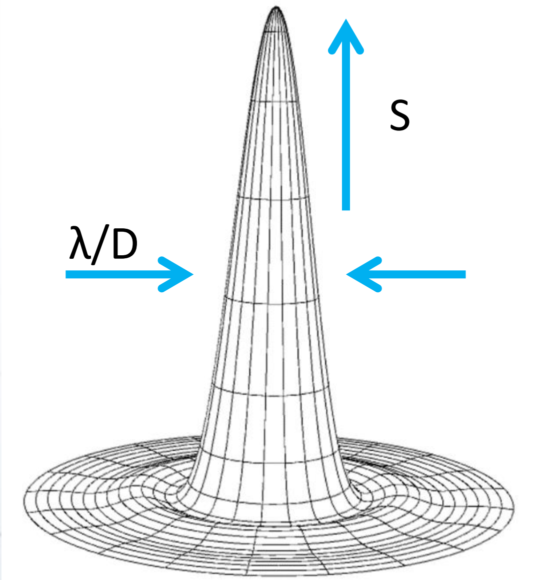
Sensitivity for background limited point sources

- D^4 advantage of an ELT (with perfect AO)
  - Area Telescope ~ D^2
  - 1/Area of Point Spread Function ~ D^2
- Degraded by
  - Wavefront Error ~ S^2
  - Optical Throughput
  - Thermal Background
    - = Function of temperature, emissivity
  - Etc.





Point Source Sensitivity

- Inverse of observing time.
- $\mathrm{PSS} \propto \frac{A}{f_{bg}} \int \varphi_{(\theta)}^{2} d\Omega$
  - $\varphi_{(\theta)}$ is 2D PSF profile normalized so $\int \varphi_{(\theta)} d\Omega = 1$
  - A is telescope aperture area
  - f_{bg} is a photon flux of background per unit area, unit time, and unit solid angle

Point Source Sensitivity - Normalized

- $\mathrm{PSSN} = \frac{A}{A_0} \times \frac{f_{bg0}}{f_{bg}} \times \frac{\int \varphi^2_{(\theta)} d\Omega}{\int \varphi^2_{0(\theta)} d\Omega} \times \cdots$
- PSS Normalized to a reference case.
  - A_0 telescope aperture as designed, unvignetted by Lyot stop
  - f_{bg0} telescope background with a perfectly aligned and sized Lyot stop
  - $\varphi_{0(\theta)}$ diffraction limited PSF

Existing PSSN Budget

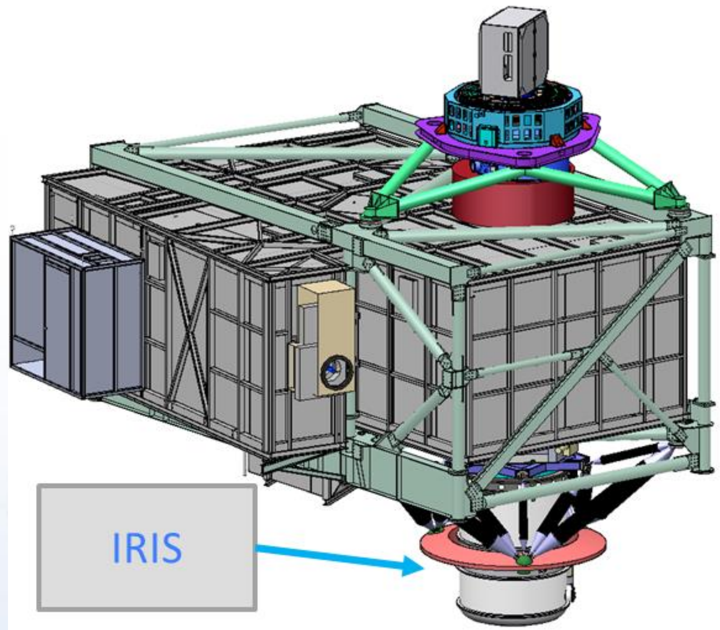
	On Axis PSSN Budget			
Item	K			
PSSN MCAO NFIRAOS + IRIS Imager	**0.123**			
Wavefront Error (PSS ∝ S^2)		**0.592**		
High Order WFE in nm -> S^2			0.617	172 nm
Lo Order WFE broadening PSF -> S			0.960	71 nm
Throughput (PSS ∝ η)		**0.328**		
Telescope Requirement			0.910	
NFIRAOS Requirement			0.800	
IRIS Imager Requirement			0.450	
Pupil Shift (1% Undersized Lyot		**0.702**		
Loss of pupil area			0.887	
Undersized Lyot mask PSF broadening			0.791	
Background [PSS ∝ $(1+I_b/I_0)^{-1}$]		**0.958**		
Thermal Background			0.960	NFIRAOS Cooled to - 30 C
Scattered Light			0.999	
Out of focus ghosts			0.999	
Image Smearing (PSS ∝ S)		**0.950**		0.5mas allocation
Image derotator				
Offset b/w OIWFS/IRIS Focal plane				
ADC errors				
Amplitude non-uniformities		**0.994**		
Atmospheric scintillation			0.994	
M1 segments T.P variation			0.9998	0.93+/-0.03
Ghosting (PSS ∝ 1-2ε)		**0.999**		
Static focused ghost			<5 x 10^{-4}	

Reducing this 30% Loss of observing time is the motivation for this talk

Pupil Alignment
The over-looked tall pole:

- 1% end-to-end pupil misalignment causes:
- 30% observing time penalty!!
  - If Telescope pupil is misaligned onto IRIS Lyot stop due to tolerances
  - Then Lyot stop should be undersized to block background

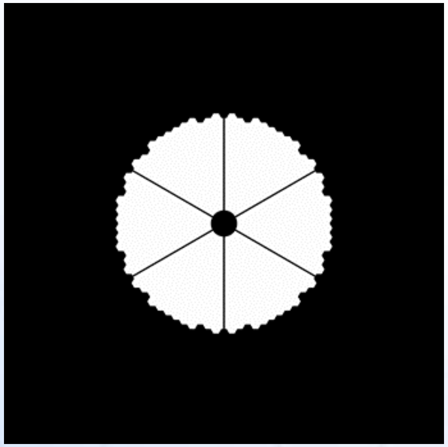
IRIS is the first light Imaging Spectrograph for TMT.

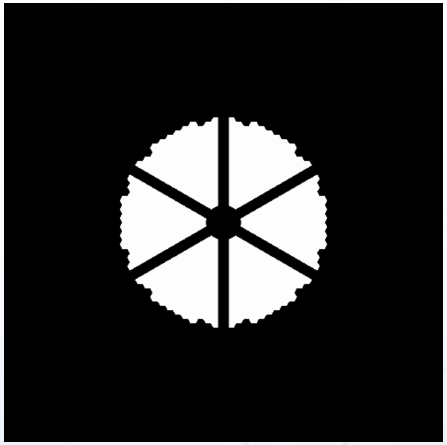


NFIRAOS

Lyot Mask Undersizing - Loss of throughput

- Lyot stop defined by undersizing factor $\alpha = 2 \times$ shift
  - fraction of the telescope pupil diameter D_{M1}.
- All interior edges intrude into aperture
  - Serrated outer perimeter is shrunk by αD_{M1}
  - Central obscuration is enlarged by αD_{M1}
  - The M2 spider widths are thickened by αD_{M1}





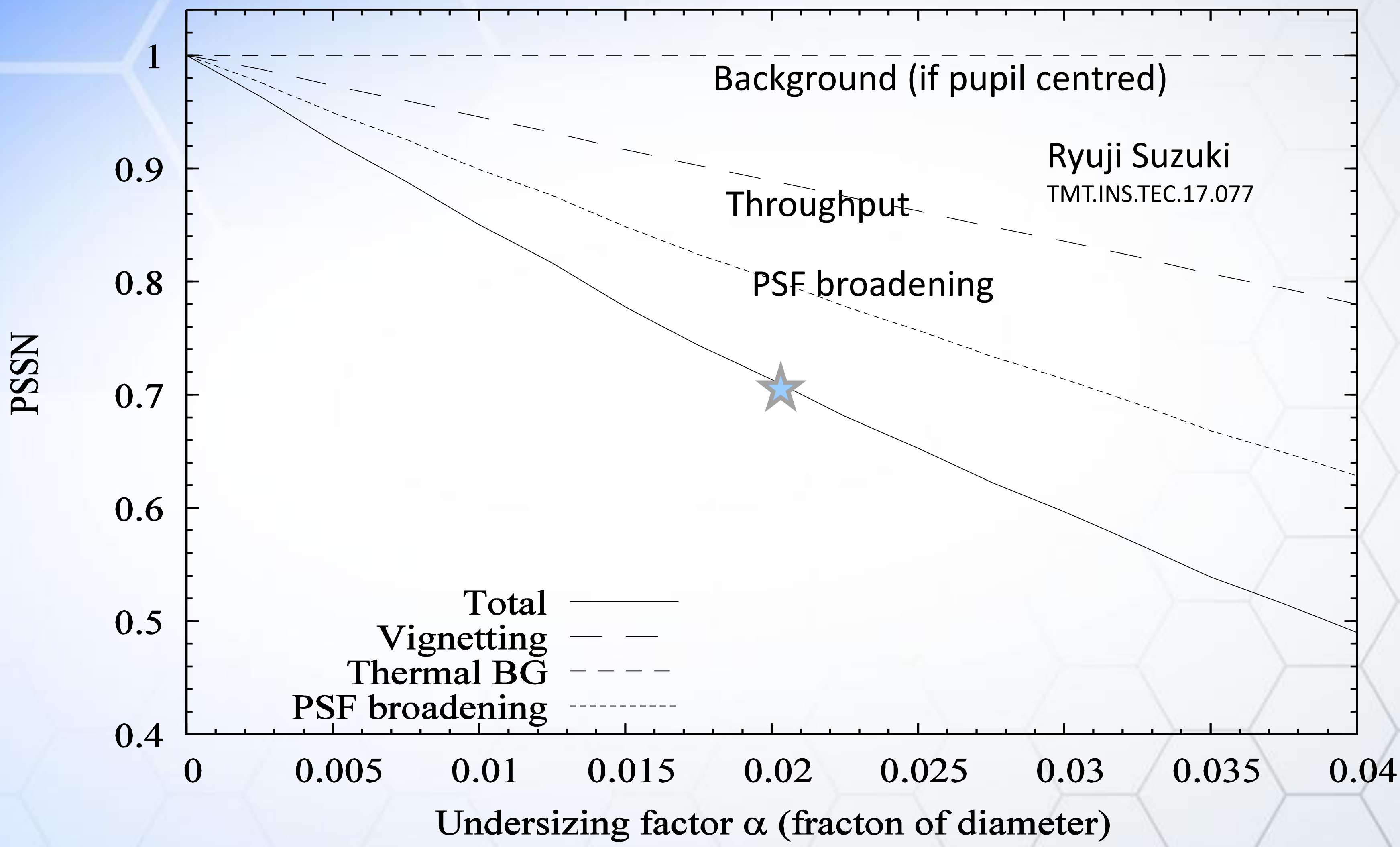
$\alpha = 0.02$ causes 11% loss of Area!

