Habitable Exoplanet Imager

Optical Telescope Concept Design

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HabEx

Habitable Exoplanet Imaging Mission (HabEx) is a concept for a mission to directly image and characterize planetary systems around Sun-like stars.

In addition to the search for life on Earth-like exoplanets, HabEx will enable a broad range of general astrophysics science enabled by 100 to 2500 nm spectral range and 3 x 3 arc-minute FOV.

HabEx is one of four mission concepts currently being studied for the 2020 Astrophysics Decadal Survey.

OTA Specification

Science Requirements
Launch Vehicle Capacity
Programmatic Constraints

→ Engineering Specifications

Exoplanet	
Habitable Zone Size	**Minimum Telescope Diameter**
Contrast	Mid/High-Spatial Wavefront Error
Contrast	**WFE Stability**
Contrast	**Polarization**
Star Size	**Line of Sight Stability**
Architecture	**Unobscured (off-axis)**
General Astrophysics	
Diffraction Limit	Low/Mid-Spatial Wavefront Error
Spatial Resolution	Line of Sight Stability
Launch Vehicle	
Up-Mass Capacity	Mass Budget
Fairing Size	Architecture (monolithic/segmented)
Programmatic	
Budget	Maximum Telescope Diameter

Design Assumptions

Mission will have an Internal Coronagraph which requires:

- Unobscured Aperture – off-axis
- Stable Wavefront.

General Astrophysics:

- 450 nm diffraction limit requires no development effort

Launch Vehicle

- SLS will exist. Therefore, for ‘baseline’ design mass and volume constraints are secondary to wavefront stability.
- ‘Backup’ designs will be considered for EELV.

The Most important Design Constraints are:

- Line of Sight Stability
- Wavefront Stability

Optical Telescope Assembly (OTA) Specifications

Architecture	**Unobscured Off-Axis F/2.5 TMA**	
Aperture Diameter	**4-meters Monolithic (Minimum)**	
	6.5-meters Segmented (Maximum)	
Mass Budget	< 10,000 kg (excluding science instruments & spacecraft)	
Line of Sight Stability	**< 5 milli-arc-second (astrophysics)**	
Diffraction Limit	450 nm (assumed to be achievable)	
Wavefront Error	35 nm rms Total (assumed achievable)	
Primary Mirror	Total SFE	< 8.0 nm rms
(cpd = cycles/diameter)	Low-Order (< 3 cpd)	< 5.6 nm rms
	Mid-Spatial (3 to 60 cpd)	< 5.6 nm rms
	High-Spatial (>60 cpd)	< 0.6 nm rms
	Roughness	< 0.2 nm rms
Wavefront Stability	**Architecture and Coronagraph Specific**	

4-meter Monolithic F/2.5 Off-Axis Concept

fits inside SLS

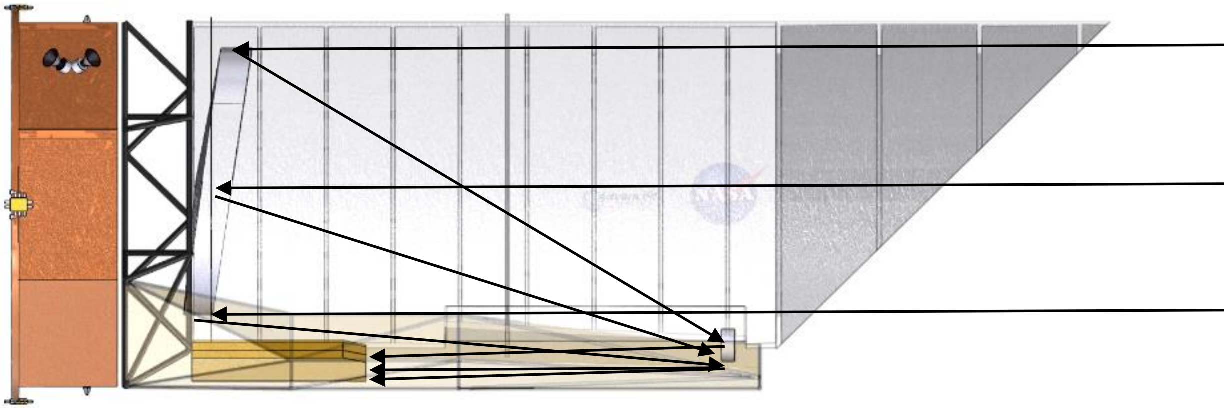
Mission Architecture Constraints

Mission Architecture design constraints:

- Minimum Aperture for science is 4 meters.
- Coronagraph desires unobscured off-axis optical design
- Because of coronagraph polarization sensitivity, the primary mirror is F/2.5 which defines a PM/SM distance of ~ 9 meters.
- For thermal stability and polarization, there is a desire to place the science instruments beside the PM rather than behind it.
- Forward Scarf limits close approach angle to Sun.

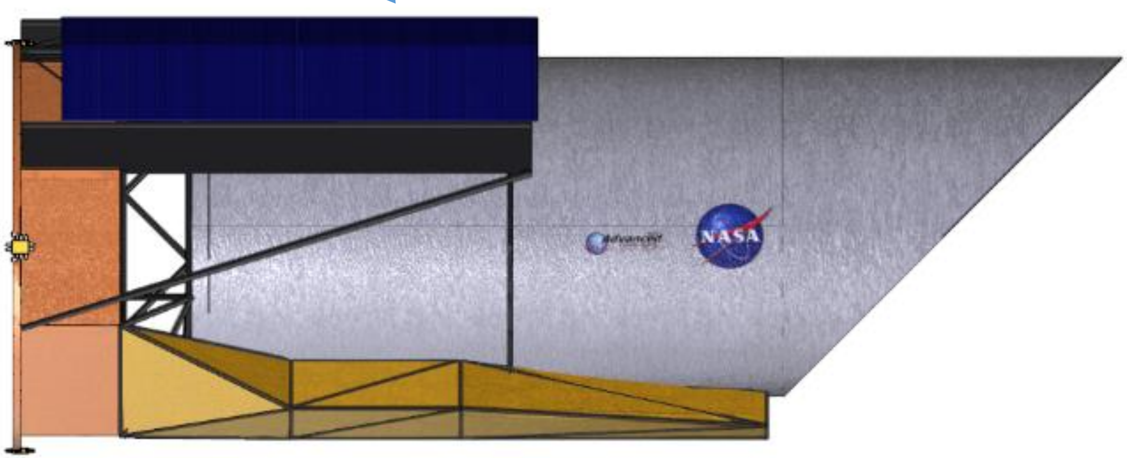
HabEx 4-m Off-Axis Initial Concept

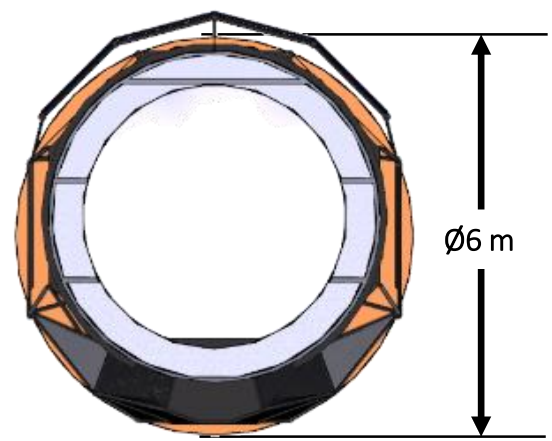
Observatory = OTA (PM/SM/Tube) & Science Instruments.



Observatory attaches to Spacecraft.

Solar Panels on Sunshade attach to Spacecraft.

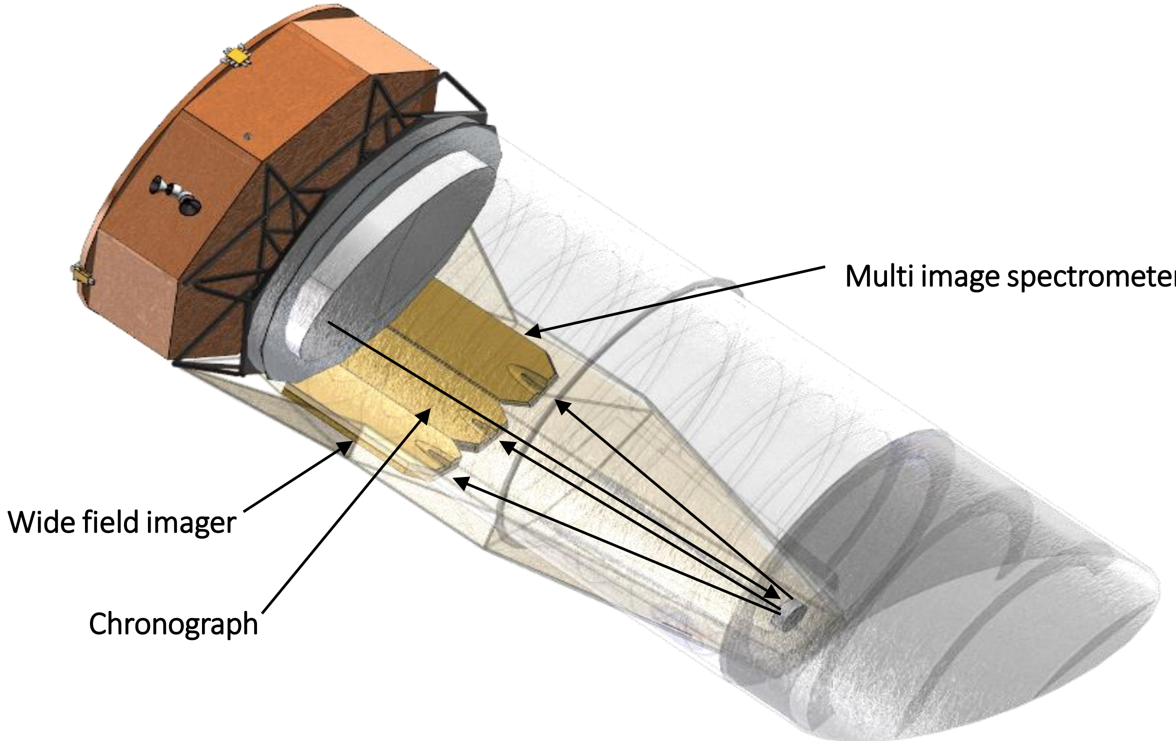




HabEx 4-m Off-Axis Initial Concept

Four Science Instruments:

- Coronagraph (imager and spectrograph)
- Starshade Imager (imager and spectrograph)
- General Astrophysics Workhorse Camera (imager and spectrograph)
- General Astrophysics UV Spectrograph

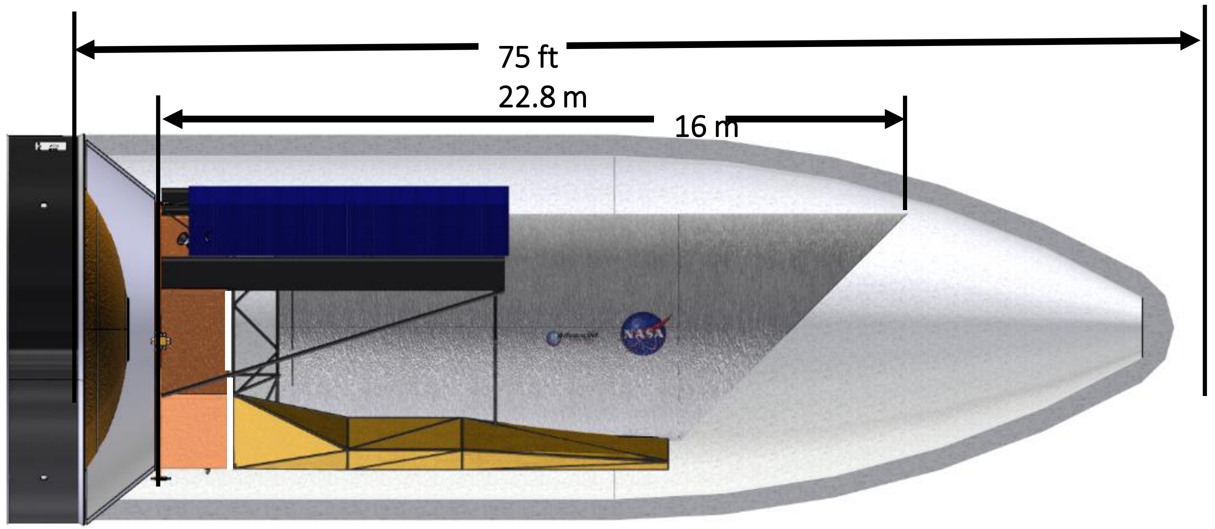


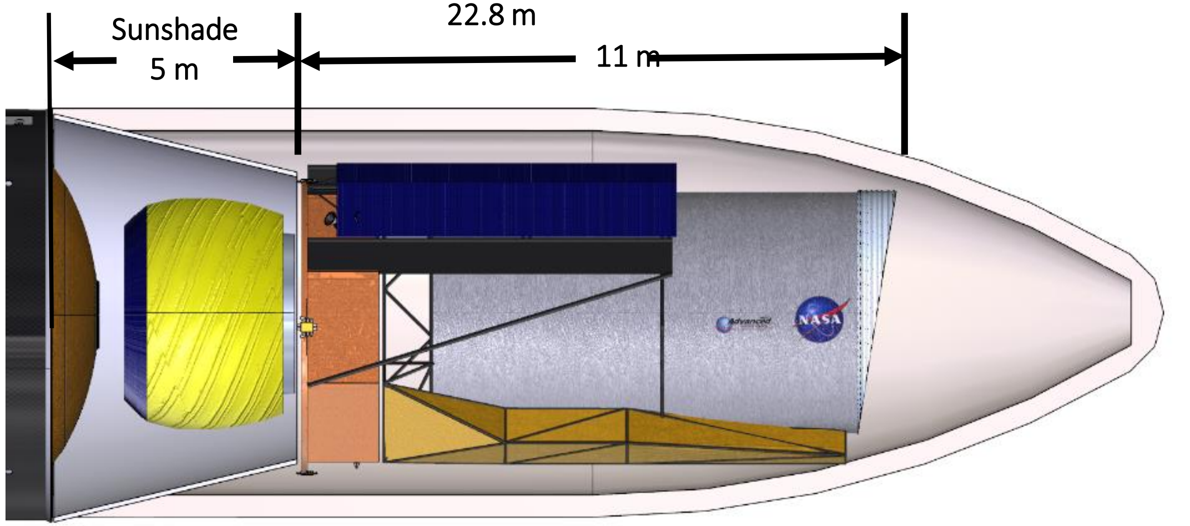
Mission Architecture vs Launch Vehicle

SLS Volume and Mass Capacity enables Mission Architecture.

- 8.4-m Long Fairing on Block I Core
- 7.5 meter dynamic envelop enables 4-m PM with SI on side
- 27.4 m height enables dual launch of observatory & star shade
  - Observatory Only could be launched with no deployments.
  - Observatory and Star Shade can be dual launched with deployment of forward scarf
- Mass to SE-L2 = 44 mt

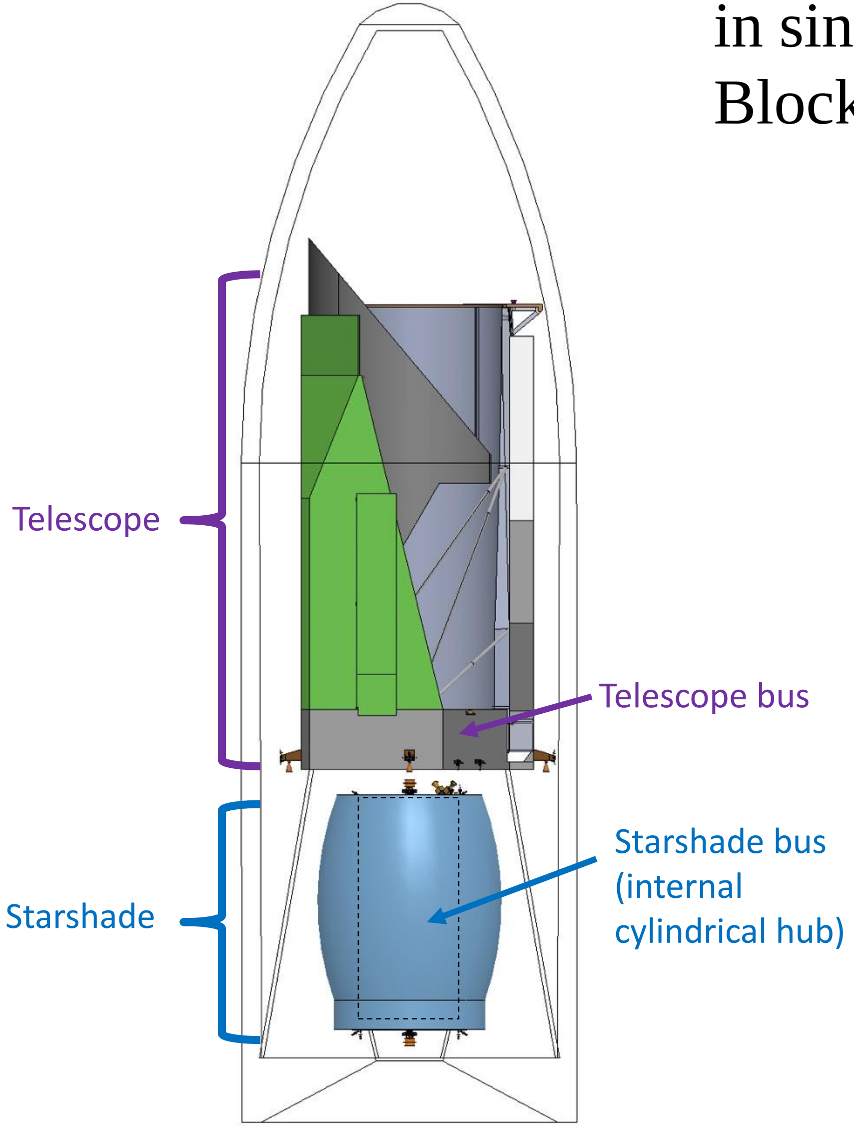
Initial Launch Configuration Options

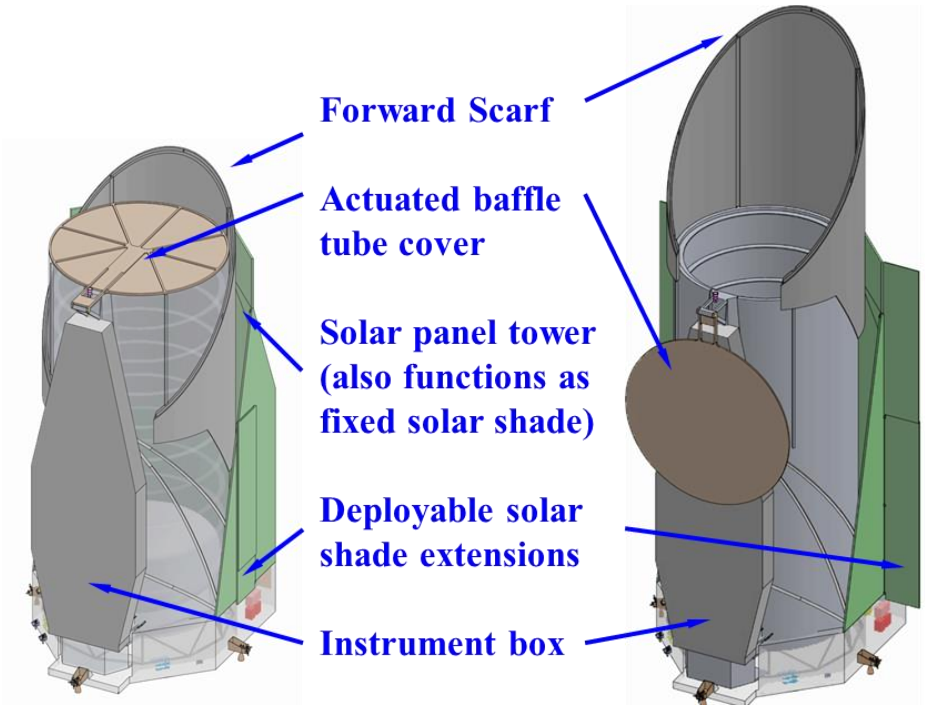




Baseline Concept

Co-Launch Observatory and Star Shade in single SLS 8.4-m Long Fairing on Block 1B core.





Telescope Specifications

Line of Sight Analysis
Wavefront Stability Analysis

Optical Telescope Assembly Structure

A primary purpose of the OTA Structure is to facilitate the alignment of the optical system and maintain that alignment to the required tolerances over all operating conditions: thermal, mechanical, space, etc.

So, the key question is – what are the required tolerances.

