Telescope Project Development Seminar

Session 4: Telescope Performance

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U. Tokyo

Session Outline

- GMT imaging
  - Image Size
  - Atmospheric dispersion
  - Wide-field corrector
- Finite Element Modeling of the GMT
  - Modal analysis
  - Optical sensitivity equations
  - Static deflections
  - Wind shake analysis
  - Seismic analysis (OLE and SLE)
- Active optics Operation

<u>Other common analyses</u>

- Tracking performance
- Throughput and emissivity
- Adaptive Optics performance
- Integrated system modeling

GMT Imaging

GMT Optical design

Aplanatic Gregorian Design
(ellipsoidal M1 and M2)

Segmented pupil:

M1: Seven 8.4 m segments

M2: Seven 1.1 m segments

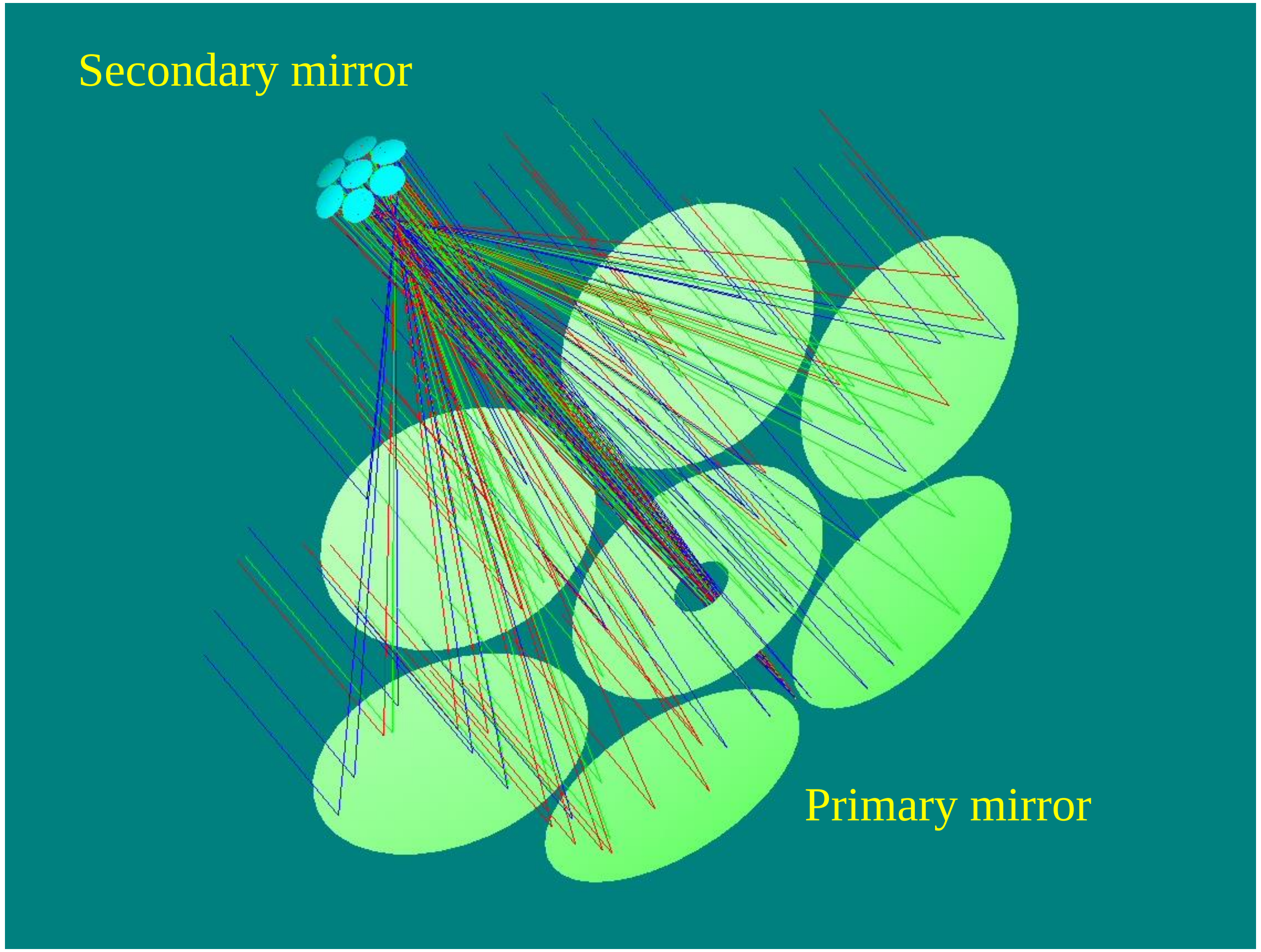
Aperture: 25.4 m

Collecting area: 368 m^2

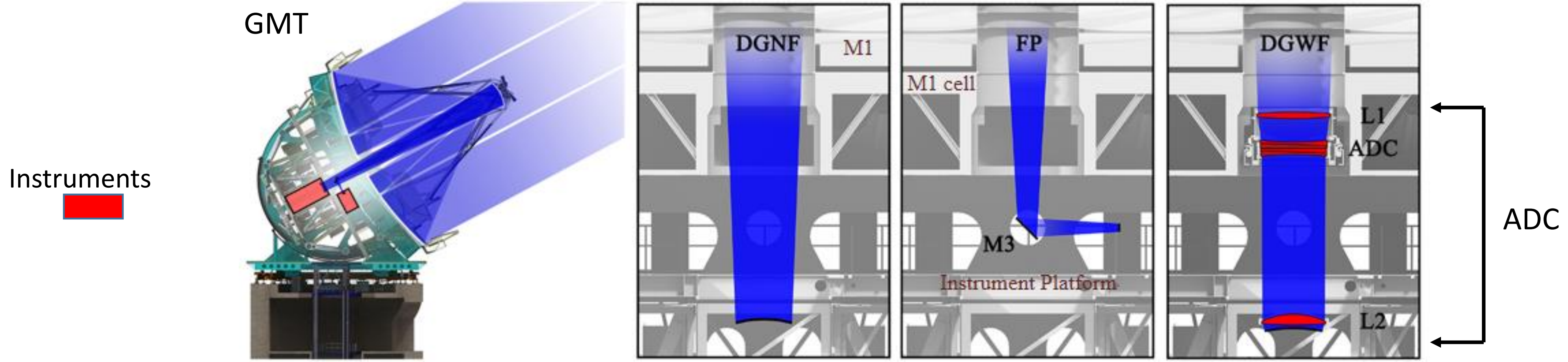
Focal ratio: f/8.2

Plate scale: 1.006 mm/arcsec

Field of view: 20 arcmin



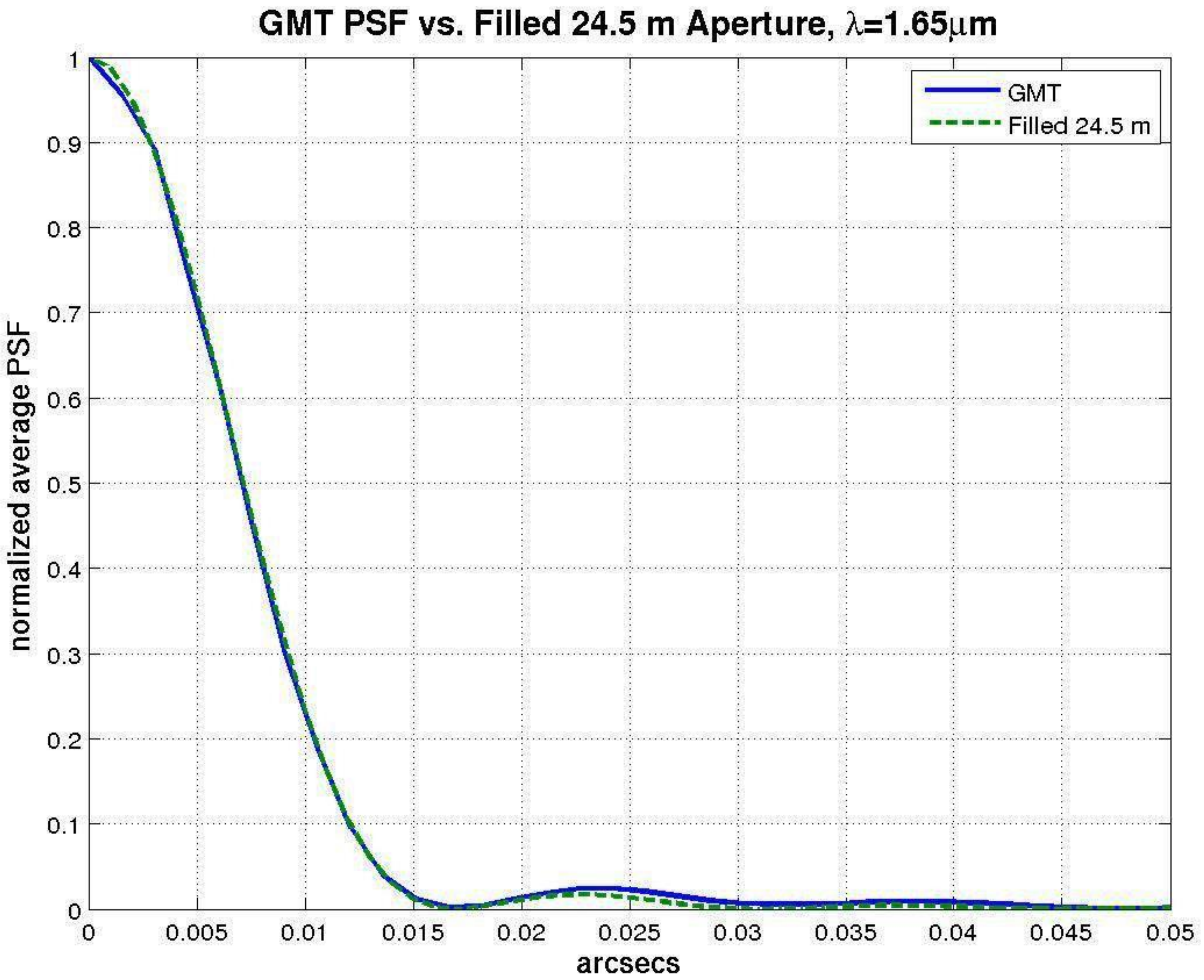
GMT Optical configurations



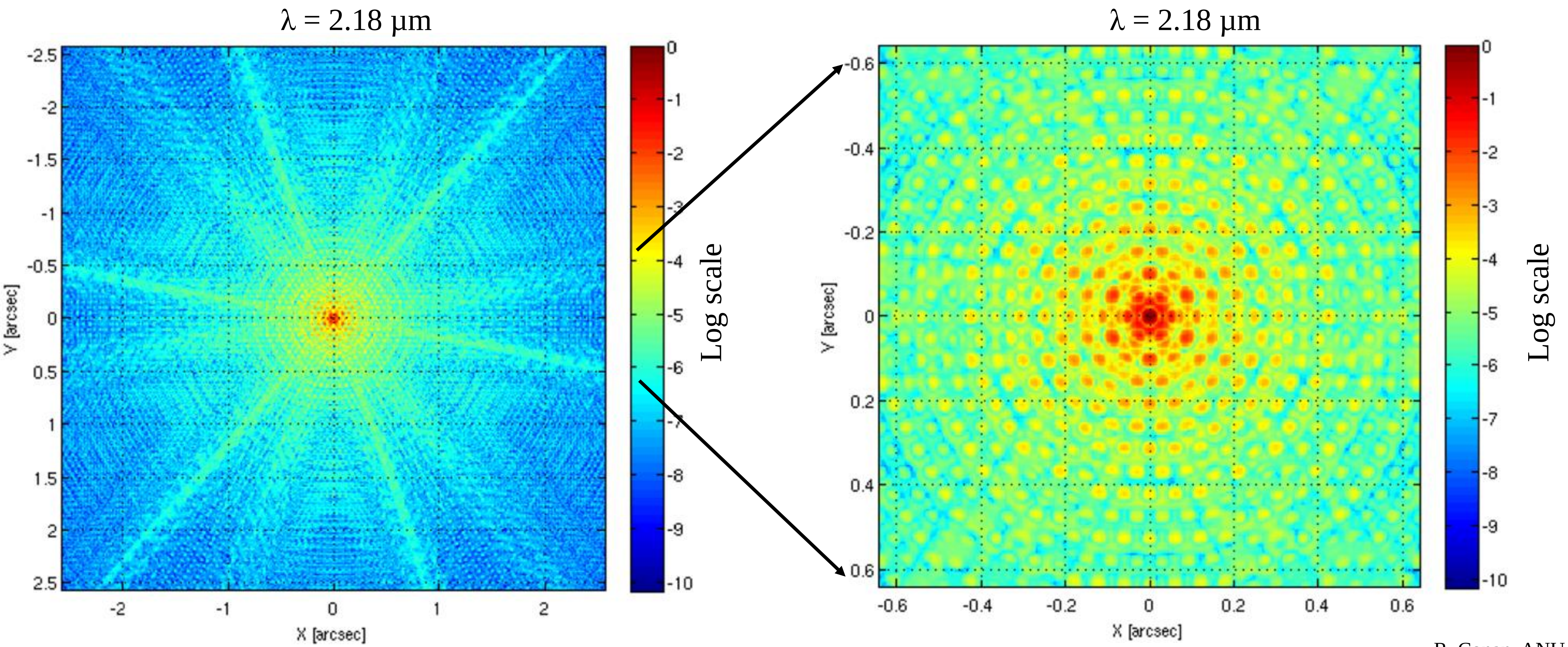
Config	Unvignetted field of view	Instrument ports/stations
DGNF	20 arcmin, ~10 arcmin well corrected	Direct Gregorian narrow-field focus
FP	3 arcmin	Folded ports Auxiliary Ports Instrument Platform stations (Gravity Invariant Station pick-off)
DGWF	20 arcmin	Direct Gregorian wide-field focus

H-band azimuthally averaged PSF

- The point spread function shows the amplitude of the light in a stellar image as a function of the radius from the peak intensity.
- It generally requires a diffraction calculation for a given optical configuration.
- GMT's segmented pupil and central obstruction will change the PSF that would be expected from a circular aperture.
- Normalized point spread function of GMT at 1.65 microns circularly averaged compared to the PSF for a 24.5 meter filled aperture telescope.



Direct Gregorian On-axis Image Intensity

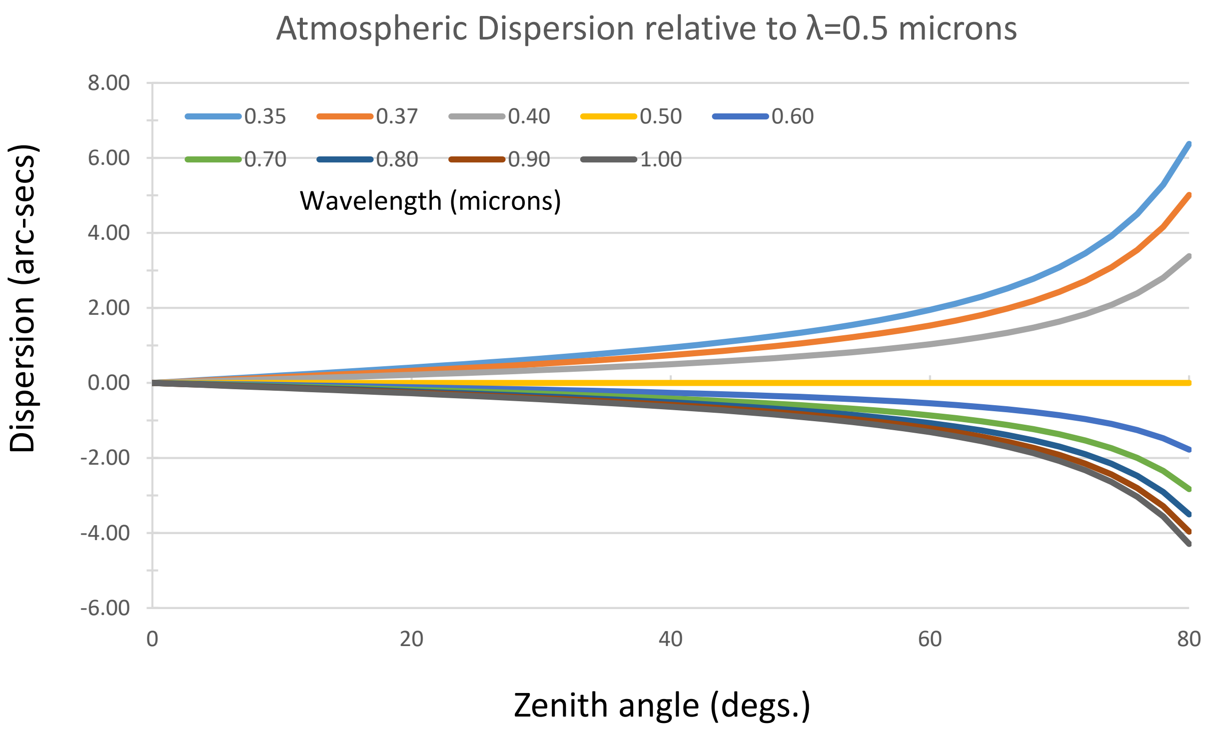


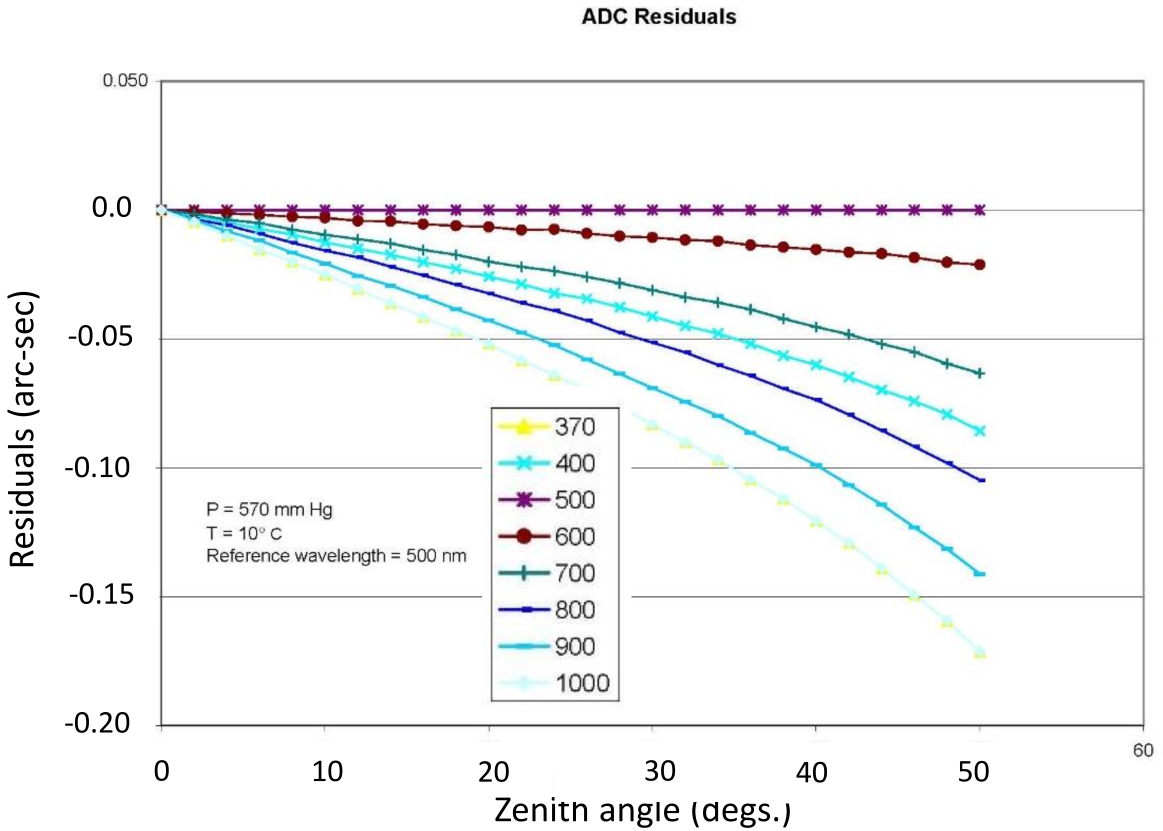
R. Conan, ANU

This pattern rotates with the pupil which will tend to wash out non-circularly symmetric structure.

EE80 = 100 mas @ 2.18 μm
= 23 mas @ 500 nm

Atmospheric Dispersion



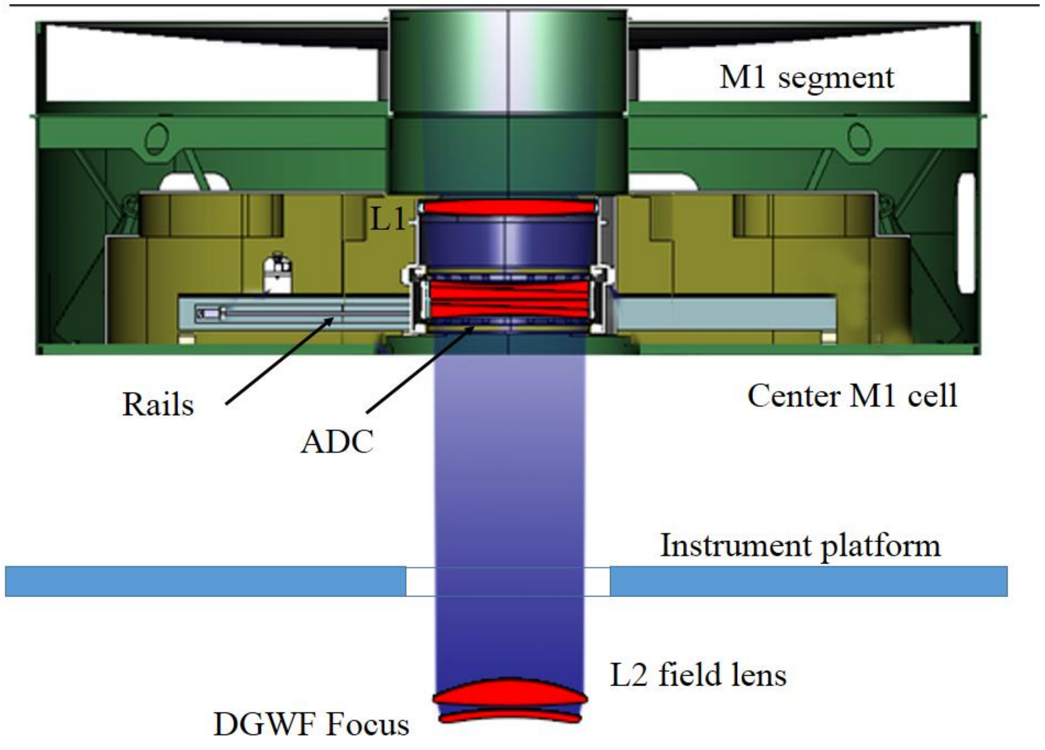


- Atmospheric refraction causes wavelength dependent pointing errors as a function of zenith angle.
- This causes significant image blur for broadband imaging and spectroscopy.