Lyot Stop Undersizing -PSF Broadening

- Smaller, less-filled pupil Mask for 1% misaligment, causes 21% decreased PSSN
- Because S^2 declines rapidly with broader PSF.
- PSF $\varphi_{(\vec{\theta})}$ is squared absolute value of the Fourier transform of pupil function $P_{tel(\vec{\rho})}$,
  - Vignetted by Lyot Stop $T_{LS(\vec{\rho},\alpha,\beta)}$; ($\beta$ is as-built pupil shift)
- $\varphi_{(\vec{\theta})} = \left|\mathrm{FT}\left[\frac{P_{tel(\vec{\rho})} T_{LS(\vec{\rho},\alpha,\beta)}}{\int P_{tel(\vec{\rho})} T_{LS(\vec{\rho},\alpha,\beta)} d\vec{\rho}}\right]\right|^2$

α = 0.02 causes 21% loss from PSF broadening alone!

PSSN loss versus Lyot stop undersizing



How did we get here?

- A decade ago we decided to do “twice as good as Gemini for Lyot masks undersizing.” So we picked +/- 1% for pupil misalignment
- It is challenging for the Telescope to steer its pupil accurately onto DM0 within NFIRAOS.
- NFIRAOS has a goal to work with D/240 pupil shift on DM0 -- causes tomography errors.
- NFIRAOS wavefront error budget allocates 27 nm for tomography effects due to pupil shift

Three related budgets

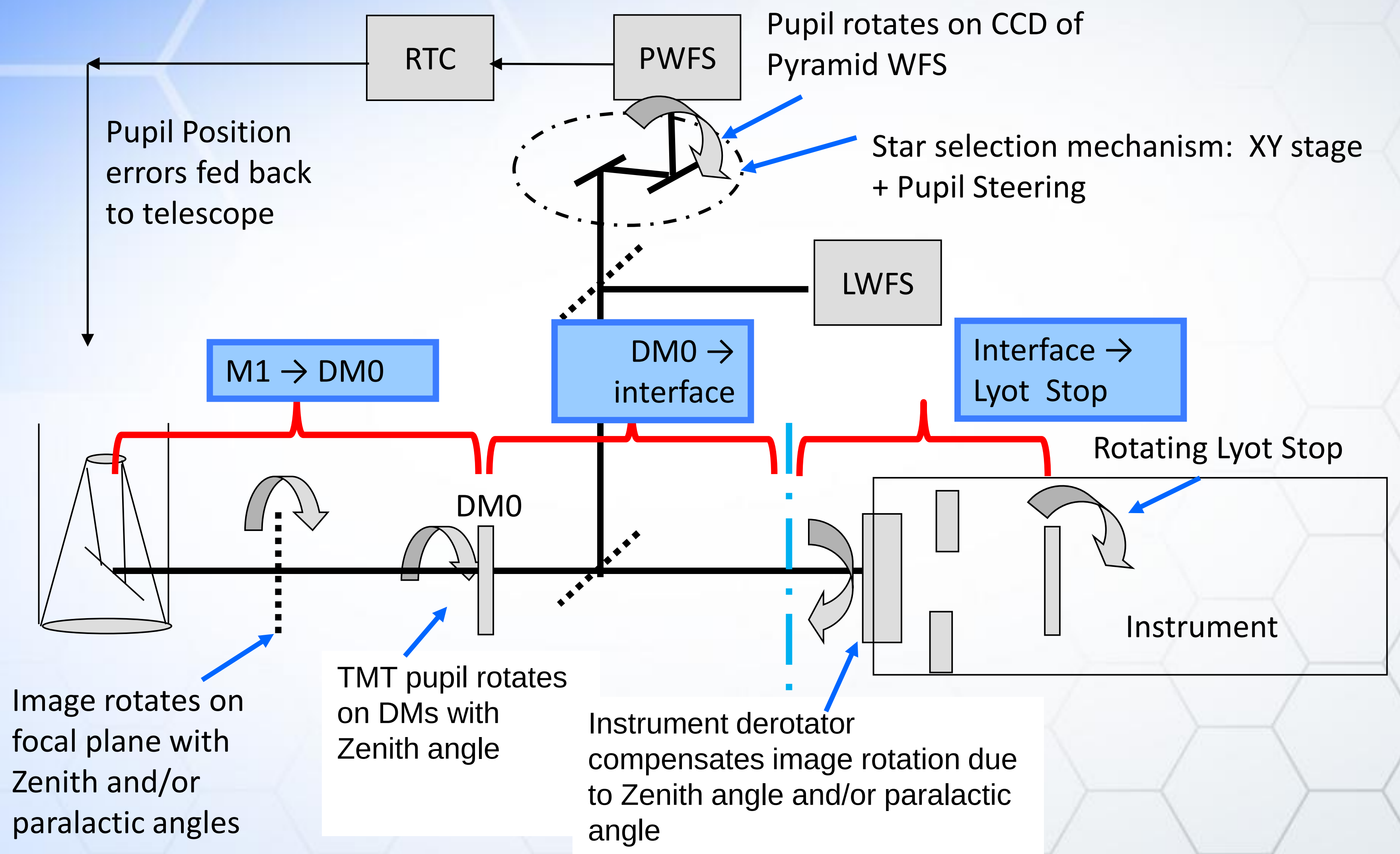
Pupil Position on Lyot mask - shift in % Dia.	Allocate Proposed ±1% Dia.
Telescope to DM0	1/240
Errors in Feedback to TCS from NFIRAOS due to segment exchange	0.2
Other errors in pupil onto DM0	0.365
Delivered pupil w.r.t. interface to IRIS	1/300
IRIS Lyot mask position w.r.t. NFIRAOS interface.	1/300

Mask Undersize (% radius)	Required (Proposed) 1% Radius	C.B.E 1.3%
Position	1%	1%
IRIS pupil aberrations		0.2
Rotator bearing Runout	(55 μ Rad)	0.08

PSSN Budget On-axis Kband	
Lyot Mask 1% Radius Undersizing - throughput losses	0.887
Lyot Mask Undersizing PSF broadening losses	0.791
Thermal Background at -30 C	0.96
NFIRAOS throughput	0.8
IRIS throughput	0.45
Etc.	---