Tolerances can be derived from:

- Line of Sight Stability Requirement
- Wavefront Stability Requirement

Line of Sight (LOS) Stability Specification

Specification: LOS incident upon the fine/fast steering mirror (FSM) should be stable to less than 5 milli-arc-seconds (mas) rms in any direction.

Discussion:

- Coronagraph wants LOS Stability before FSM of <5.0 mas for two reasons:
    1. Beam Walk on Secondary and Tertiary Mirrors introduces wavefront error
    2. Coronagraph wants internal LOS stability to be < 0.5 mas and assumption is that FSM can produce 10X LOS reduction.
- Assume that General Astrophysics Instruments will not have FSM and requires LOS to be stable to 1/8th to 1/10th of PSF.
- For the 4-m telescope, PSF (2.44λ/D full-angle) at 450 nm is ~275 nano-radian (~ 57 mas)

State of Art OTA Line of Sight Stability

HST LOS stability is 8 mas (1/10 full PSF angle)

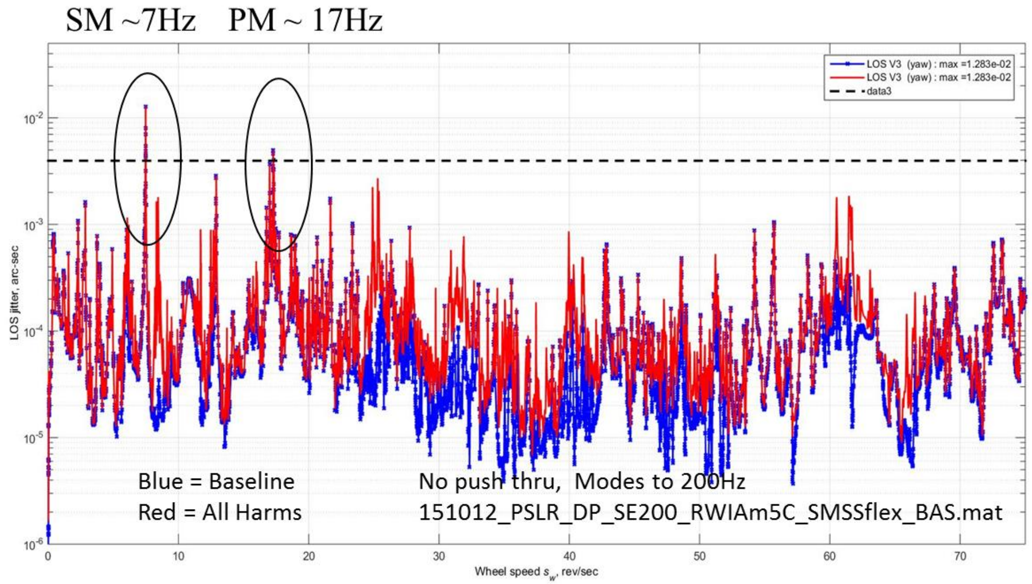
JWST LOS Jitter before FSM is < 7 mas (1/10 half PSF angle)

JWST LOS Jitter specification after FSM < 3.7 mas

- SM motion @ ~7 Hz
- PM motion @ ~17 Hz

Because of dampening, a warm JWST might have LOS stability of < 0.5 mas.

JWST Observatory LOS V3 Specification 4 mas



Feinberg, et. al., “A Cost-effective and Serviceable ATLAST 9.2m Telescope Architecture”, *Proc. SPIE*. 9143. (August 02, 2014) doi: 10.1117/12.2054915

LOS Stability Sensitivities

Zemax Tolerance Analysis of the LOS error produced by Rigid Body (6-DOF) Misalignments of the Primary, Secondary and Tertiary Mirrors.

Table 1. LOS Sensitivity to Component Rigid Body Alignment

Alignment	ZEMAX	Tolerance	Units	X-Tilt	Y-Tilt	RSS	Units
PM X-Tilt (Y-Rotation)	TY	1	n-radian	-16.0	0	16.0	mas
PM Y-Tilt (X-Rotation)	TX	1	n-radian	0	16.3	16.3	mas
PM Z-Rotation	TZ	1	n-radian	3.72	0	3.72	mas
PM X-Decenter	DX	1	nm	1.49	0	1.49	mas
PM Y-Decenter	DY	1	nm	0	1.39	1.39	mas
PM Z-Despace	DZ	1	nm	0	0.36	0.36	mas
SM X-Tilt (Y-Rotation)	TY	1	n-radian	-1.12	0	1.12	mas
SM Y-Tilt (X-Rotation)	TX	1	n-radian	0	-1.13	1.13	mas
SM Z-Rotation	TZ	1	n-radian	-0.29	0	0.29	mas
SM X-Decenter	DX	1	nm	-1.32	0	1.32	mas
SM Y-Decenter	DY	1	nm	0	-1.23	1.23	mas
SM Z-Despace	DZ	1	nm	0	-0.36	0.36	mas
TM X-Tilt (Y-Rotation)	TY	1	n-radian	0.32	0	0.32	mas
TM Y-Tilt (X-Rotation)	TX	1	n-radian	0	-0.31	0.31	mas
TM Z-Rotation	TZ	1	n-radian	0	0	0	mas
TM X-Decenter	DX	1	nm	-0.14	0	0.14	mas
TM Y-Decenter	DY	1	nm	0	-.014	0.14	mas
TM Z-Despace	DZ	1	nm	-0.01	0	0.01	mas

Preliminary LOS Stability Tolerances

Using alignment sensitivity matrix, excel spreadsheet evaluates different alignment allocations to achieve specification.

Table 2. Rigid Body Stability Specifications for < 5 mas LOS Stability				
Alignment	Specification	Units	RSS	Units
PM X-Tilt (Y-Rotation)	0.1	n-radian	1.60	mas
PM Y-Tilt (X-Rotation)	0.1	n-radian	1.63	mas
PM Z-Rotation	0.5	n-radian	1.86	mas
SM X-Tilt (Y-Rotation)	1	n-radian	1.12	mas
SM Y-Tilt (X-Rotation)	1	n-radian	1.13	mas
SM Z-Rotation	1	n-radian	0.29	mas
SM/PM X-Decenter	1	nm	1.32	mas
SM/PM Y-Decenter	1	nm	1.23	mas
SM/PM Z-Despace	5	nm	1.80	mas
TM X-Tilt (Y-Rotation)	5	n-radian	1.55	mas
TM Y-Tilt (X-Rotation)	5	n-radian	1.62	mas
TM/PM X-Decenter	10	nm	1.40	mas
TM/PM Z-Despace	50	nm	0.50	mas
		LOS Stability RSS	5.00	mas

Notes:

- For a 4-meter PM, 0.1 nano-radian of tilt is equal to 200 picometers PV.
- For a 0.5-meter SM, 1 nan-radian of tilt is equal to 250 picometers PV.
- Eliminated TM/PM Y-Decenter by coupling PM to TM in Y-axis.

WFE Stability

WFE Stability specification is spatial frequency dependent

Different Coronagraphs are sensitive to different spatial frequencies

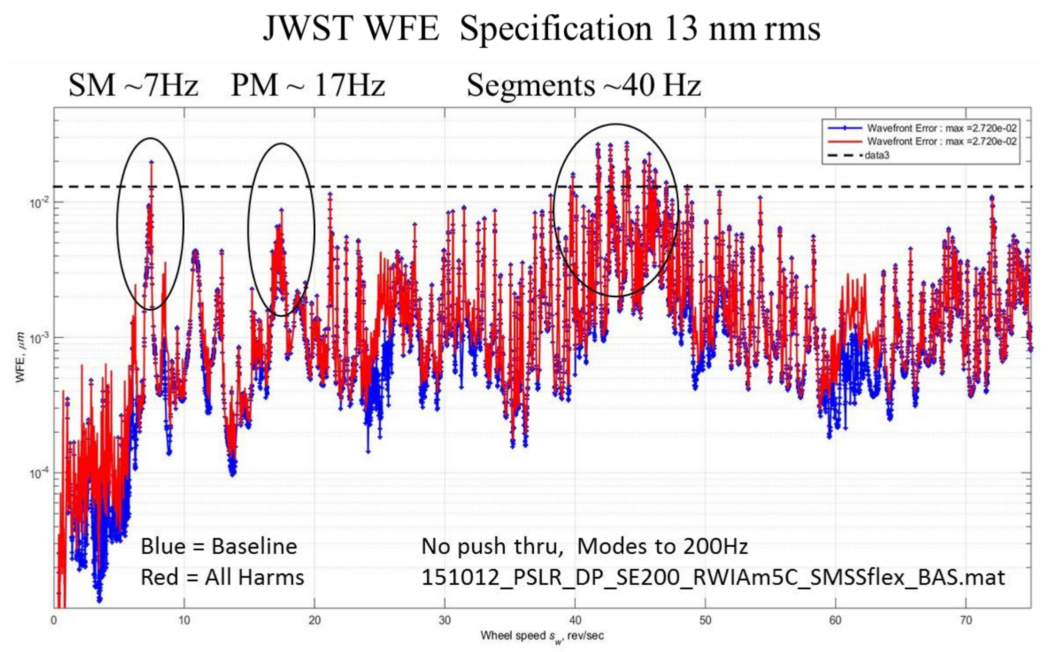
Initial ROM WFE stability specification

- Low-Order < 0.3 nm rms.
- Mid-Spatial Frequency < 0.02 nm pm

JWST WFE stability specification < 13 nm rms

- SM motion @ ~7 Hz
- PM motion @ ~17 Hz

Per Feinberg, et. al., because of dampening, a warm JWST may have WFE stability of < 2 nm rms.



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Wavefront Error (WFE) Stability Specification

For Vector Vortex, higher charge rejects more WFE

Implication is that Charge 6 or 8 is better than Charge 4.

Aberration	Indices		Allowable RMS wavefront error (nm) per mode			
	n	m	charge 4	charge 6	charge 8	charge 10
Tip-tilt	1	±1	1.1	5.9	14	26
Defocus	2	0	0.8	4.6	12	26
Astigmatism	2	±2	0.0067	1.1	0.90	5
Coma	3	±1	0.0062	0.66	0.82	5
Spherical	4	0	0.0048	0.51	0.73	6
Trefoil	3	±3	0.0072	0.0063	0.57	0.67
2nd Astig.	4	±2	0.0080	0.0068	0.67	0.73
2nd Coma	5	±1	0.0036	0.0048	0.69	0.85
2nd Spher.	6	0	0.0025	0.0027	0.84	1
Quadrafoil	4	±4	0.0078	0.0080	0.0061	0.53
2nd Trefoil	5	±3	0.0051	0.0056	0.0043	0.72
3rd Astig.	6	±2	0.0023	0.0035	0.0034	0.81
3rd Coma	7	±1	0.0018	0.0022	0.0036	1.18
3rd Spher.	8	0	0.0018	0.0018	0.0033	1.49

Garreth Ruane, June 2017

not rejected
first-order rejection
> first-order rejection

Each Aberration can be mapped to a PM & SM rigid body motions; amplitudes given by Zemax alignment tolerance.

Preliminary Wavefront Stability Tolerances

Using optical design sensitivity analysis, can calculate the maximum amount of rigid body motion allowed by the primary and secondary mirrors. Tertiary Mirror motion is negligible.

Vector Vortex Telescope Rigid Body Alignment Tolerances					
Zernike	VVC-4	VVC-6	VVC-8	VVC-10	Units
Allowed Focus	0.8	4.6	12	26	nm rms
Allowed Astigmatism	0.0067	1.1	0.9	5	nm rms
Allowed Trefoil	0.0072	0.0063	0.57	0.67	nm rms
Calculated Focus	0.05	4.5	8.5	25	nm rms
Calculated Astigmatism	0.0065	0.5	0.9	5	nm rms
Calculated Trefoil	0.0001	0.0065	0.012	0.07	
DOF					
PM X-Decenter	3	200	400	3000	nm
PM Y-Decenter	3	200	400	3000	nm
PM Z-Despace	5	500	1000	2500	nm
PM X-Tilt	3	200	400	2000	n-rad
PM Y-Tilt	2	150	200	1000	n-rad
PM Z-Rotation	1	100	150	500	n-rad
SM X-Decenter	3	200	400	3000	nm
SM Y-Decenter	3	200	400	3000	nm
SM Z-Despace	5	500	1000	2500	nm
SM X-Tilt	3	200	400	2000	n-rad
SM Y-Tilt	3	200	400	2000	n-rad
SM Z-Rotation	10	200	1000	2000	n-rad

These tolerances are larger than what is allow for LOS Stability.

Note: Analysis does not include dynamic WFE from PM.

WFE Stability Produced by LOS Tolerances

5 mas LOS Rigid Body Motion Tolerances **<u>DO NOT</u>** produce any WFE larger than even the VVC-4 Specification.

ISO Zernikes	TOTAL RMS WFE	VVC-4	VVC-6	VVC-8	VVC-10
Z1 X-Tilt	0.0014	1.1	5.9	14	26
Z2 Y-Tilt	0.0016	1.1	5.9	14	26
Z3 Focus	0.0209	0.8	4.6	12	26
Z4 X-Astig	0.0021	0.0067	1.1	0.9	5
Z5 Y-Astig	0.0022	0.0067	1.1	0.9	5
Z6 X-Coma	0.0005	0.0062	0.66	0.82	5
Z7 Y-Coma	0.0006	0.0062	0.66	0.82	5
Z8 Sphere	0.0000	0.0048	0.51	0.73	6
Z9 X-Trefoil	0.0000	0.0072	0.0063	0.57	0.67
Z10 Y-Trefoil	0.0000	0.0072	0.0063	0.57	0.67
Z11 X-2nd Astig	0.0000	0.0080	0.0068	0.67	0.73
Z12 Y-2nd Astig	0.0000	0.0080	0.0068	0.67	0.73
Z13 X-2nd Coma	0.0000	0.0036	0.0048	0.69	0.85
Z14 Y-2nd Coma	0.0000	0.0036	0.0048	0.69	0.85
Z15 2nd Sphere	0.0000	0.0025	0.0027	0.84	1
Z16 X-Quadrafoil	0.0000	0.0078	0.0080	0.0061	0.53
Z17 Y-Quadrafoil	0.0000	0.0078	0.0080	0.0061	0.53
Z18 X-2nd Trefoil	0.0000	0.0051	0.0056	0.0043	0.72
Z19 Y-2nd Trefoil	0.0000	0.0051	0.0056	0.0043	0.72
Z20 X-3rd Astig	0.0000	0.0023	0.0035	0.0034	0.81
Z21 Y-3rd Astig	0.0000	0.0023	0.0035	0.0034	0.81
Z22 X-3rd Coma	0.0000	0.0018	0.0022	0.0036	1.18
Z23 Y-3rd Coma	0.0000	0.0018	0.0022	0.0036	1.18
Z24 3rd Sphere	0.0000	0.0018	0.0018	0.0033	1.49

Note: Analysis does not include Dynamic WFE from PM.

Why is LOS more sensitive that WFE

WFE changes more rapidly with F/# than LOS.

Typically one designs the optical system to be as fast an F/# as possible for the required WFE stability. If the system is sufficiently mechanically stable for WFE, it will be ok for LOS.

HabEx has a slow F/2.5 optical design to minimize Polarization.

At F/2.5 WFE is not as sensitive to mis-alignments as LOS.

Seidel Coma Sensitivity							
Alignment	Tolerance	Units	F/2.5	F/2	F/1.5	F/1.25	Units
PM X-Tilt	1	micro-degree	642	969	1602	2150	pico-meters
PM Y-Tilt	1	micro-degree	664	1019	1742	2411	pico-meters
SM X-Tilt	1	micro-degree	53	79	129	172	pico-meters
SM Y-Tilt	1	micro-degree	54	83	142	196	pico-meters
SM X-Decenter	10	nanometer	37	69	153	246	pico-meters
SM Y-Decenter	10	nanometer	34	60	117	165	pico-meters
SM Z-Despace	10	nanometer	18	42	119	223	pico-meters

Zernike Defocus Sensitivity							
Alignment	Tolerance	Units	F/2.5	F/2	F/1.5	F/1.25	Units
PM X-Tilt	1	micro-degree	0	0	0	0	pico-meters
PM Y-Tilt	1	micro-degree	7	14	38	70	pico-meters
SM X-Tilt	1	micro-degree	0	0	0	0	pico-meters
SM Y-Tilt	1	micro-degree	6	9	16	22	pico-meters
SM X-Decenter	10	nanometer	0	0	0	0	pico-meters
SM Y-Decenter	10	nanometer	-37	-69	-151	-242	pico-meters
SM Z-Despace	10	nanometer	-145	-217	-353	-467	pico-meters

Line of Sight Sensitivity							
Alignment	Tolerance	Units	F/2.5	F/2	F/1.5	F/1.25	Units
PM X-Tilt	1	micro-degree	35.2	35.4	35.6	35.8	nano-radian
PM Y-Tilt	1	micro-degree	34.6	34.5	34.2	33.9	nano-radian
SM X-Tilt	1	micro-degree	3.93	4.48	5.54	6.50	nano-radian
SM Y-Tilt	1	micro-degree	2.87	2.85	2.79	2.75	nano-radian
SM X-Decenter	10	nanometer	0.91	1.11	1.45	1.71	nano-radian
SM Y-Decenter	10	nanometer	0.89	1.11	1.45	1.71	nano-radian

Zernike Astigmatism Sensitivity							
Alignment	Tolerance	Units	F/2.5	F/2	F/1.5	F/1.25	Units
PM X-Tilt	1	micro-degree	-648	-983	-1643	-2231	pico-meters
PM Y-Tilt	1	micro-degree	-668	-1030	-1780	-2493	pico-meters
SM X-Tilt	1	micro-degree	53	80	133	179	pico-meters
SM Y-Tilt	1	micro-degree	55	84	144	201	pico-meters
SM X-Decenter	10	nanometer	-37	-70	-157	-256	pico-meters
SM Y-Decenter	10	nanometer	36	67	145	228	pico-meters
SM Z-Despace	10	nanometer	-9	-21	-61	-116	pico-meters

Design for Stability

Wavefront and Line of Sight Stability has design consequences.

- Mechanical
  - Secondary Mirror Support Structure Dynamic Response – make higher
  - Primary Mirror Dynamic Response – make higher
  - Passive/Active Vibration Isolation – lower acceleration/better isolation
  - Passive/Active Dampening/Control – mass damping
- First Order Scaling
  - WFE & LOS Stability is proportional to frequency^2.

    3.3X increase in frequency response = 10X improvement in stability
  - WFE & LOS Stability is proportional to acceleration.

    1X decrease in acceleration force = 1X improvement in stability
  - WFE & LOS Stability is proportional to mass. (Mass Dampening)

    1X increase in mass = 1X improvement in stability

Design for Stability

Wavefront and Line of Sight Stability has design consequences.