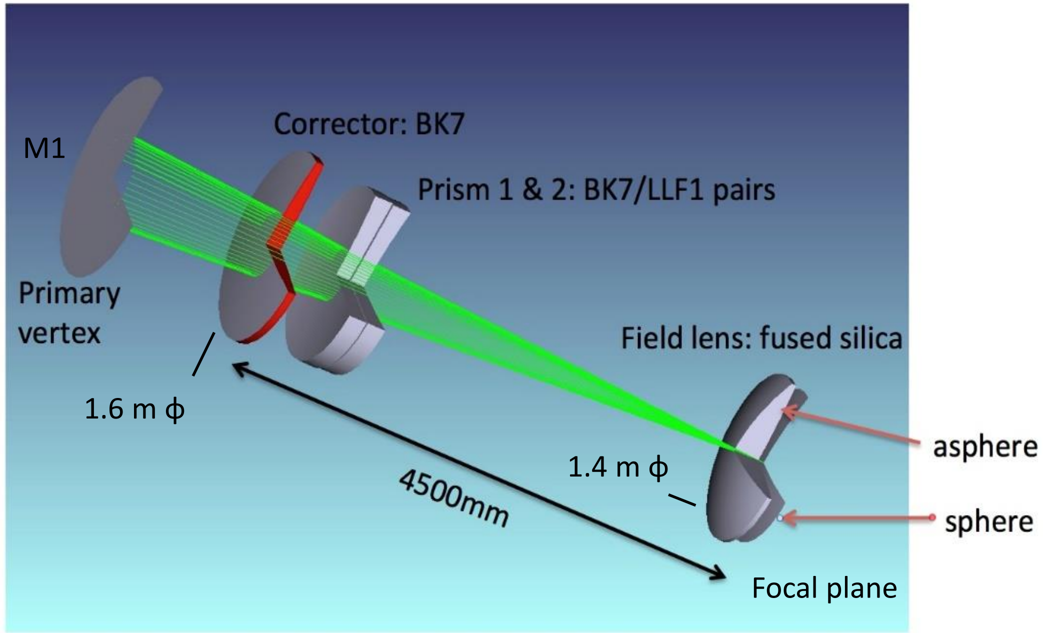
C. W. Allen, “Astrophysical Quantities”, 1973

Corrector-ADC

- An Atmospheric Dispersion Corrector (ADC) is inserted in the telescope beam to correct the dispersion and field aberrations.
- One type of ADC consists of a pair of zero-deviation prisms that are counter-rotated about the optical axis to “dial out” the dispersion.
- The rotation angle is a function of zenith distance.
- Note: these optics are around 1.5 m in diameter for GMT!

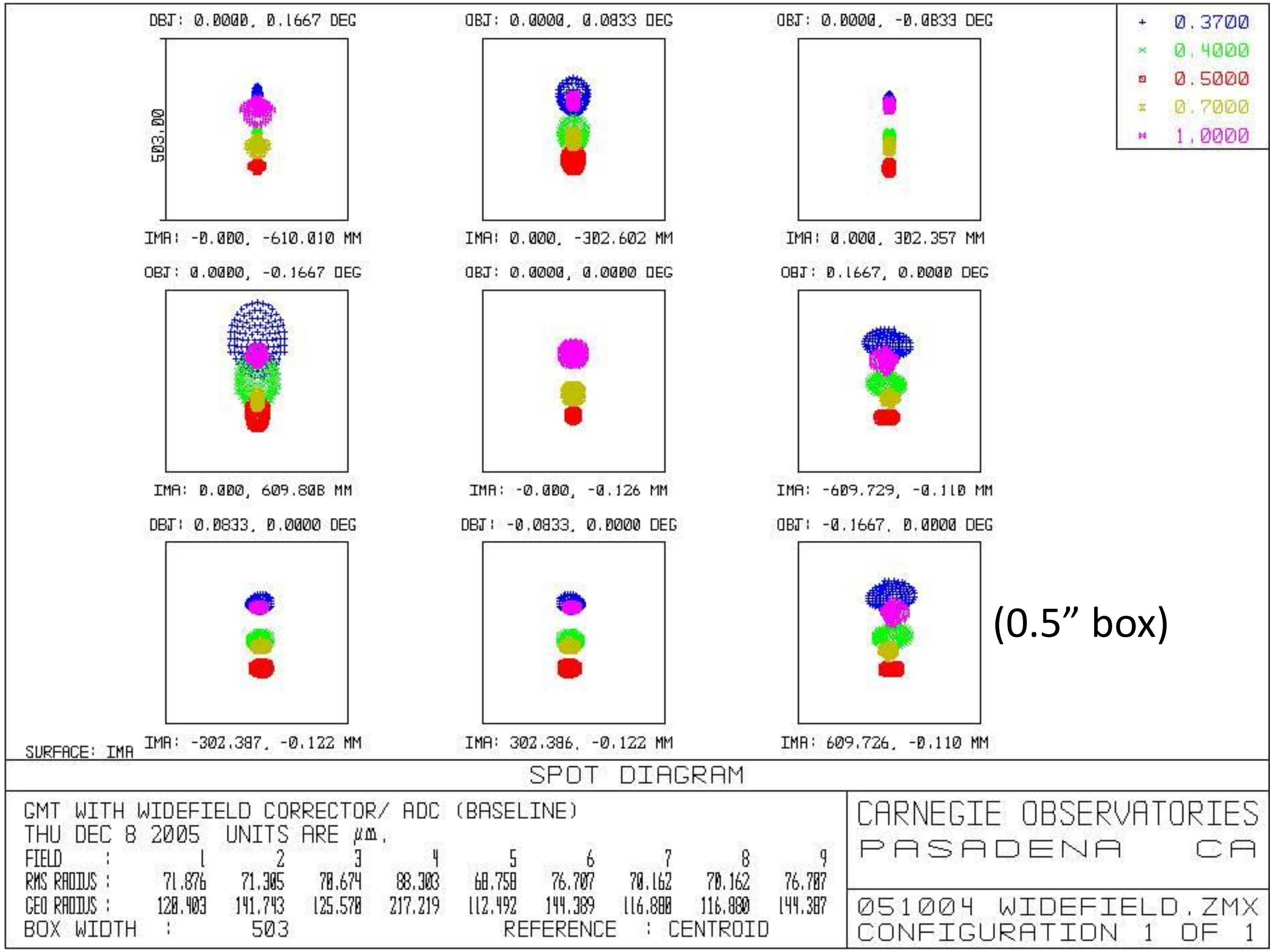


GMT ADC/wide-field corrector



- Corrector-ADC upper part is located in the center M1 cell
  - Unit is inserted on rails for DGWF configuration
- Field lens (L2) is mounted in the instrument

ADC Performance



(0.5" box)

Optimization Conditions

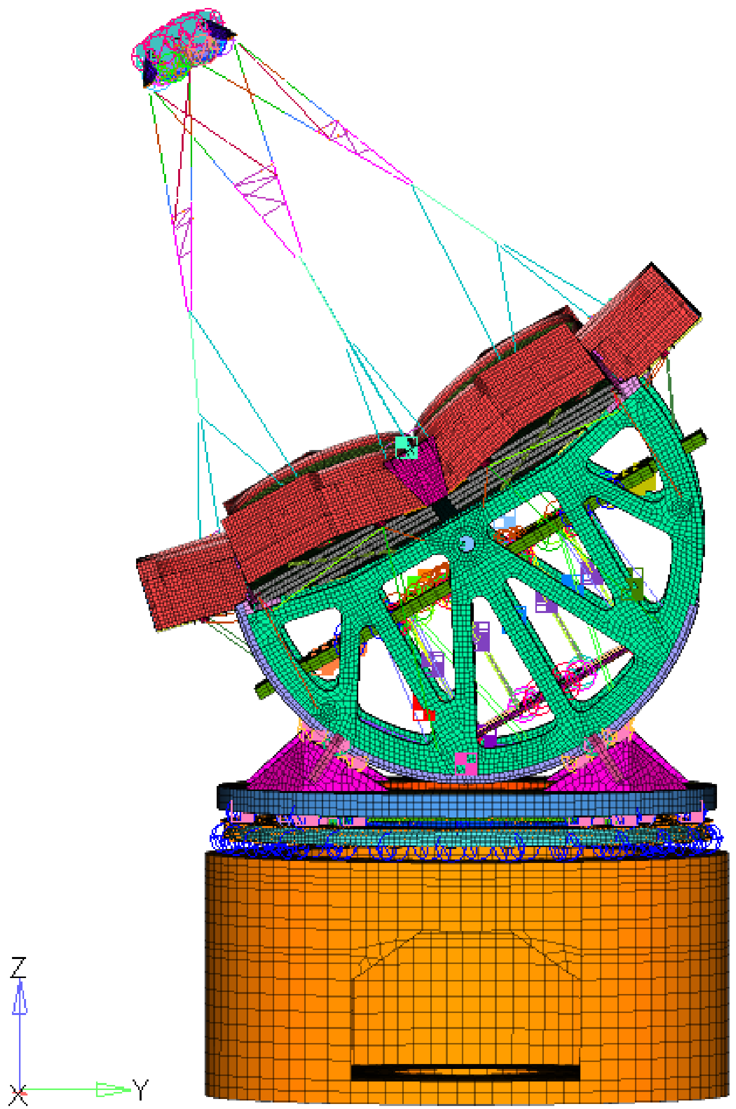
- Zenith distance: 0˚ to 50˚
- Wavelength: 0.37 µm to 1.0µm
- FOV: 20 arc-min diameter
- Prism glass types: FK5 and LLF6

Dispersion at ZD = 50 deg:
uncorrected = 1.98 arcsec
corrected = 0.17 arcsec

Structure Finite Element Modeling

GMT Modeling and Simulations

- Finite Element Modeling of the GMT
  - Modal analysis from GMT
  - Optical sensitivity equations
  - Static deflections
  - Wind shake analysis
  - Seismic analysis (OLE and SLE)

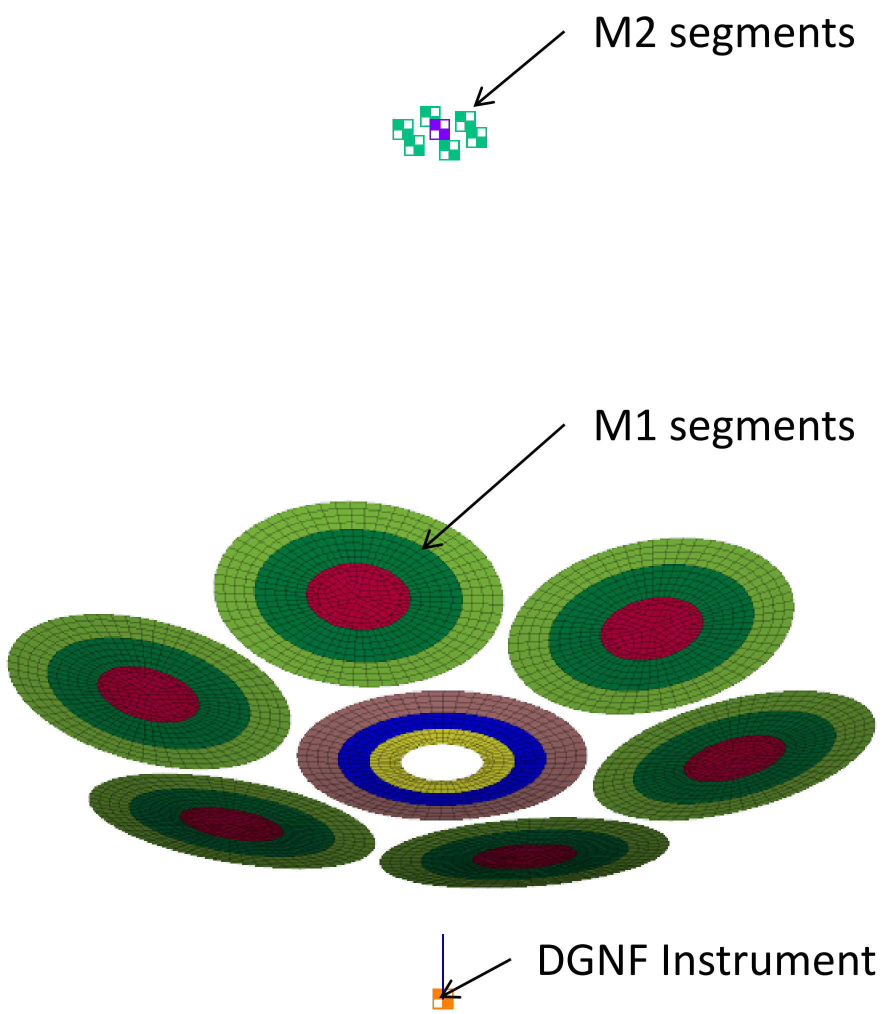


Finite Element Models

- Finite element model (FEM) created from solid CAD model for analysis using NX/Nastran 8.5
  - ~165k nodes, 170k element
- Majority of structure uses thin shell and 1D beam elements with A36 steel material
- Pier modeled using linear solid elements with reinforced concrete material
- Actuators, hydrostatic bearings, & drives modeled using 6 DOF spring elements
- Lumped mass elements utilized throughout FEM (M2, GIS, GIR instruments, Laser Guide Star Telescopes)
- FEM mass and MOI correlated to design mass
  - Non-structural mass is included to balance OSS
  - Total OSS mass = 940,500 kg
  - Total FEM mass = 5,590,190 kg (including pier)
- Multiple configurations of FEM are specialized for various analyses: gravity, wind, & seismic
  - Baseline FEM created for wind analysis at 30° zenith angle

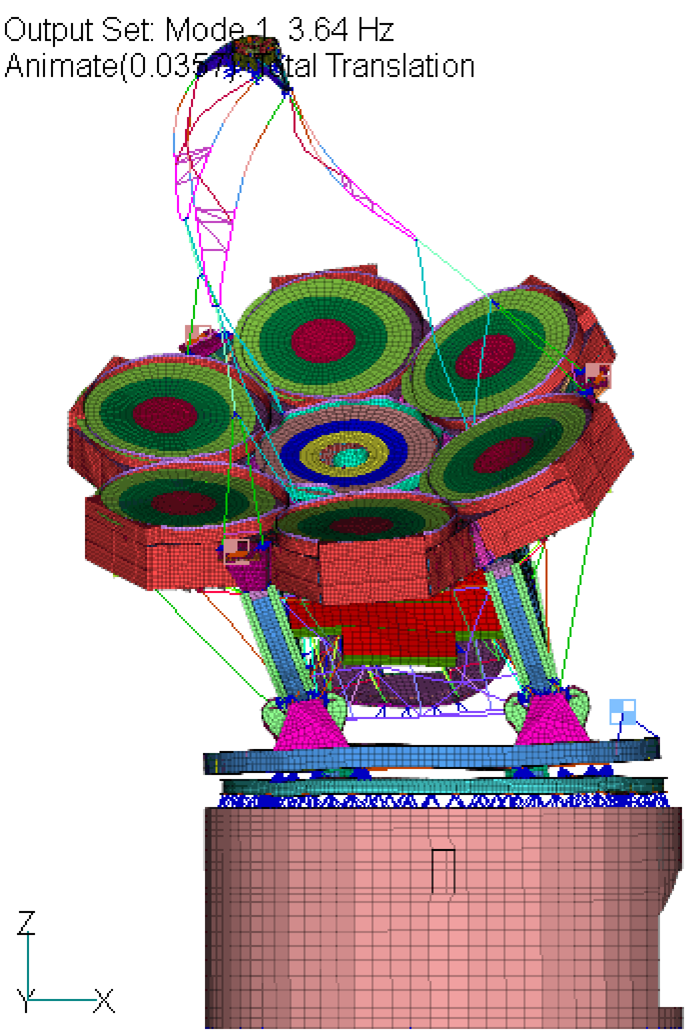
Line of Sight Equations

- An optical design program (Zemax) is used to determine image motion and defocus in the focal plane caused by translations and rotations of nodes in the FEM representing the optical elements (M1, M2, M3) and the instrument focal plane.
- Line of sight equations are built into the FEM using multi-point constraint equations (MPCs)
- MPCs sum the contributions of individual nodes scaled by a coefficient representing the optical sensitivity
  - Maintains phase data within dynamic (random) solutions
- Equations included for each of the 7 subapertures and weighted mean for DGNF, Folded Port X, and Folded Port Y