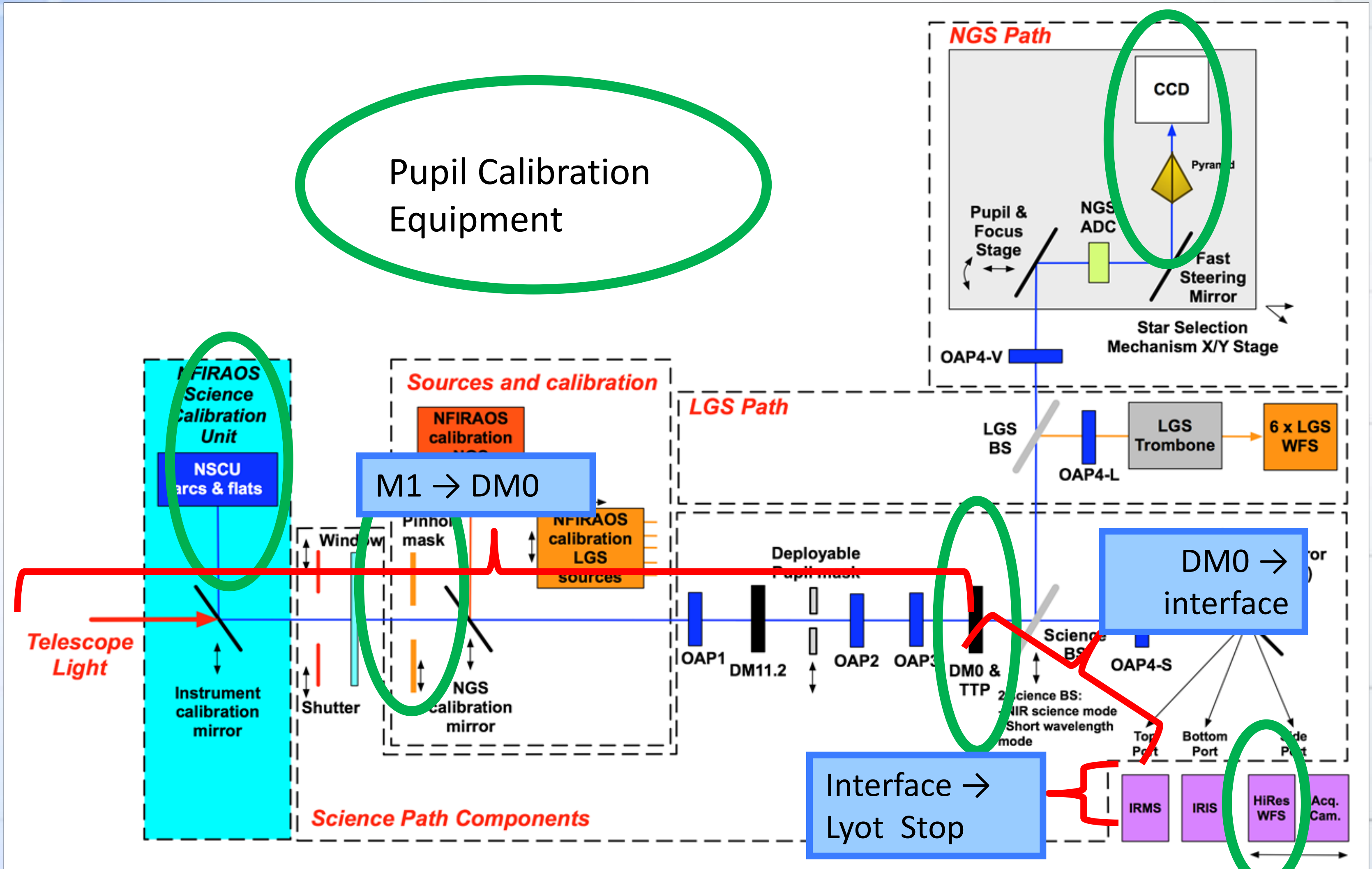
TMT.AOS.TEC.15.103.DRF01

Pupil and Image rotation

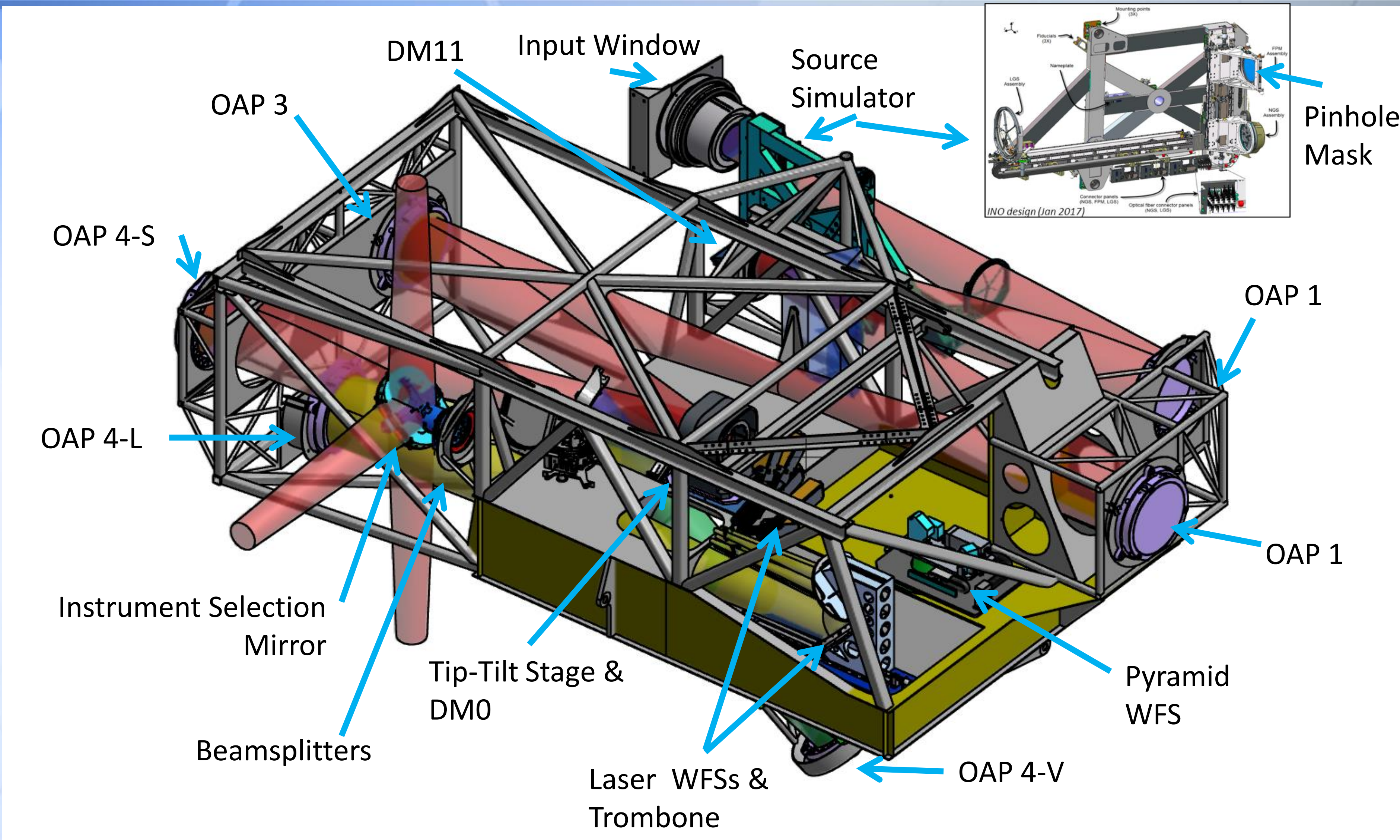


NFIRAOS Optical Block Diagram

- Science Path is blue horizontal line



NFIRAOS Opto-mechanics



Pupil Feedback to Telescope Control System (TCS)

- On-sky, NFIRAOS will feed back to the telescope control system:
  - Image position
  - Quasi-static wavefront error
  - Pupil shift error signals

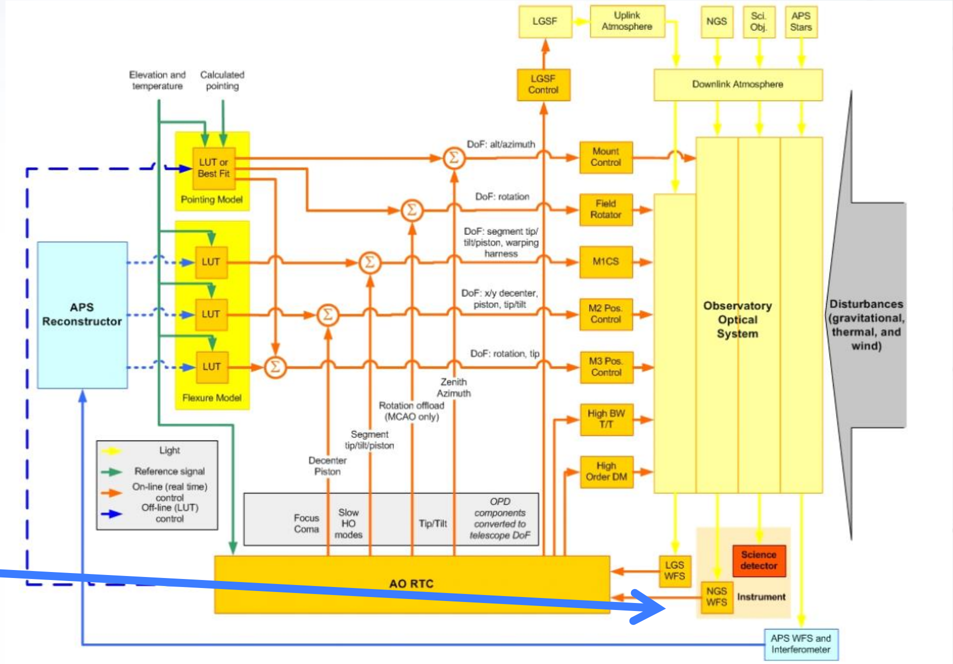
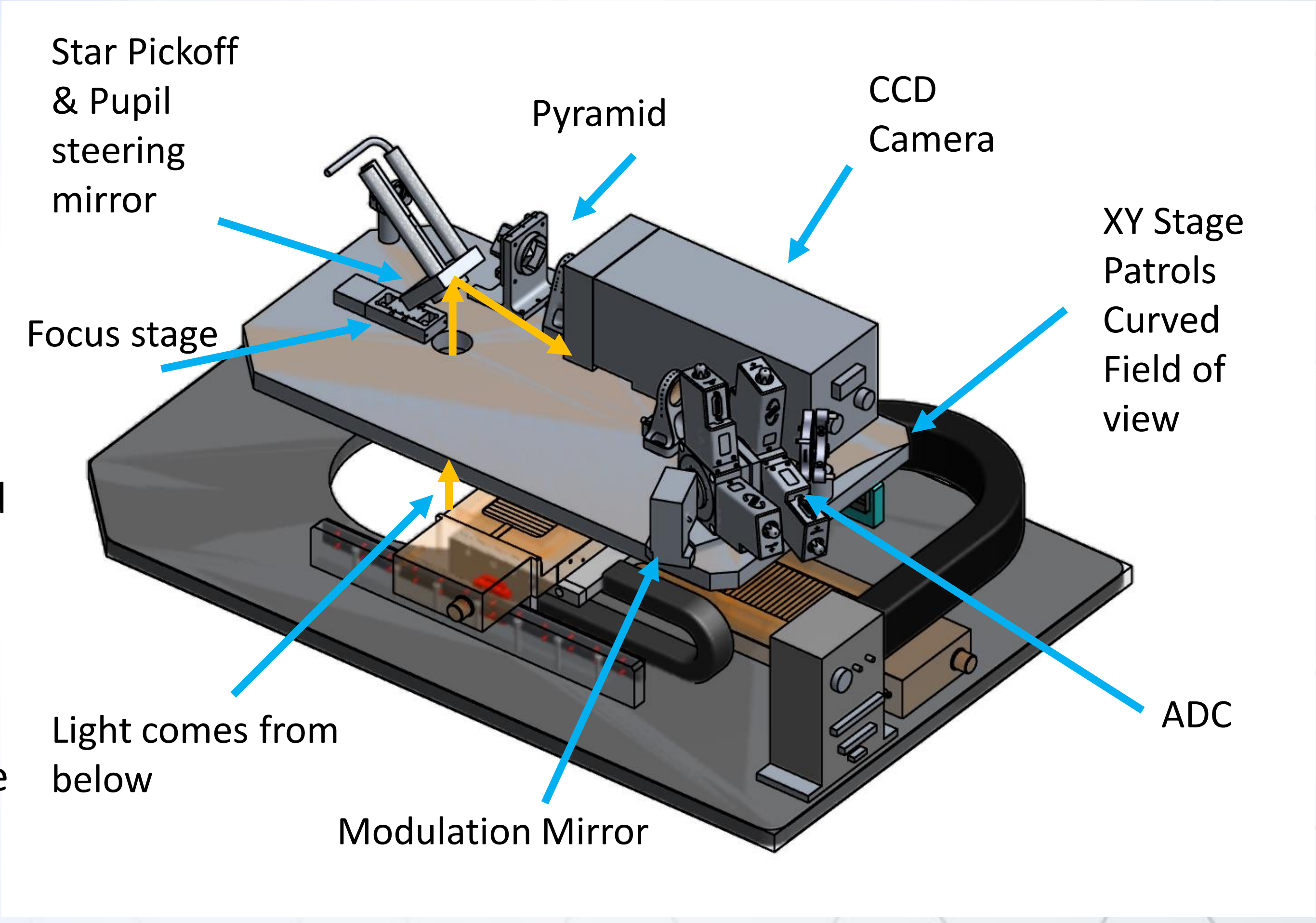


Figure: Control Architecture for adaptive optics observations

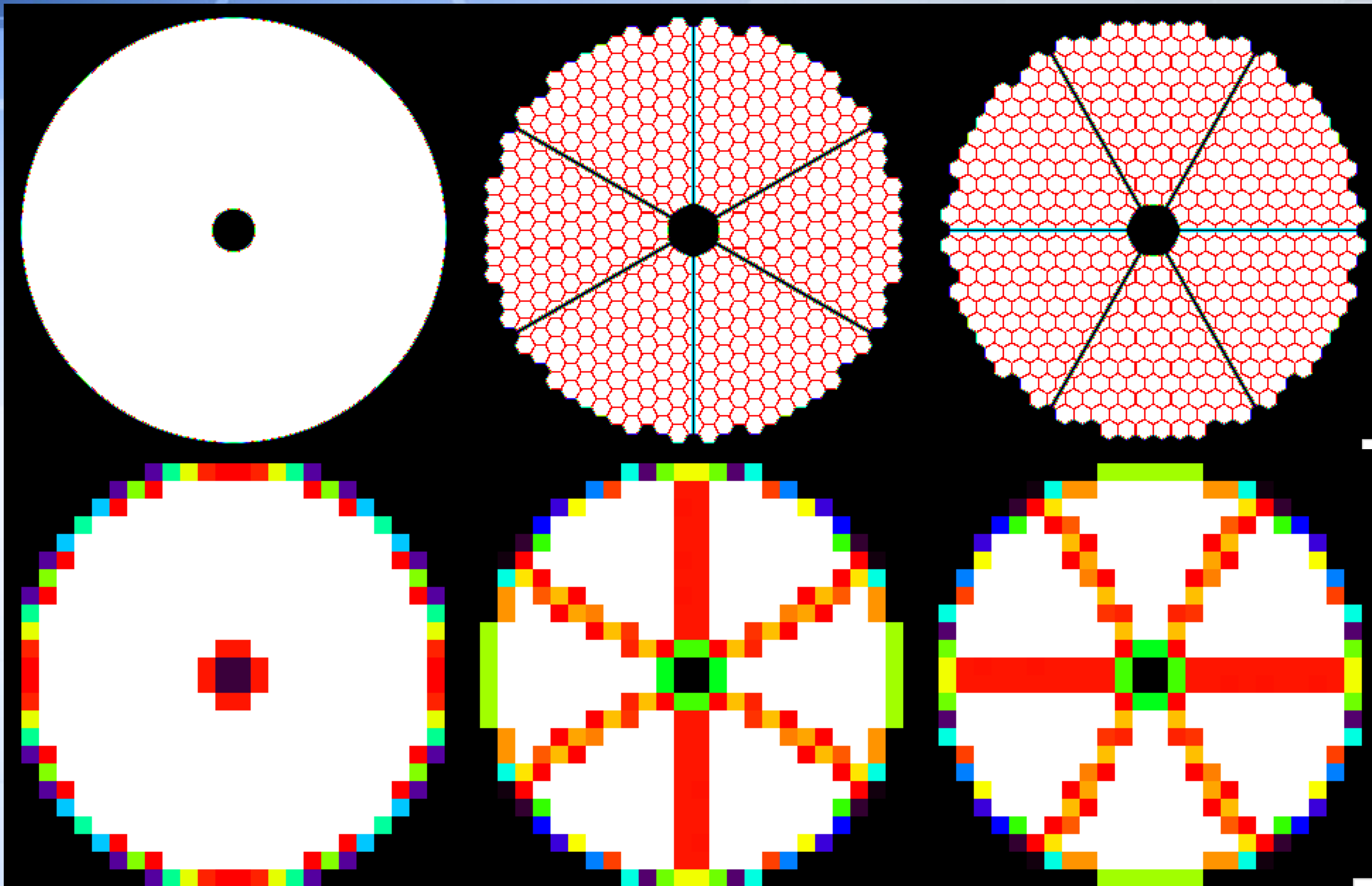
- TCS will adjust the alignment of TMT's three mirrors