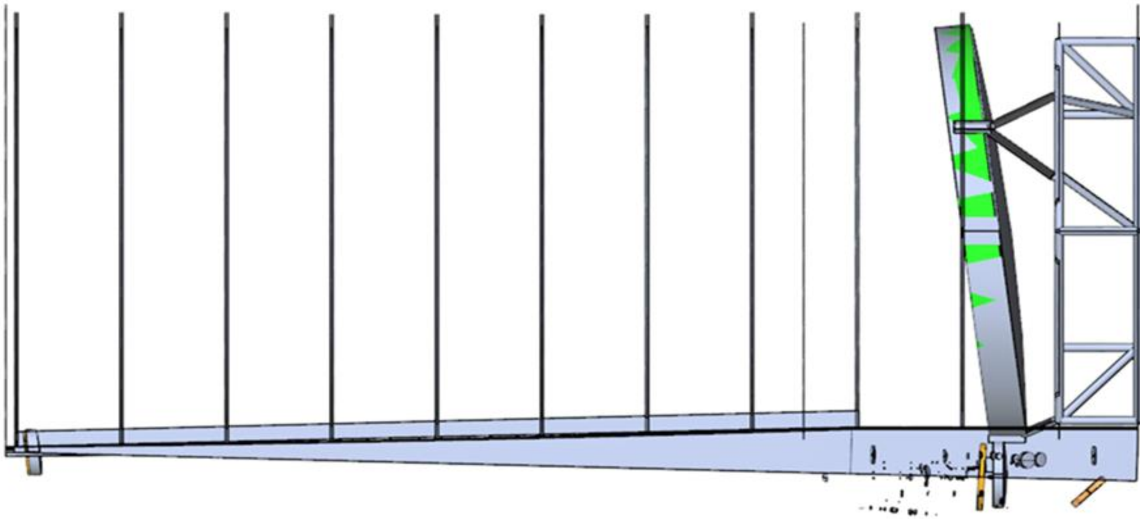
- Thermal
  - PM & SM Mirror CTE – want small and very homogeneous
  - Structure CTE – want small and very homogeneous
  - Passive Thermal Isolation - mass
  - Active Thermal Control – predictive thermal control

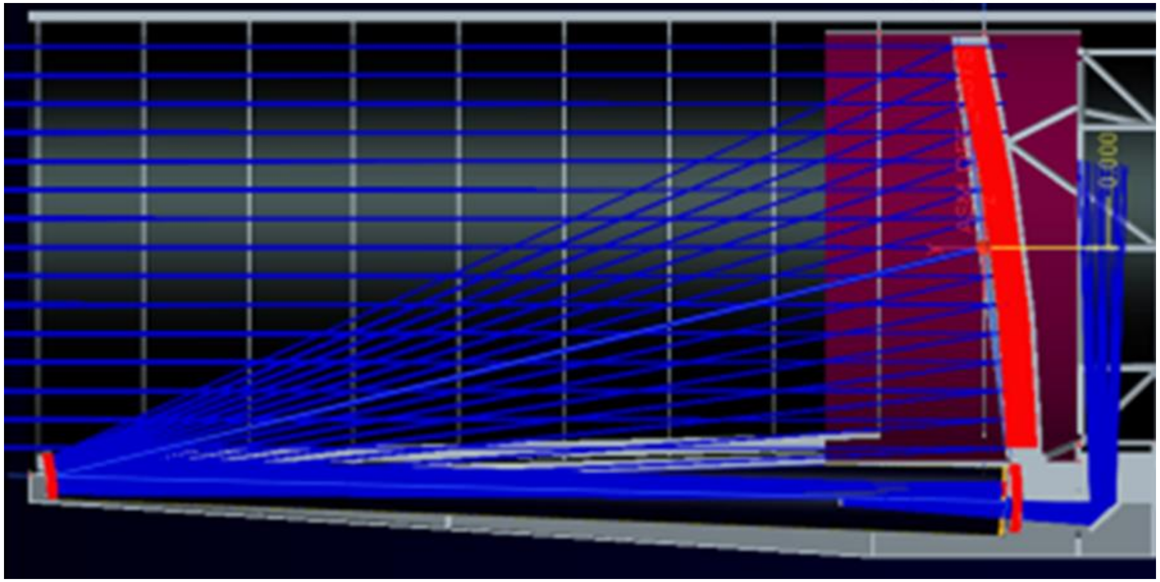
Telescope Structure Design:

Volume & Mass

HabEx Telescope Design: CAD

Imported OTA & Instrument Optical Designs (via STEP files).





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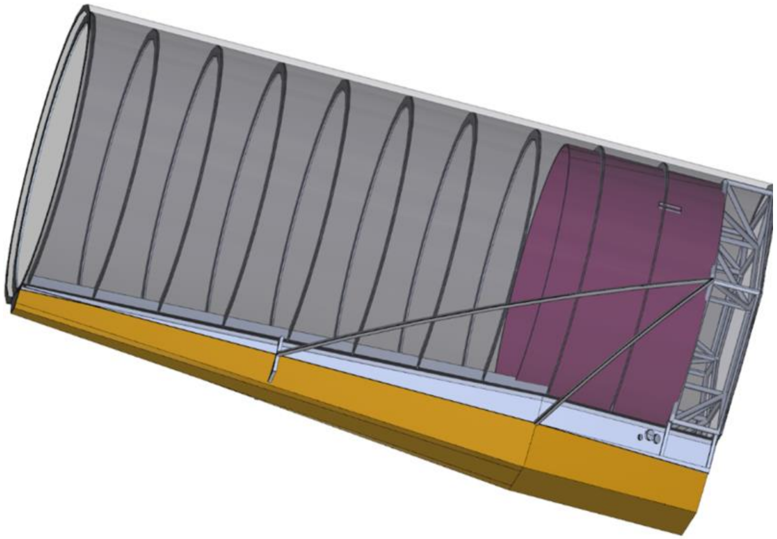
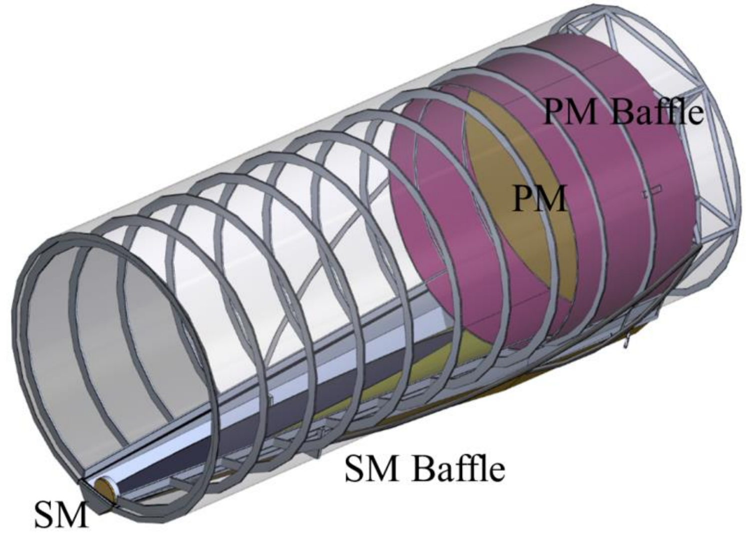
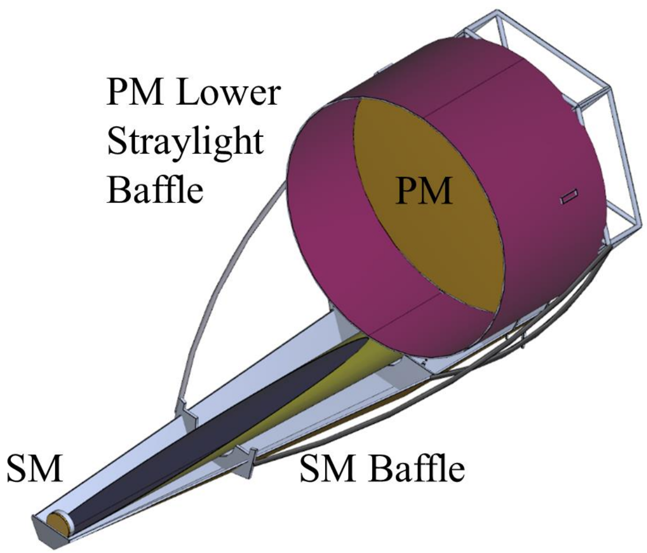
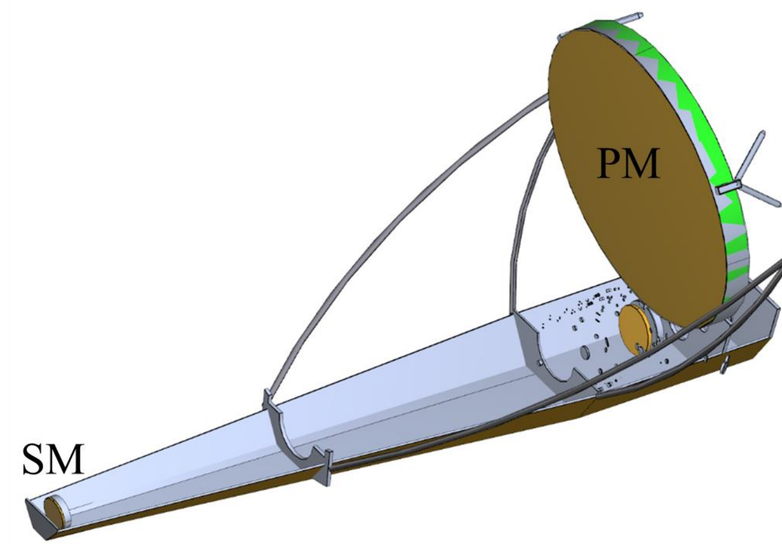








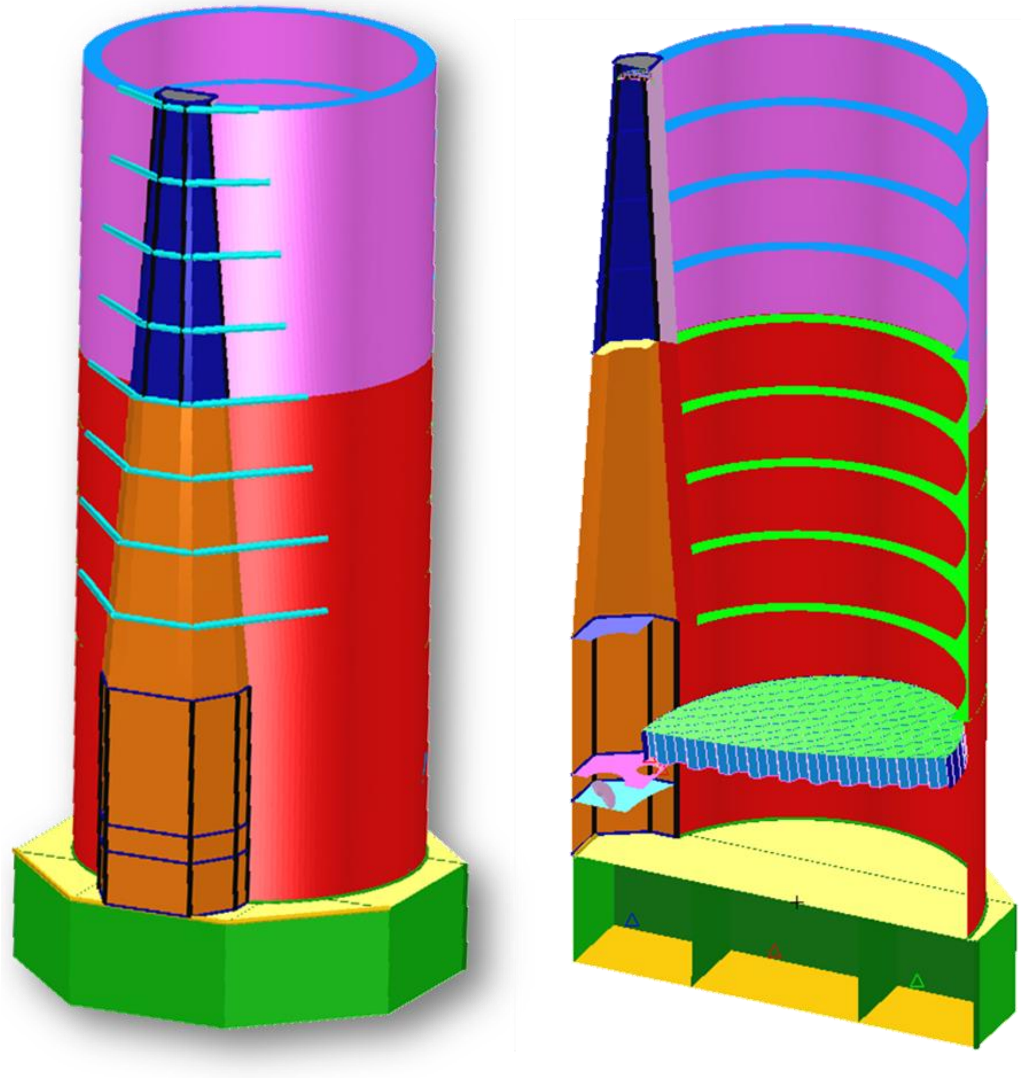
HabEx Telescope Design: FEM

To evaluate opto-mechanical performance, created FEM of Structural Elements.

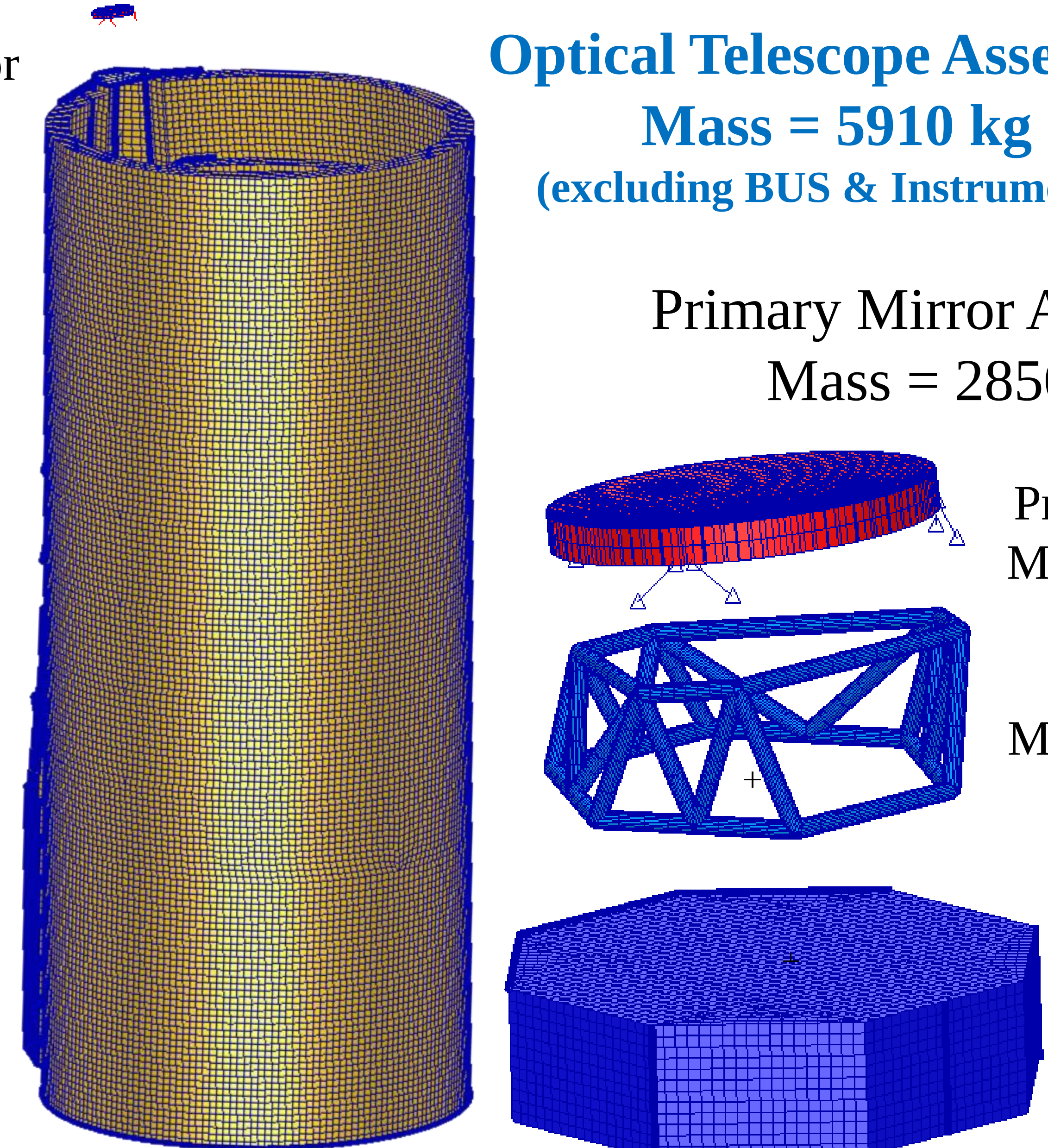
Changed exo-skeleton to lateral exo-truss elements connecting to the internal straylight baffles.

Internal straylight baffles are not continuous, because of PM to SM light beam.

PM Truss depth arbitrarily set at 2-meters based on available SLS fairing height. Could be less.



HabEx Telescope Design: Mass Estimate



Secondary Mirror
Mass = 10 kg

Optical Telescope Assembly
Mass = 5910 kg
(excluding BUS & Instruments)

Primary Mirror Assembly
Mass = 2850 kg

Primary Mirror
Mass = 1652 kg

Tube / Tower
Mass = 3052 kg

PM Truss
Mass = 1198 kg

Sci Instruments
Mass = 1300 kg

Spacecraft BUS
Mass = 4745 kg

Telescope Structure:

Predicted LOS Performance

Dynamic Analysis

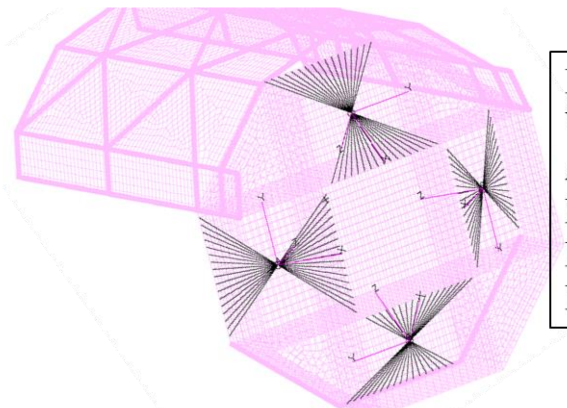
To determine OTA dynamic opto-mechanical performance:

- Construct a finite element model of the OTA structure.
- Expose model to expected mechanical disturbances:
    - JWST Reaction Wheel Specification
- Calculate Rigid Body motions of SM and PM relative to OTA coordinate system and relative to each other
    - X-, Y-, Z-despace
    - X-, Y-, Z-rotation
- Are Rigid Body motions less than Specification?
- Apply Vibration Isolation:
    - JWST 1-Hz Passive Vibration Isolation
    - Active Isolation
    - Micro-Thrusters

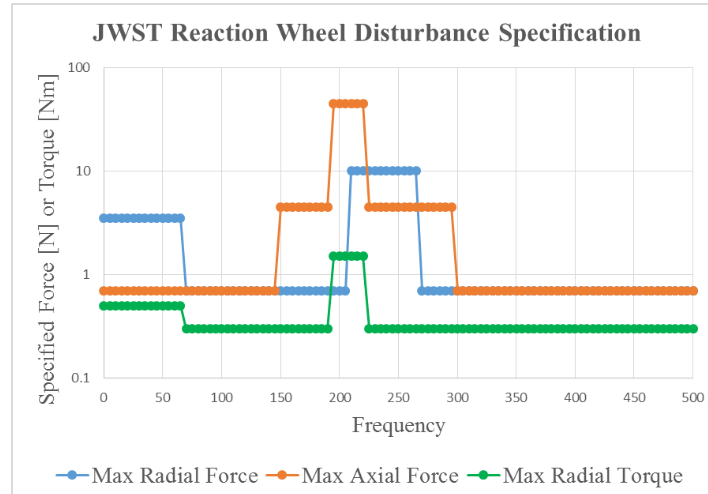
Mechanical Disturbance Input

JWST reaction wheel specification is input into spacecraft at 4 points for standard pyramid arrangement.

This is very conservative worst case.