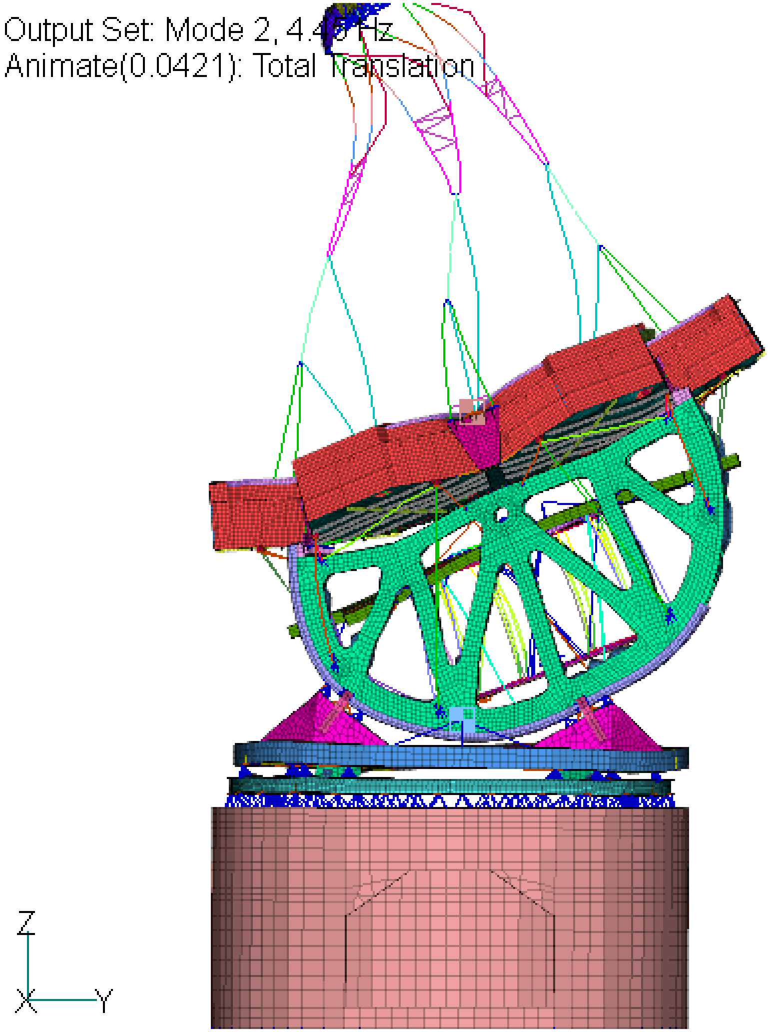


Primary Mode Shapes

1st Lateral

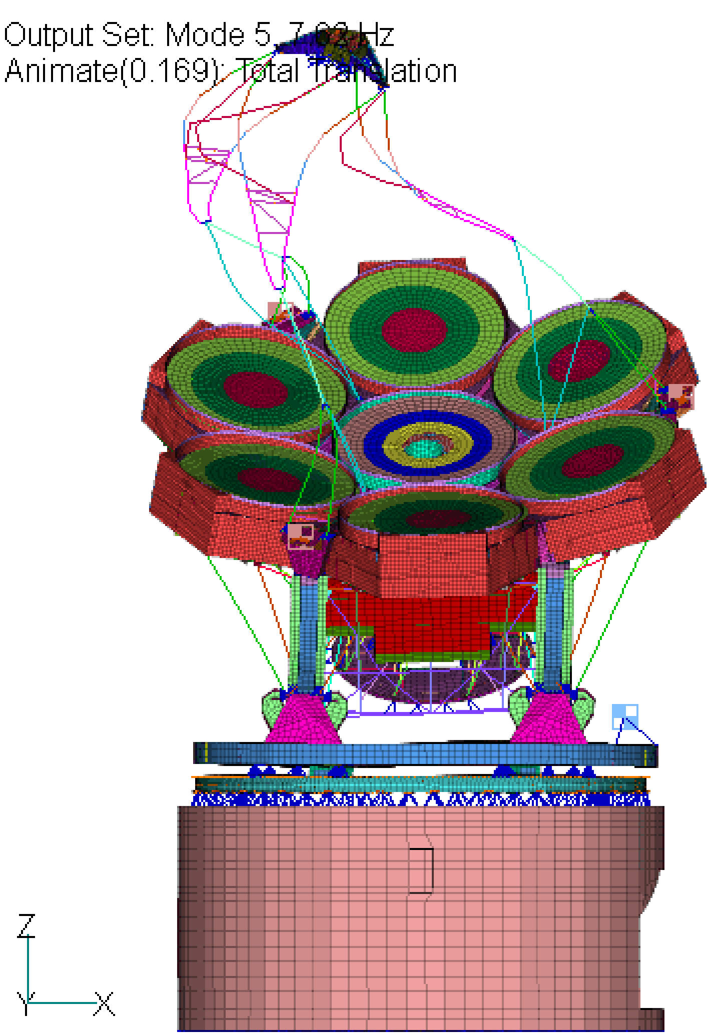


1st Fore-aft

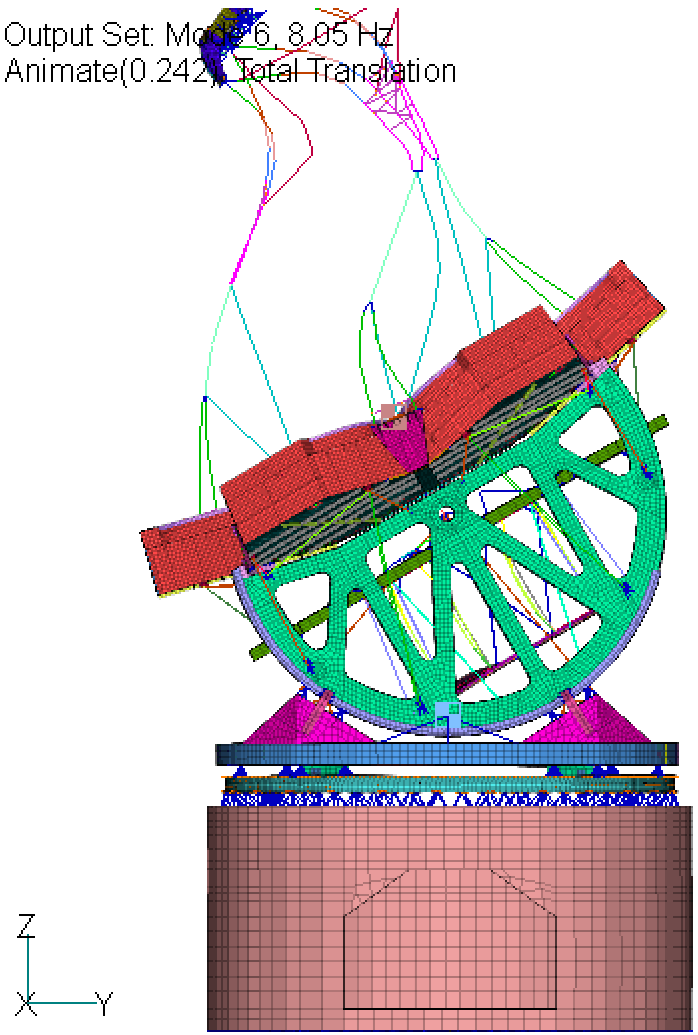


Secondary Mode Shapes

2nd Lateral

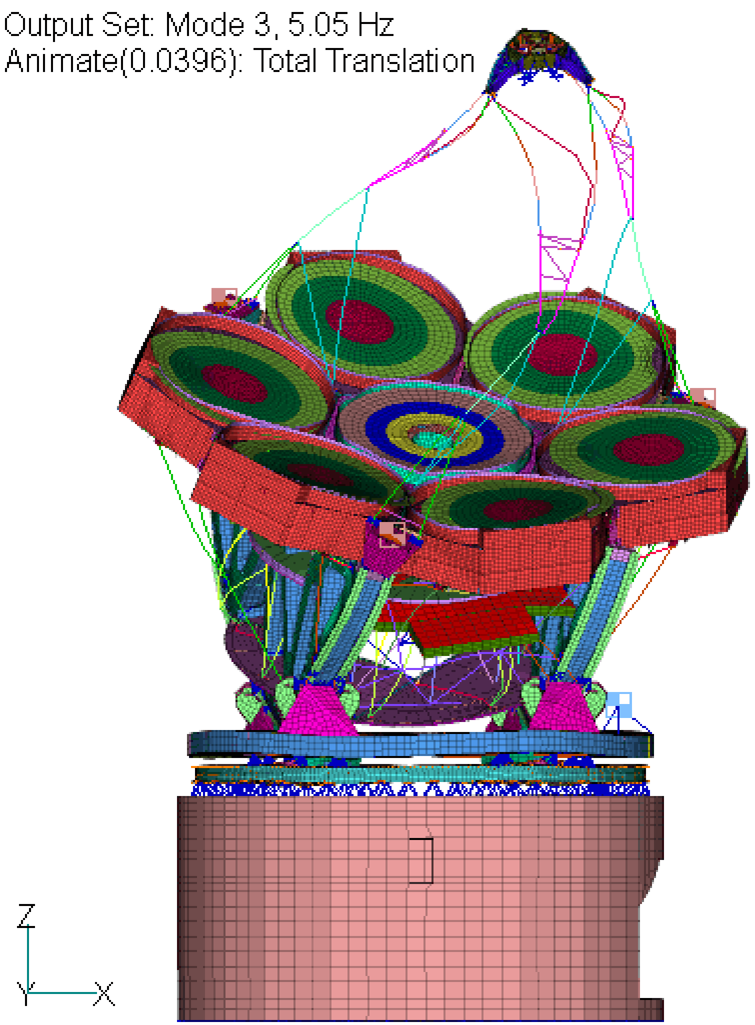


2nd Fore-aft

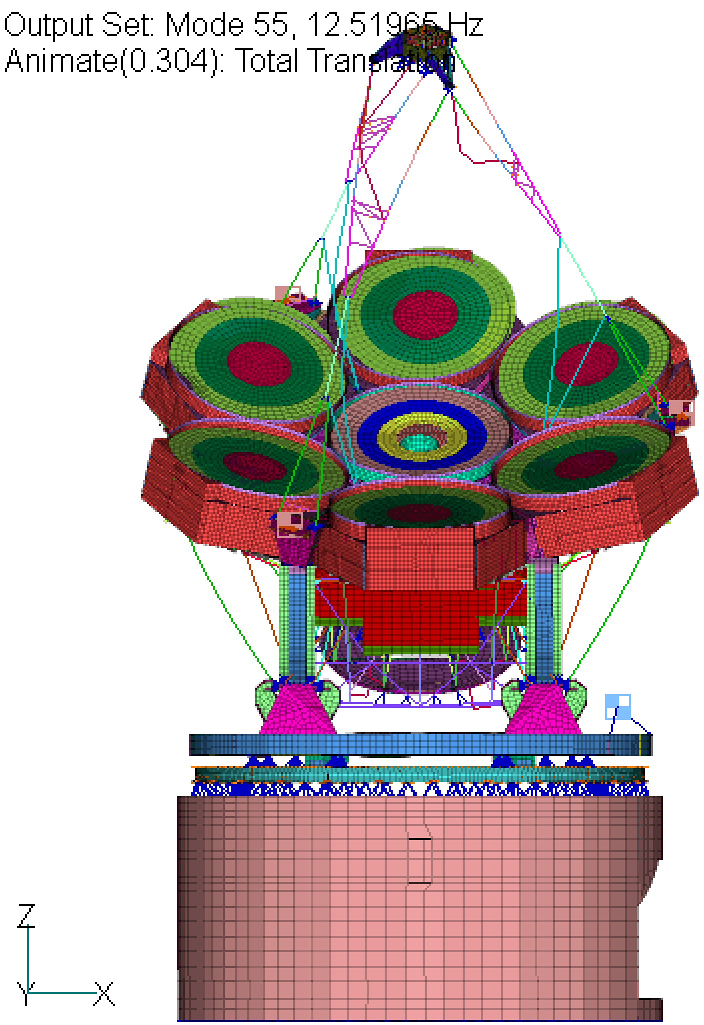


Additional Mode Shapes of Interest

Z Torsion



M1 Mirror Segments



Gravitational Deflection Analysis

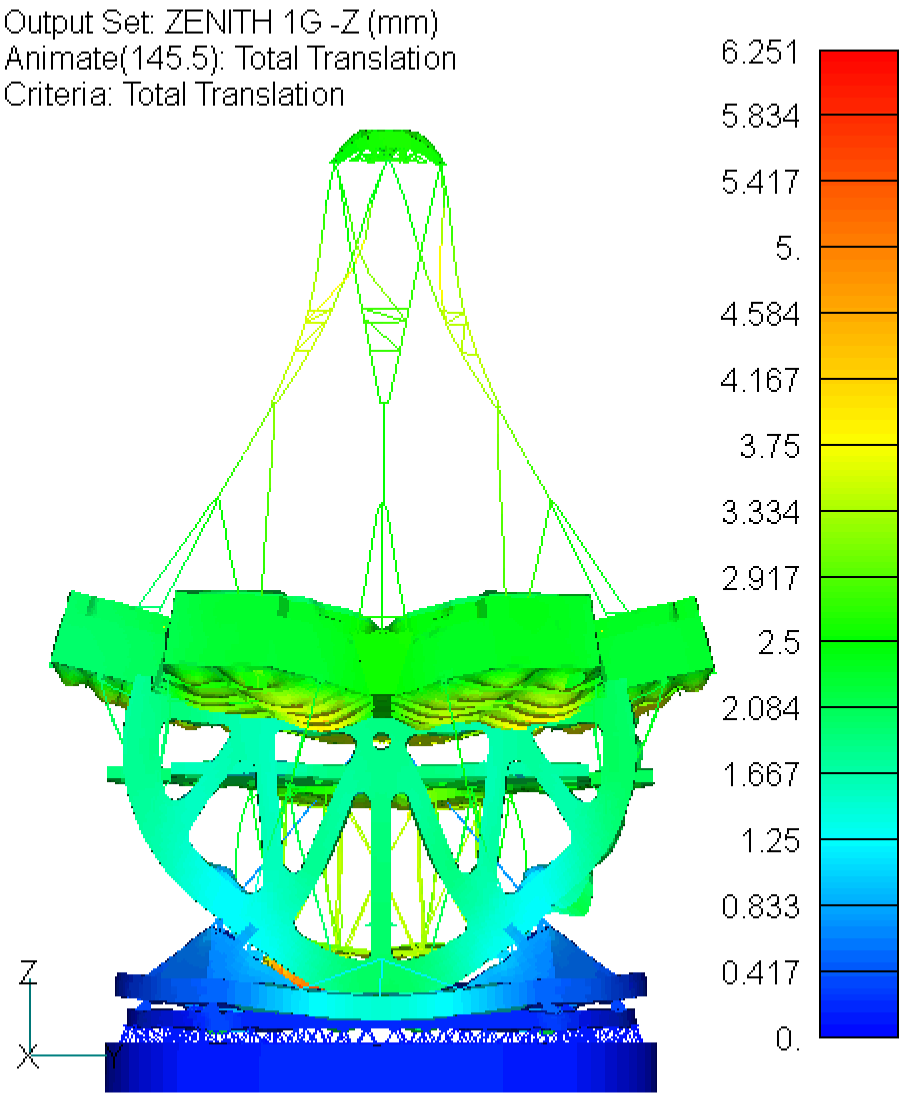
- Determine relative deflection of optics when rotating through gravity field from zenith to 60°

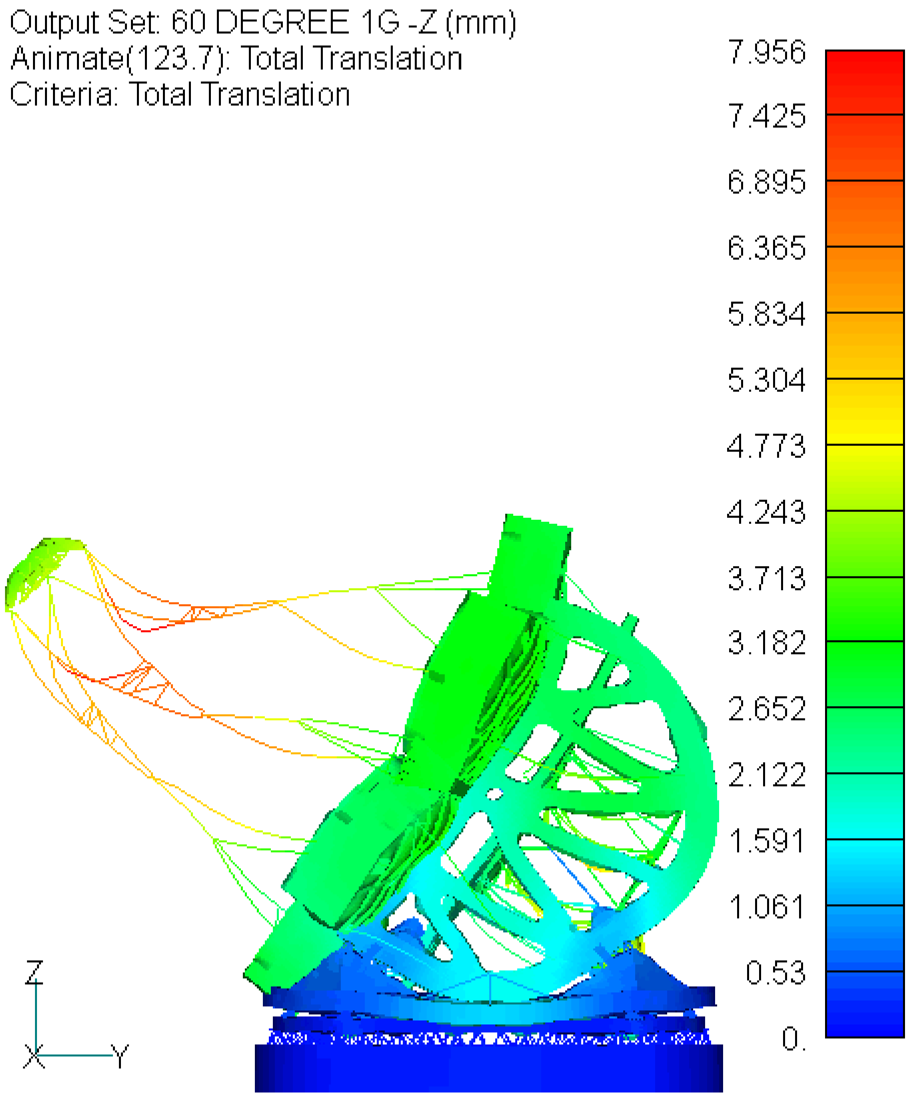
- 1G acceleration applied to telescope at zenith and 60° off zenith
  - Zenith load case is subtracted from 60° load case to determine relative displacements
  - All displacements are relative to the plane defined by the center cell of the CCF

- M1 segment mass is applied to cell top plates
  - M1 segments will displace through hexapods based on movement of the cells under gravity

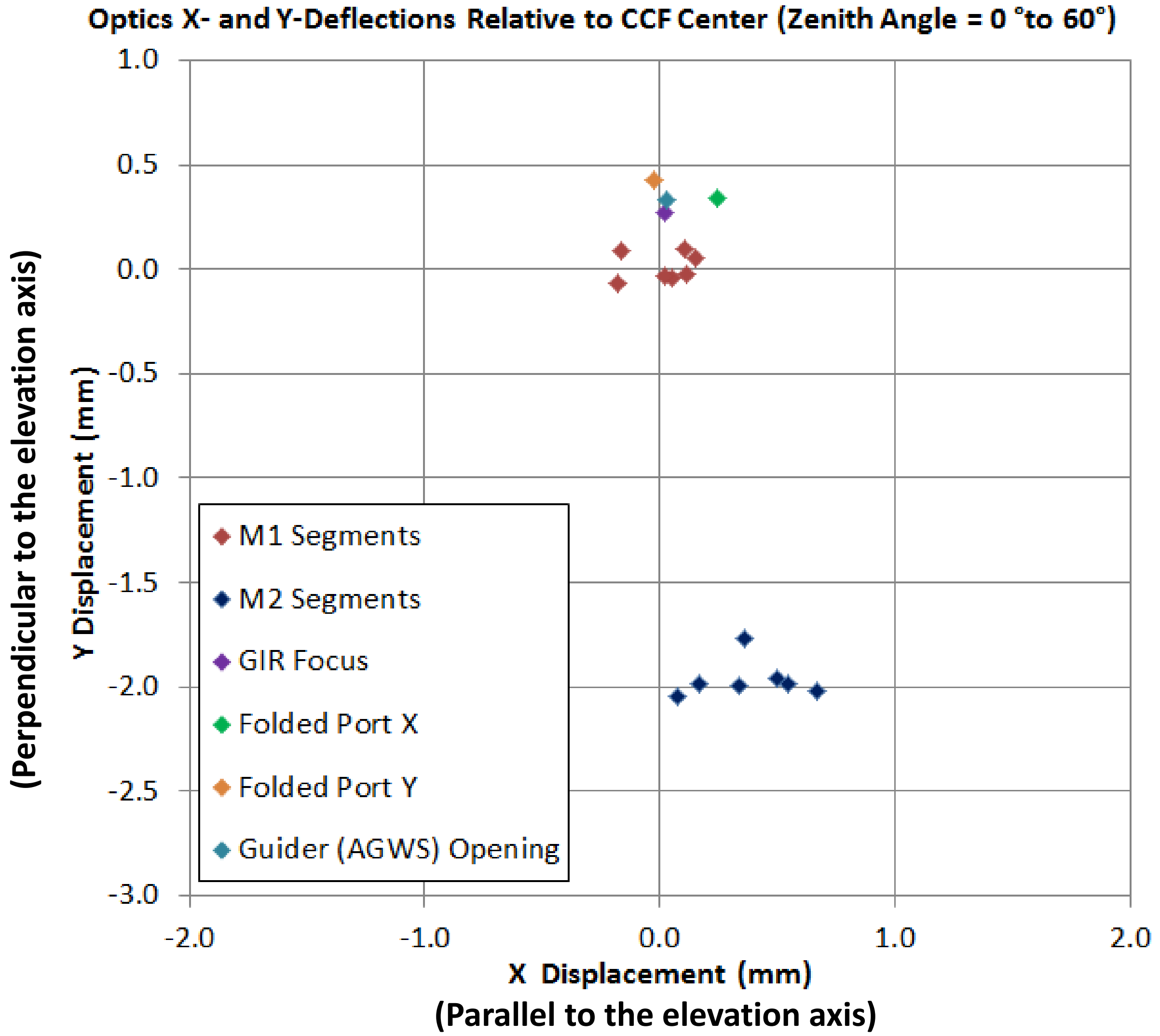
Visiting Professor Lecture

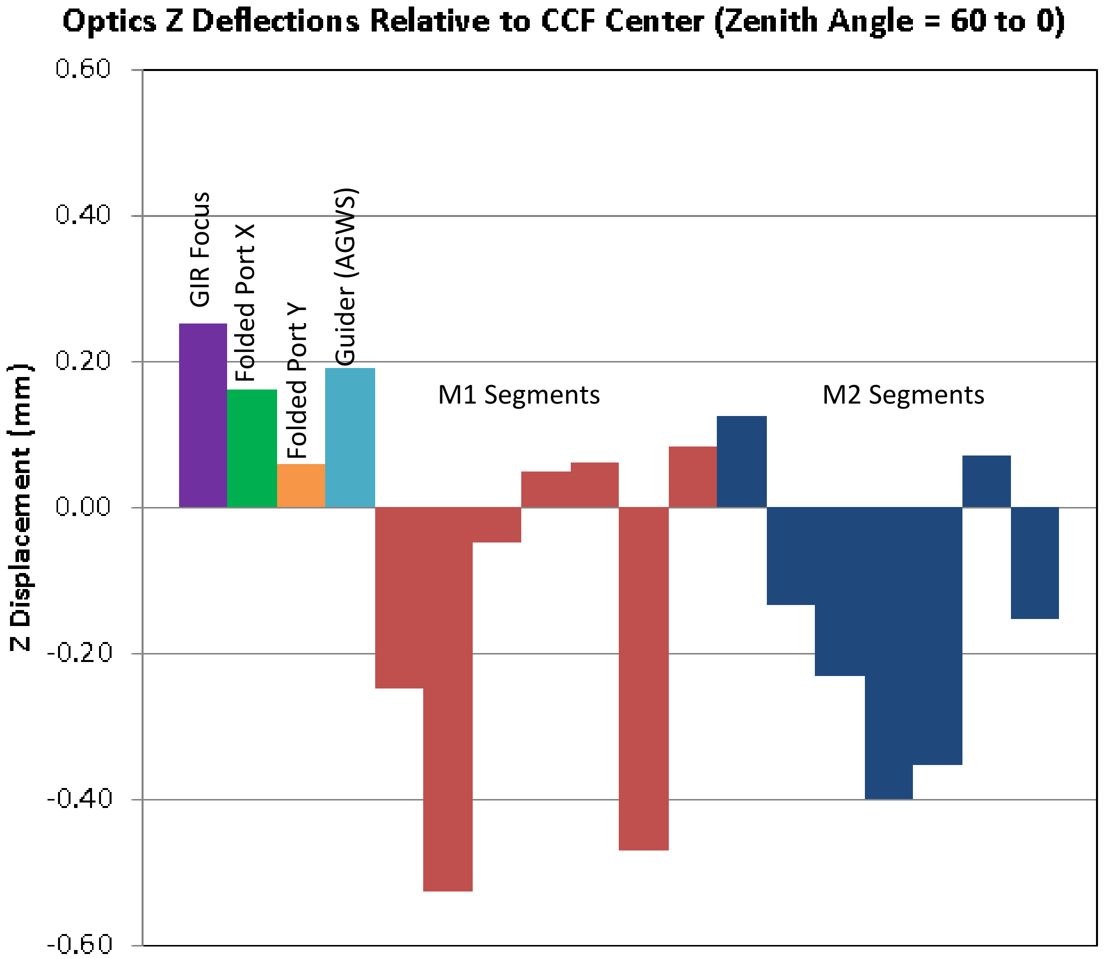
1G Zenith and 60° Deformations





1G Optics X & Y Deflections





Optics deflections relative to CCF are calculated from 0° to 60° for M1, M2, and GIR

Image Displacement in the Focal Plane

- LOS sensitivity equations are used to determine relative image motion and focus shift from 0° to 60°
- Values represent deflections with *NO* active optics corrections
- All deflections are easily correctable with lookups tables & active optics

Segment #	DGNF Image Motion and Focus Shift (Zenith Angle = 60° to 0°)		
	X Motion (arcsec)	Y Motion (arcsec)	Focus Shift (mm)
Segment 7	1.99	-51.93	-30.56
Segment 1	-0.70	-49.23	-21.27
Segment 2	-12.22	-55.86	-32.54
Segment 3	-24.40	-52.88	-50.42
Segment 4	-14.63	22.75	-186.61
Segment 5	36.02	-78.16	-55.78
Segment 6	40.47	-59.22	-58.29
Weighted Mean	3.84	-46.22	-63.02