NFIRAOS Pyramid WFS Visible-Light Natural Guide Star

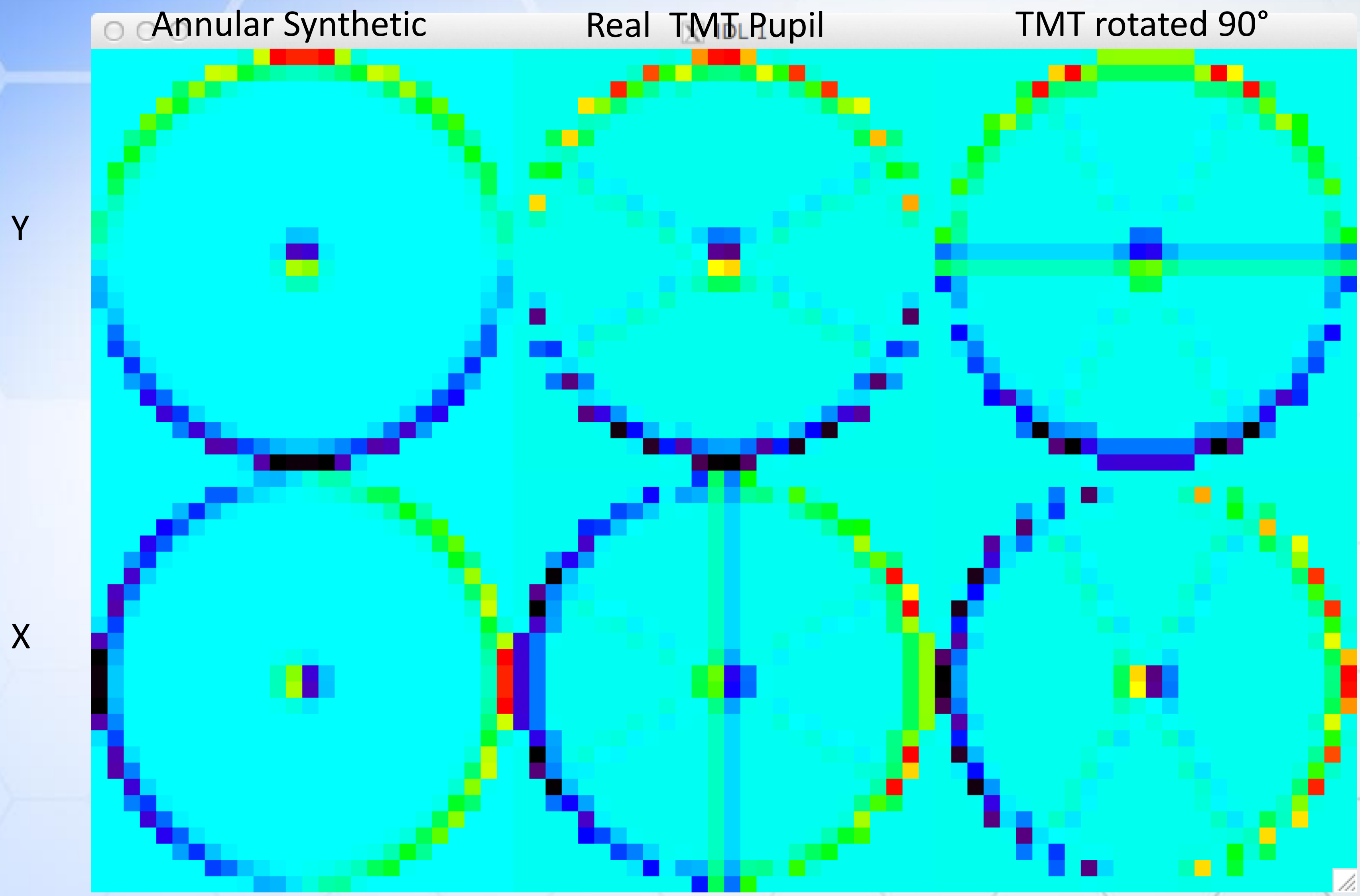
- Calibrated in daytime via Focal Plane Pinhole mask and DM0 actuator pokes.
- Pointing Model for 7 motors (XYZTT +ADC)
- Zero point of pupil images on CCD verified by actuator pokes in afternoon
- PWFS then is pupil reference for telescope feedback on-sky



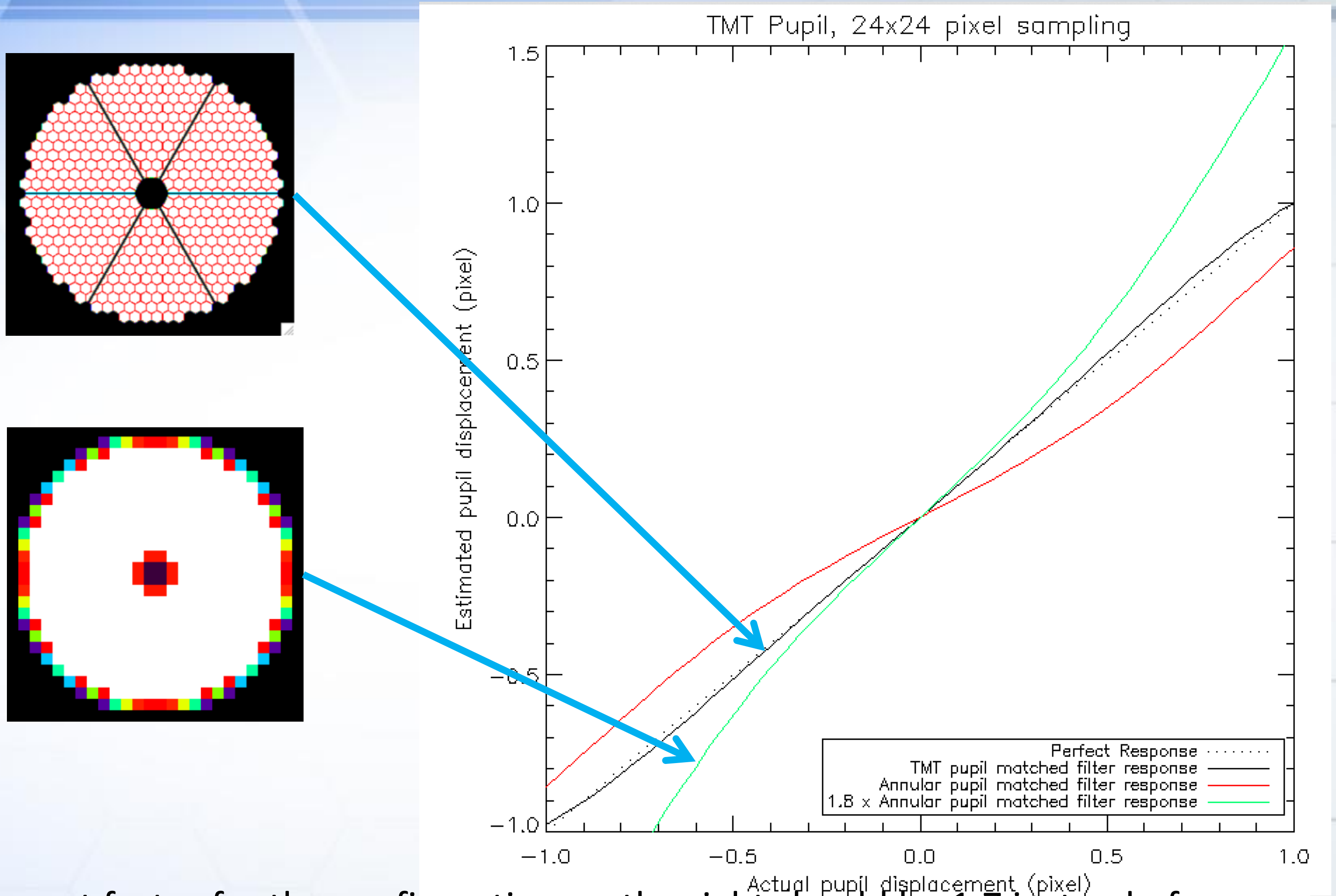
TMT Pupils: full resolution and 24x24 binning on PWFS



Matched filters



Circular matched filter is OKAY



Gain adjustment factor for the configuration on the right should be 1.7 instead of 1.8: negligible effect

Results

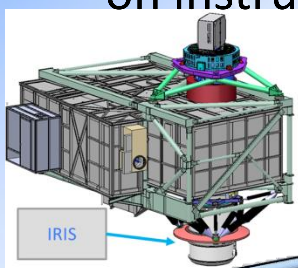
- In dark time (no Moon), background light is 10x lower and with matched filters, the pupil position estimation error increases from ~0.010% RMS to ~0.022% RMS
  - Error due to M1 segment reflectivity non-uniformity remains at ~0.005% RMS
- Using an annular matched filters that ignores the spiders only increases pupil estimation error from ~0.022% RMS to ~0.028% RMS
  - Error due to segment reflectivity non-uniformity reduces to ~0.004% RMS