Reaction Wheel Assembly Forcing Function Points



- Radial force and moment disturbances are applied in 10 degree increments around wheel rotation axis. Result is 144 load cases.
- Radial force and moment disturbances are swept through 360 degree wheel rotation to calculate maximum relative displacement between primary and secondary mirror for each wheel.
- Critical Damping is set at 1%

3.3.1.6 Wheel Unbalance

After exposure to the environments defined in section 3.2.5 of this specification, the unbalance magnitude of the RWA rotating components shall not exceed the following values:

a. Static Unbalance: Less than 1.0 (g-cm) over the operating speed range.

b. Dynamic Unbalance: Less than 14.0 (g.-cm^2) over the operating speed range.

c. The peak radial forces and moments produced by the RWA at any operating speed (including resonant conditions) shall not exceed the values listed in the table below:

Peak Radial Disturbance Limits Including Resonant Conditions

Parameter	Frequency	Max. Limit	Parameter	Frequency	Max. Limit
Force (F_X)	0-70 Hz	3.5 N	Torque (M_X)	0-70 Hz	0.5 N-m
	70-210 Hz	0.7 N		70-195 Hz	0.3 N-m
	210-270 Hz	10 N		195-225 Hz	1.5 N-m
	270-500 Hz	0.7 N		225-500 Hz	0.3 N-m

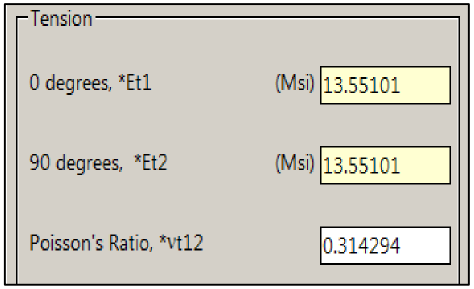
3.3.1.7 Axial Induced Vibration

The peak force (amplitude) produced by the RWA in the direction parallel to the its spin axis shall not exceed 0.2 N within the frequency range 2-200 Hz, when measured at constant speeds that are within the operational speed range and that are free of major structural resonances. The peak axial force produced by the RWA at any operating speed (including resonant conditions) shall not exceed the following limit values:

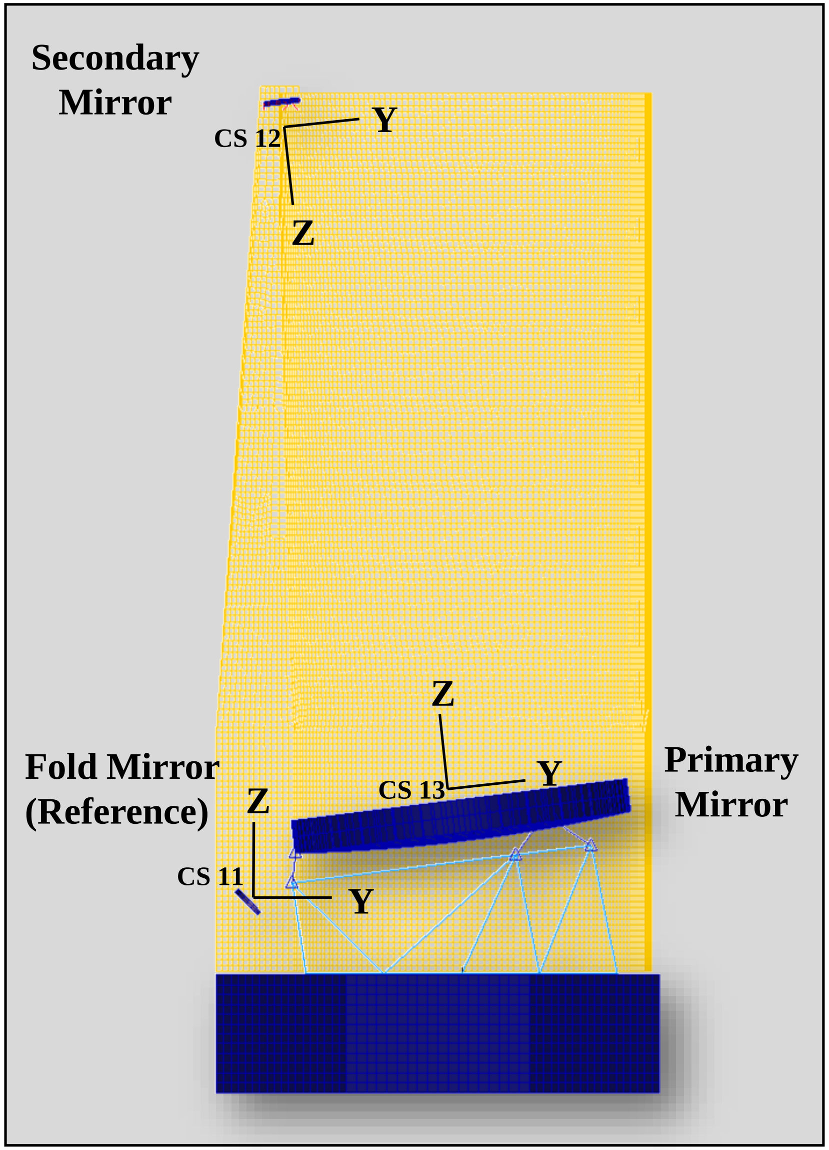
Frequency Range (in Hz):	0-150	150-195	195-225	225-300	300-500
Axial Force (Fz) Limit:	0.7 N	4.5 N	45 N	4.5 N	0.7 N

PM/SM Rigid Body Motion vs Disturbance

- PM, SM motion (relative to Fold Mirror) is calculated using MPC (NASTRAN Multi Point Constraint).
- **Motions are reported in a local optical coordinate system:**
  - **PM in CS13,**
  - **SM in CS12 and**
  - **Relative PM/SM in CS11.**
- Material properties based on quasi-isotropic M46J



M46J Quasi-Isotropic Laminate Properties
(25%0, 50%45, 25%90)
Density = 1.58 gram/cm^3 (0.057 lb/in^3)



Analysis Coordinate Systems (11, 12, 13)

Secondary Mirror Rigid Body Motion

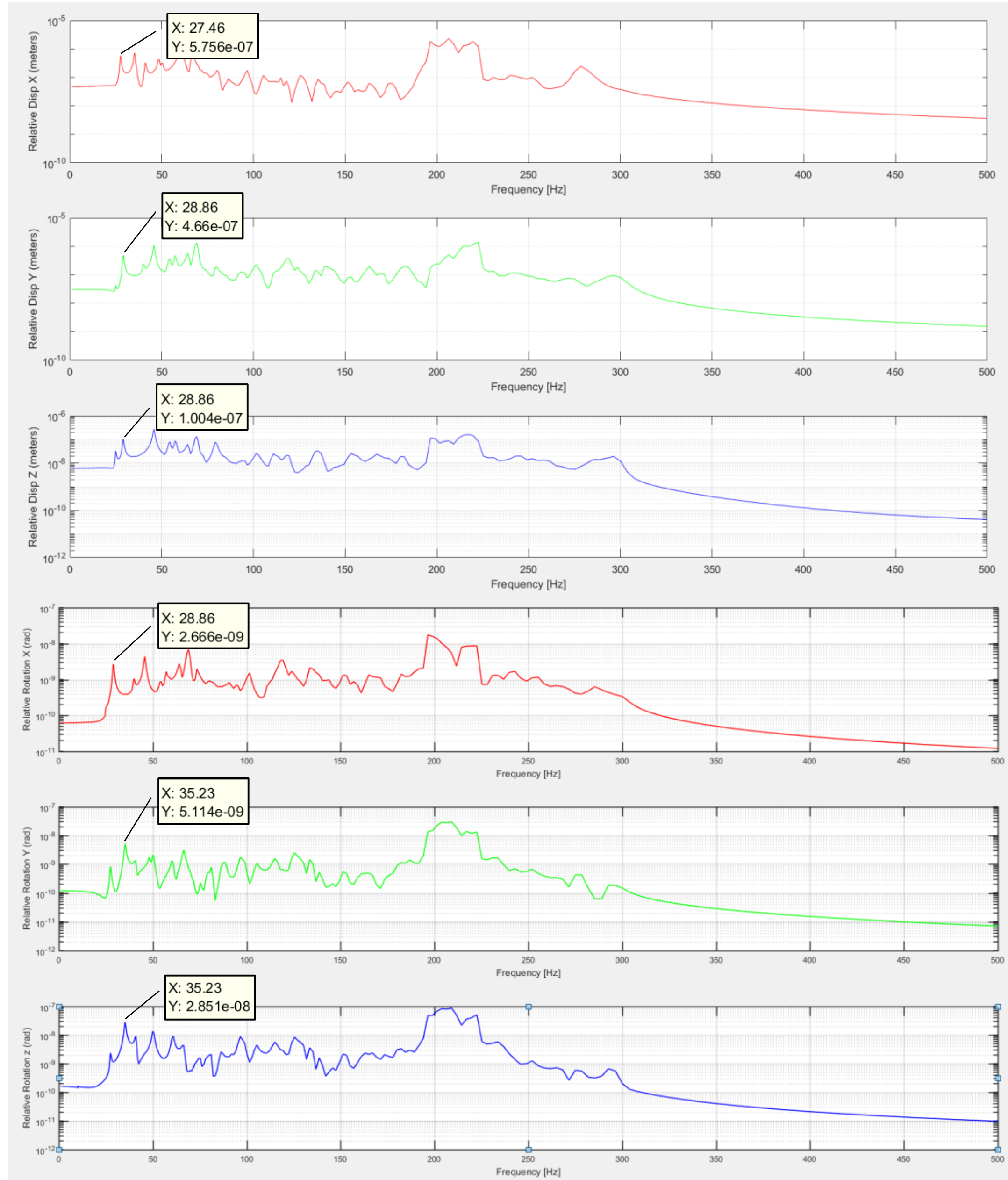
SM first mode motion relative to Fold Mirror:

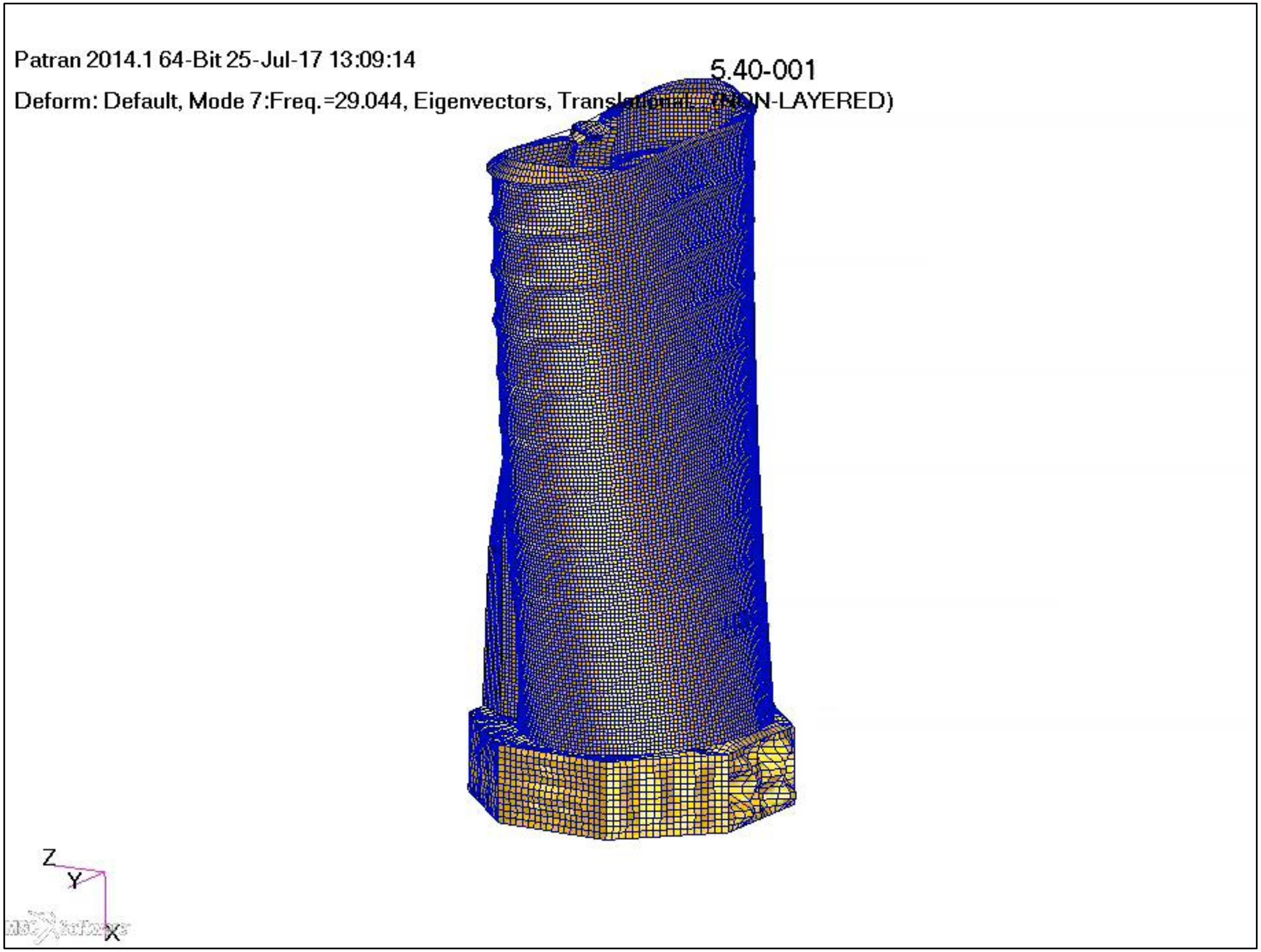
- ΔX = 0.6 μm at 28 Hz
- ΔY = 0.5 μm at 29 Hz
- ΔZ = 0.1 μm at 29 Hz
- ΘX = 2.6 nrad at 29 Hz
- ΘY = 5 nrad at 35 Hz
- ΘZ = 29 nrad at 35 Hz

Are all larger than specified LOS Tolerances:

- ΔX = 1 nm
- ΔY = 1 nm
- ΔZ = 5 nm
- ΘX = 1 nrad
- ΘY = 1 nrad
- ΘZ = 1 nrad

Need Vibration Isolation

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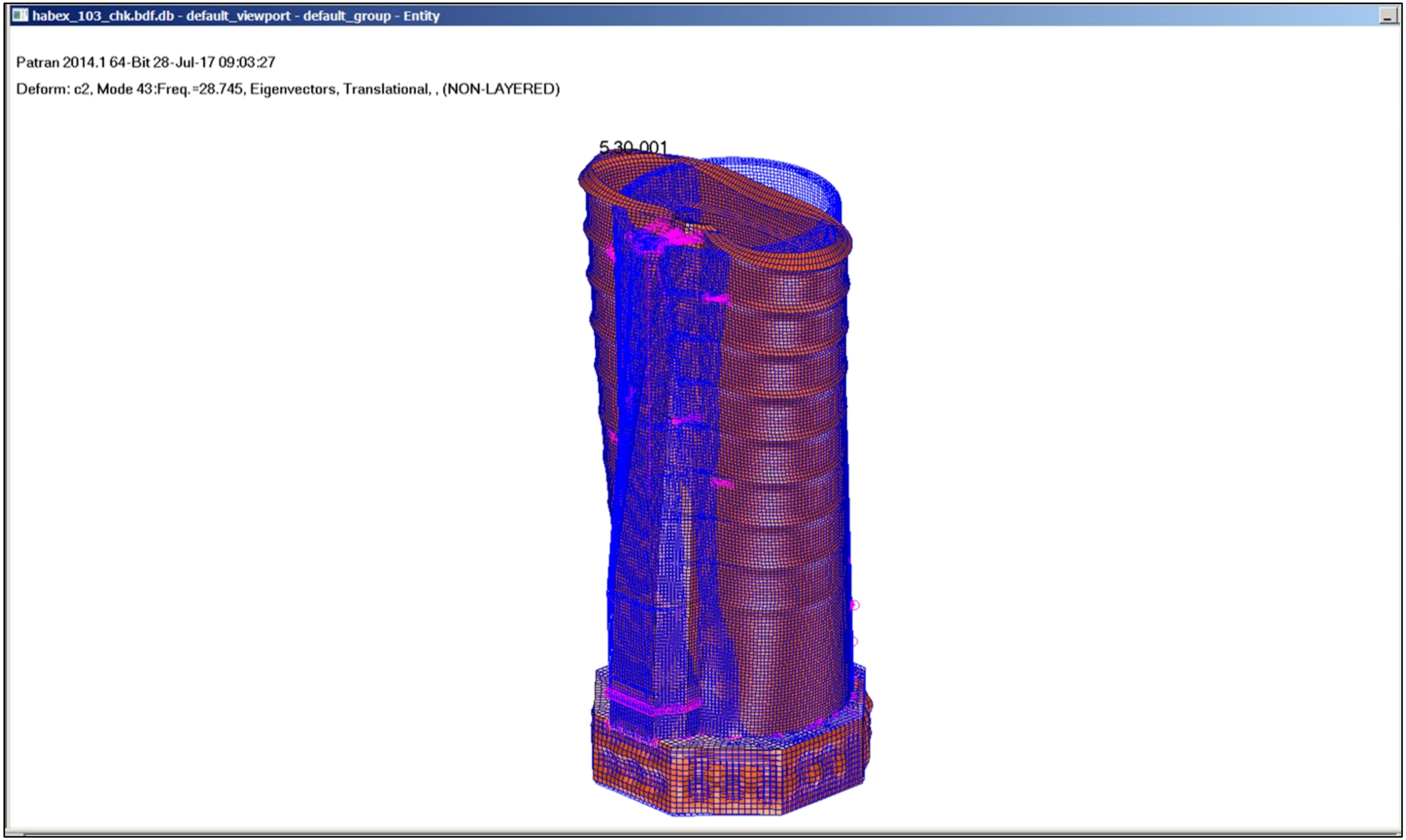
5.40-001
Z
Y
X



First Tube Mode

Primary Mirror Rigid Body Motion

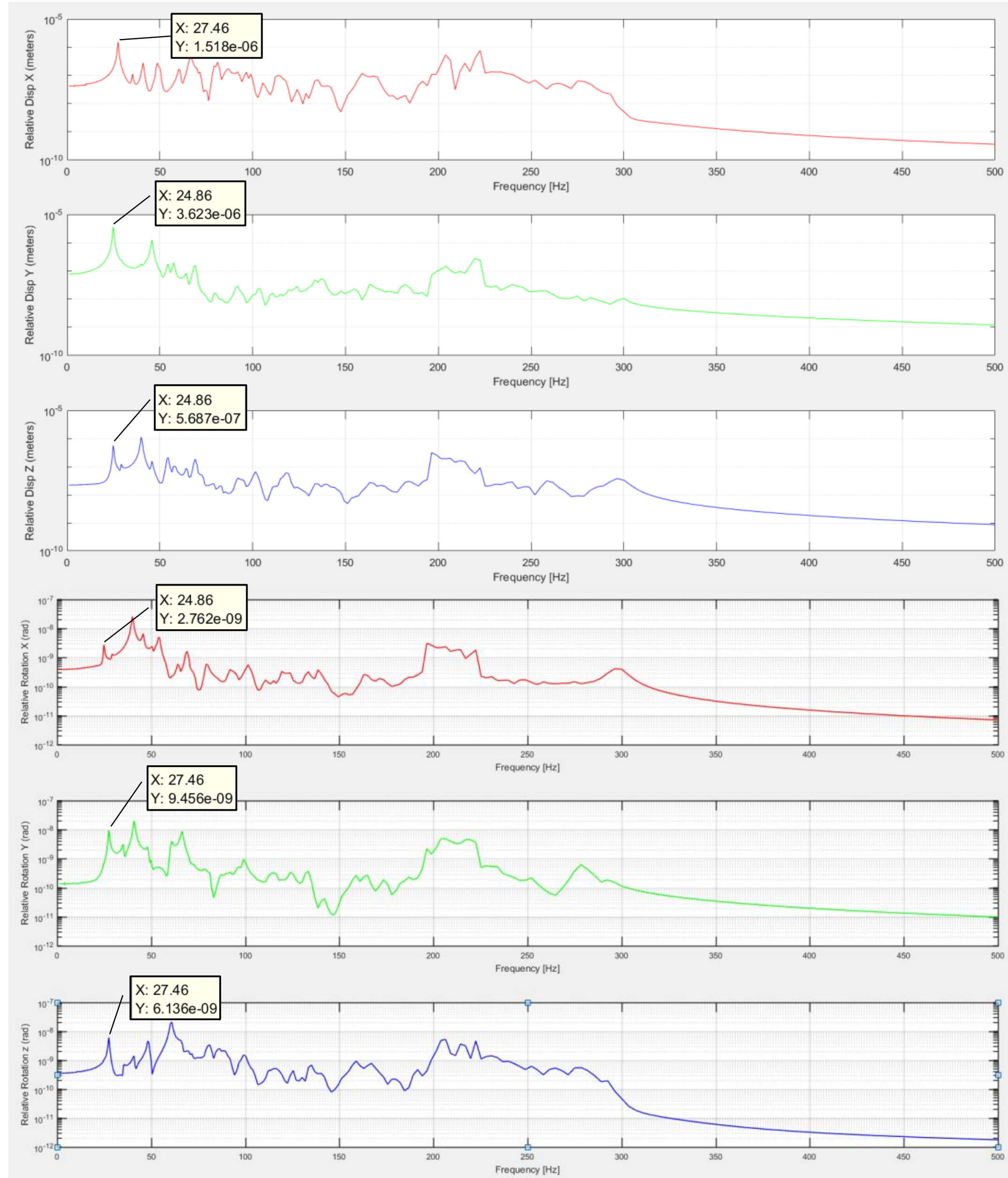
PM first mode motion relative to Fold Mirror:

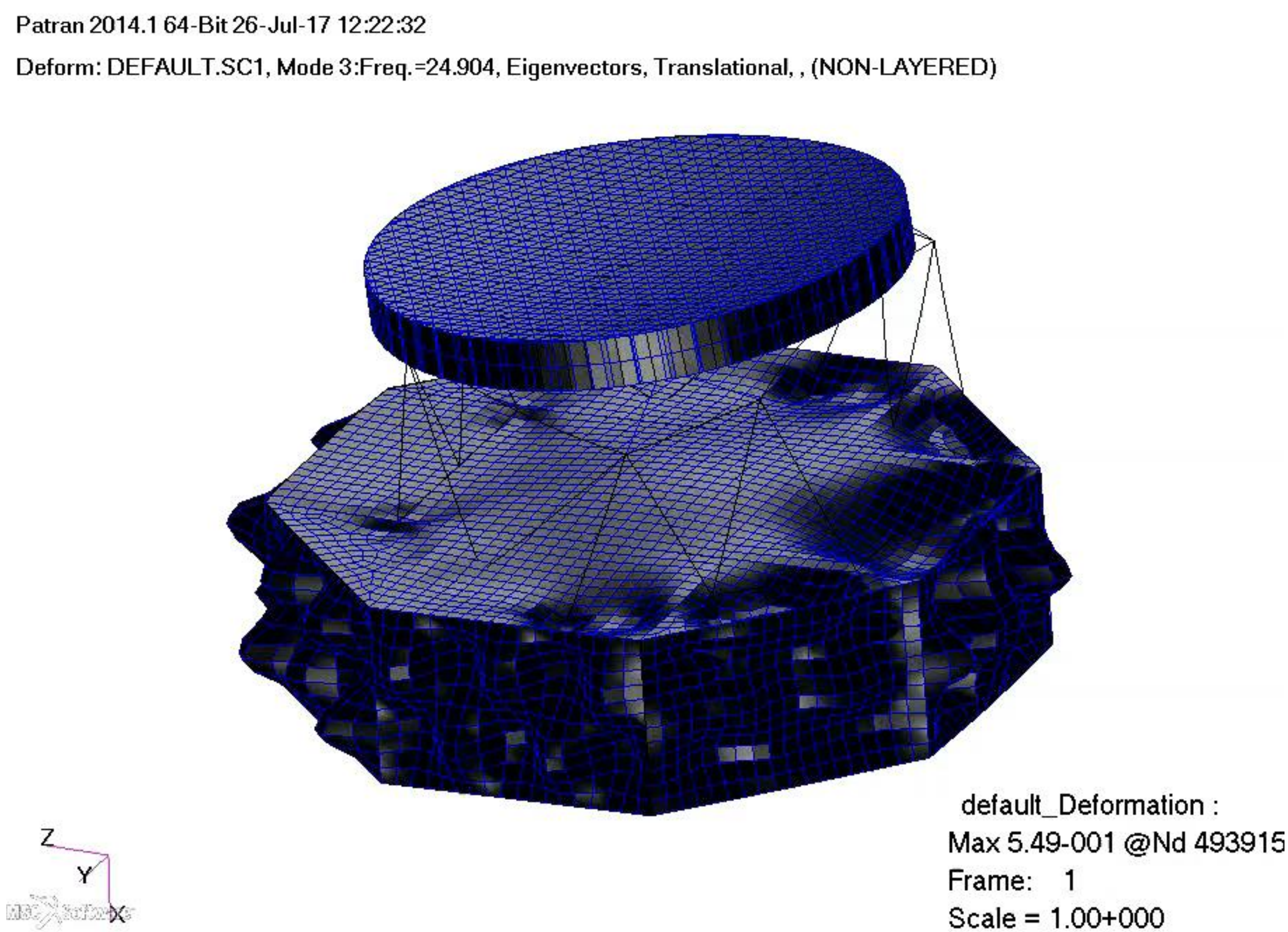
- ΔX = 1.5 μm at 27 Hz
- ΔY = 3.6 μm at 25 Hz
- ΔZ = 0.6 μm at 25 Hz
- ΘX = 2.7 nrad at 25 Hz
- ΘY = 9.5 nrad at 27 Hz
- ΘZ = 6.1 nrad at 27 Hz

Are all larger than specified LOS Tolerances:

- ΔX = 1 nm
- ΔY = 1 nm
- ΔZ = 5 nm
- ΘX = 0.1 nrad
- ΘY = 0.1 nrad
- ΘZ = 0.5 nrad

Need Vibration Isolation

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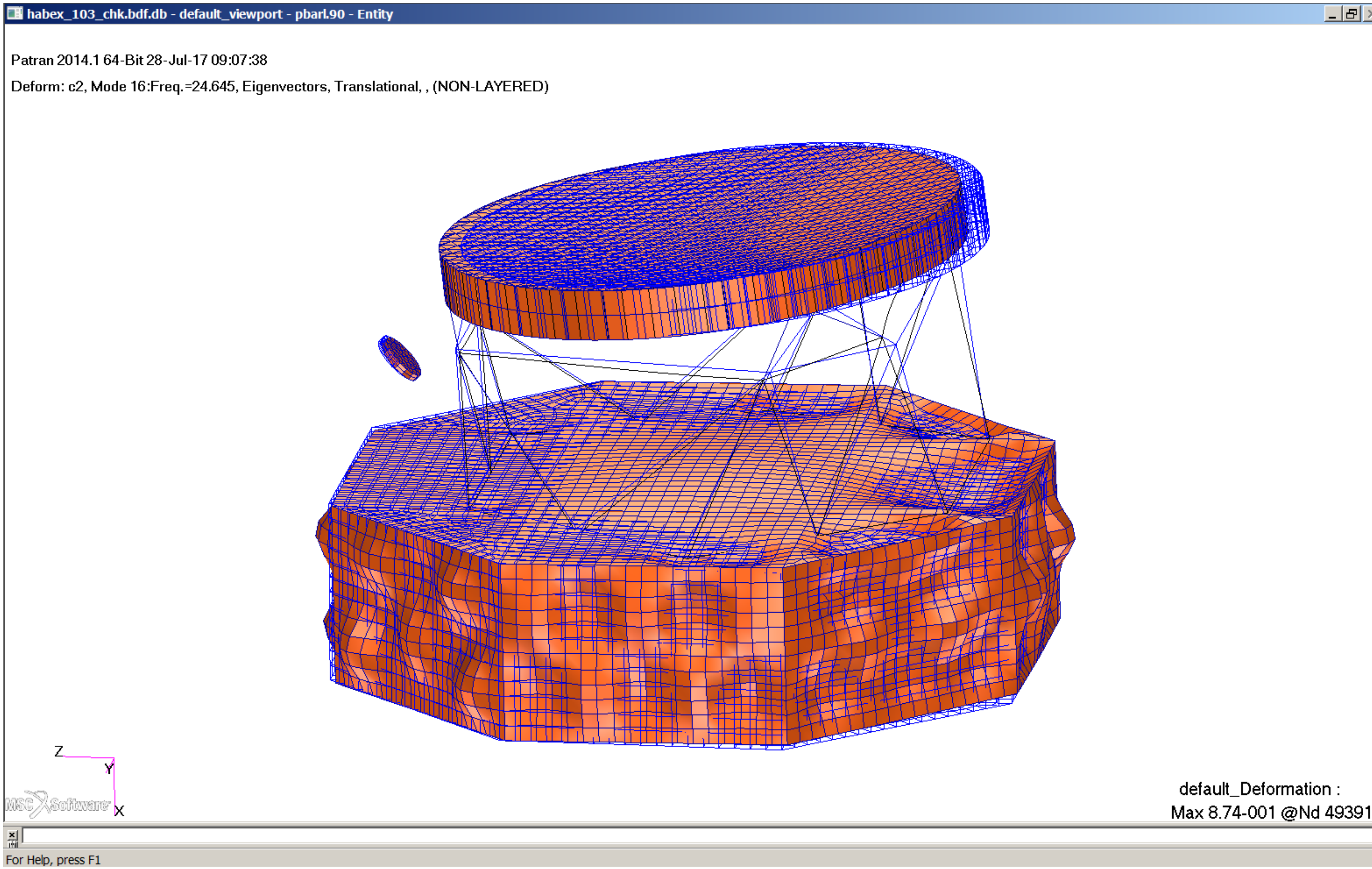
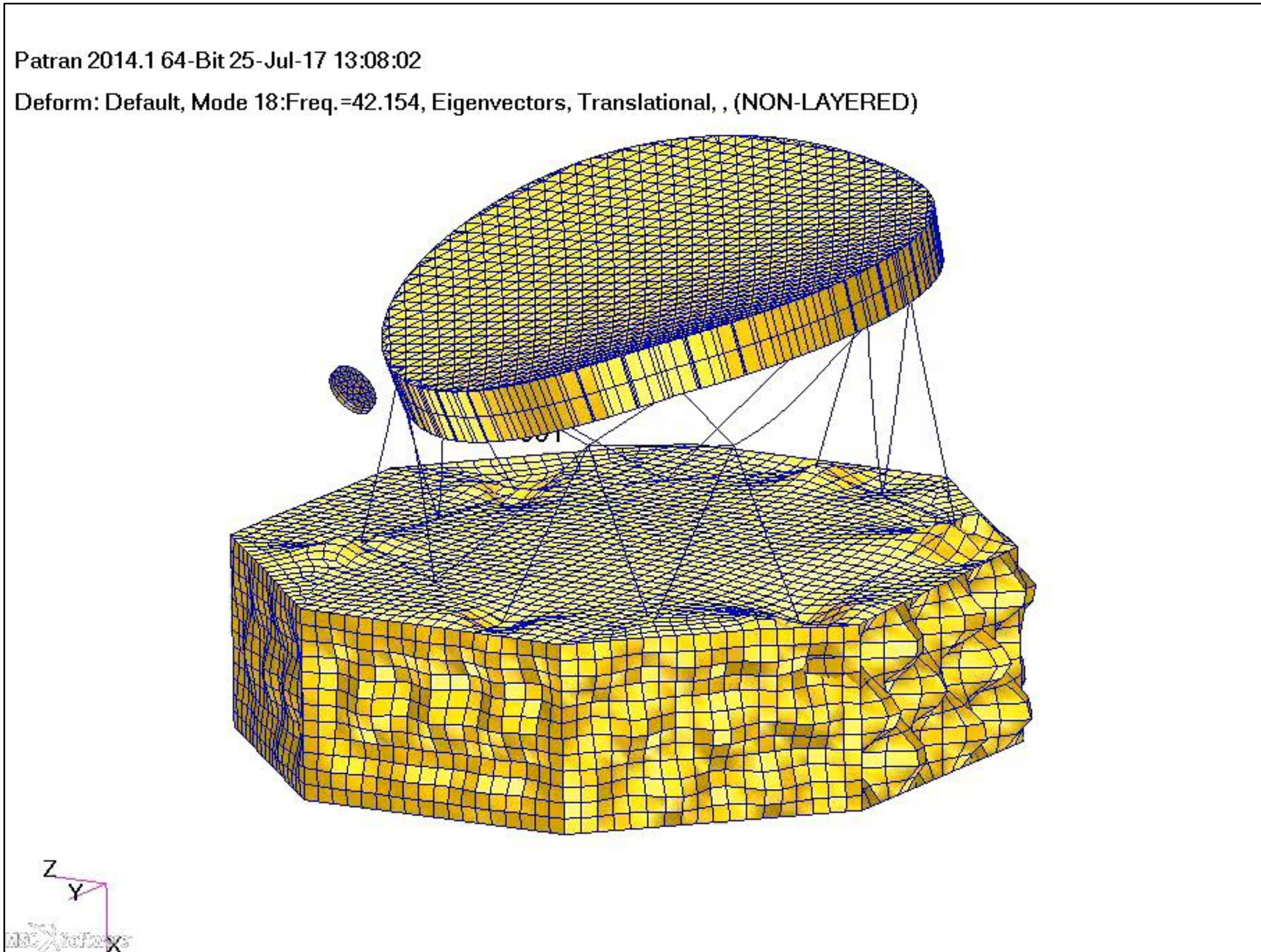
default_Deformation :
Max 5.49-001 @Nd 493915
Frame: 1
Scale = 1.00+000
Z
Y
X



First Mirror Mode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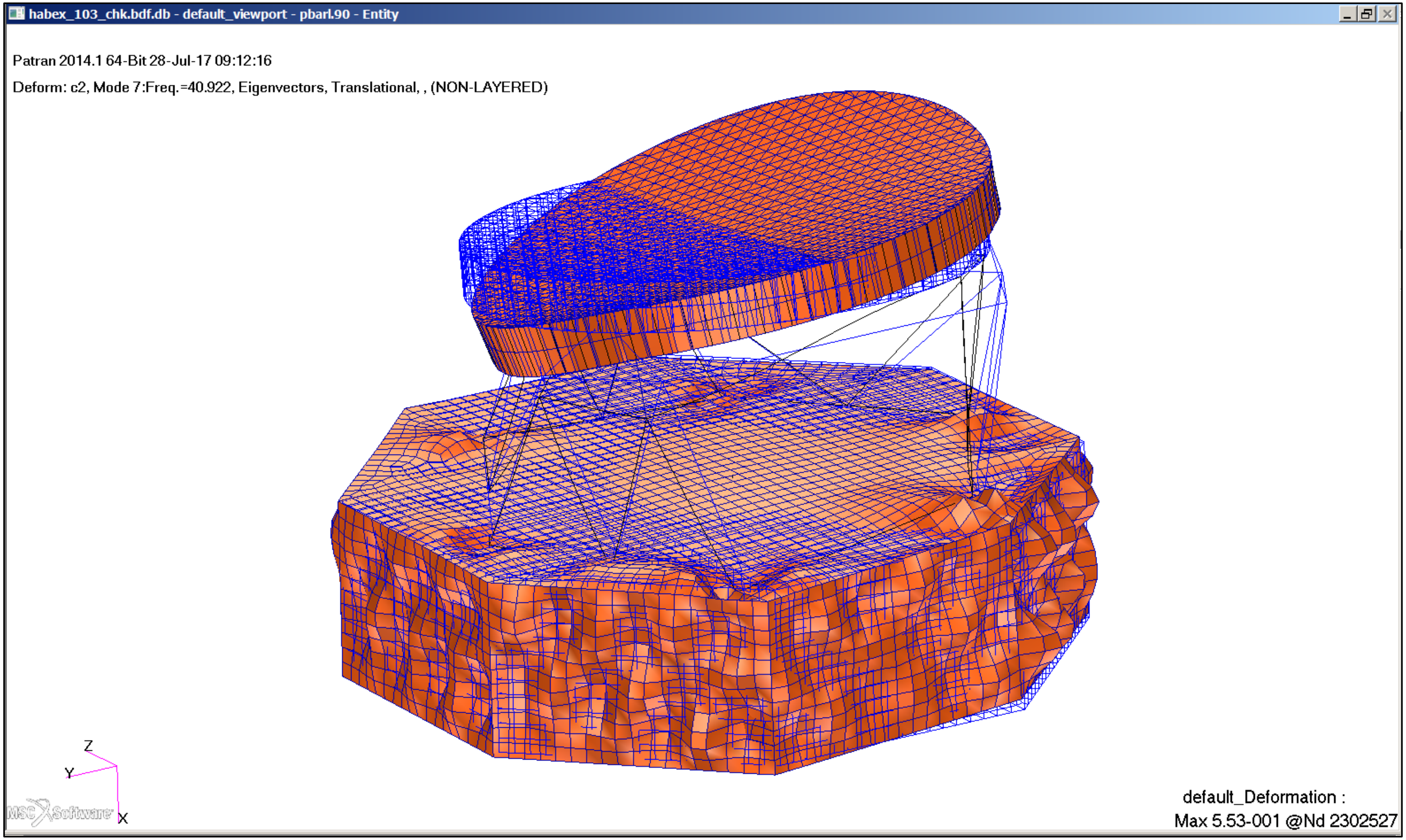
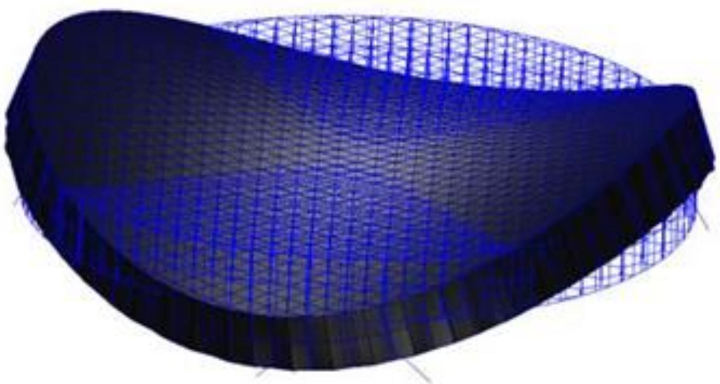
Z
Y
X



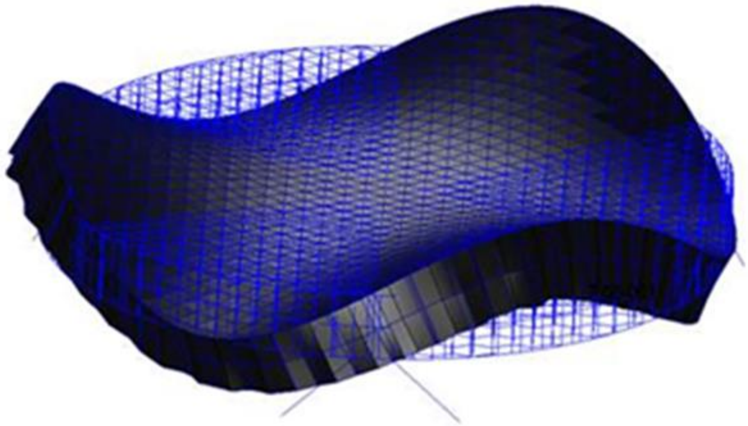
Second Mirror Mode

Primary Mirror Bending Modes

1st Bending Mode at 80 Hz

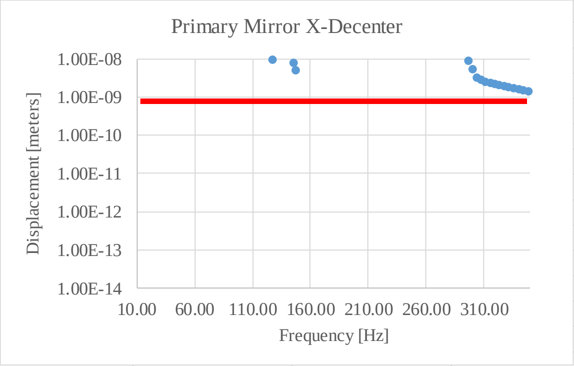


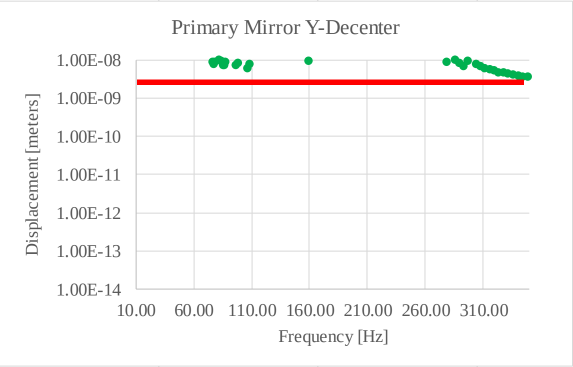
2nd Bending Mode at 180 Hz

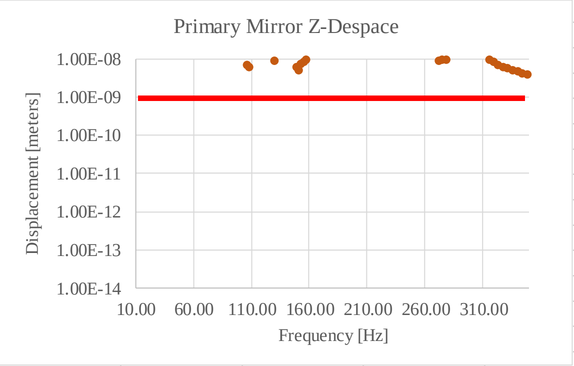


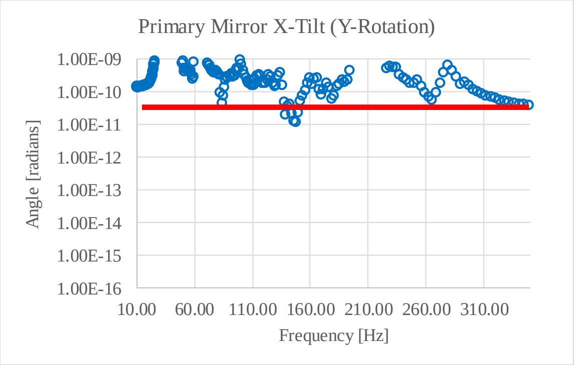
Telescope Structure LOS Stability: PM Tolerances

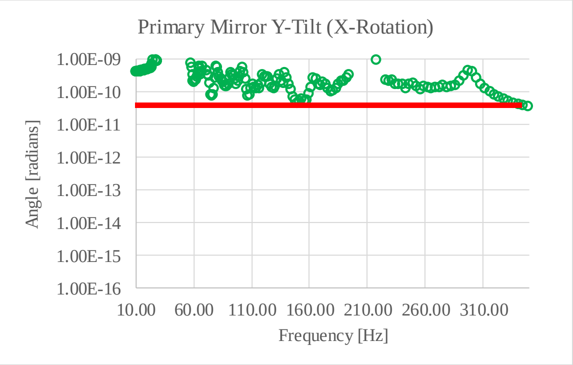
HabEx LOS Stability Tolerances can not be achieved without isolation. Motions induced by a JWST RWA Mechanical Disturbance Spectrum exceeds the LOS Tolerances (red lines)