Segment #	Folded Port X Image Motion and Focus Shift (Zenith Angle = 60° to 0°)		
	X Motion (arcsec)	Y Motion (arcsec)	Focus Shift (mm)
Segment 7	1.87	-52.20	-31.07
Segment 1	-0.82	-49.50	-21.78
Segment 2	-12.34	-56.12	-33.05
Segment 3	-24.52	-53.14	-50.93
Segment 4	-14.75	22.48	-187.11
Segment 5	35.90	-78.43	-56.29
Segment 6	40.35	-59.48	-58.80
Weighted Mean	3.72	-46.49	-63.53

Segment #	Folded Port Y Image Motion and Focus Shift (Zenith Angle = 60° to 0°)		
	X Motion (arcsec)	Y Motion (arcsec)	Focus Shift (mm)
Segment 7	2.31	-53.12	-30.83
Segment 1	-0.38	-50.42	-21.54
Segment 2	-11.90	-57.04	-32.81
Segment 3	-24.08	-54.06	-50.69
Segment 4	-14.31	21.56	-186.87
Segment 5	36.34	-79.35	-56.05
Segment 6	40.79	-60.40	-58.56
Weighted Mean	4.15	-47.41	-63.28

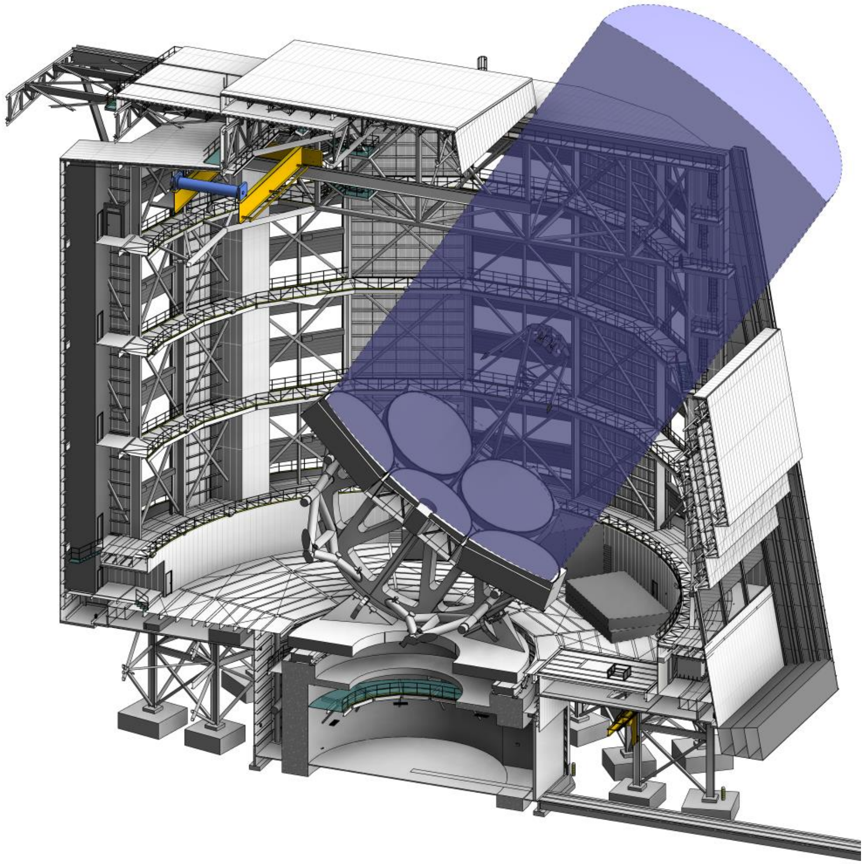
Wind shake analysis

Wind Vibration Analysis Overview

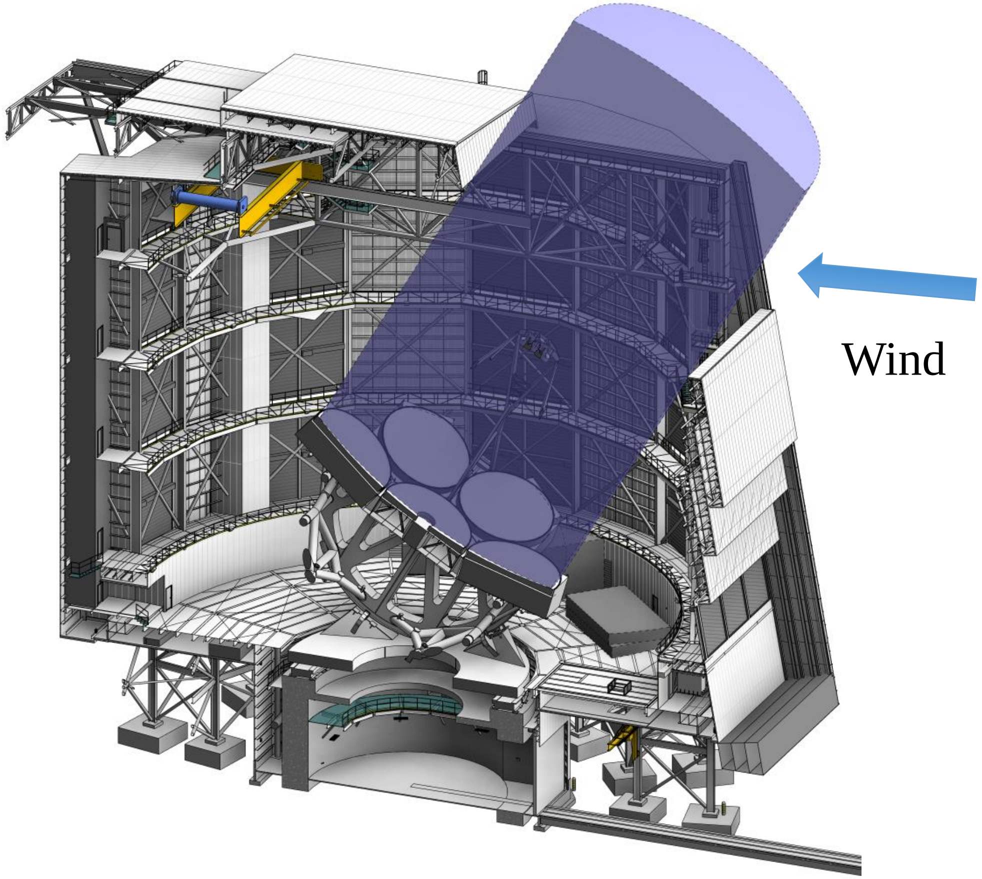
- Telescope performance under wind loading is analyzed under both static and dynamic conditions
  - Both static and dynamic analysis utilize loads mapped from CFD model to FEM
- Three load cases are examined with telescope pointed into the wind at 30° zenith angle and 10 m/s external mean wind velocity (represents 75th percentile conditions)
  - 100% open vent-gates and shutters
  - 50% open vent-gages and shutters
  - Minimum Aperture: vent-gates closed & shutters at minimum aperture
- LOS equations are used to calculate image motion and focus shift spectral densities and cumulative RMS errors
- Neither active optics corrections nor fast tip/tilt corrections are included in this simulation

Wind load scenarios C & D – high wind

Case C
10 m/s, *za*=30°, into wind,
enclosure 50% open



Case D
10 m/s, *za*=30°, into wind,
enclosure min. aperture

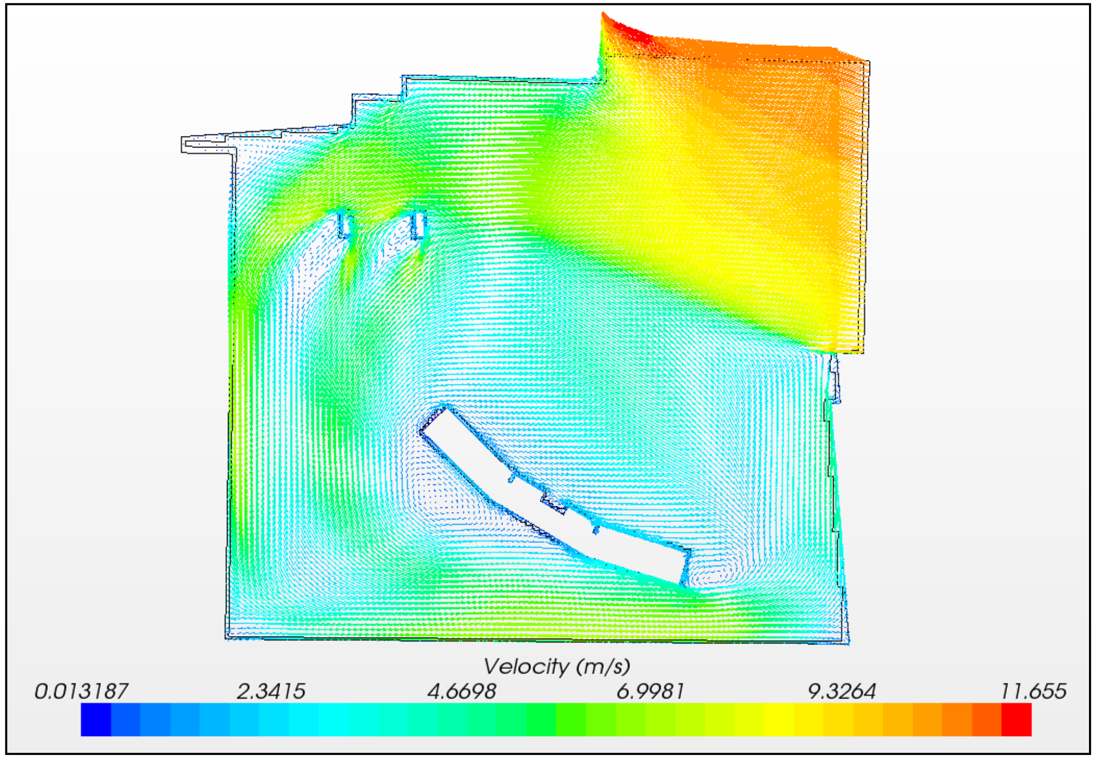


Wind Loading Derivation

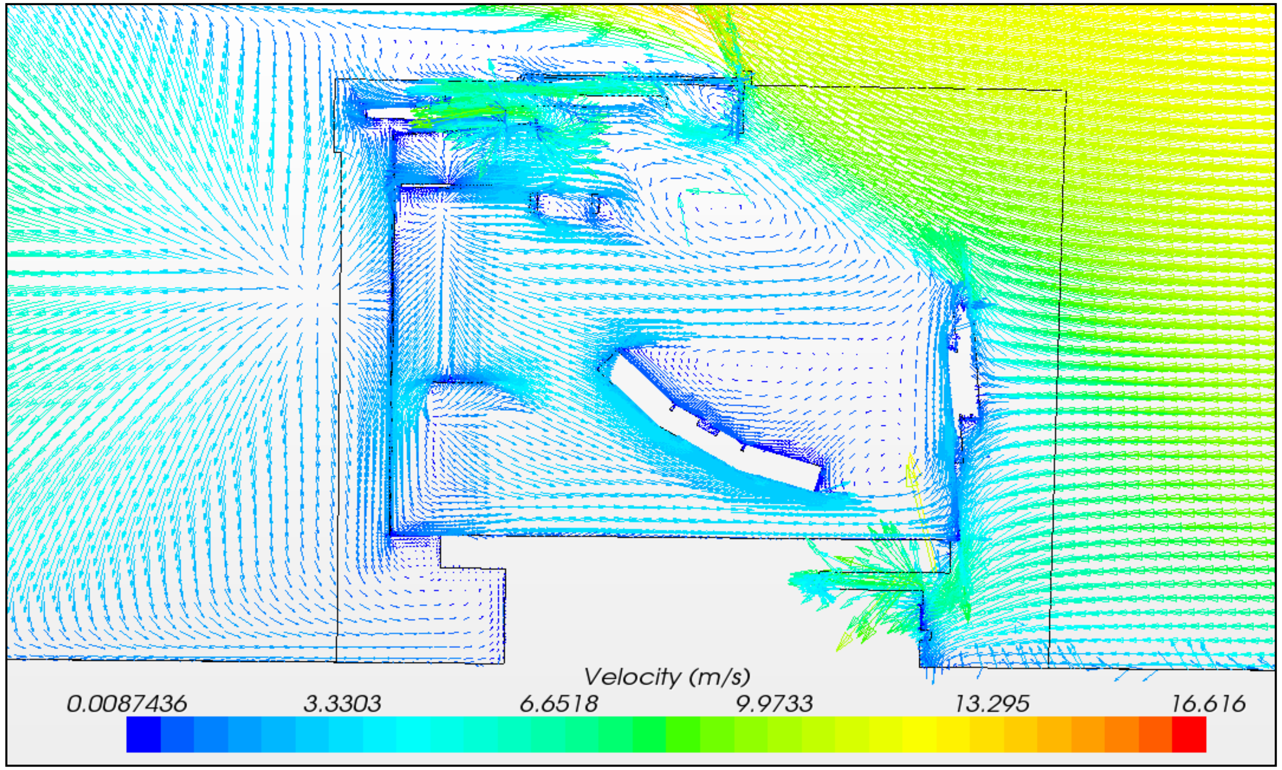
- Extract the pressure from the CFD model and apply it to the FEM
  - Remove static pressure from the mapped total pressures
    - Only the velocity portion of the pressure is applied to the model
  - Areas mapped include Mirror Surfaces, Mirror Cell Sides, and Mirror Cell Bottoms
- Apply forces to the Truss and M2
  - Applied using drag coefficient for representative shapes and velocity at the location
- PSD applied to scale pressures and forces
  - Determined from Gemini pressure & velocity test data
- Analyze wind loading with random vibration solution
  - Frequencies examined from 0-50 Hz with 2% modal damping
  - Drive stiffness for locked rotors used for azimuth, elevation, and GIR drives
  - Telescope zenith angle is 30° for all cases
- Use MPC equations to determine the LOS error and cumulative RMS error for each segment as well as the weighted average of all seven segments

CFD Enclosure Internal Velocity

50% Open Enclosure



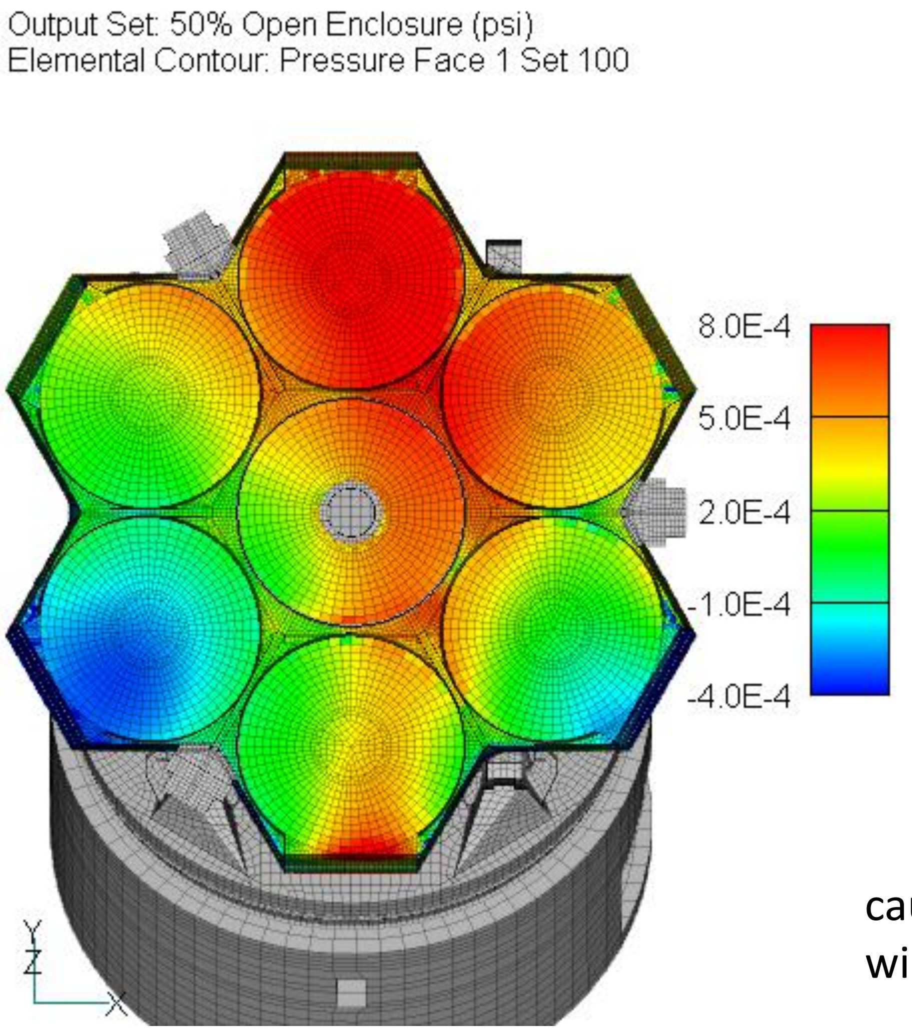
Minimum Aperture Enclosure



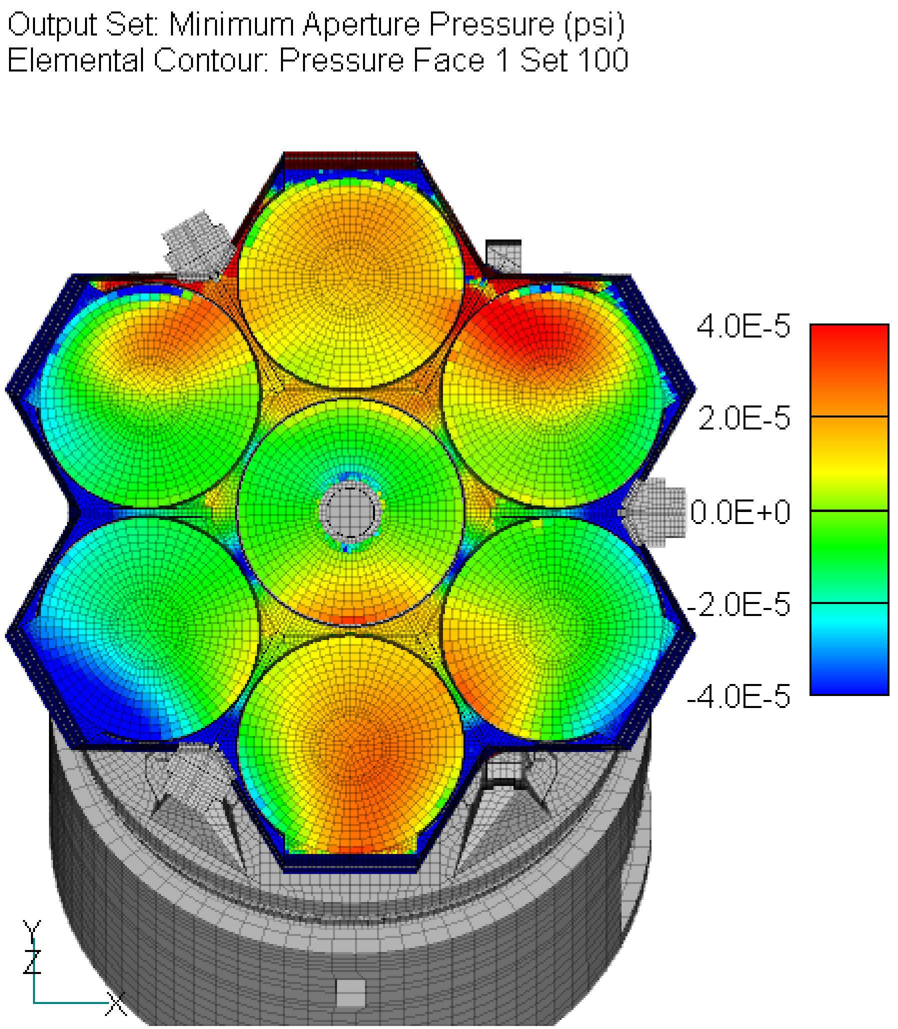
Wind velocity: 10 m/s
Enclosure pointed into the wind

M1 Pressure Comparison

50% Open Enclosure



Minimum Aperture Enclosure



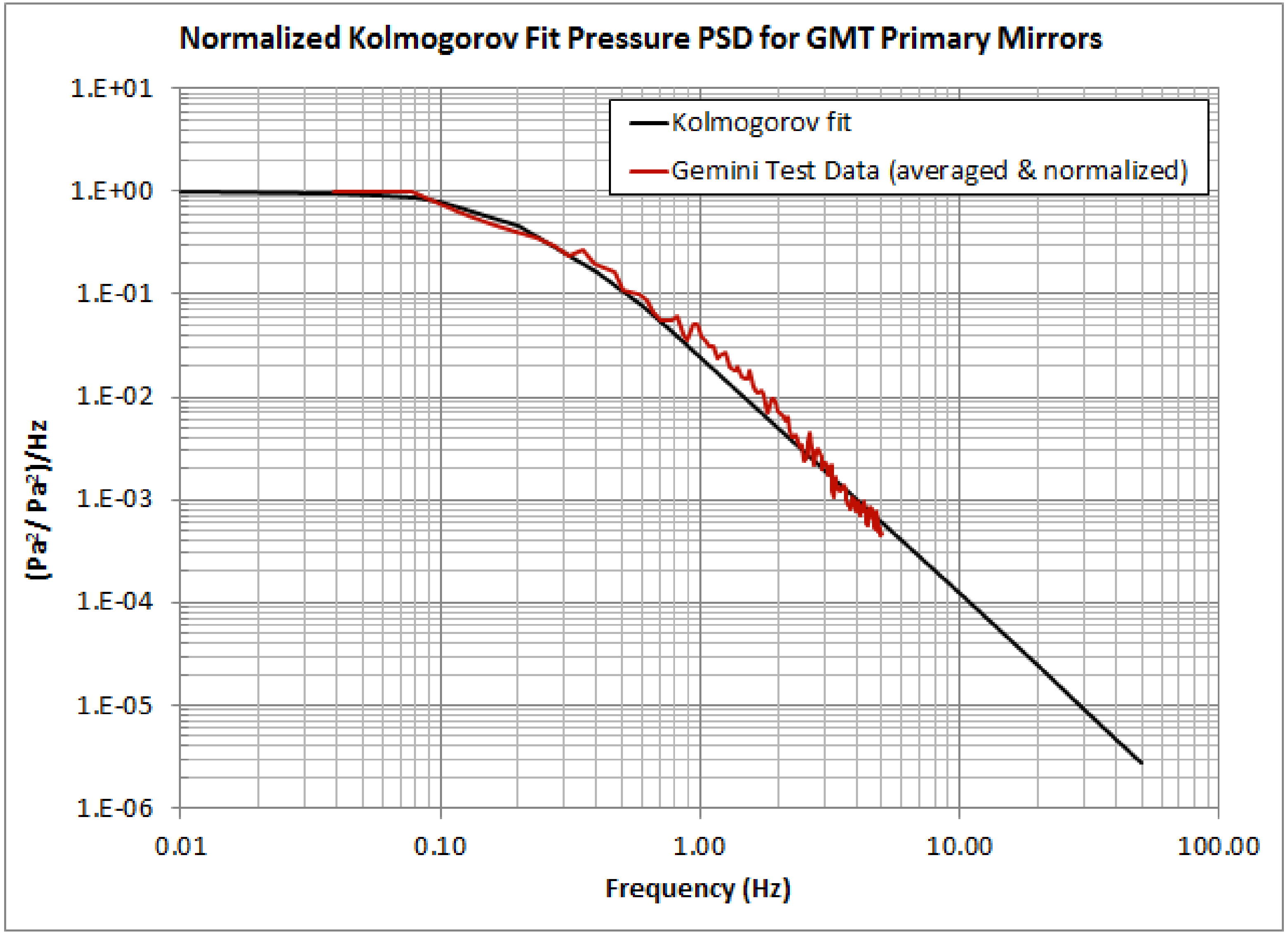
Asymmetrical secondary truss causes asymmetrical wind loading on M1.