New M1-DM0 pupil position error breakdown

116	**M1- DM0 pupil position**		0.417%		Budget = 1/240 of pupil diameter
117					
118					
119	Pupil position estimation error		0.010%		Based on simulations of how well pupil position can be determined on the PWFS
120	M3 pointing error		0.002%		How well M3 can repoint (see section 4.2 of TMT.AOS.TEC.15.103.DRF01)
121	Sensitivity of pupil steering mirror(%D / mrad of mechanical motion)	2.985%			
122	Angular resolution of motors (urad)	10	0.030%		NFIRAOS pupil centering mirror requriement
123	Repeatability of motors (urad)	20	0.060%		NFIRAOS pupil centering mirror requriement
124	Accuracy of motors (urad)	40	0.119%		NFIRAOS pupil centering mirror requriement. Must be no more than ~0.1pix no to lose to much flux
125	Poiniting model error		0.050%		Ability to build a model
126	Non-uniformity of M1 segment reflectivity		0.005%		Due to recoating schedule
127					
128					
129					
130	RSS (yellow and orange terms)		0.146%		
131	Sum (yellow and orange terms)		0.276%		
132	RSS (orange terms)		0.032%		
133	Sum (yellow terms)		0.234%		
134	RSS (orange terms) + Sum (yellow terms)		0.329%		

Instrument alignment features at interface

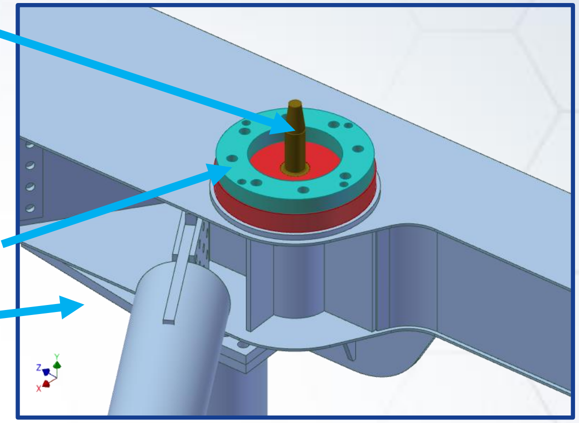
- 2 pins go into slot & hole on instrument truss

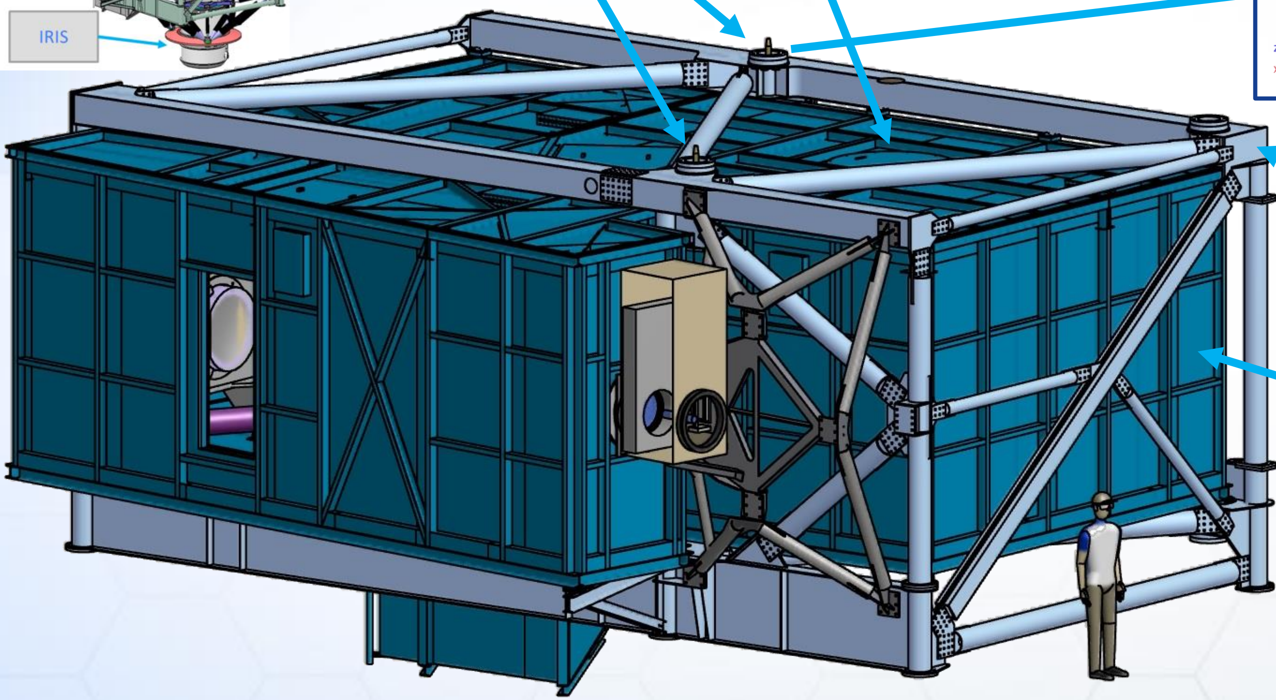


Port hole

Pins adjusted laterally via clearance holes

Tip/Tilt and axial adjustment shims

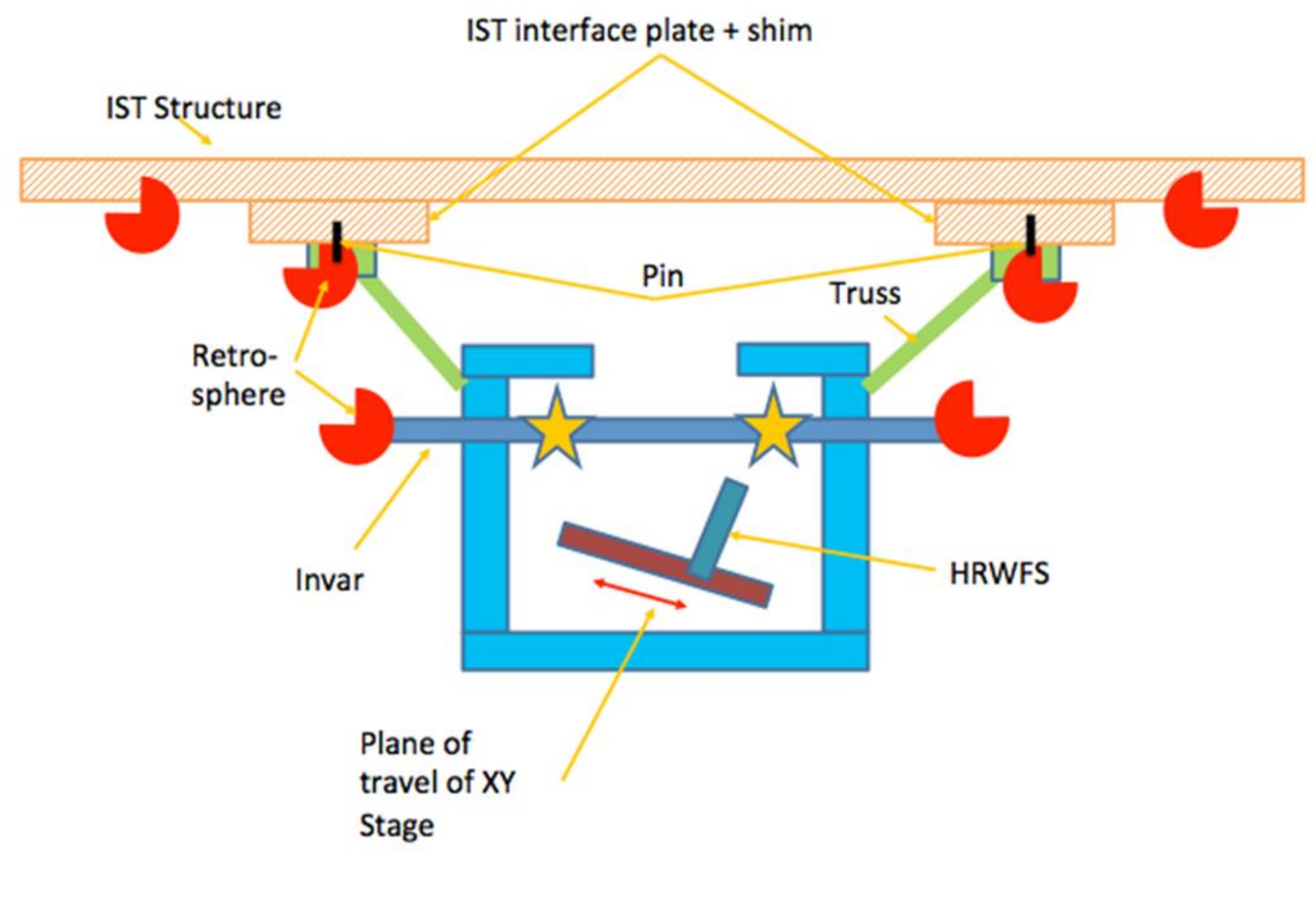




Flat

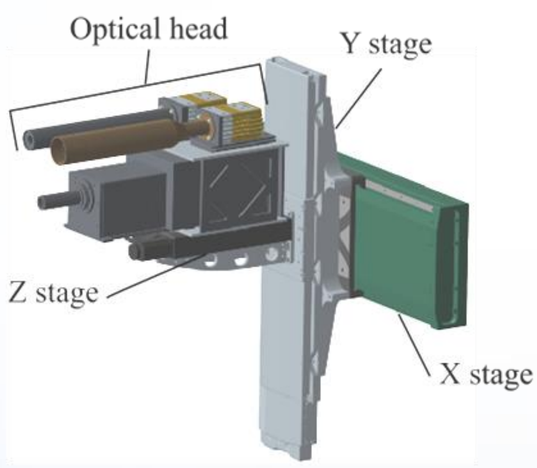
- Cooled enclosure
- -30 deg C
- Class 10,000 clean room

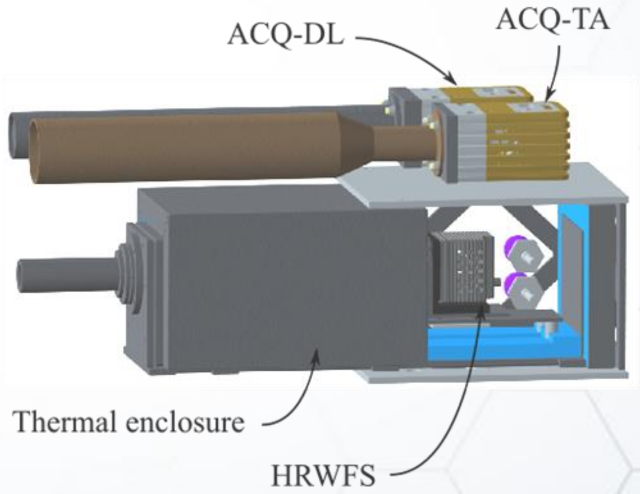
Measuring Pupil Shift DM0- Interface Cross Section through NSEN



Stages and Cameras in NSEN (NFIRAOS Sensors)