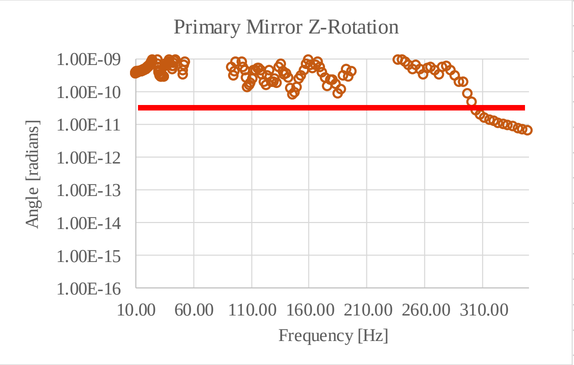












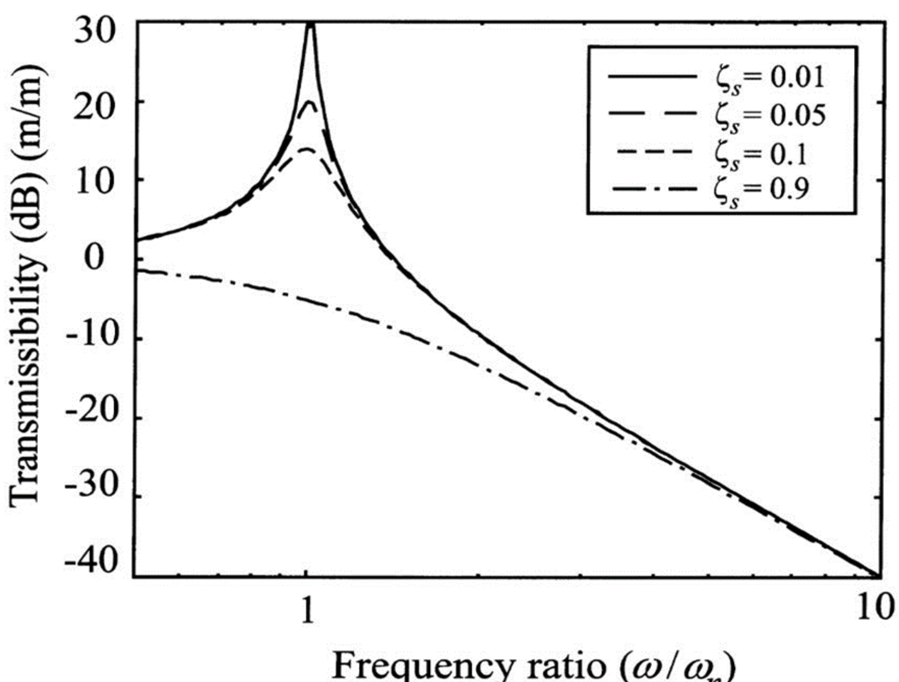
Vibration Isolation

JWST has 2 passive stages producing 70dB of isolation:

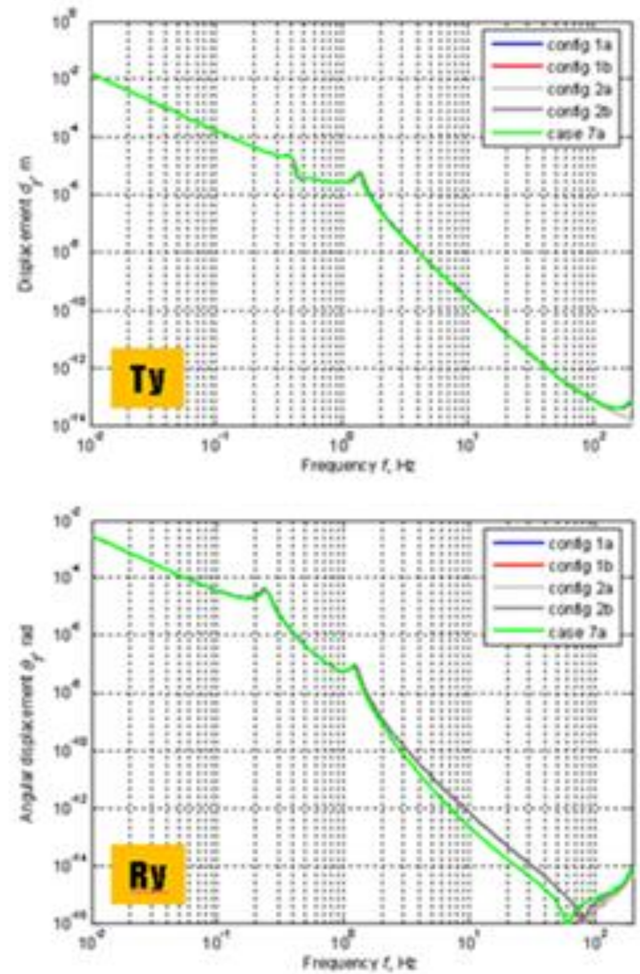
- 8-Hz between reaction wheels & spacecraft.
- 1-Hz between spacecraft and OTA.

Passive Isolation

- ~ 10dB/octave
- Damping is important



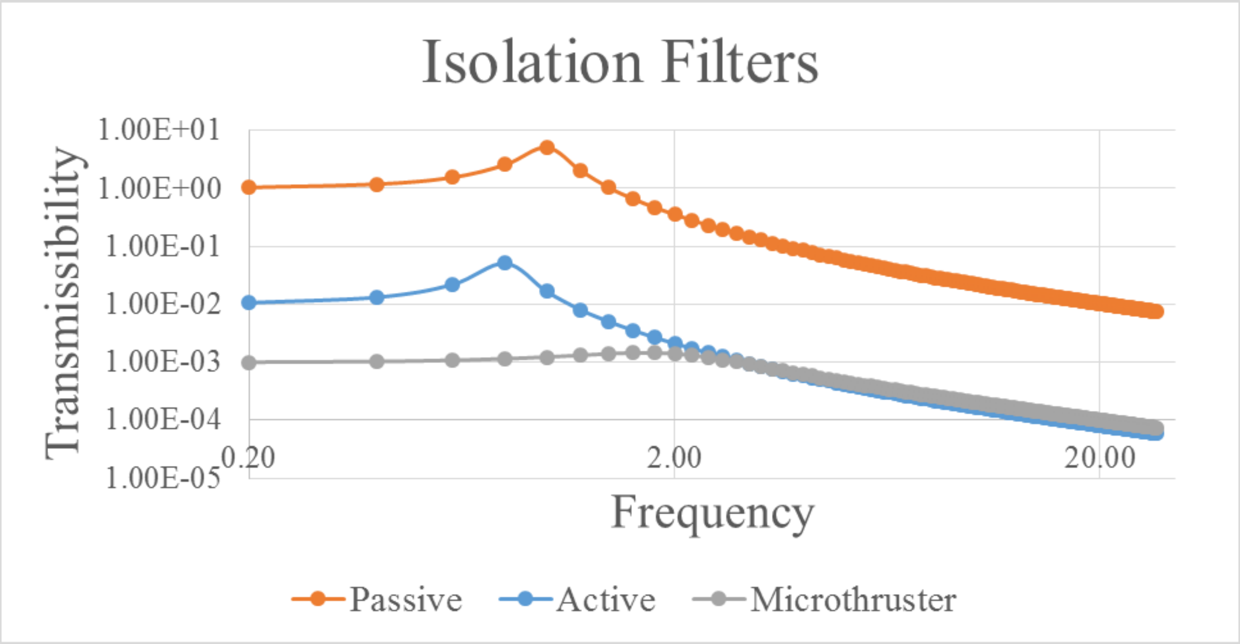
JWST Isolation



Passive vs Active Vibration Isolation

Theoretical Isolation Filters:

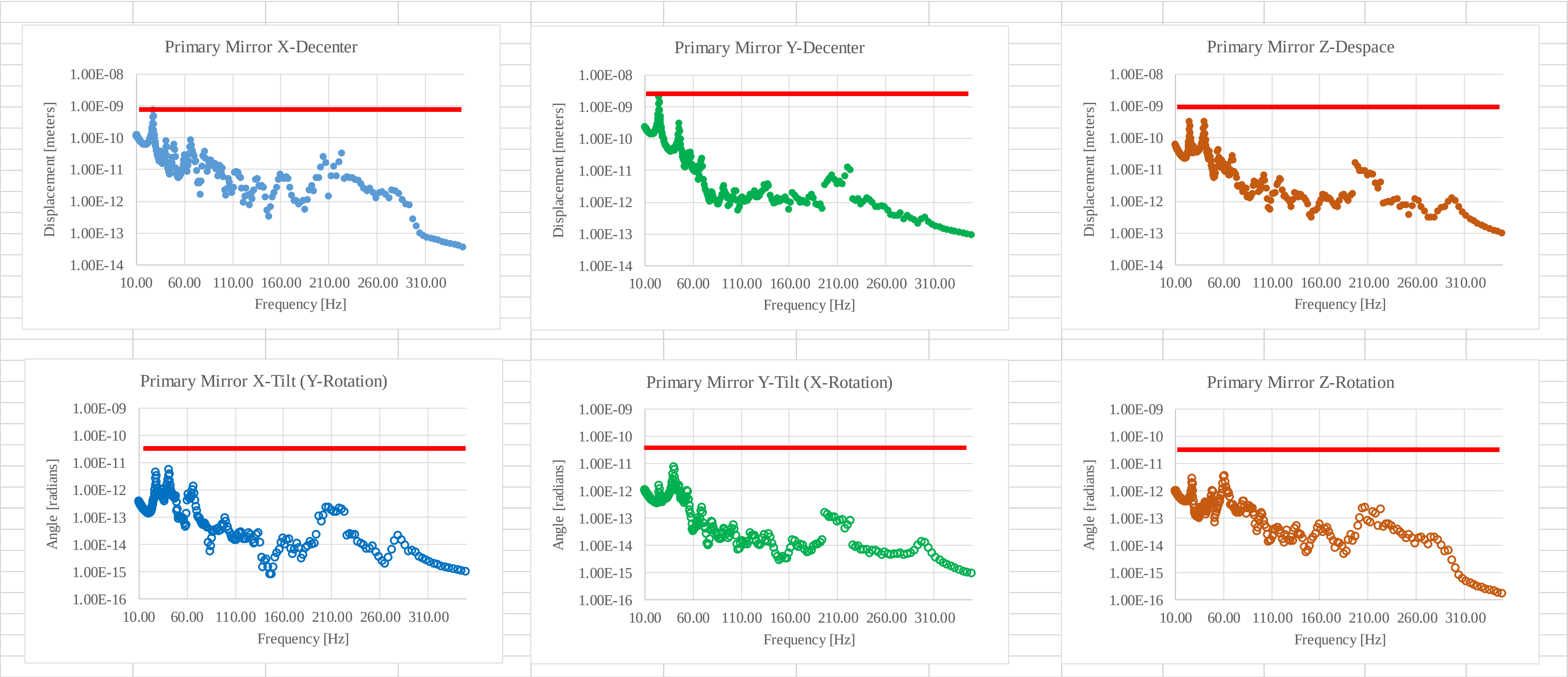
- Passive = 1 Hz, 10% damping
- Active = 40 dB initial reduction, 0.8 Hz, 10% damping
- Micro-Thrusters initial 60 dB reduction, 2 Hz 50% damping



Telescope Structure LOS Stability: PM Tolerances

THabEx LOS Stability Tolerances can be achieved via applying a Passive 0.5 Hz with 1% damping isolation filter to the rigid body dynamic opto-mechanical response data.

Red Lines are ‘new’ tolerance limits – X-Decenter & Y-Decenter



Alignment Stability Tolerances

Structural Response (with Isolation) analysis shows that the most important parameter is PM X- & Y-Decenter.

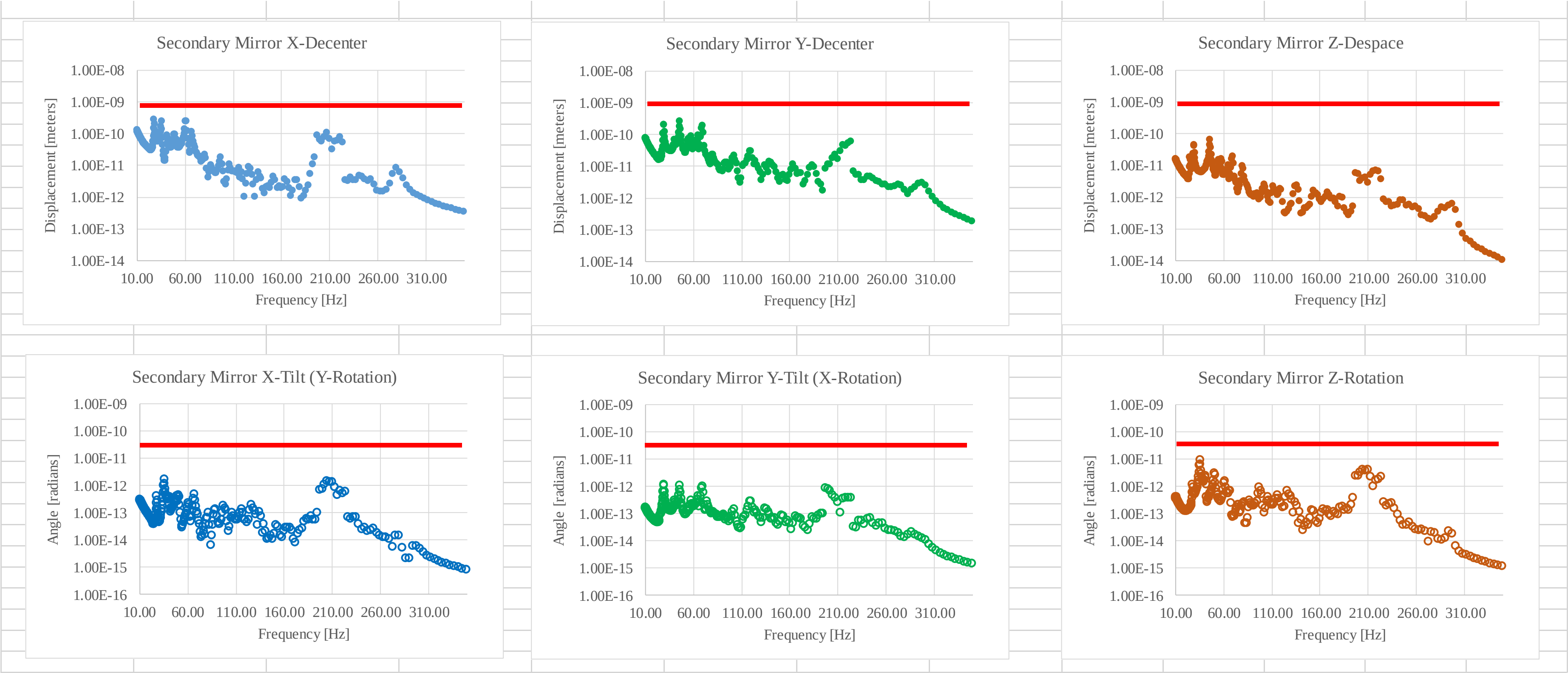
Structural Response analysis allows reallocation of tolerances.

LOS RSS Error										5.11	mas
						Sensitivity at FSM		ERROR			
Alignment	ZEMAX	Input	units	Tolerance	Units	Y-Tilt	X-Tilt	Y-Tilt	X-Tilt	RSS	Units
PM X-Decenter	DX	**1.5**	nanometer	1	nanometer	1.49	0	2.24	0.00	2.24	mas
PM Y-Decenter	DY	**2.5**	nanometer	1	nanometer	0	1.39	0.00	3.48	3.48	mas
PM Z-Despace	DZ	1	nanometer	1	nanometer	0	0.36	0.00	0.36	0.36	mas
PM Y-Tilt	TX	0.05	nano-radian	1	mas	0.19	79.08	0.00	0.82	0.82	mas
PM X-Tilt	TY	0.05	nano-radian	1	mas	-77.75	-0.08	-0.80	0.00	0.80	mas
PM Z-Rotation	TZ	0.05	nano-radian	1	mas	18.05	0.02	0.19	0.00	0.19	mas
SM X-Decenter	DX	1	nanometer	1	nanometer	-1.32	0	-1.32	0.00	1.32	mas
SM Y-Decenter	DY	1	nanometer	1	nanometer	0	-1.23	0.00	-1.23	1.23	mas
SM Z-Despace	DZ	1	nanometer	1	nanometer	0	-0.36	0.00	-0.36	0.36	mas
SM Y-Tilt	TX	0.05	nano-radian	1	mas	-0.01	-5.46	0.00	-0.06	0.06	mas
SM X-Tilt	TY	0.05	nano-radian	1	mas	5.45	0.01	0.06	0.00	0.06	mas
SM Z-Rotation	TZ	0.05	nano-radian	1	mas	-1.41	0	-0.01	0.00	0.01	mas
TM X-Decenter	DX	10	nanometer	1	nanometer	-0.14	0	-1.40	0.00	1.40	mas
TM Y-Decenter	DY	1	nanometer	1	nanometer	0	-0.14	0.00	-0.14	0.14	mas
TM Z-Despace	DZ	50	nanometer	1	nanometer	-0.01	0	-0.50	0.00	0.50	mas
TM Y-Tilt	TX	3	nano-radian	1	mas	0	-1.5	0.00	-0.93	0.93	mas
TM X-Tilt	TY	3	nano-radian	1	mas	1.57	0	0.97	0.00	0.97	mas
TM Z-Rotation	TZ	100	nano-radian	1	mas	0.02	0	0.41	0.00	0.41	mas
							SUM	-0.17	1.94	1.94	mas

Telescope Structure LOS Stability: SM Tolerances

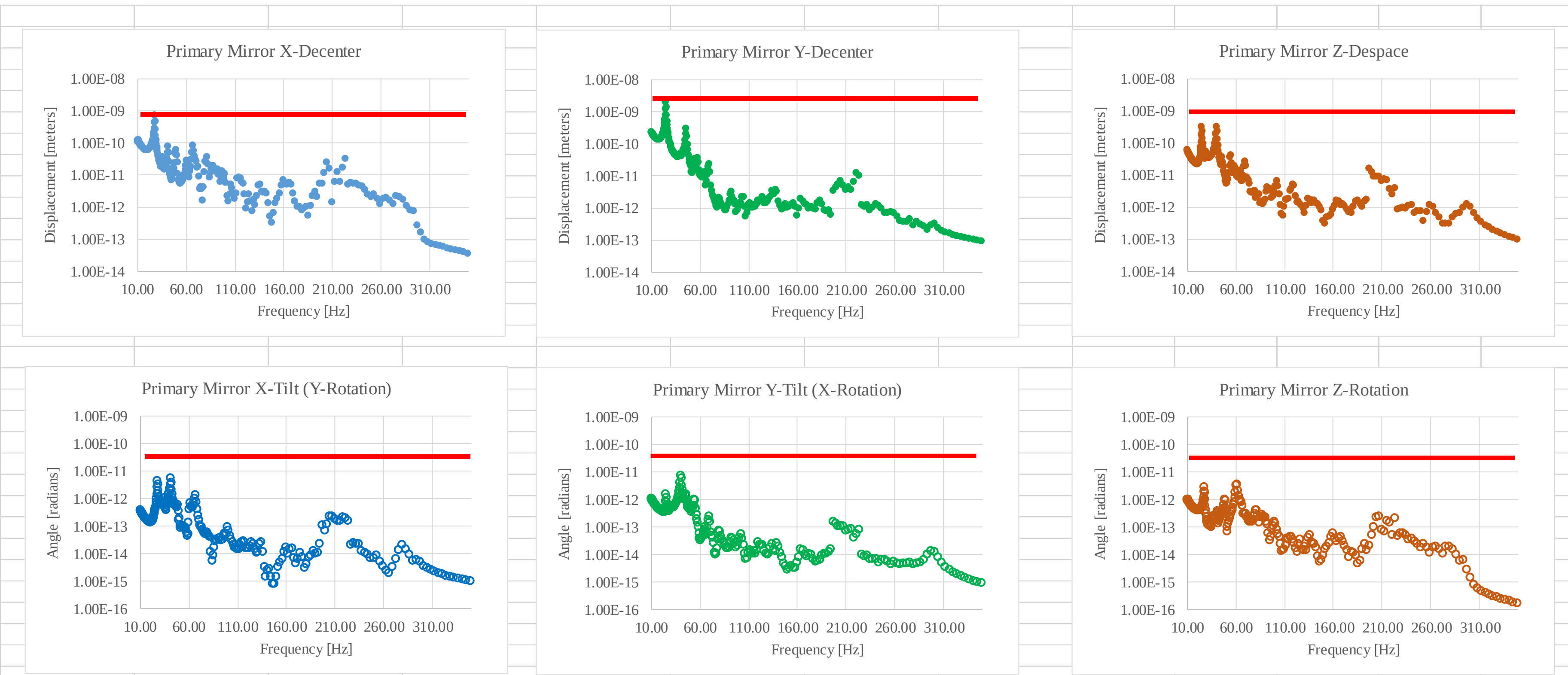
Secondary Mirror rigid body motions have margin against the tolerance limits.