M1 Pressure PSD

- PSD shown on right is used to scale M1 Pressures
  - Gemini test data averaged and scaled to match GMT CFD data
  - Sampling up to 5 Hz
  - Data follows Kolmogorov fit
- Equation for Kolmogorov fit:

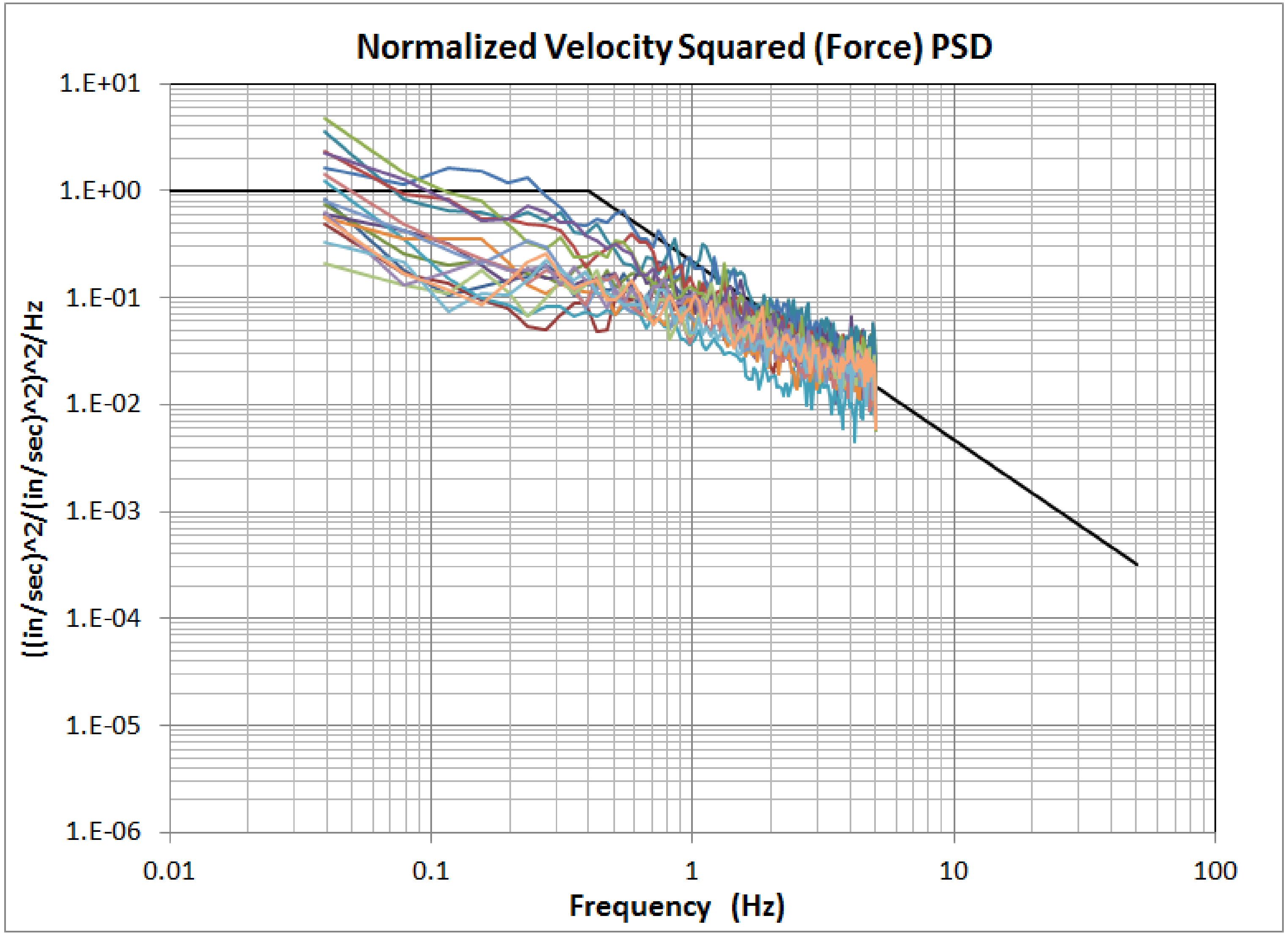
$$\Phi_{pt}^{vK}(f) = \frac{C_{pt}^{vK}}{\left[1+\left(\frac{f}{f_0}\right)^2\right]^{7/6}}$$

- Normalized Kolmogorov fit PSD applied to the defined pressures



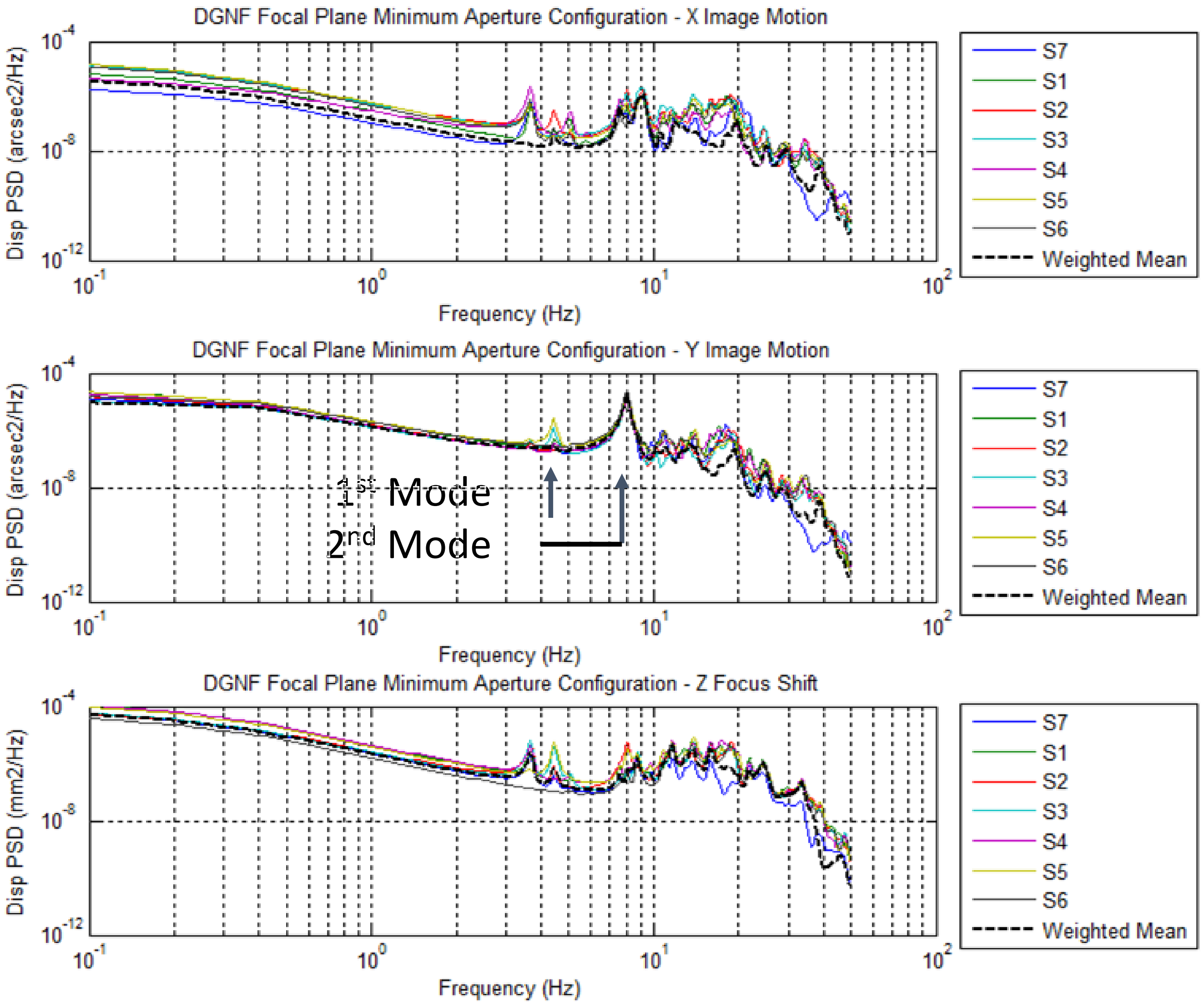
M2 & Truss Force PSD

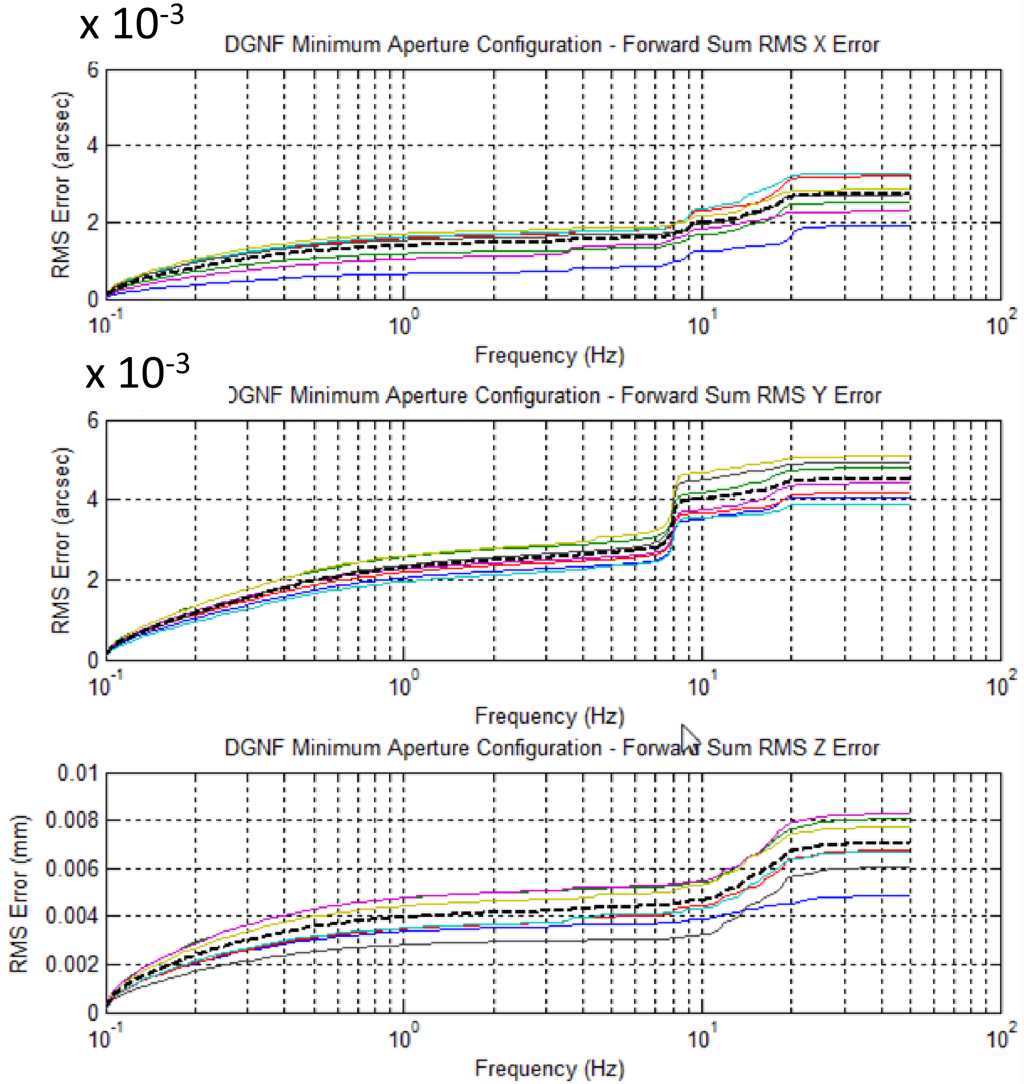
- PSD shown at right is used to scale M2 & Truss forces
  - Gemini M2 velocity data is squared and normalized
  - Sampling up to 5 Hz



Minimum Aperture Image Motion & Focus Shift PSD

Tracking req't < 0.043 arcsec RMS

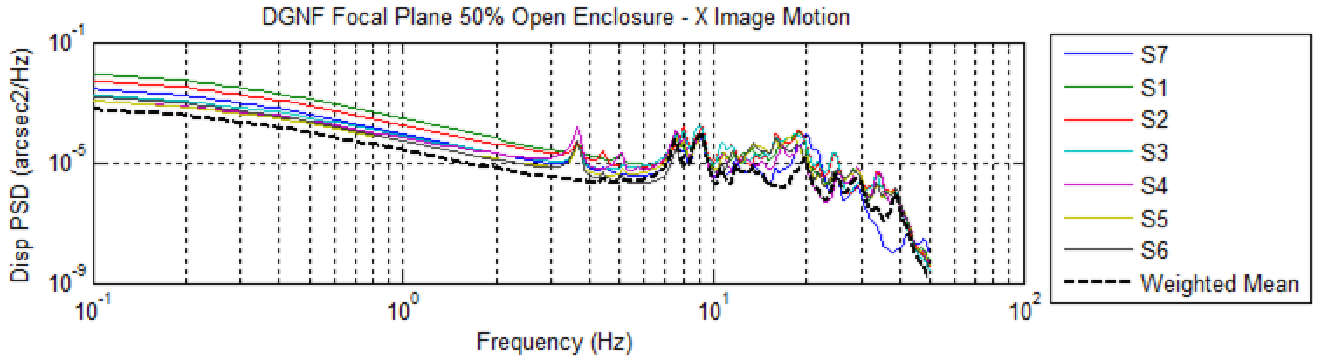


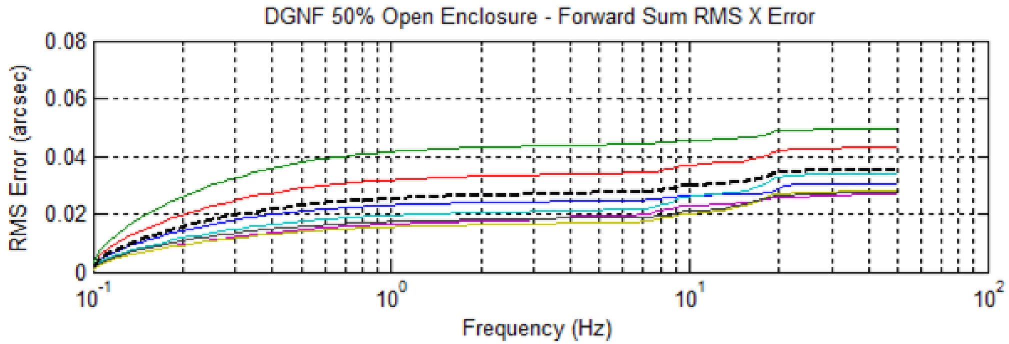


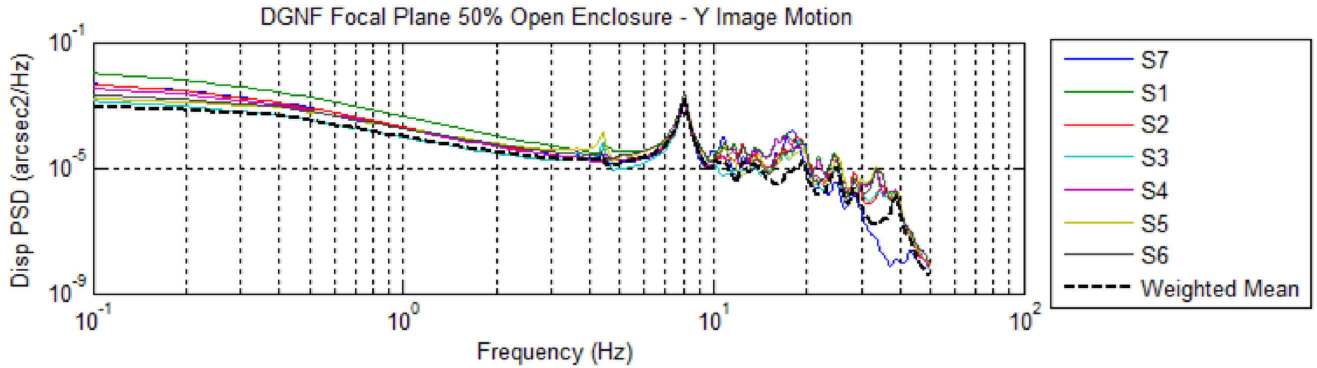
Focus Shift Req't < 0.11 mm

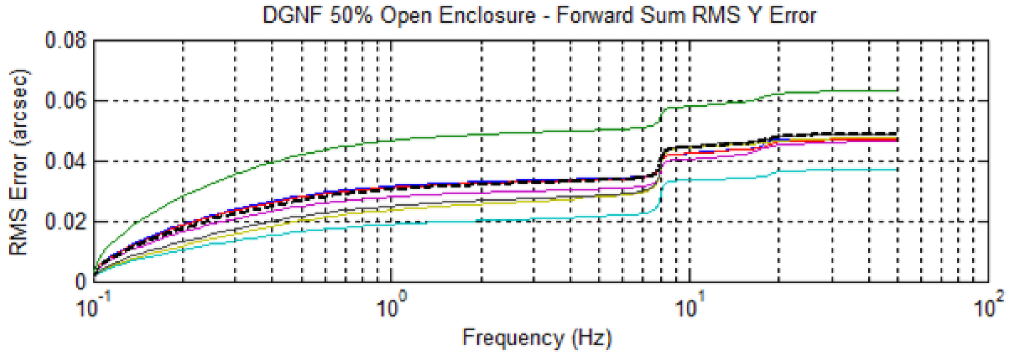
50% Open Enclosure Image Motion & Focus Shift PSD