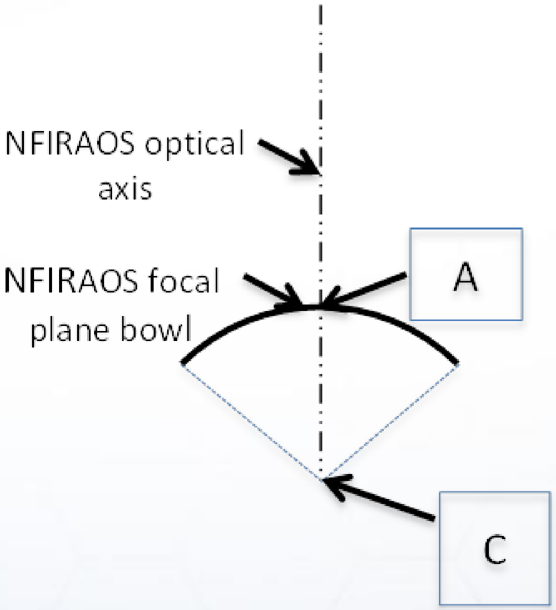
- Cameras & WFS inside NSEN





NSEN Maps focal plane bowl and location of central pinhole

- C is the XYZ centre of curvature of the focal plane
- C should have same XY coordinates as A
- A is the measured XYZ location of central pinhole image



Delivered focal plane position and tilt

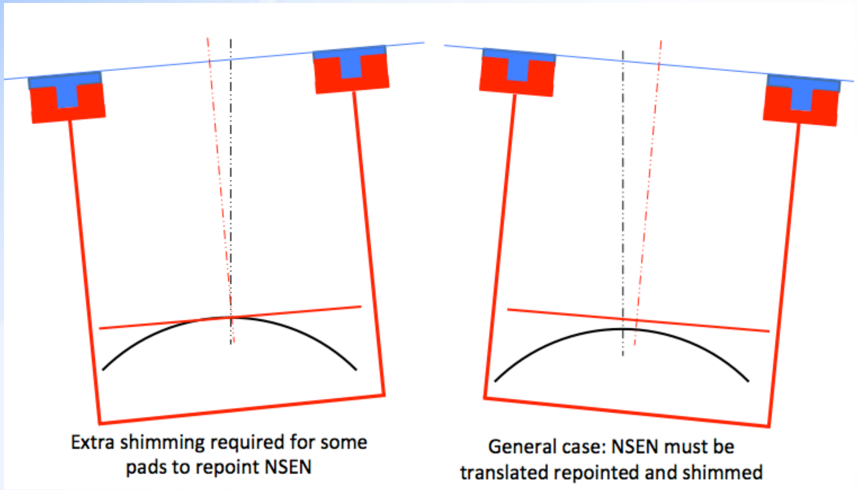
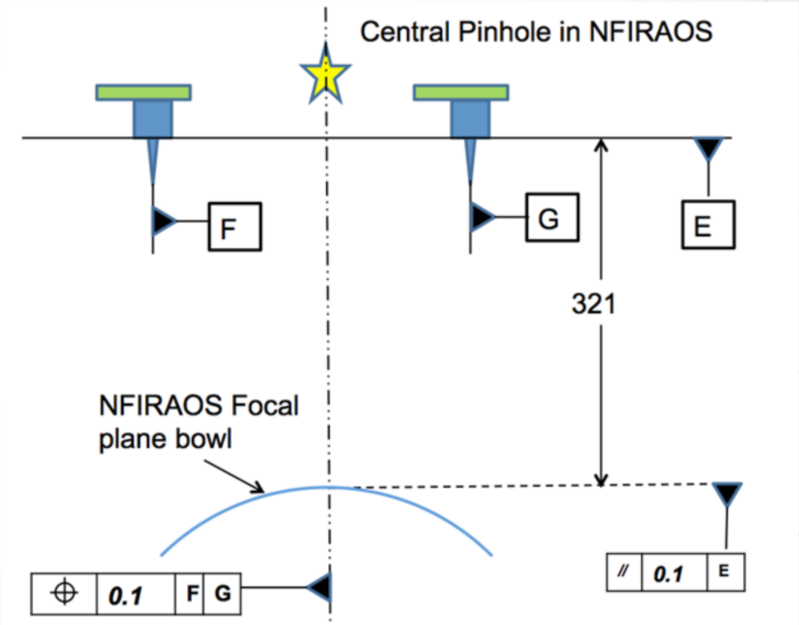


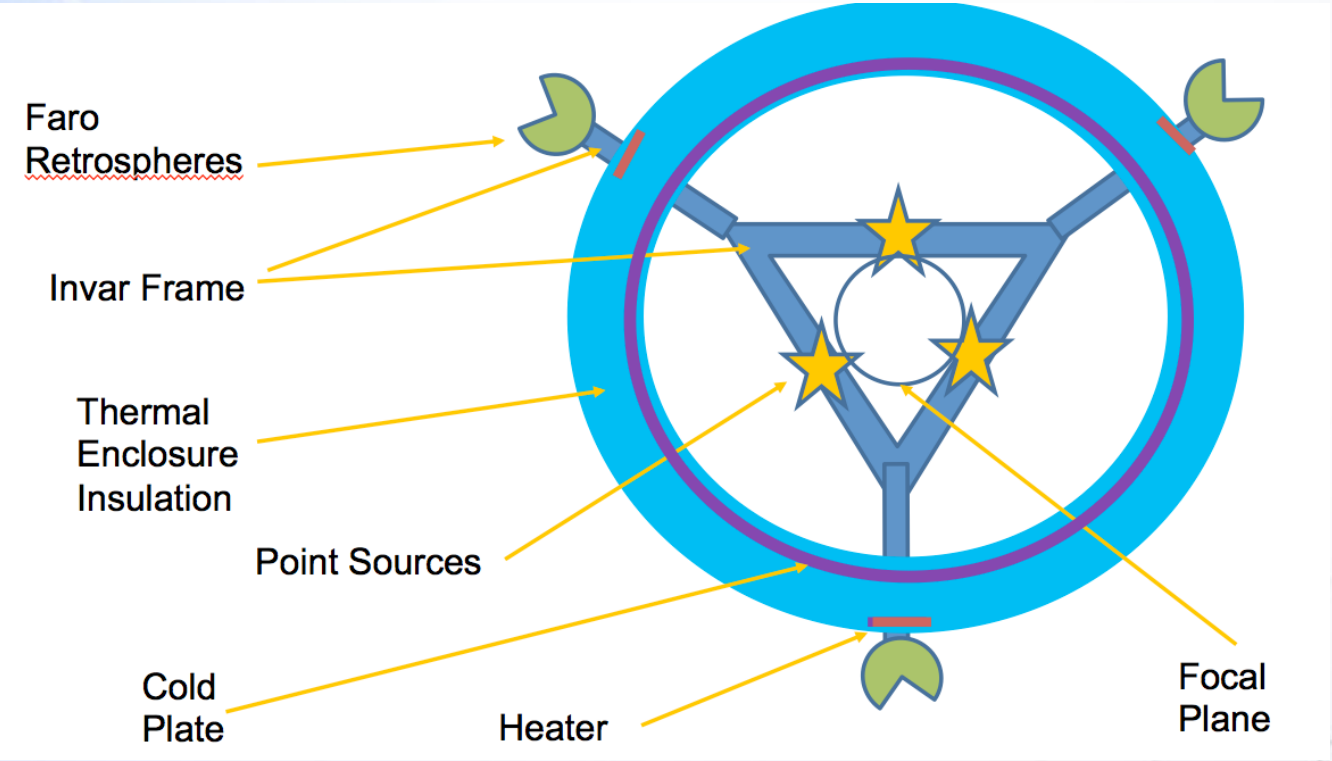
Image is centred, but pupil is off-centre

Alignment tolerance Delivered focal plane w.r.t. interface to instruments

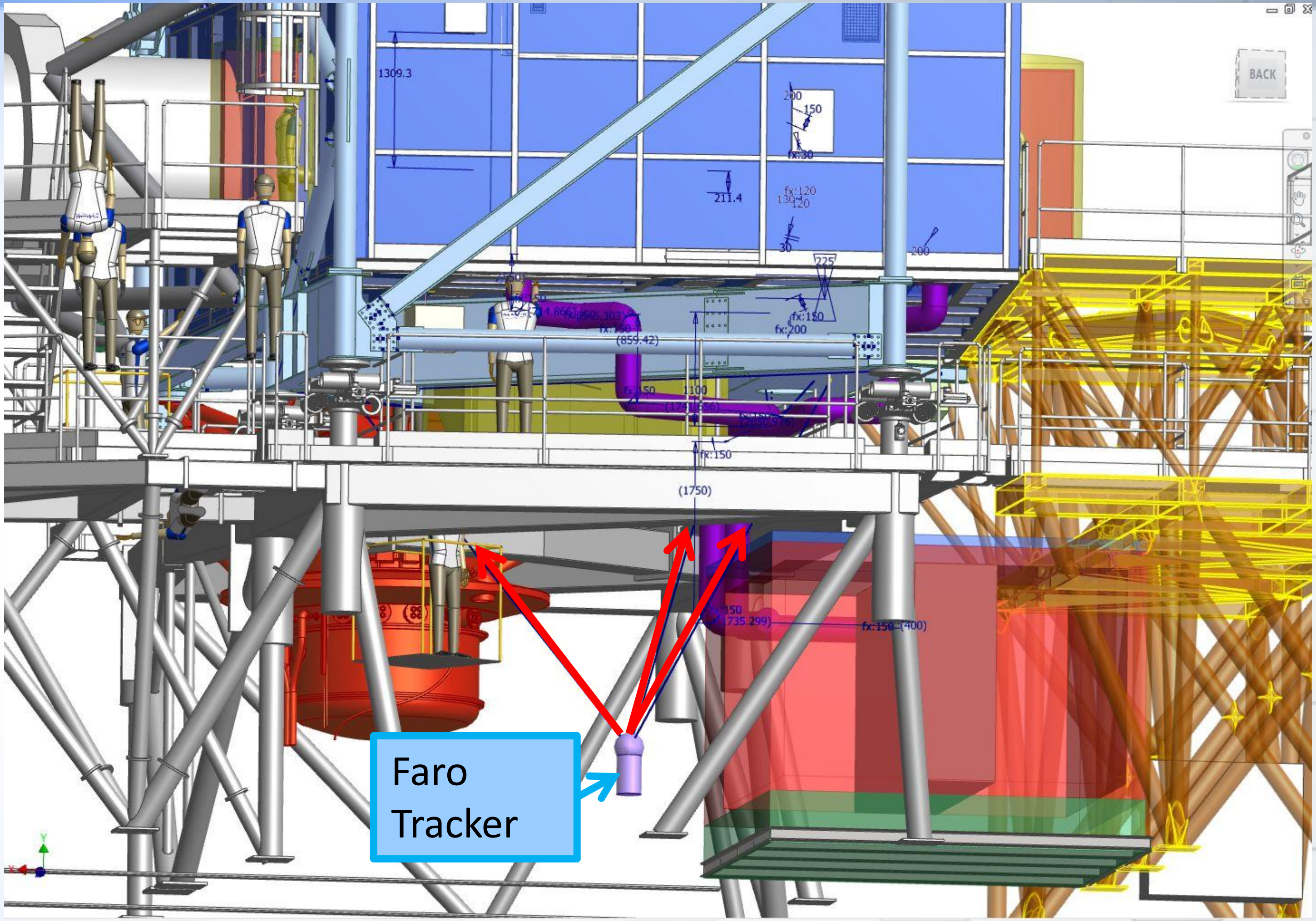


NSEN FOCAL Plane reference sources

- View looking towards NFIRAOS from NSEN WFS.