Again, X-Decenter & Y-Decenter are the biggest challenging.



Telescope Structure LOS Stability: PM Tolerances

Passive 0.5 Hz resonance frequency filter with 1% damping just barely meets LOS Stability Tolerances.

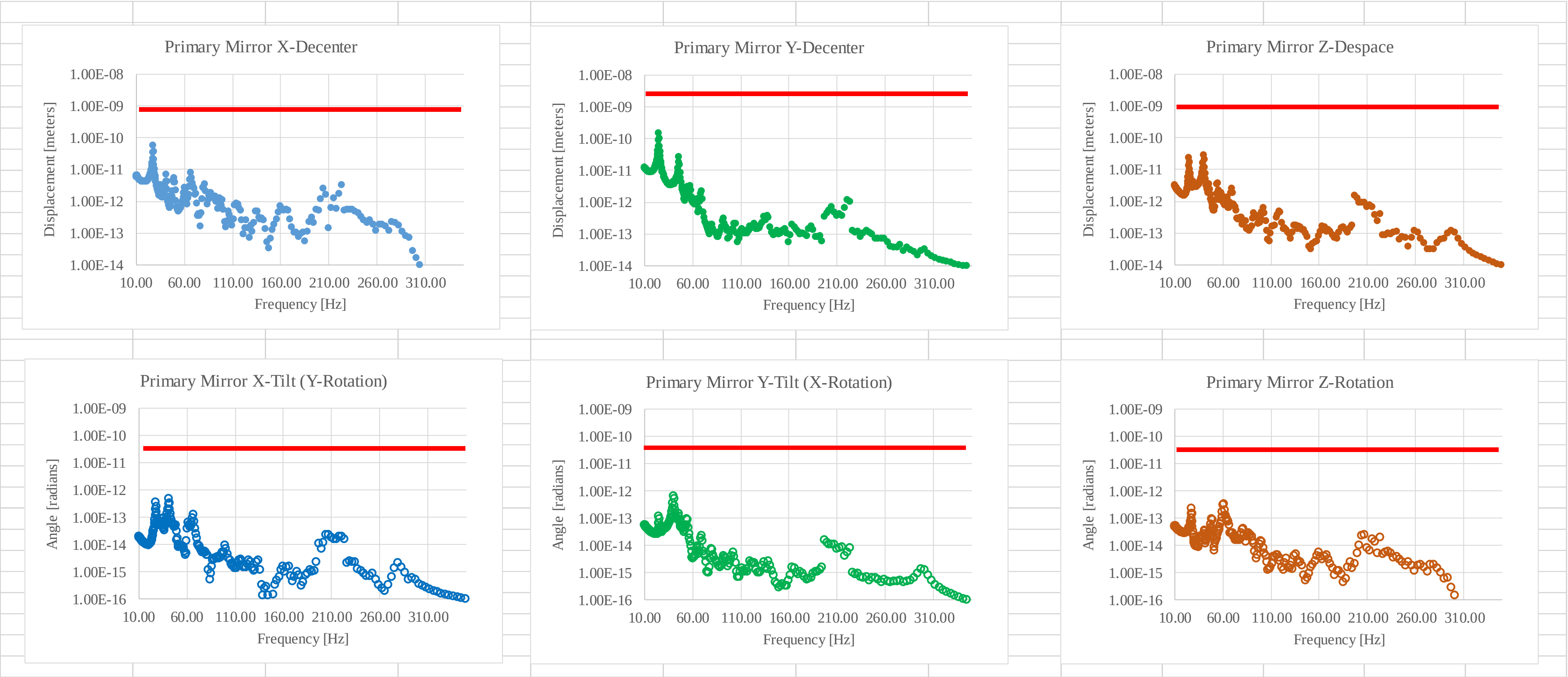


Telescope Structure LOS Stability: Margin

LOS Stability Tolerances met with margin with:

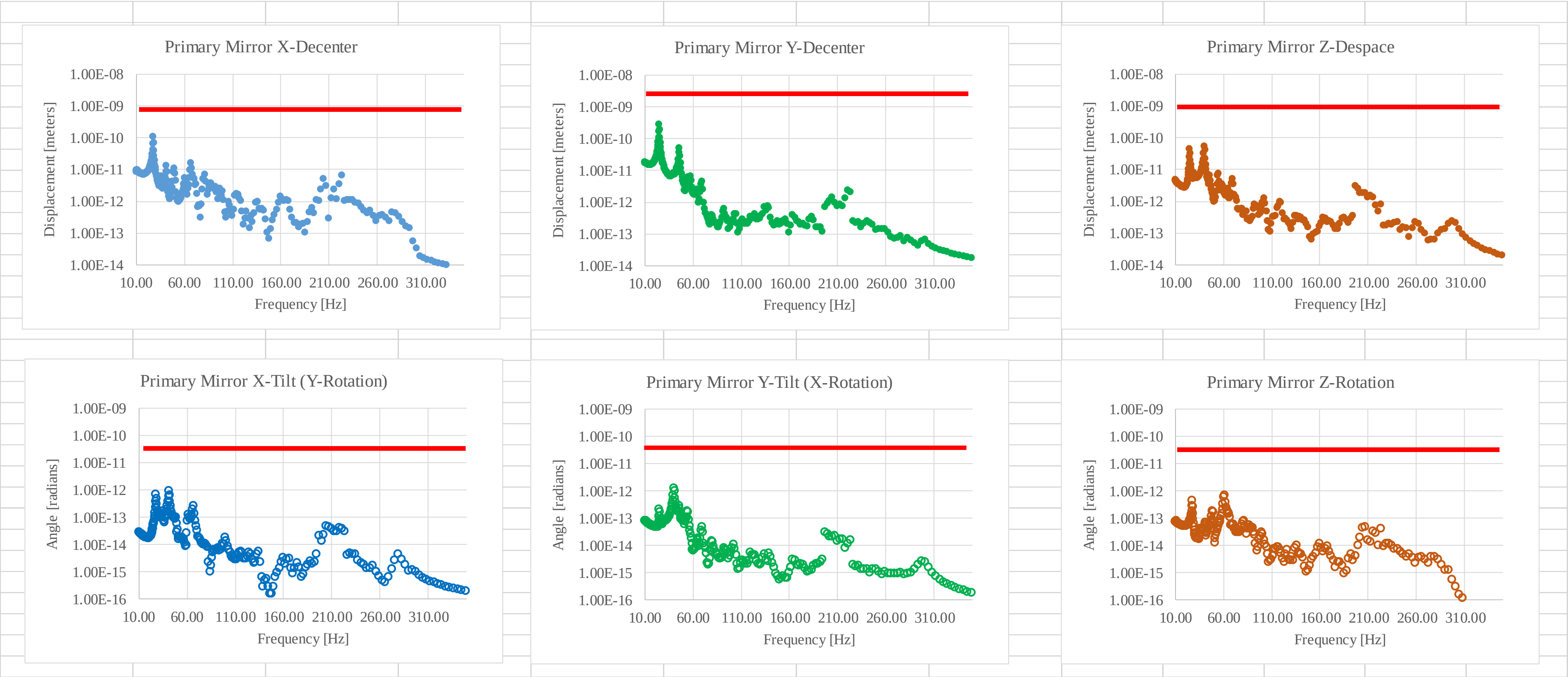
- Active -40dB, 1-Hz filter with 5% damping

  Specification similar to Lockheed Disturbance Free Payload (DFP) Vibration Isolation System



Telescope Structure LOS Stability: Micro-Thrusters

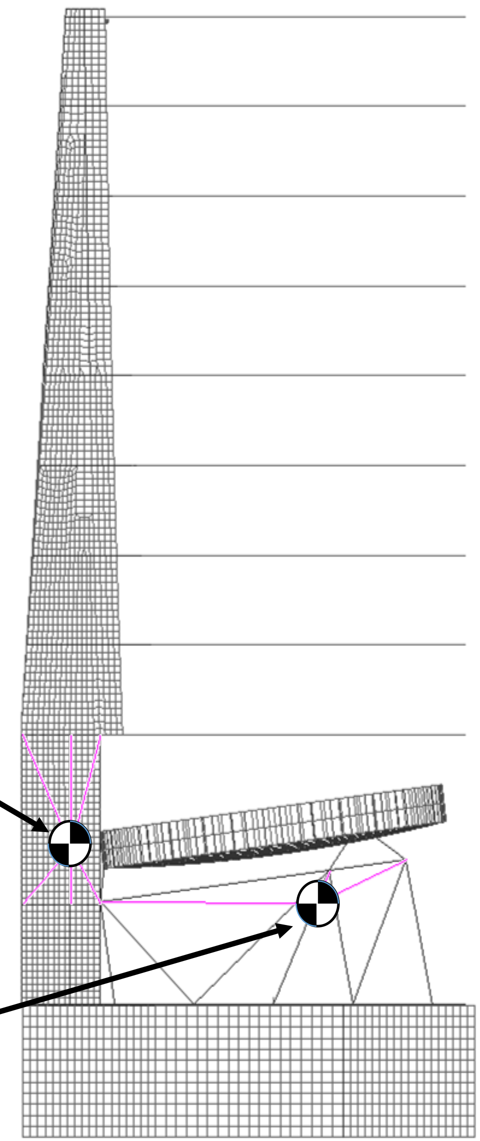
Micro-Thrusters reduce jitter amplitude by a uniform 0.001 (-60dB isolation) with 2 Hz resonant frequency and 50% damping.



Science Instrument Mass

Analysis with and without Science Instrument lump mass in telescope structure has negligible effect on dynamic line of sight performance.

UV Spectrometer	170kg
Coronagraph	650kg
Wide Field Imager	230kg
Star Shade Camera	210kg



UV Spectrometer
Focal Plane 40kg

Dynamic Wavefront Error:

Mechanical Stability

Primary Mirror Dynamic Wavefront Error

Dynamic PM WFE arises from two sources:

- Mechanical
- Thermal

Mechanical Vibrations have a temporal spectrum:

- Specific vibration frequencies induce harmonic modal response.
- All other vibration frequencies cause inertial response.

These responses produce structural motions that cause:

- Optical mis-alignment aberrations
- Optical component bending and deformations from mount stress

Primary Mirror Dynamic WFE

PM Dynamic Error is proportional to Gravity Sag.

- 1 G acceleration = 1 Gravity Sag
- 1 μG acceleration = 1 μ_Gravity Sag

To minimize PM Dynamic WFE:

- Design the PM Substrate to be as stiff as possible
- Consider the Mount stiffness and location.

Depending on mirror design (stiffness) & mount (3 vs 6 point)

- If Trefoil Gravity sag is 60 micrometers.
- And, if Coronagraph requires < 6 nm of Trefoil
- Then mirror acceleration must remain < 100 μG.

Primary Mirror Dynamic WFE

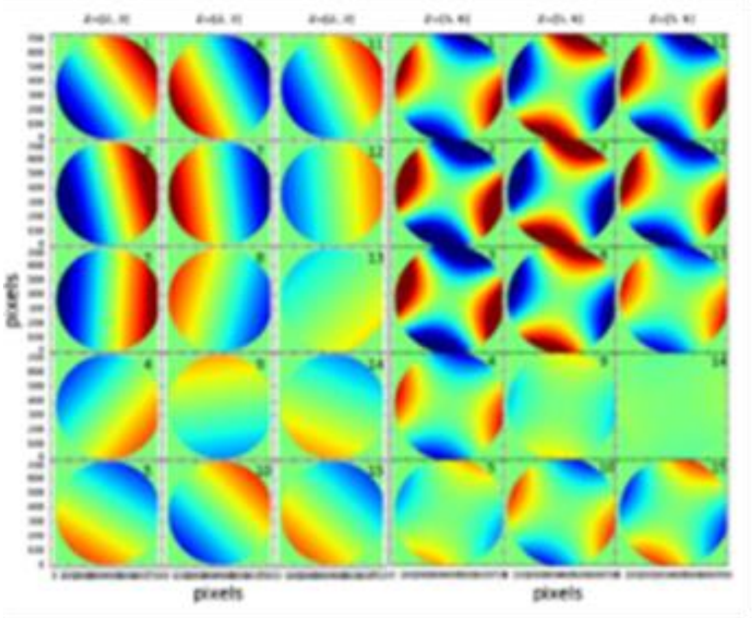
Dynamic WFE depends on the mirror's mounted self-weight deflection (G-sag) and its inertial response function.

G-sag defines the maximum possible WFE for a 1G driving force and a unity response function.

G-sag depends on stiffness of mirror substrate and how it is mounted.

For example, JWST's 220-Hz open-back beryllium primary mirror segments on a 3-point mount have a static horizontal G-sag of approximately 200 nm.

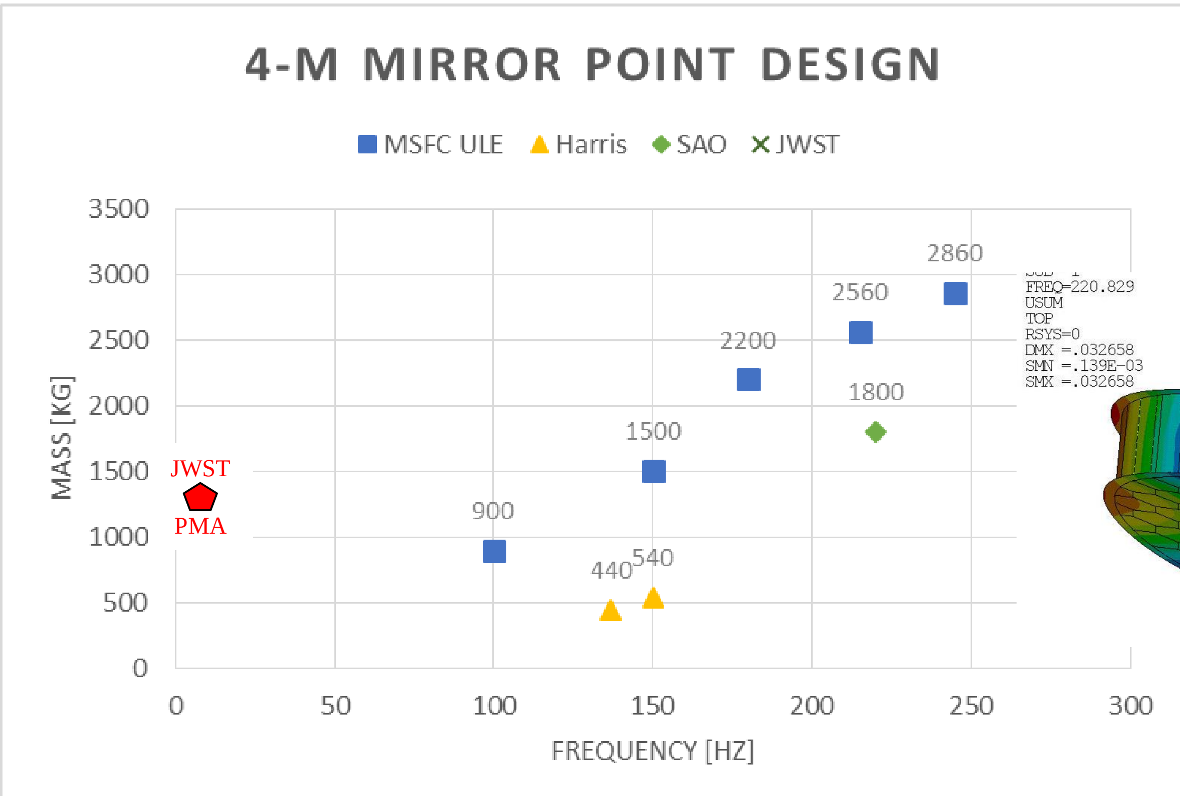
When driven at 87.3 Hz, they have a dynamic Astigmatic WFE of 220 nm per G of driving force.

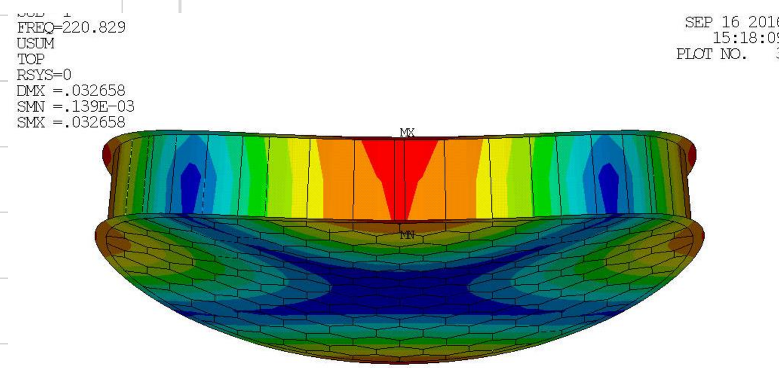


Saif, et. al., Nanometer level characterization of the James Webb Space Telescope optomechanical systems using high-speed interferometry, Applied Optics, Vol.54, No.13, pg.4295, doi:134285-14, 2015

ULE 4-m Mirror Trade Studies

MSFC explored range of higher mass, more robust designs.
Harris Corporation explored lower limit of mass.





JWST total mass of primary mirror segment assemblies (PMSA) is 700 kg, Total PM Assembly mass is 1250 kg. Individual JWST PM substrates are 220 Hz. Individual PMSA are 40 Hz. Total PMA is 16 Hz.

ULE PM Trade Study: Substrate Stiffness

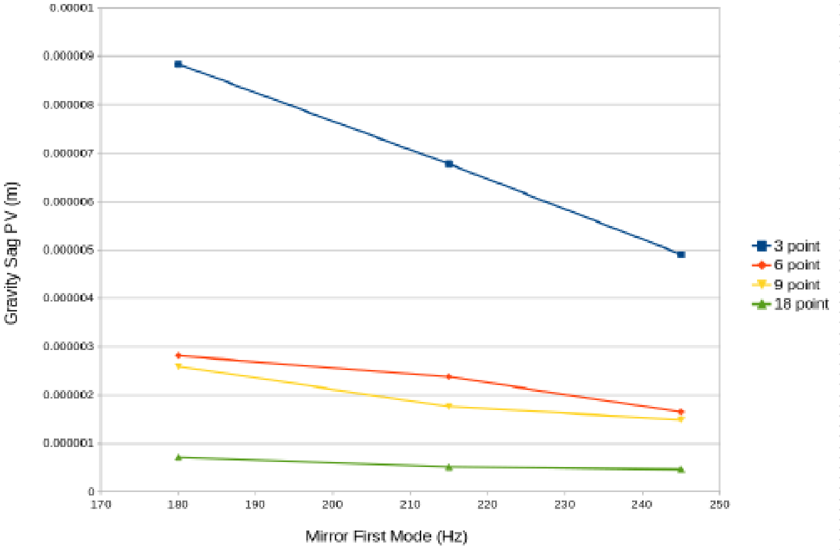
ULE mirrors can be Closed-Back Architectures.

State of Practice Thickness is 35 cm, SOA is 40 cm, 60-cm is developmental.

depth (m)	0.45	0.6	0.75
mass (kg)	1388	1707	1835
cell size (m)	0.167	0.167	0.167
front fs (m)	0.0277	0.0277	0.0277
back fs (m)	0.0231	0.0231	0.0231
1st mode (Hz)	180	215	245

Gravity Sag:

- Stiffer mirror less G-Sag
- More Mount Points less G-Sag

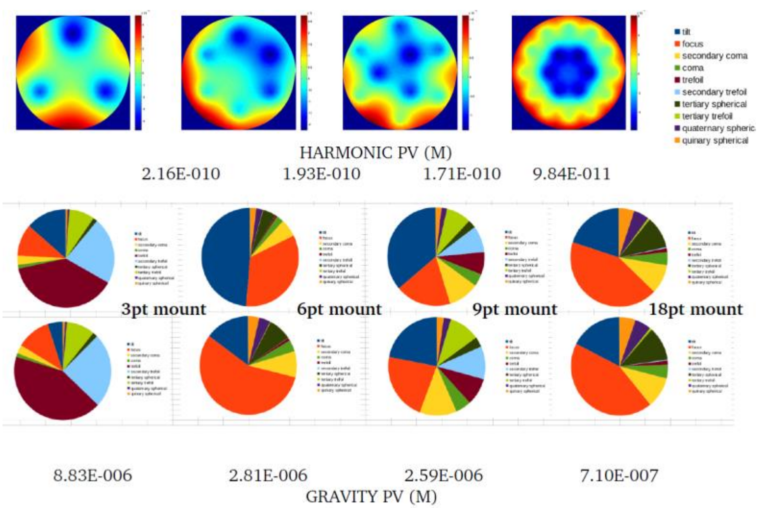


ULE PM Trade Study: Dynamic WFE

Dynamic WFE for 4-m off-axis 180-Hz 1388-kg Mirror as a function of mount support system when excited at 49.9-Hz by a 1 Newton sinusoidal driving force.