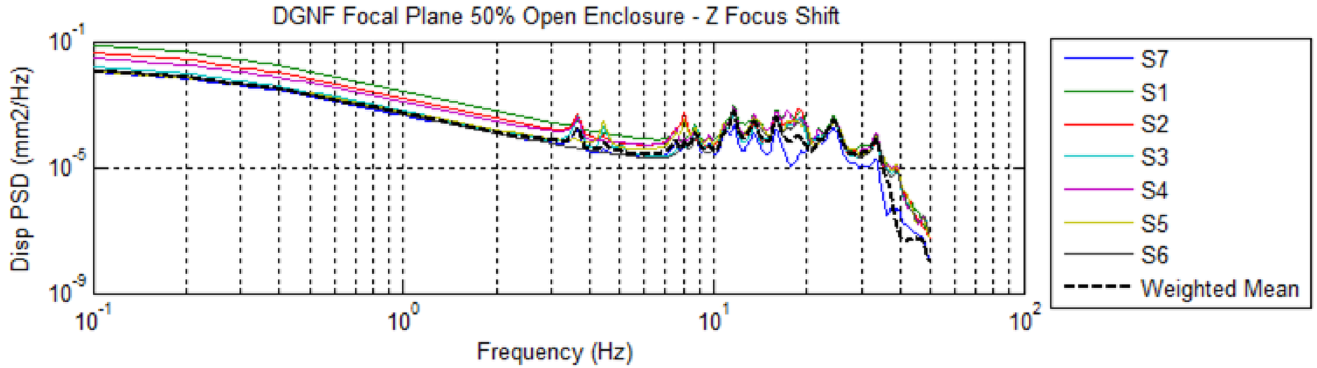
Tracking req't < 0.043 arcsec RMS

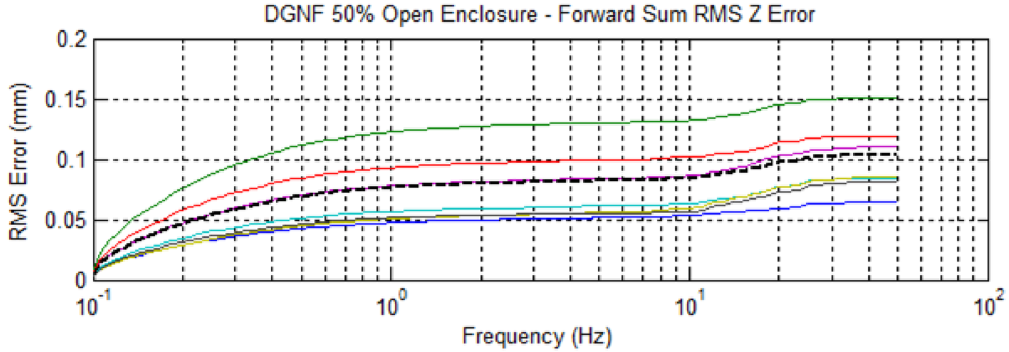








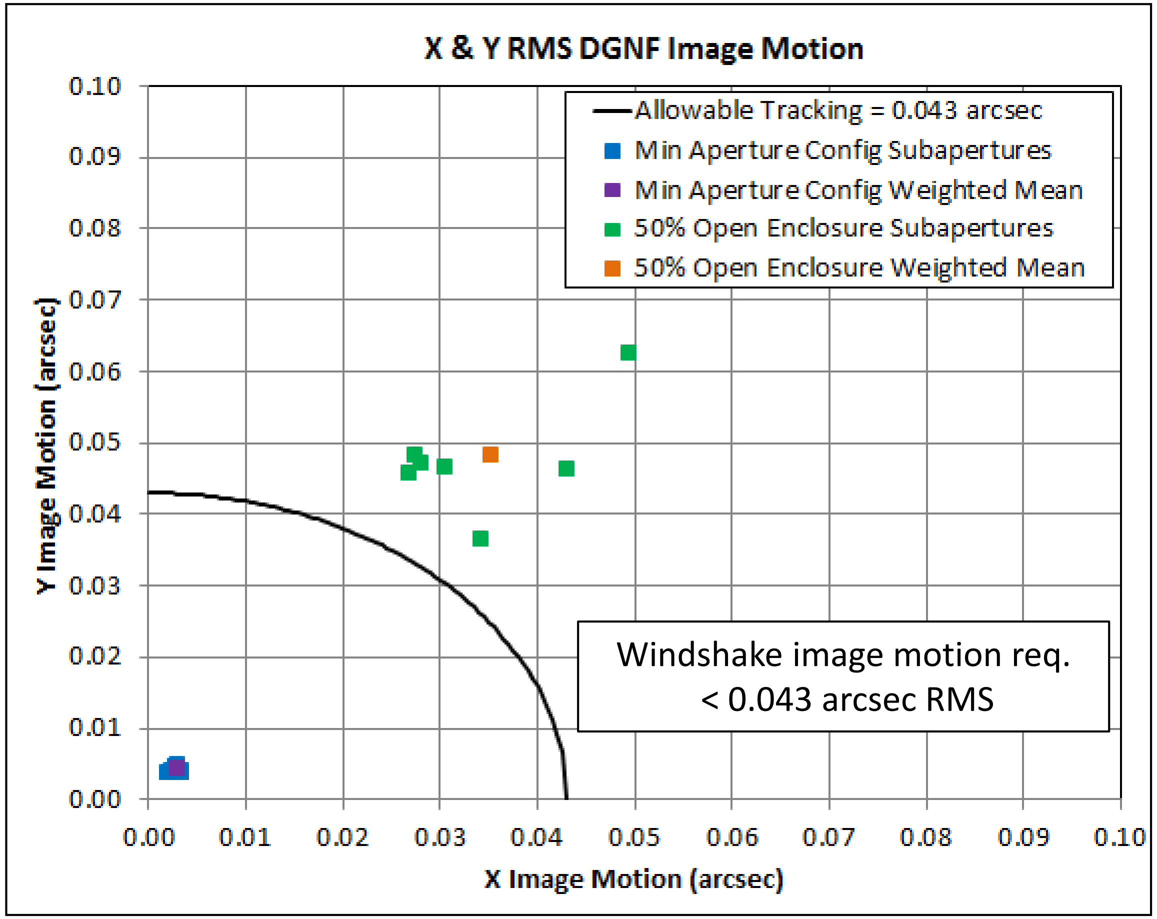




Focus Shift Req't < 0.11 mm

Windshake Image Motion & Focus Shift

- Image Motion and Focus shift 1σ RMS errors for Minimum Aperture & 50% Open Enclosure are shown below for DGNF
- Image quality pointing error meets requirements for Minimum Aperture case
  - 50% Open Enclosure case requires active tip-tilt correction
- Focus shift meets performance requirements for both cases



Windshake Focus Shift requirement
< 0.11 mm

DGNF Focus Shift (mm)		
Segment #	50% Open Enclosure	Minimum Aperture
Segment 7	0.064	0.005
Segment 1	0.151	0.008
Segment 2	0.119	0.007
Segment 3	0.085	0.007
Segment 4	0.110	0.008
Segment 5	0.085	0.008
Segment 6	0.081	0.006
Weighted Mean	0.104	0.007

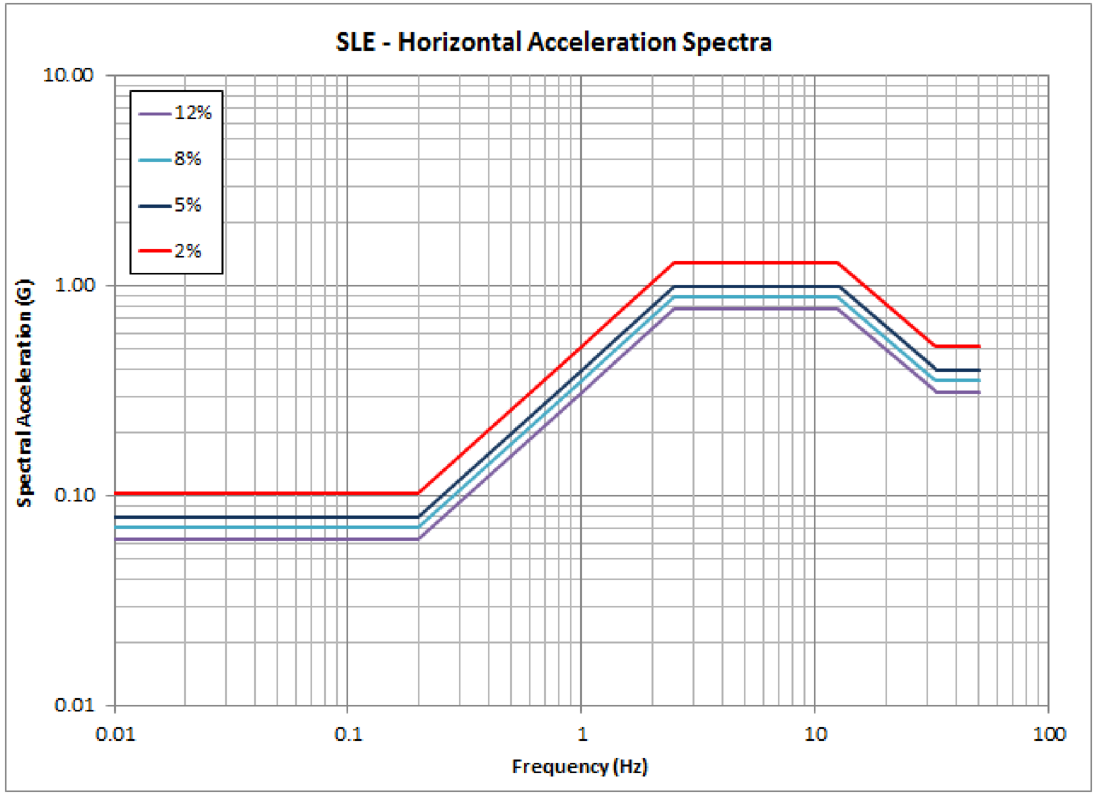
Seismic Analysis

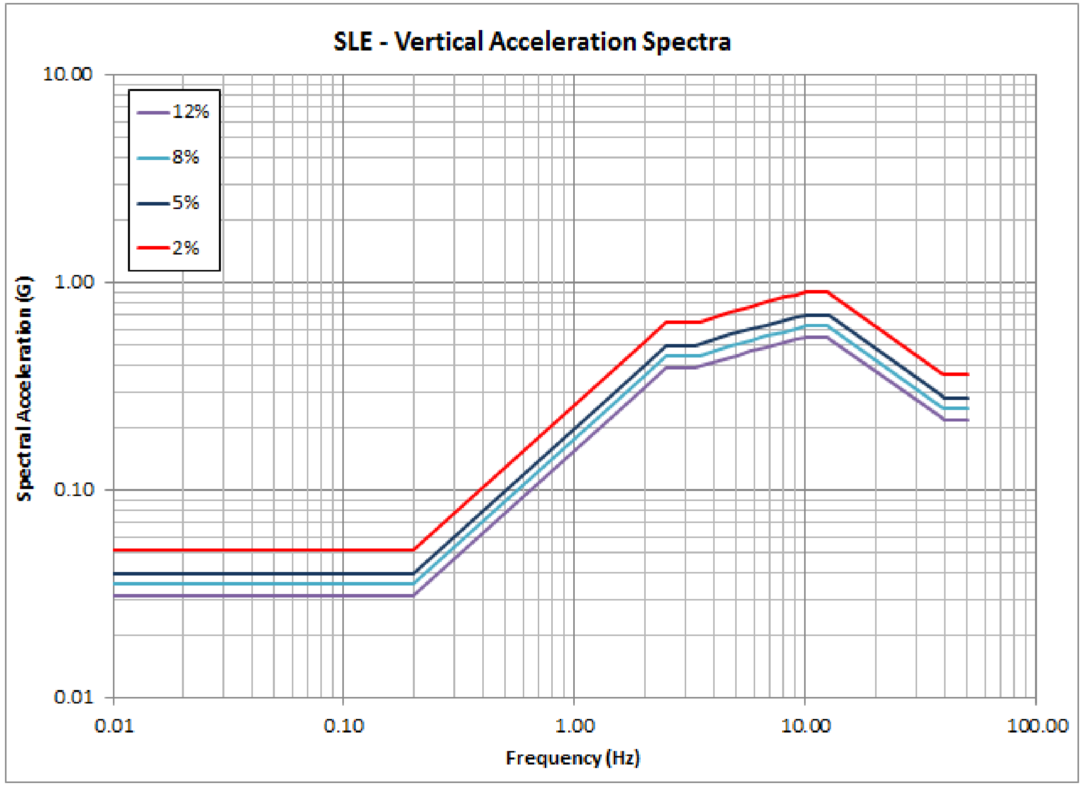
FE Seismic Modeling

- Dynamic FEM models are required to demonstrate telescope and enclosure safety in the event of major OLE or SLE events.
- GMT mount seismic performance was initially modeled using the linear technique of Shock Response Spectra (SRS) wherein damped vibration modes are excited with an assumed earthquake power spectra density distribution and the resulting excited modes are combined in RSS. These results are included in this presentation.
- A more computationally non-linear analysis using as input time series seismic accelerations has been performed for subsequent studies by GMT and Magellan.
  - This type of analysis allows the non-linear behavior of the hydrostat bearings and other subassemblies to be more accurately modeled.
  - The phases of the harmonic components of the input driving function are preserved.
  - A time series of the structure deformation is created for viewing.
  - See the presentation “Magellan Project Experience Building a 6.5 M Optical/IR Telescope”, M. Johns, 2017.
- The output of these analyses are RMS and maximum accelerations and displacements at points of interest within the structure. Internal stress in the structural elements of the FEM are also obtained.

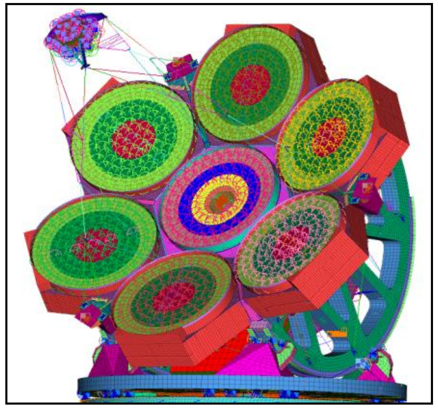
Seismic Analysis Overview

- Shock response spectra (SRS) analysis performed in X, Y, and Z directions using modes from 0-50 Hz
  - Complete Quadratic Combination (CQC) utilized within each primary direction (X, Y, Z)
  - X, Y, and Z results are then combined by RSS to determine total responses
- Spectra given for two different levels of earthquakes
  - Survival Level Earthquake (SLE) (shown below)
  - Operational Level Earthquake (OLE)
  - Spectra derived in the Seismic Hazard report prepared by URS Corporation



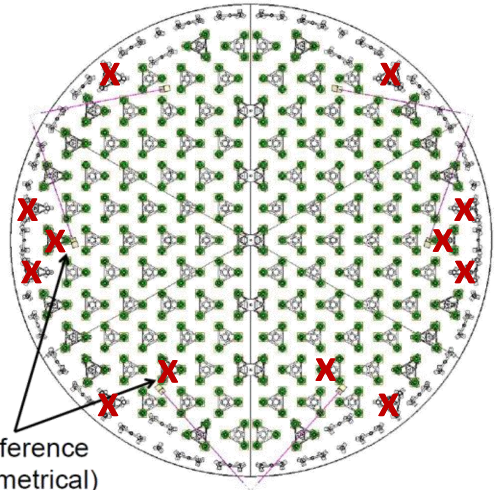


FEM M1 Static Supports



- Mirrors are supported by static support springs during earthquake loading
  - Primary mirror segment positioning hexapods are released
  - Static support details to be discussing in up-coming presentation
- Stiffnesses of individual static support springs were linearized
  - Lateral stiffness = 553 lb/in
  - Vertical stiffness = 1800 lb/in

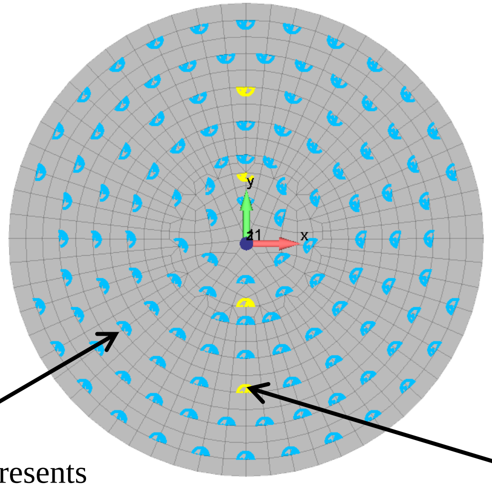
Schematic of Static Support Springs
(Off-Axis Mirror Segment Shown)



Interference (symmetrical)

X = no support springs

FEM Representation
(Off-Axis Mirror Segment Shown)

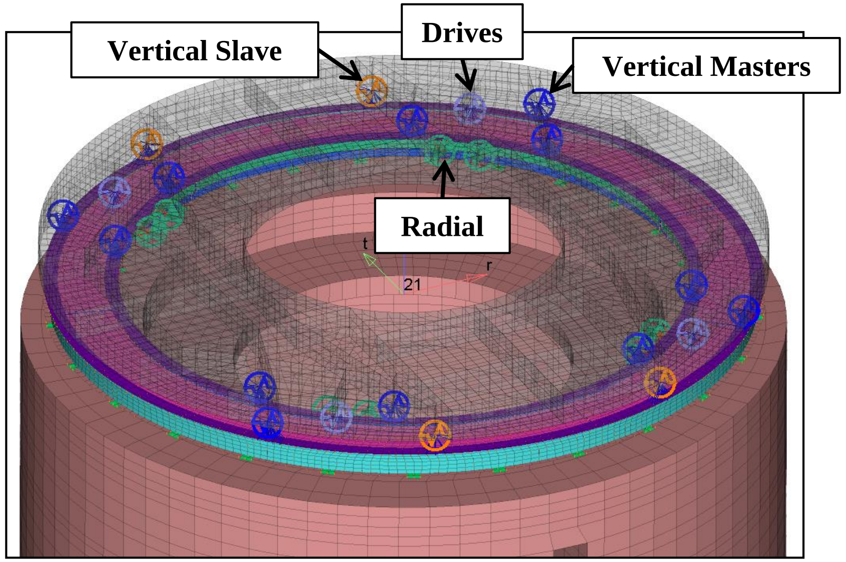


Blue property represents 3-spring-groups

Yellow property represents 4-spring-groups

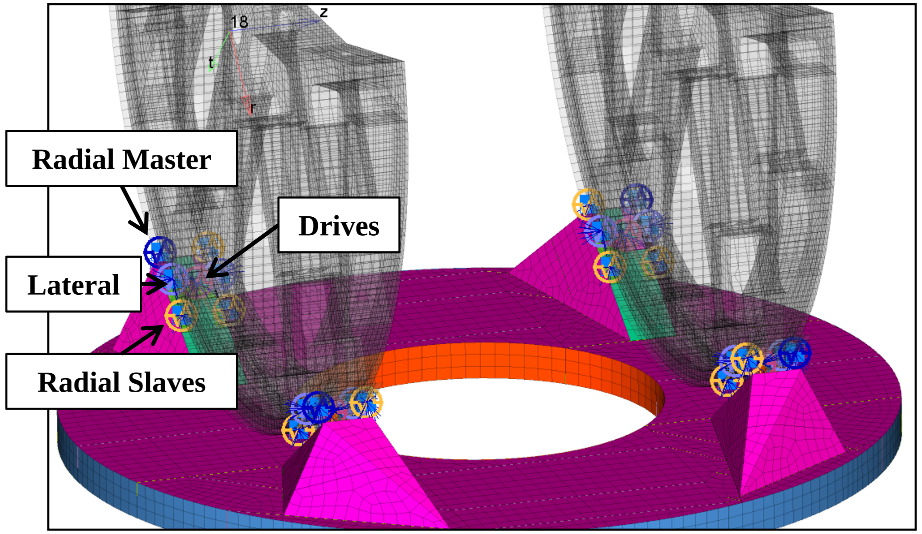
FEM Hydrostatic Bearings

- Friction forces at bearing contact surfaces would *not* be enough to prevent sliding
  - Bearings modeled without in-plane stiffness
- Springs react tension and compression in linear analysis
  - Nonlinear analysis in progress to determine bearing response when only compression is reacted



Azimuth Bearing Stiffnesses

- Vertical Masters = 34E6 lb/in
- Vertical Slaves = 48E6 lb/in
- Radial = 28E6 lb/in
- Drives = free

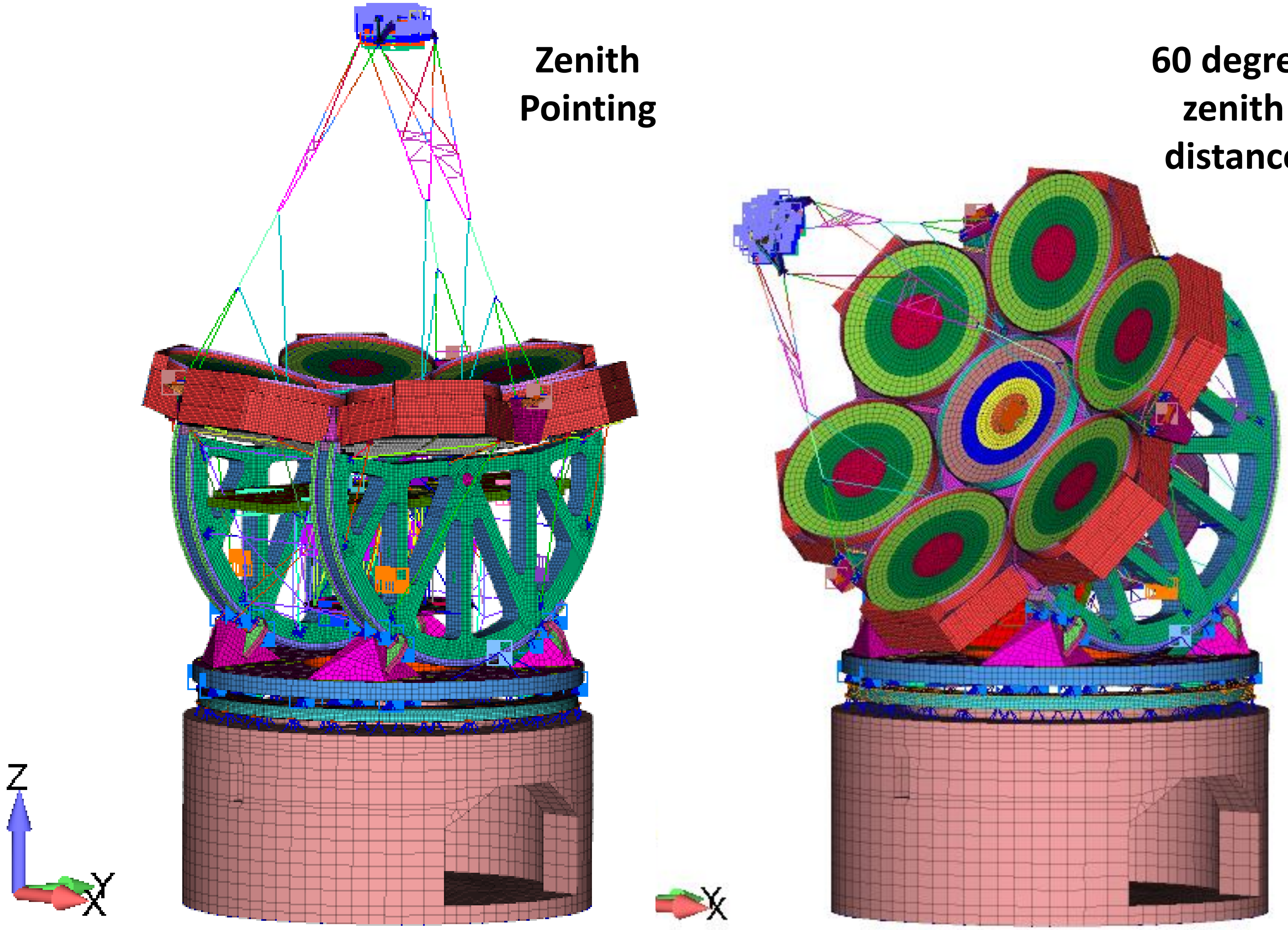


Elevation Bearing Stiffnesses

- Radial Masters = 34E6 lb/in
- Radial Slaves = 48E6 lb/in
- Lateral = 28E6 lb/in
- Drives = free

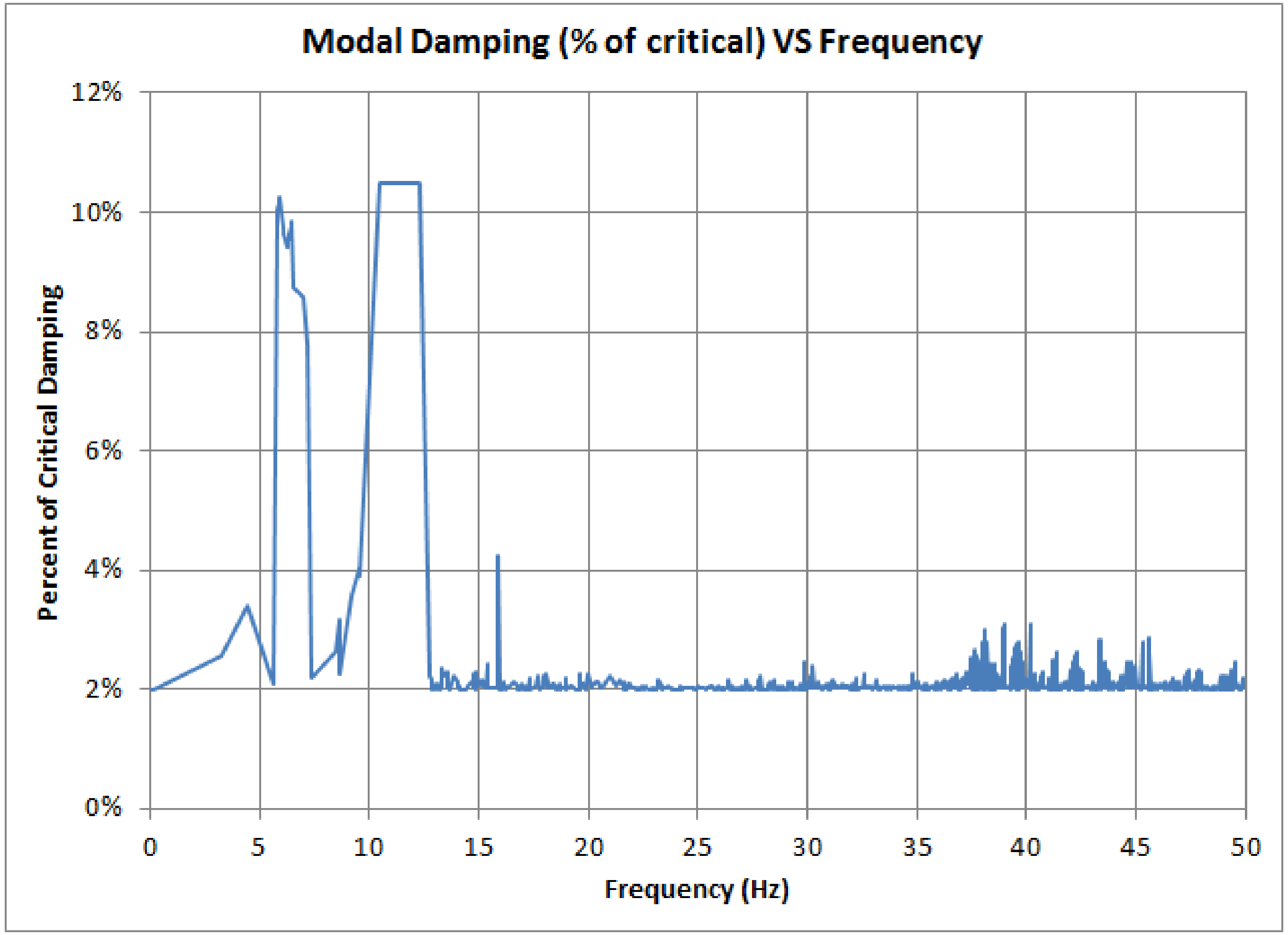
Seismic Telescope Orientations

- Seismic analysis performed in 2 different orientations
- Survival level earthquake (SLE) and operational level earthquake (OLE) analyzed.