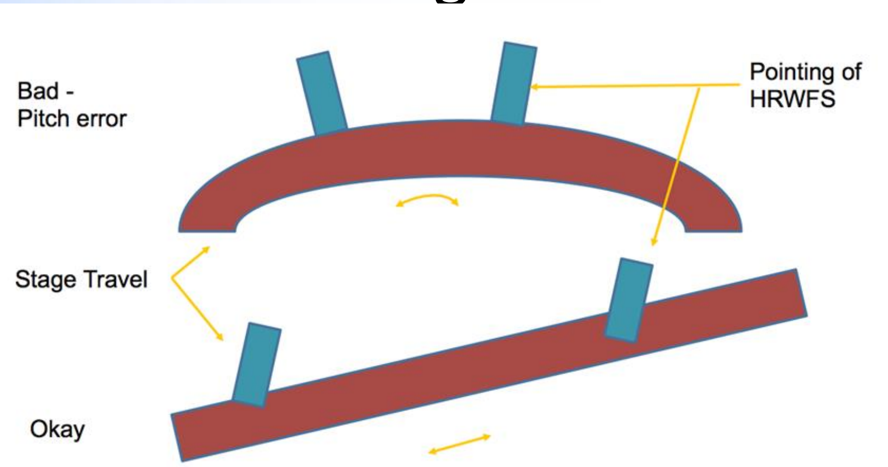


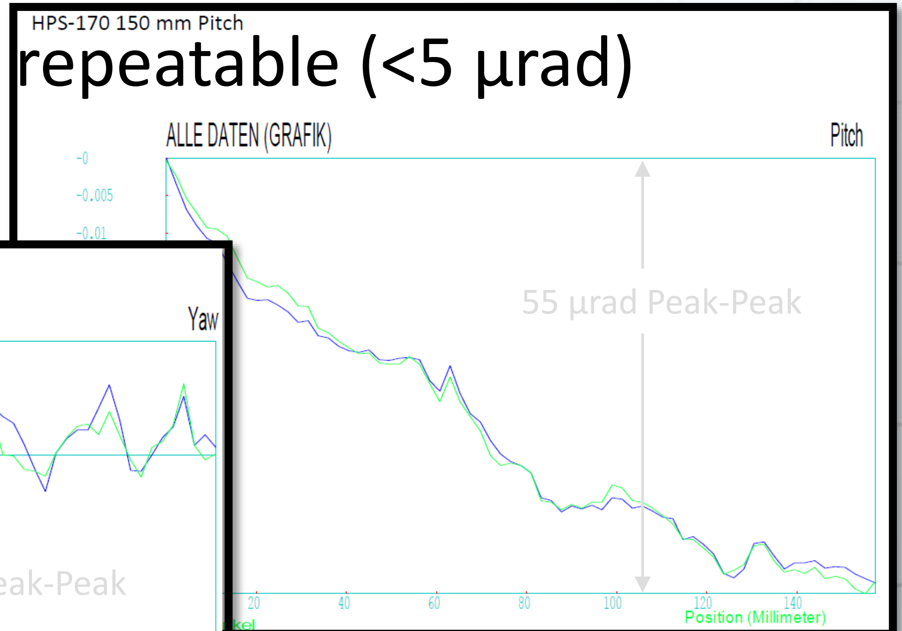
Faro Tracker views instrument mounting pads & NSEN cal src

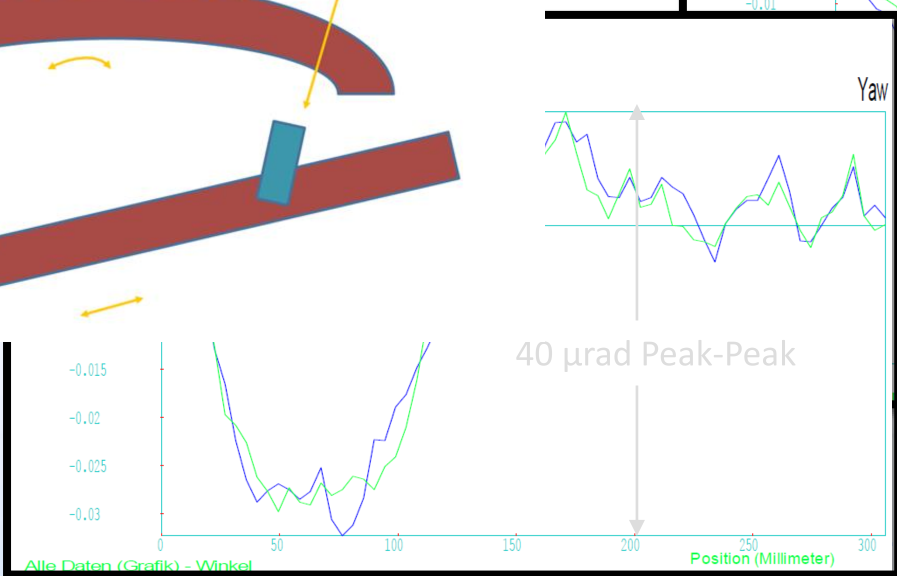


NSEN Stage Runout

- Deviation varies from unit to unit with somewhat random shapes.
- Unmounted/unloaded values are typically <100 µrad
- Each stage deviation is very repeatable (<5 µrad)



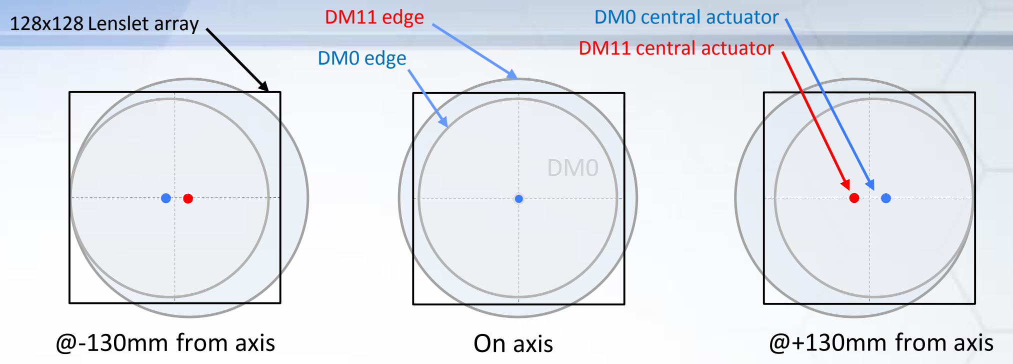




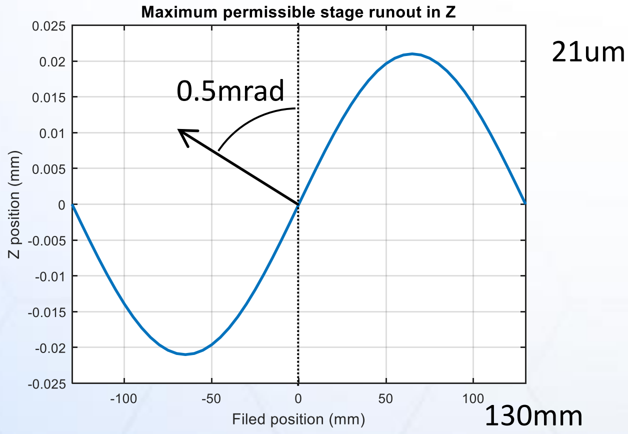
PI stage measurements

DMs conjugation & parallax

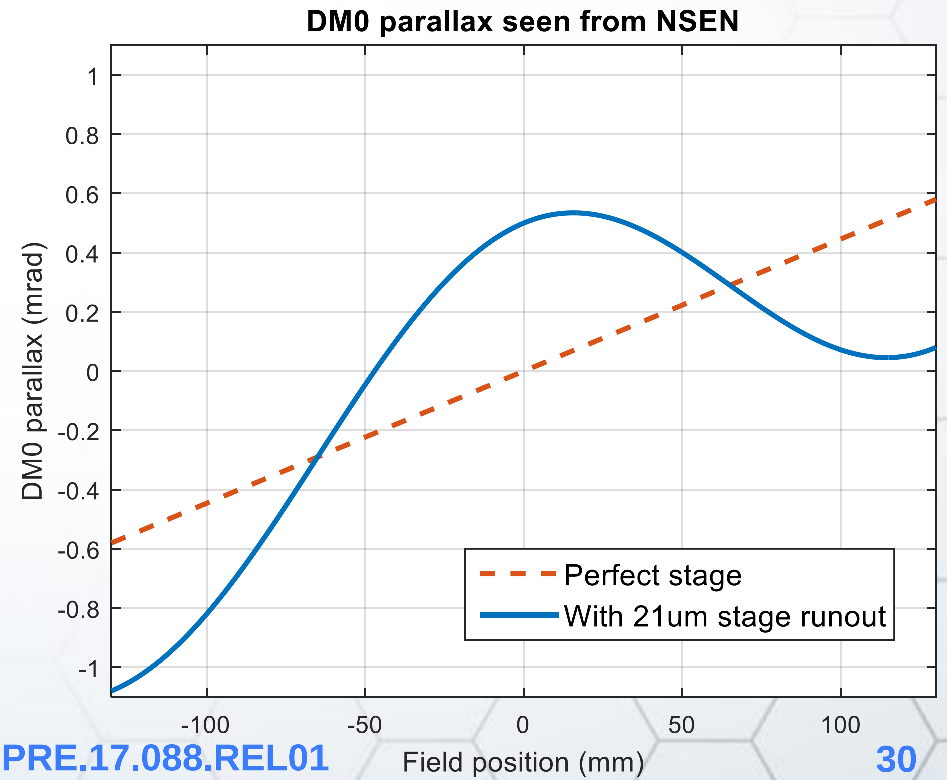
	DM0	DM11
Considered CA (mm)	300	366
Exit diameter (mm)	14939	1487
Exit distance (mm)	-224085	+18575
Relative dia. on HASO	1	1.2
Parallax @+130mm (mrad) (% of dia.) (actu pitch)	 0.58 0.87 0.523	 -7.00 -8.7 -6.374
Sensitivity (mrad/actu)	1.11	1.10



- DM11 image is virtual (beyond focal plane)
- DM0 and DM11 shift in opposite directions
- DM11 blurring is 13% of actu pitch if no field lens (f=-17.153m)



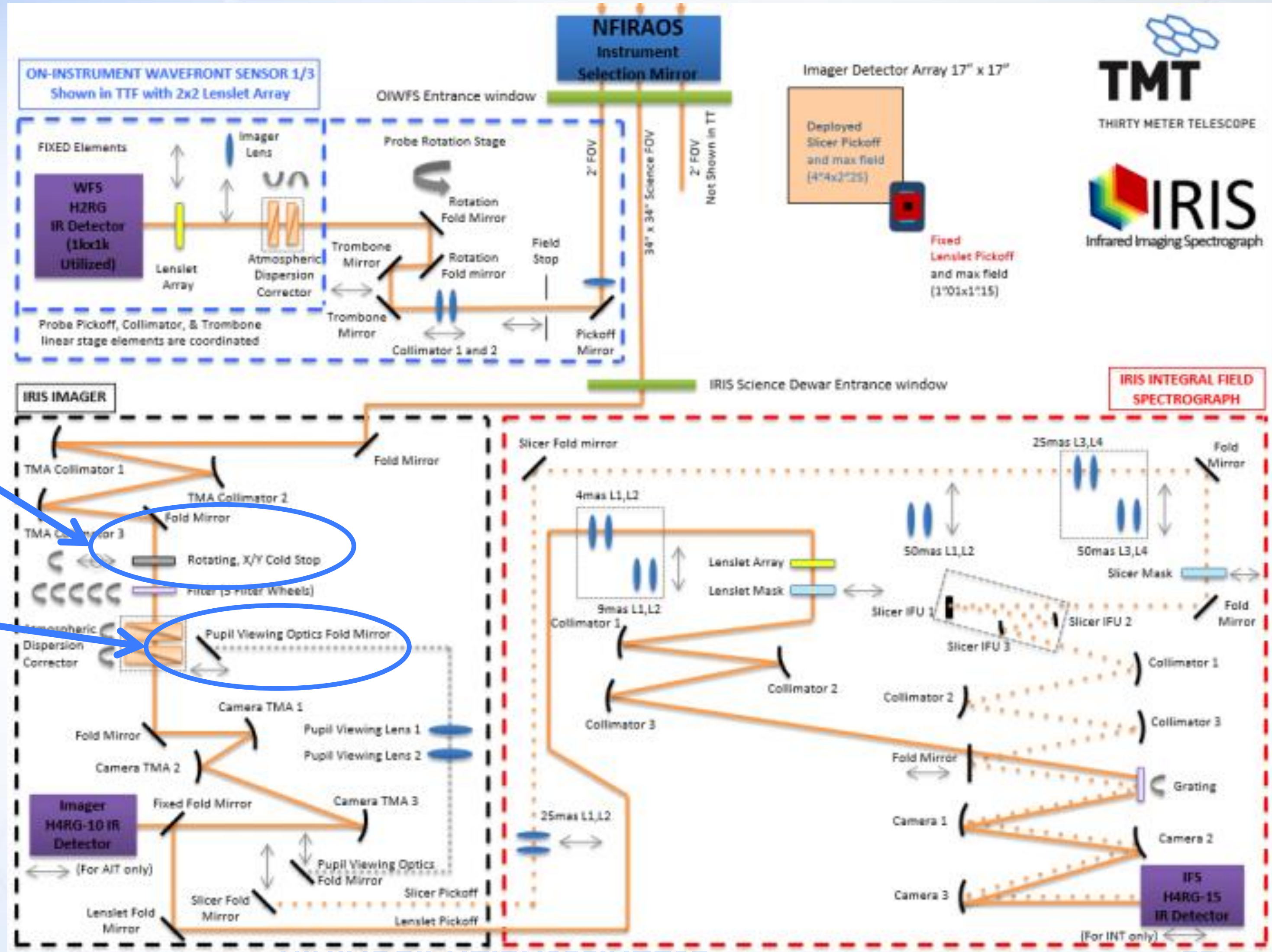
Worst case 1-period sine wave (i.e. smallest slope)



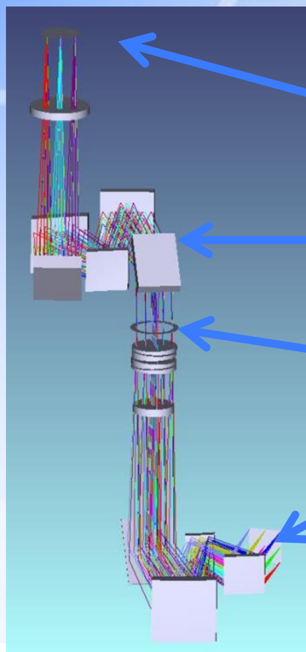
IRIS (Imaging Spectrograph)

Rotating & XY Cold Stop

Pupil viewing optics (deployable)



Prototype IRIS Cold Stop XY & Rotate Stage



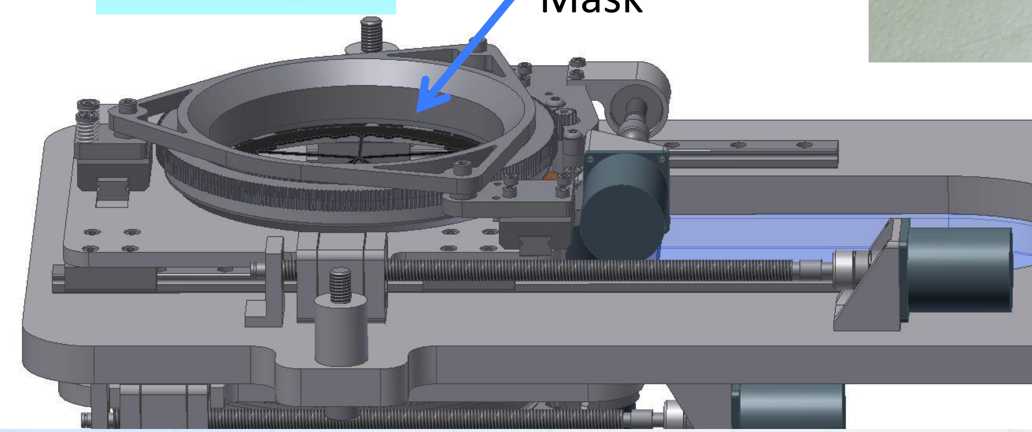
NFIRAOS output focus

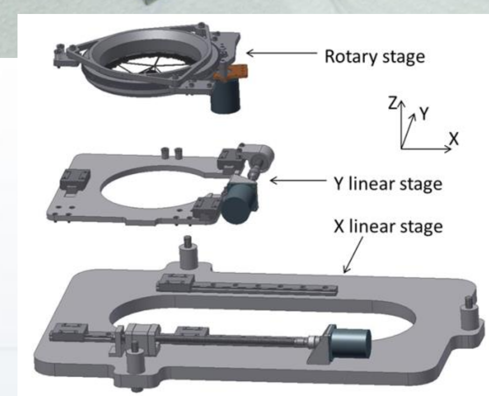
Collimator

Cold Stop

Camera

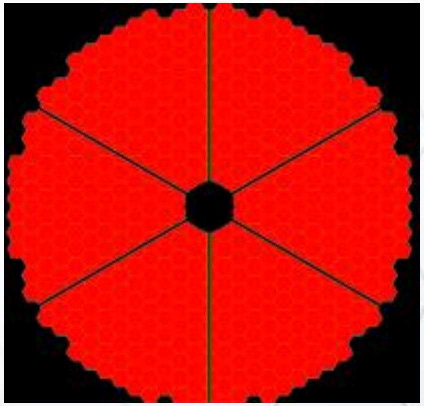
Serrated Pupil Mask





What does IRIS pupil viewing camera see during calibration?

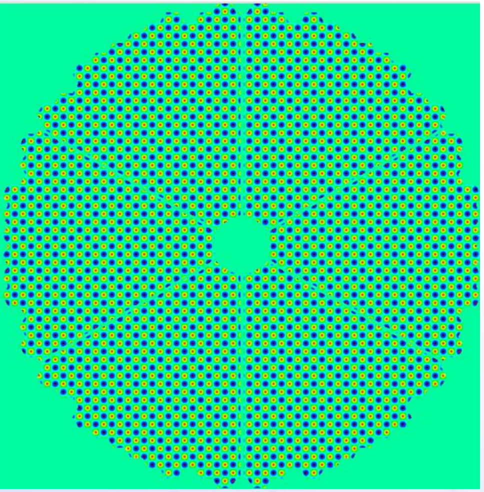
- Must calibrate pupil alignment and wander on IRIS Lyot mask during the daytime
  - Derive XY & Rotation pointing model for IRIS pupil mask
  - As a function of Dewar rotation - in situ installed on NFIRAOS



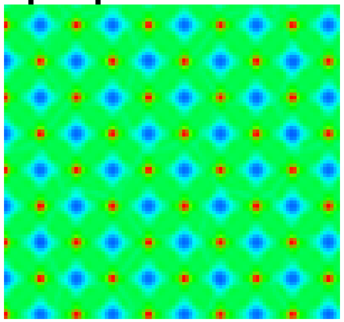
Poke Waffle on high-altitude DM11

- What does Pupil Viewing Camera see?
  - 1.5 μm P-V waffle, H-band → +225% / -75% intensity modulation at pupil imager
  - Measure location to <<0.1% of pupil diameter via correlation

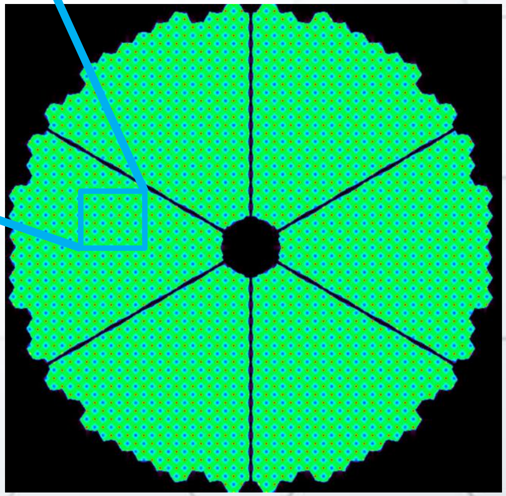
Waffle on DM11 (Phase)



Talbot propagation creates intensity spots on pupil viewing camera



Amplitude at Pupil viewing Camera



See Véran Friday Morning

Ideas to improve PSS errors due to pupil position

1. Verify DM0 to PWFS by poking DM actuators in daytime
2. Record zero-point on CCD
3. Use matched filters to measure pupil during observation
4. Feed back errors to telescope
5. Jointly calibrate DM0 to Interface, and Interface to Lyot stop using IRIS Pupil viewing camera
6. Move Lyot stop in XY as instrument rotates

7. PSSN due to pupil alignment & Lyot stop undersizing expected to improve by ~3x, resulting in 10% loss

	On Axis PSSN Budget		
Item	K		
PSSN MCAO NFIRAOS + IRIS Imager	**0.157**		
Wavefront Error (PSS ∝ S^2)		**0.592**	
High Order WFE in nm -> S^2			0.617
Lo Order WFE broadening PSF -> S			0.960
Throughput (PSS ∝ η)		**0.328**	
Telescope Requirement			0.910
NFIRAOS Requirement			0.800
IRIS Imager Requirement			0.450
Pupil Shift (1/3% Undersized Lyot		**0.896**	
Loss of pupil area			0.962
Undersized Lyot mask PSF broadening			0.930
Background [PSS ∝ $(1+I_b/I_0)^{-1}$]		**0.958**	
Thermal Background			0.960
Scattered Light			0.999
Out of focus ghosts			0.999
Image Smearing (PSS ∝ S)		**0.950**	
Image derotator			
Offset b/w OIWFS/IRIS Focal plane			
ADC errors			
Amplitude non-uniformities		**0.994**	
Atmospheric scintillation			0.994
M1 segments T.P variation			0.9998
Ghosting (PSS ∝ 1-2ε)		**0.999**	
Static focused ghost			$<5 \times 10^{-4}$