Modal Damping in SRS Analysis

- Individual modes get their own damping value in SRS analysis
  - Each mode shape has a unique combination of 2 damping sources
    - 2% of critical damping applied to general structure
    - 10% of critical damping applied at primary mirror static supports
      - Static support damping ranges from 10-20%, 10% is chosen as a conservative estimate
- Custom modal damping tables created for structure in 2 orientations
  - Tables are similar for 0° and 60°



SLE Accelerations

- Loads include seismic shock only
  - Gravity does not affect acceleration results
- Telescope has been designed for accelerations below

Location	Coordinate System	Acceleration (G) 0 Degree Zenith Angle			Acceleration (G) 60 Degree Zenith Angle		
		X	Y	Z	X	Y	Z
Top of Pier	Global CS	0.48	0.80	0.15	0.48	0.86	0.15
AZ Track	Global CS	0.52	0.77	0.21	0.53	0.82	0.21
AZ Disk	Global CS	0.59	0.85	0.30	0.61	0.91	0.32
GIS	Global CS	1.06	0.87	0.67	1.06	0.93	0.69
GIR DG Instruments	Optical Axis CS	1.00	1.19	1.19	1.25	1.11	1.44
GIR FP Instruments	Optical Axis CS	1.25	1.42	1.05	1.31	1.39	1.34
M1 Mirror Cell	Local CS	1.37	1.18	1.06	1.68	0.90	1.44
M1 Mirror Segment	Local CS	1.96	2.57	1.72	2.40	1.88	1.66
Top Center of M2 Frame	Optical Axis CS	3.62	1.50	0.85	2.25	1.51	1.43
Secondary Mirror Cell	Optical Axis CS	3.81	1.57	0.93	2.44	1.64	1.52
Secondary Mirror Vertex	Optical Axis CS	4.17	1.97	1.00	2.72	2.00	1.58

SLE Displacements

- Loads include seismic shock and gravity
- Displacements are within allowable range with exception of M1 segments relative to Mirror Cells
  - Values are larger than desired for the current design, additional details will be shown in an up-coming presentation

Location	Coordinate System	Displacement (mm) 0 Degree Zenith Angle			Displacement (mm) 60 Degree Zenith Angle		
		X	Y	Z	X	Y	Z
Ground to Top of Pier	Global CS	0.36	0.52	-0.33	0.37	0.58	-0.35
Ground to AZ Track	Global CS	1.01	-0.85	-1.39	1.09	0.94	-1.57
Ground to Azimuth Disk	Global CS	5.92	3.93	-2.24	6.43	-4.67	-2.83
M1 Mirror Segment Relative to Mirror Cell	Local M1 CS	14.31	-19.05	-4.90	14.43	-18.89	-3.73
Ground to M1 Mirror Cell	Local M1 CS	32.08	14.80	-18.21	37.57	-12.54	-18.61
Ground to M1 Mirror Segment	Local M1 CS	45.35	32.36	-20.81	51.08	-26.60	-21.07
Ground to Top Center of M2 Frame	Global CS	62.08	12.64	-4.70	44.64	-14.31	-9.00
Ground to M2 Mirror Vertex	Local M2 CS	-62.53	54.12	18.20	-46.38	42.39	17.45
M2 Mirror Vertex Relative to Center of M2 Frame Bottom	Optical Axis CS	-2.06	-1.33	1.08	-2.86	-2.40	1.26
Off-Axis M2 Mirror Vertex Relative to On-Axis M2 Mirror Vertex	Optical Axis CS	-1.19	0.93	1.10	-2.38	-1.96	1.26
Off-Axis M2 Mirror Vertex Relative to Neighbor Off-Axis M2 Mirror Vertex	Optical Axis CS	1.14	1.30	1.33	-2.39	-1.98	-1.62

Primary Mirror Motion Budget

GMT Primary Mirror Motion Budget (mm)

	All units mm		Full Range					
		Sign	Actuators		Static Supports		Hardpoints	
			Axial	Lateral	Axial	Lateral	Axial	Lateral
6	**Margin**							
7	Linear Manufacturing Allowance	+/-	2.00	2.00	2.00	2.00	2.00	2.00
8	Angle Manufacturing Allowance	+/-	0.35	0.00	0.33	0.00	0.27	0.00
9	Air Gap	+/-	0.00	0.00	1.00	1.00	0.00	0.00
10	Allowed Mirror Motion	+/-	1.00	1.00	1.00	1.00	1.00	1.00
12	**Installation Tolerances**							
13	Cell installation	+/-*	1.00	1.00	1.00	1.00	1.00	1.00
14	Load-spreaders	+/-	0.51	0.51	0.70	0.78	0.00	0.00
15	Actuators	+/-	1.00	1.00	0.00	0.00	0.00	0.00
16	Static supports	+/-	0.00	0.00	0.25	0.00	0.00	0.00
17	Hardpoints	+/-	0.00	0.00	0.00	0.00	2.00	2.00
18	Glass wedges	+/-	0.00	0.00	0.00	0.00	2.00	1.60
20	**Operation Distortions**							
21	Cell gravity deflection	+/-	0.60	0.00	0.60	0.00	0.60	0.00
22	Telescope gravity deflection	+/-*	0.25	0.25	0.25	0.25	0.25	0.25
23	Cell thermal	+/-	0.00	0.63	0.00	0.60	0.00	0.48
24	Telescope thermal	+/-*	0.16	1.36	0.16	1.36	0.16	1.36
25	Loadspreader compliance	+/-	0.32	0.38	0.00	0.00	0.00	0.00
26	Static support hysteresis	+/-	0.00	0.00	0.50	1.00	0.00	0.00
27	Bond creep to cylinders	+/-	0.00	0.75	0.00	0.75	0.00	0.00
29	**Contact Allocation**							
30	Max air space	+/-			**7.79**	**9.74**		
31	Usable position range	+/-			**2.41**	**3.61**		
33	**Operational Range**	+/-	**7.19**	**8.88**			**9.28**	**9.69**
35	**Gravity, Seismic and Thermal**							
36	gravity	+	3.35	2.54	3.35	2.54	3.35	2.54
37	thermal survival	+/-	0.00	0.45	0.00	0.43	0.00	0.34
38	seismic	+/-	9.53	5.56	9.53	5.56	9.53	5.56
40	**Total**							
41	Downward	+	**20.67**	**18.28**	**20.67**	**18.26**	**12.63**	**12.23**
42	Upward	-	**17.31**	**18.28**	**17.31**	**18.26**	**9.28**	**12.23**
44	**Break-away Travel**							
45	Downward	+					**29.95**	**30.49**
46	Upward	-					**29.95**	**30.49**

			Axial	Lateral
35	**Gravity, Seismic and Thermal**			
36	gravity	+	3.35	2.54
37	thermal survival	+/-	0.00	0.45
38	seismic	+/-	9.53	5.56

Combined GMT gravity and seismic M1 motion budget allocations:

- Axial: 12.9 mm
- Lateral: 8.1 mm (seismic does not coincide with thermal)

Maximum displacements from the SLE seismic modeling:

- Axial: 4.9 mm
- Lateral: 19.1 mm

This analysis indicates that additional design of the mirror support system or re-allocation of the motion budget is required to bring the system into compliance with requirements.

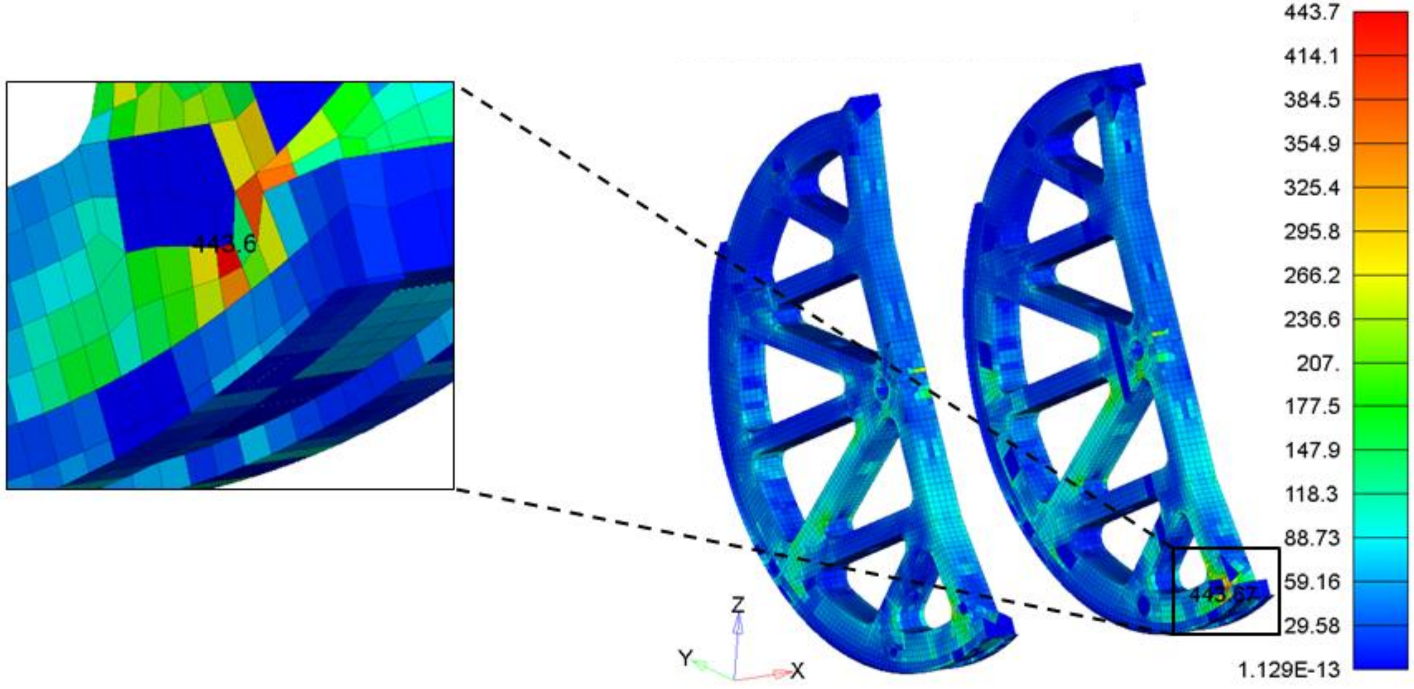
SLE Hydrostatic Bearing Force Results

- Loads include seismic shock and gravity.
- Linear analysis requires hydrostatic bearing elements to react tension and compression forces.
  - Nonlinear analysis in progress to determine bearing forces when only compression is allowed.
- Detailed design will attempt to increase bearing capacities, however bearings damaged during SLE could be replaced.

Location		Design Capacity	Force (N) 0 Degree Zenith Angle	Force (N) 60 Degree Zenith Angle
		Axial Compression	Axial Compression	Axial Compression
Azimuth Vertical Bearings	Masters	3.12E+06	3.94E+06	4.61E+06
	Slaves	7.00E+06	2.38E+06	2.95E+06
Azimuth Radial Bearings		5.00E+06	3.56E+06	3.80E+06
Elevation Radial Bearing	Masters	3.12E+06	2.22E+06	2.72E+06
	Slaves	7.00E+06	4.05E+06	4.03E+06
Elevation Lateral Bearing		5.00E+06	1.44E+06	1.59E+06

SLE Von Mises Stress Results

- The FEM seismic analysis computes internal stresses in the structural members of the mount. Stresses that approach the yield strength of the steel can be addressed by reinforcing those areas or by using higher strength steel.
- High stress occurs on C-Rings
  - 60° orientation
  - Occurs where a rigid element attaches C-Ring to the C-Ring bracing
- Peak Stress = 444 MPa
- A36 Steel Yield Stress = 248 MPa



Von Mises stresses in the c-rings for elevation 30 degrees.

FEM Analysis Summary

- The lowest structure vibrational frequency of 3.6 Hz was determined by modal analysis. This sets a limit of under 2 Hz on the main drive servo controls which affects the highest frequency tracking and pointing errors can be corrected by the drives.
- Static gravity deflections of the mount rotating through 60 degrees of elevation provide the data for creating lookup tables for active alignment of the telescope optical system as a function of elevation.
- The ventilation windows and main shutters provide sufficient shielding of the telescope to reduce wind shake to levels that meet the requirements.
- Seismic ground accelerations are significantly magnified in the stiff and lightly damped structure.
- Internal stresses are generally well below the steel yield strength with a few exceptions that are readily addressed with local modeling and modifications of the structure design and/or steel type.
- Motion of the primary mirror segments in a SLE exceed their M1 Motion Budget allowances. This requires modifying the design of the M1 support system to reduce the amplitude and come into compliance.
- A non-linear time-series analysis will be able to better model the performance of the hydrostatic bearings that are only capable of applying compressive force.

Active Optics

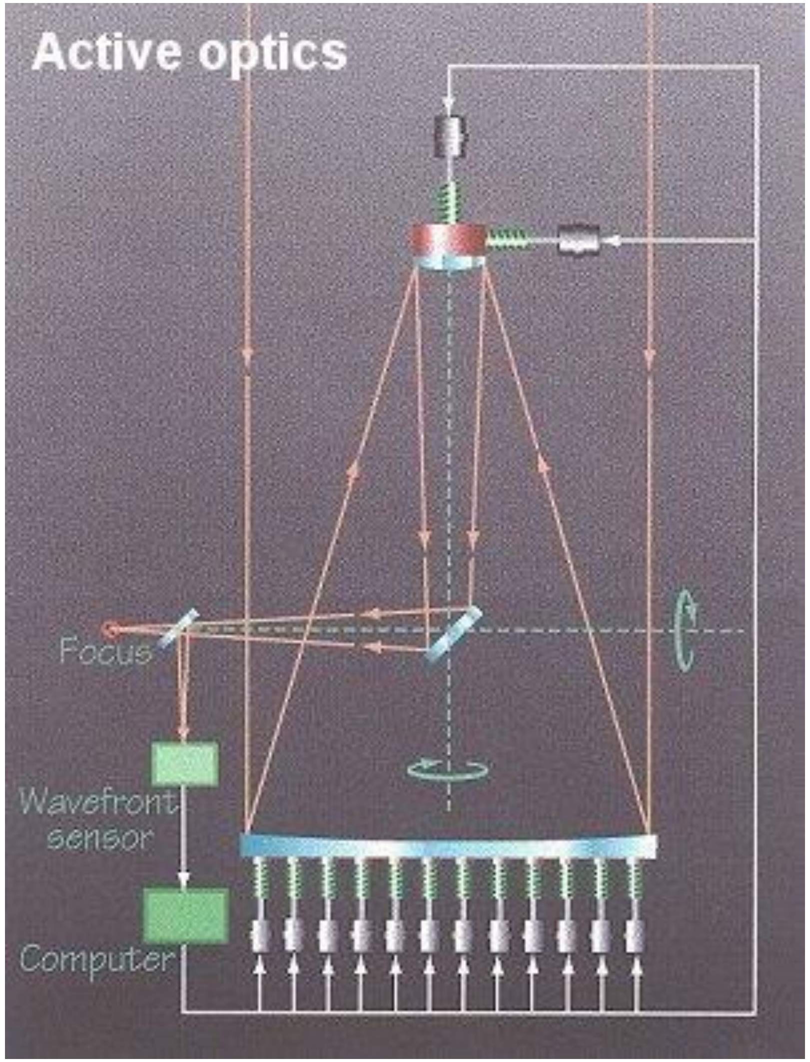
Active and Adaptive Optics

- Modern telescopes include active and adaptive optical systems
- Active optics maintain the telescope optical alignment and focus and adjust mirror figure(s) to correct for slowly varying thermal and gravity distortions within the structure.
- Fast tip/tilt corrects for fast-varying low-order tracking errors and can be used to reduce the stroke of adaptive optics mirrors.
- Adaptive optics corrects for fast-varying wavefront errors that originate in the atmosphere and vibrations of the telescope structure.
- Tracking and wavefront errors are measured by sensors in the focal plane.

System	Typical update rate (Hz)	Hardware
Active optics (AcO)	$\leq$0.03	WF sensor, mirror supports
Guide	10	Guide camera
Fast-tip/tilt	100	Tip/tilt mirror
Adaptive optics (AO)	$\geq$200	WF sensor(s), AO mirror AcO system

Active optics

- Active optics is active control of alignment (primary and secondary) and shape of primary, based on WF measurements in telescope.
  - Necessary because no 8 m mirror is rigid
  - Built into all modern telescopes
- Active optics is slow (~1 minute) and corrects only large-scale errors (~ 10-50 modes).
- Implication for manufacturing:
  - No need to eliminate lowest-order shape errors, because they will be controlled with active optics at telescope.
  - Must reduce large-scale shape errors to be within range of active-optics correction in telescope.
- When mirror surface error is measured in lab, simulate active-optics correction of low-order components.
  - Compute actuator forces and optimized shape.
  - Optimized shape must meet accuracy requirement.

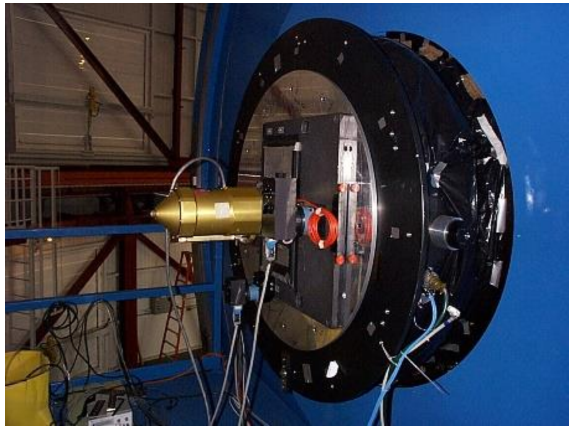


Guider & Active Optics

- Guider assembly
  - Small & medium instrument mounting at the f/11 ports
  - Dual probes with independent field acquisition, high & low spatial resolution wavefront sensors
  - 14 x 14 arc-minute FOV
- Active optics corrections
  - Primary mirror figure correction
  - Secondary mirror collimation & focus
  - Guiding using tilt terms
  - Automatic off-axis operation (focus, coma, astigmatism adjustment)

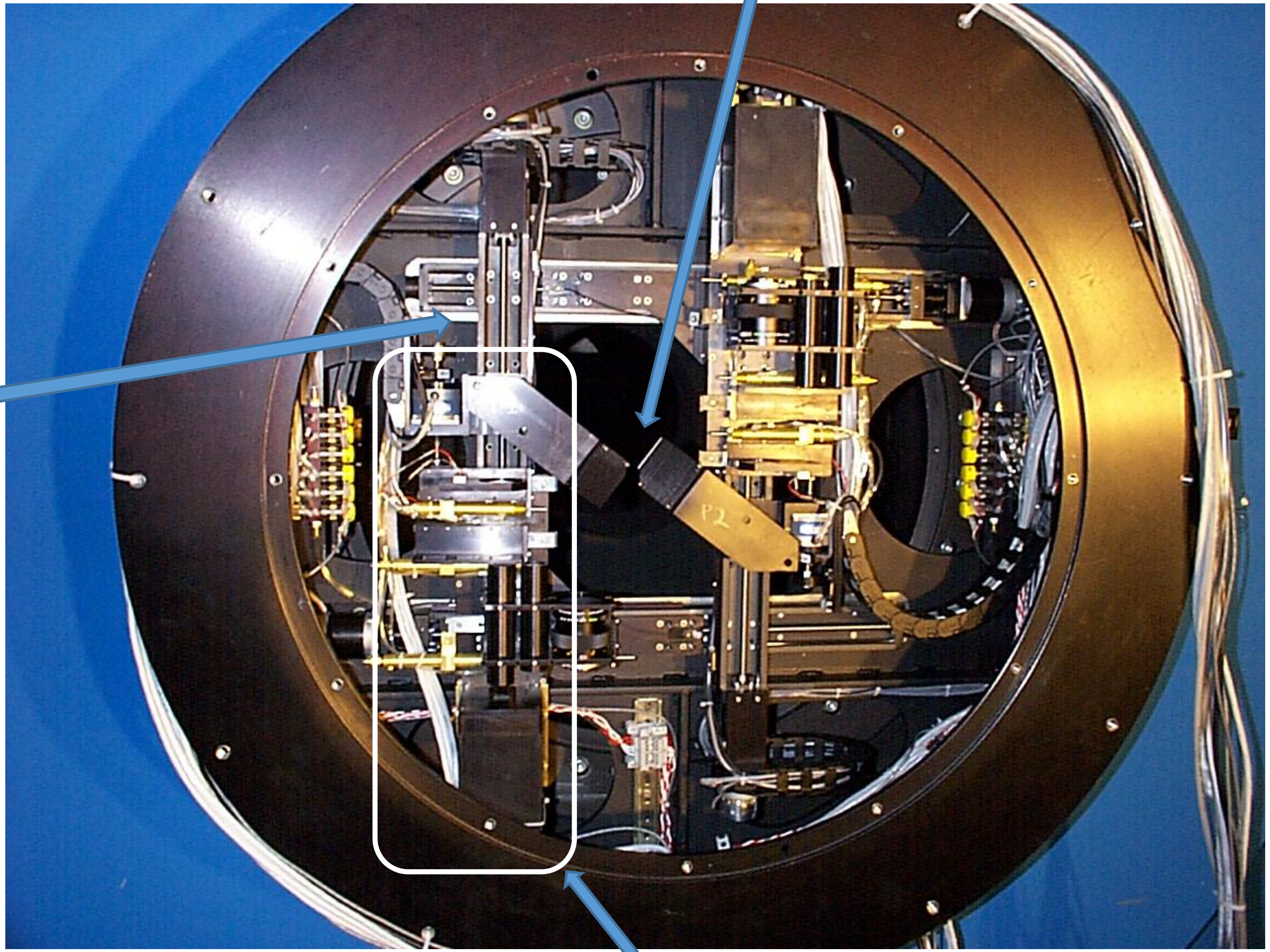
Guider Assembly, shutter/filterwheel and CCD Imager on Magellan

Guider Assembly



Pickoff mirrors

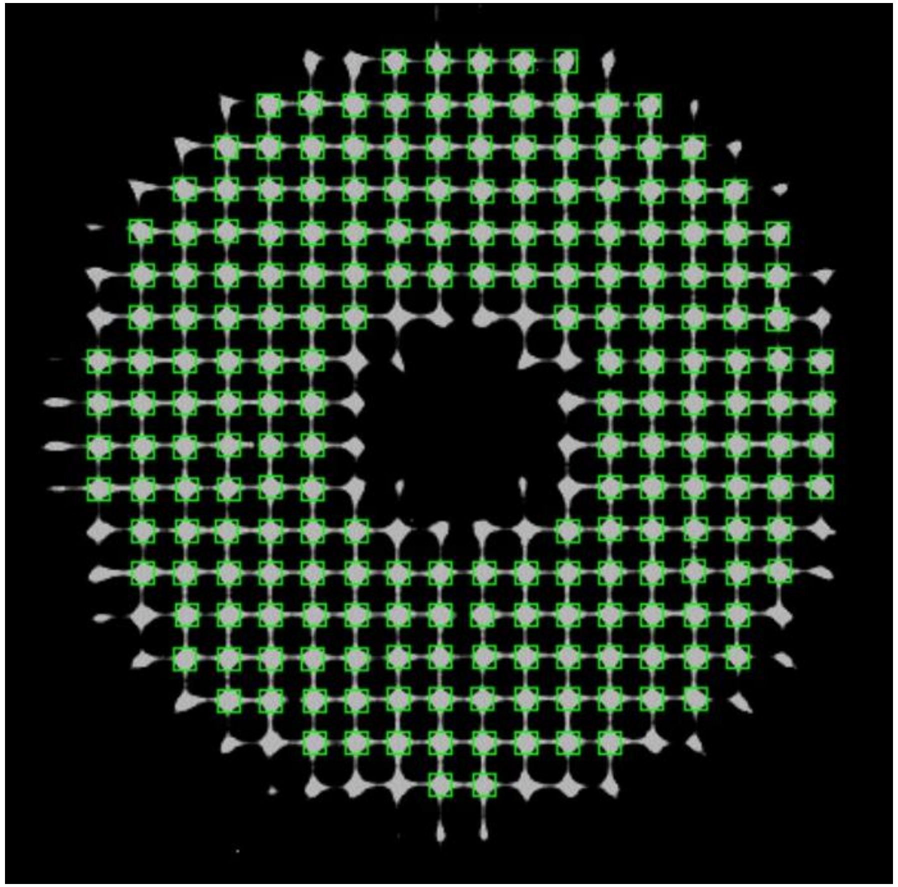
X-y stages

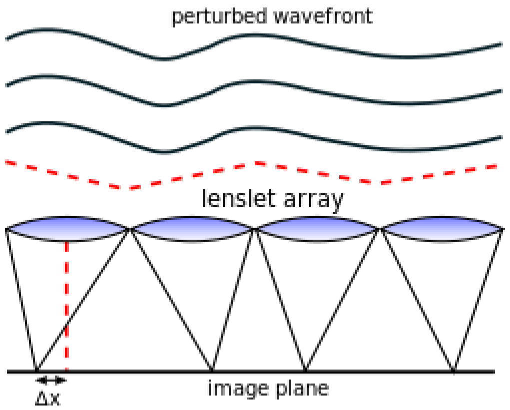


Guide camera/wavefront sensor

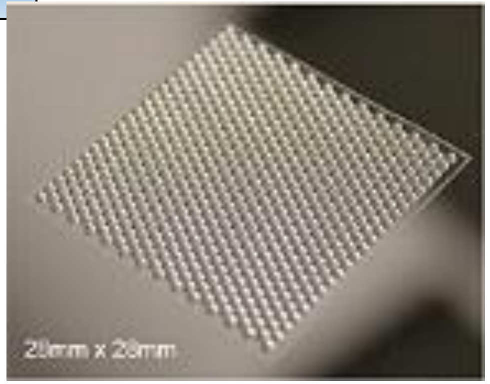
Two guide cameras/wavefront sensors mounted on x-y stages to acquire stars over a 3 square arcmin. field.

Shack-Hartman Spots





Pupil conjugate



- High-resolution 28 x 28 lenslet array
- The deformable mirror (DM), in this case the primary mirror, is re-imaged on the lenslet array.
- Green boxes indicate star spots passed quality check for acceptance.
- Elongated spots around the center hole and perimeter show diffraction effects.
- Displacement of the spots from their calibrated positions gives the local slope error of the wavefront.

Wavefront analysis

Pointing, focus, & alignment

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new image received
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/home/skip/public_html/images/mg200011230743000297.fits pc 213.75 255.66
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z1=1417.579 z2=1740.745
RMS deflection after correction (pixels)  =    0.239
z01 =   -8.432 tilt-c
z02 =    7.431 tilt-s
z03 =    0.789 focus
z04 =   -0.321 astigmatism-c
z05 =   -0.307 astigmatism-s
z06 =    0.147 coma-c
z07 =    0.329 coma-s
z08 =   -0.025 spherical
z09 =    0.280 trefoil-c
z10 =    0.272 trefoil-s
z11 =   -0.028 (4*r^4-3*r^2)*cos(2phi)
z12 =   -0.007 (4*r^4-3*r^2)*sin(2phi)
z13 =   -0.015 (10*r^5-12*r^3+3*r)*cos(phi)
z14 =   -0.002 (10*r^5-12*r^3+3*r)*sin(phi)
z15 =    0.075 20*r^6-30*r^4+12*r^2-1
z16 =   -0.093 quadrafoil-c
z17 =   -0.039 quadrafoil-s
z18 =   -0.086 (5*r^5-4*r^3)*cos(3phi)
z19 =   -0.109 (5*r^5-4*r^3)*sin(3phi)
        secondary correction xstr =     9.89 ystr =   -22.15 zstr =    -6.94
sending secondary correction xstr =     9.89 ystr =   -22.15 zstr =    -6.94
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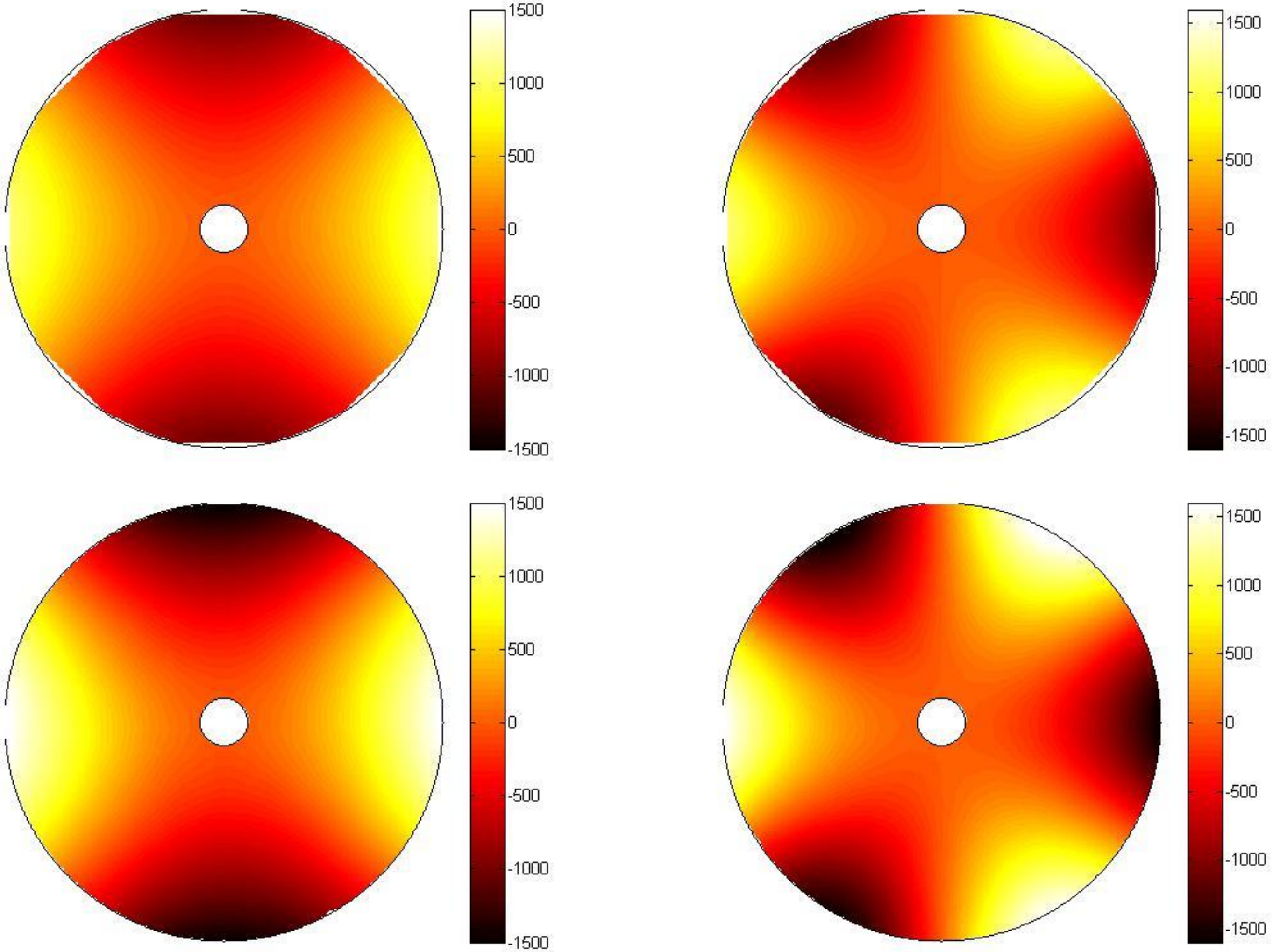
- Zernike decomposition of slope errors up to Z19.
    - The series is truncated to avoid introducing noise and fitting errors into the result.
- Telescope pointing : Z01 and Z02
- Focus: Z03
- M1/M2 collimation: Z06 and Z07
- The remaining terms are wavefront aberrations corrected by the active M1 supports after subtraction of the pointing, focus and collimation terms and re-analysis using bending modes in place of Zernike polynomials.

Measured bending modes for LBT primary mirror

calculated by finite-element analysis

measured in lab



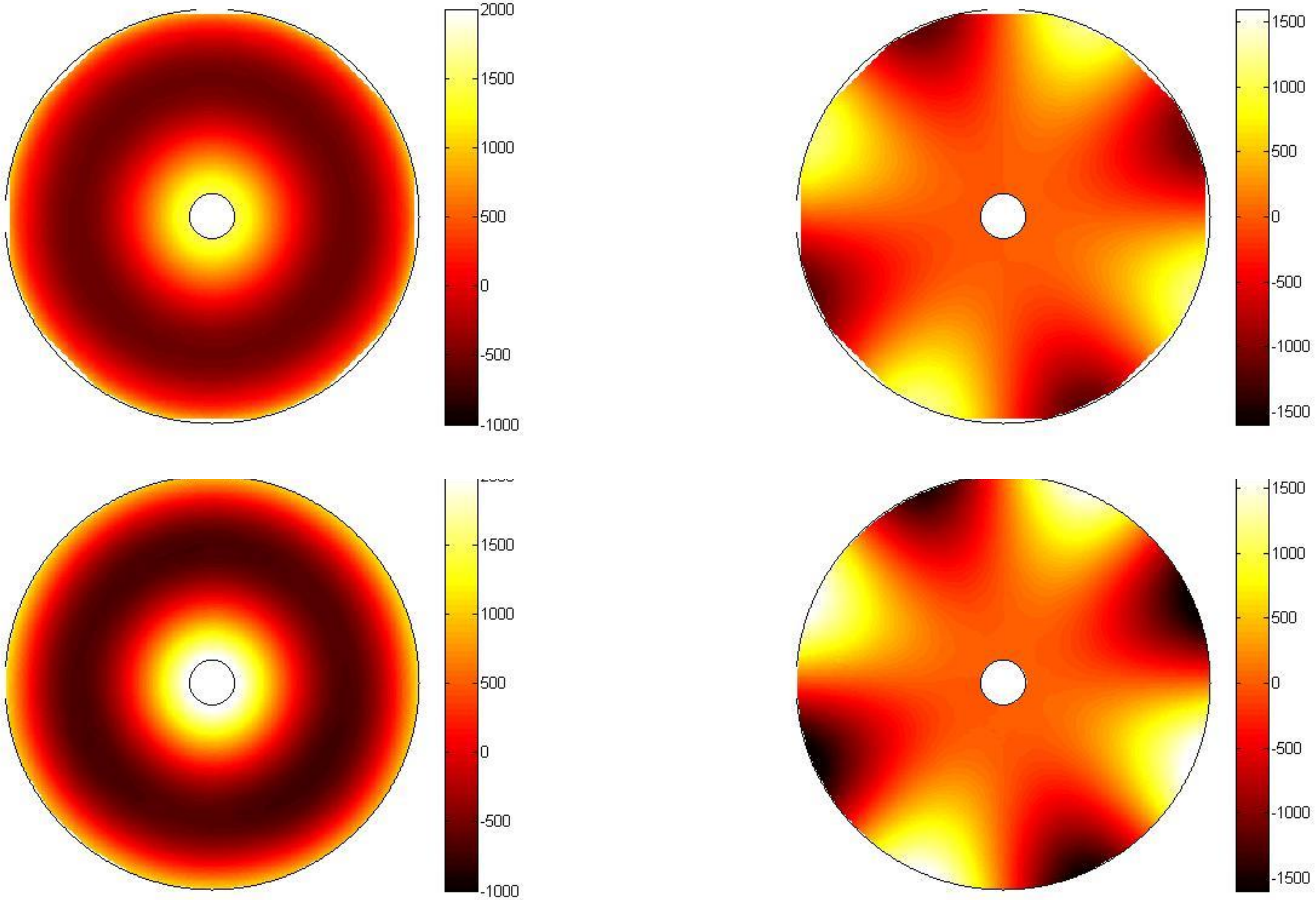
mode 1
5 N rms force

mode 3
30 N rms force

Measured bending modes for LBT primary mirror

calculated

measured



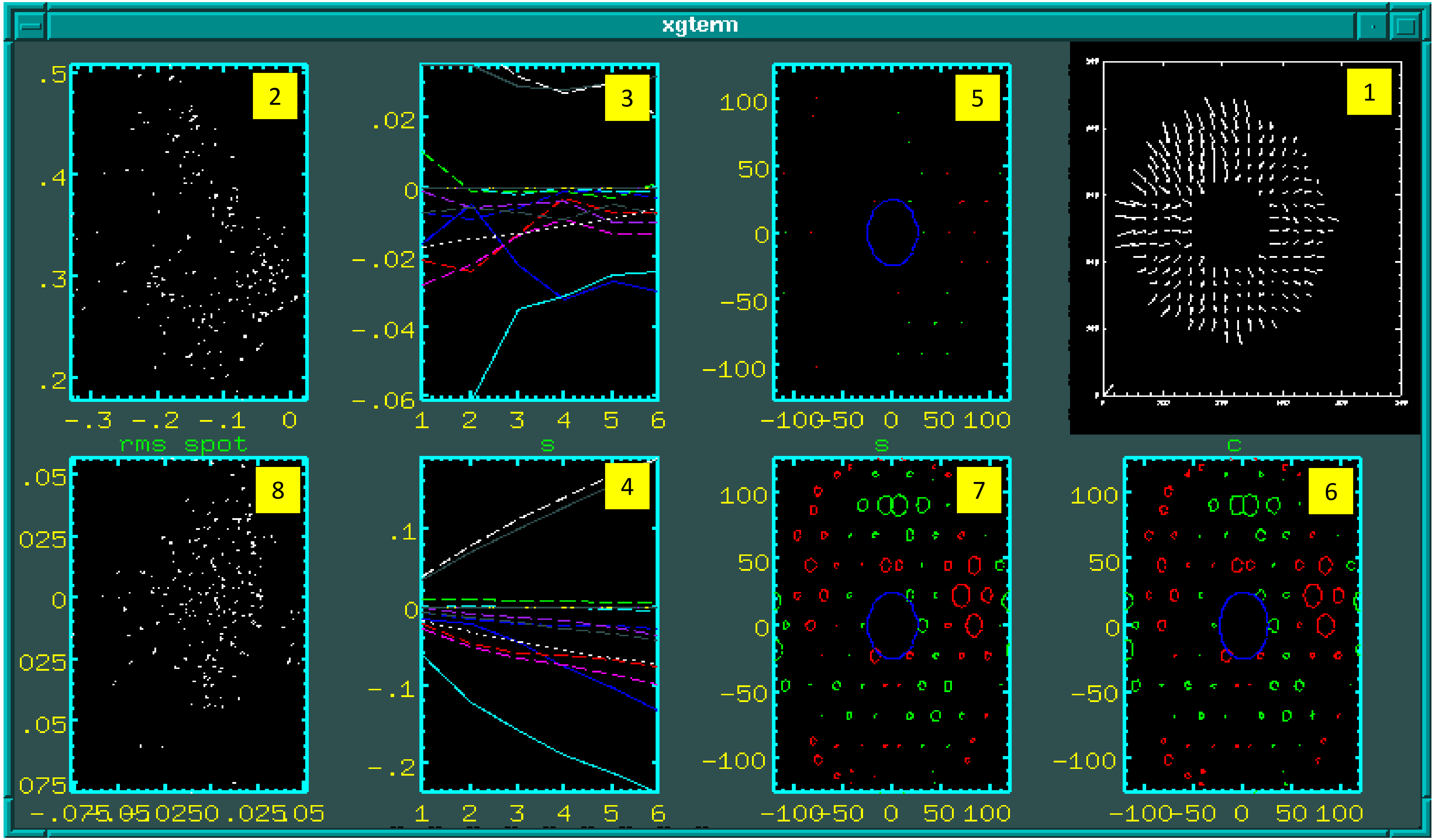
mode 5
60 N rms force

85 N rms force

Active Correction Procedure

- Acquire a star in the wavefront senor.
- Integrate for around 30 seconds to build up statistics and average out wavefront aberrations due to seeing.
- Analyze the slope errors in terms of Zernike polynomials. Correct for any field aberrations that result from the probe being off-center in the FOV.
- Ignore the pointing (wavefront tilt) terms. Telescope pointing errors are sensed by the guide probe and used to close the servo loop in the telescope azimuth and elevation drives.
- Send the focus correction to the telescope focus mechanism, in this case located the M2 mount.
- Send the collimation correction to the alignment system, in this case also the M2 mount.
- Subtract the tilt, focus and collimation terms from the displacement measurements.
- Re-analyze the slope errors in terms of mirror bending modes. Bending modes are a better fit to the corrections that can be applied with the active supports and reduce the correction forces.
- Apply the correction forces to the mirror supports with a gain factor between 0 and 1. Using a gain less than 1 ensures stability and convergence of the system in the presence of sensor noise and residual atmospheric seeing.
- Active correction operates continuously during science data collection.

Active Correction



<u>Correction Steps</u>

(1) Spot displacements
(2) Synthetic spot diagram (“)
(3) Calculated correction
(4) Cumulative correction
(5) Actuator force adjustments
(6) Current forces
(7) New forces
(8) Predicted synthetic spot diagram (“)

End of Session 4