	3POINT	6POINT	9POINT	18POINT
1ST MOUNTED MODAL (HZ)	47.2	50.4	54.1	55.4
HARMONIC PV (M)	2.16E-010	1.93E-010	1.71E-010	9.84E-011
AT FREQUENCY (HZ)	49.9	49.9	49.9	49.8
GRAVITY PV (M)	8.83E-006	2.81E-006	2.59E-006	7.10E-007
SCALE	2.45E-005	6.86E-005	6.61E-005	1.38E-004

Dynamic WFE amplitude is similar to gravity sag.



ZERODUR PM Trade Study: Substrate Stiffness

ZERODUR mirrors are constrained to Open-Back architectures with a maximum thickness of 42 cm.

Trade Studies:

#1: Isogrid (triangular) Pockets

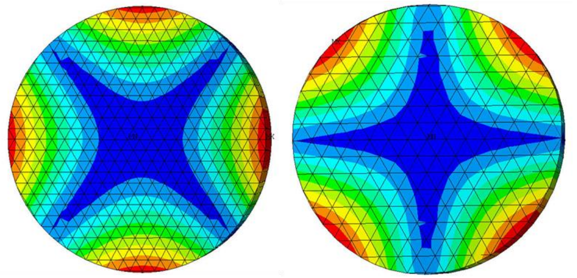
- First mode ~ 70 Hz.
- Mass ~ 2600 kg

#2: Hex Pockets with T-back

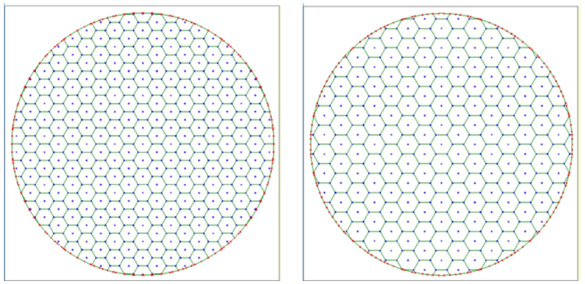
- First mode ~ 120 Hz.
- Mass ~ 1800 kg

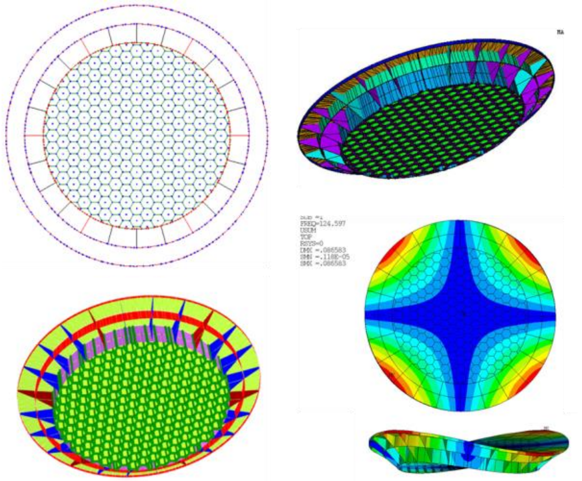
#3: SOFIA Style

- First mode ~ 125 Hz.
- Mass ~ 1350 kg

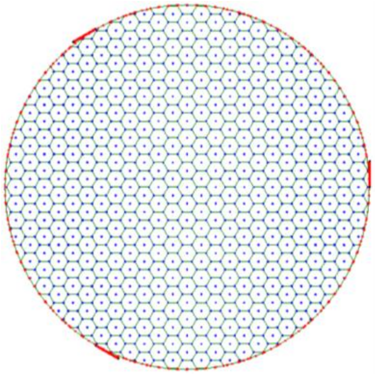


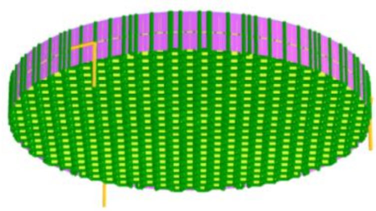
Cell=200Ø   Cell=300Ø



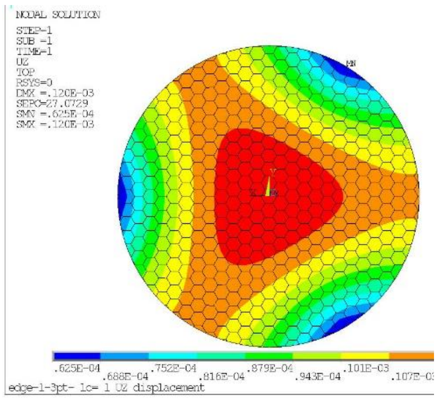


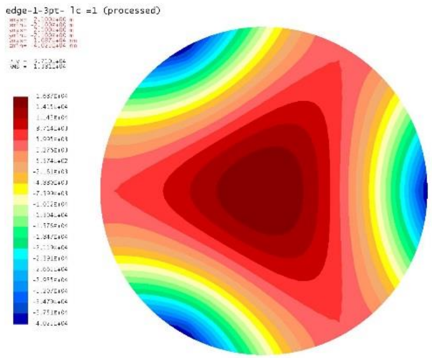
Support trade studies

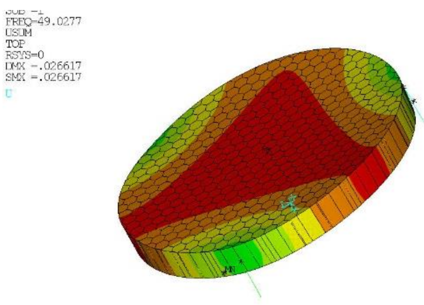




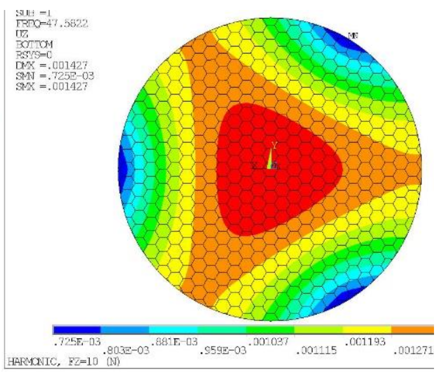
STATIC RESPONSE

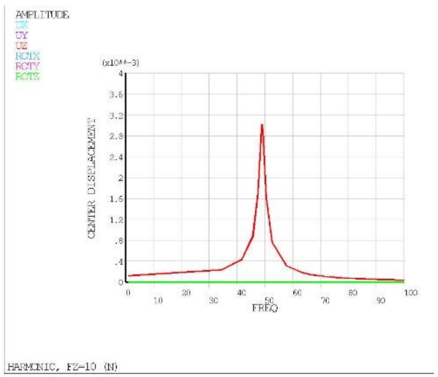


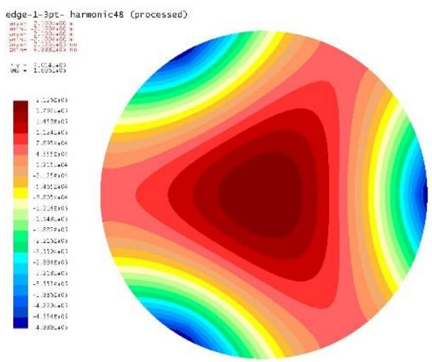




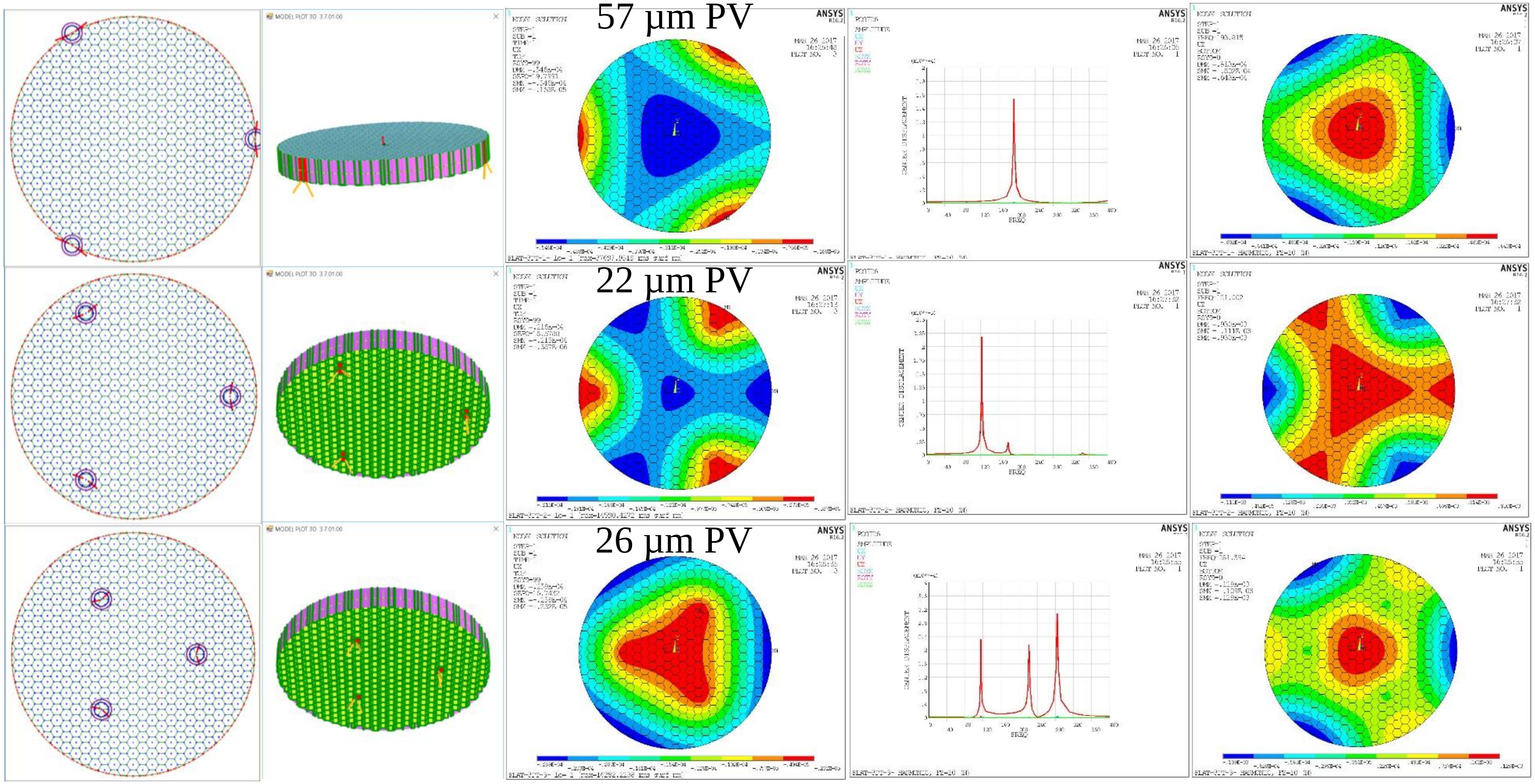
HARMONIC RESPONSE







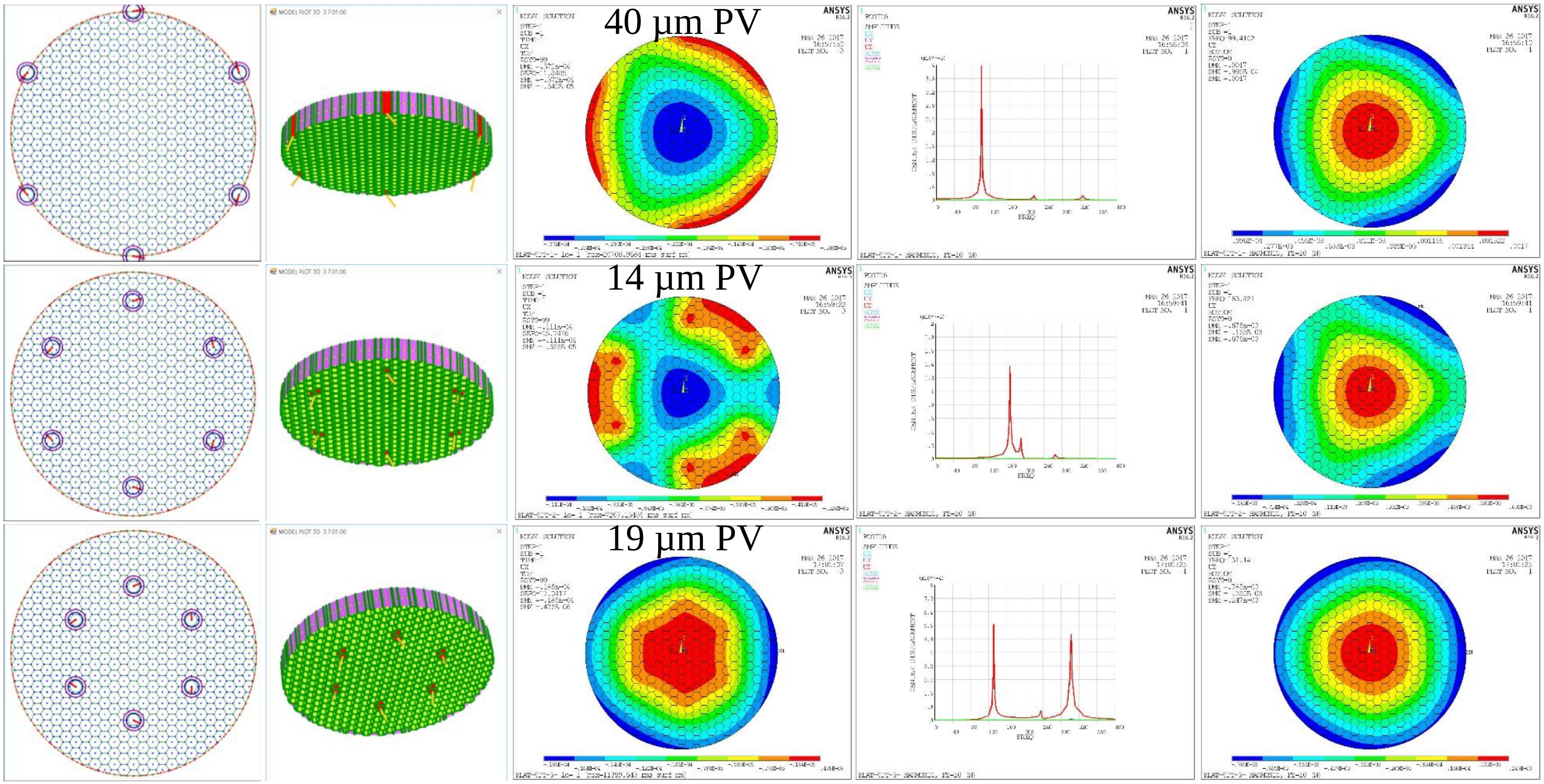
FLAT 3PT TRADE STUDY



Suspension system consists of beam elements with the desired stiffness and geometry.

Mirror and Mount system assumes 0.5% dampening give a Q (amplification factor) about 100X on transmissibility.

FLAT 6PT TRADE STUDY

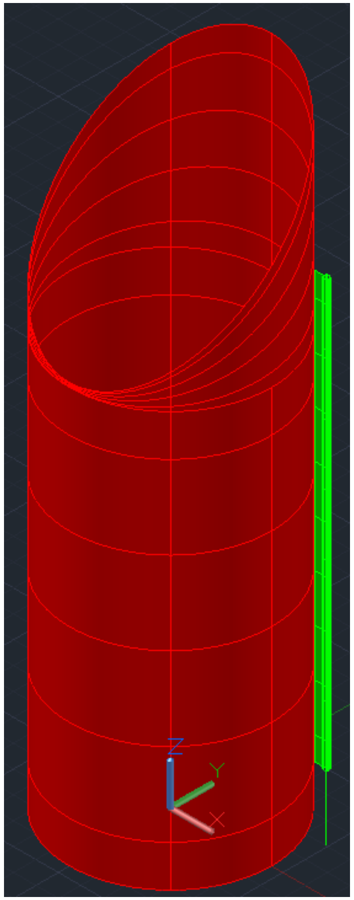


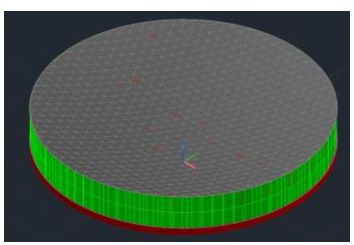
Dynamic Wavefront Error:

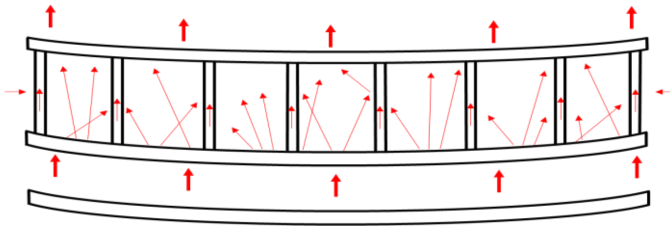
Thermal Stability

Thermal changes produce structural and component motions as a result of material response (bulk CTE and CTE homogeneity)

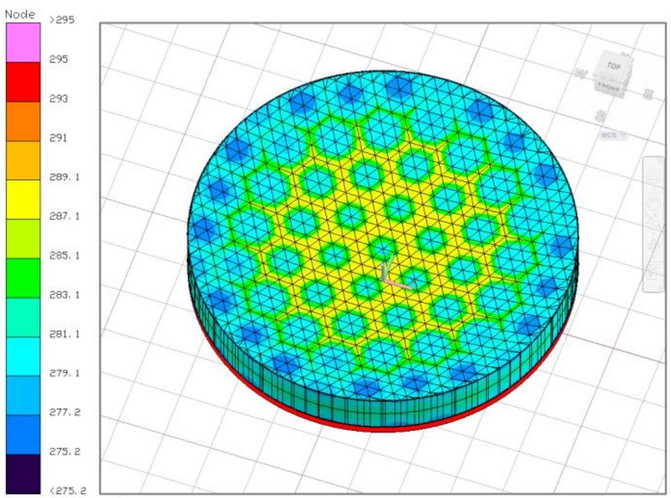
Static Thermal WFE



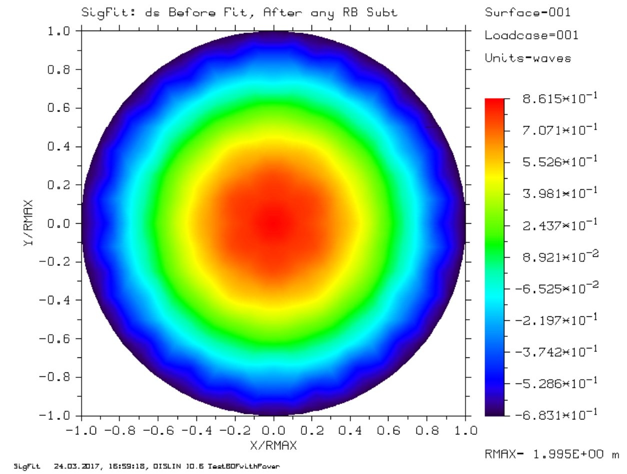




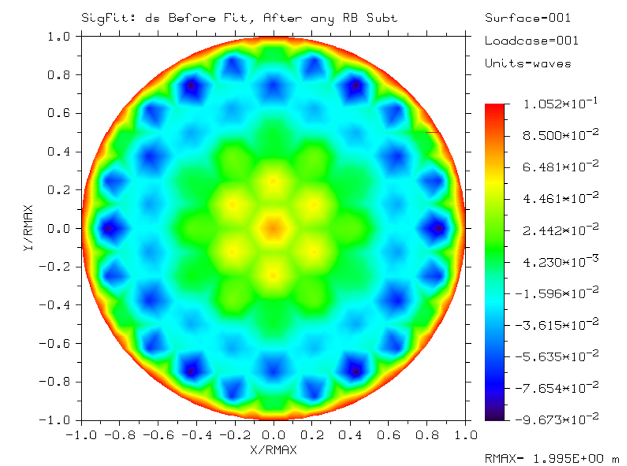
0.5 m thick closed-back ULE mirror
Radial Gradient depends on view factor and side insulation.



Temperature gradient
Keeping Front Surface > 273K
20C Axial; 10C Radial



SFE from isothermal with defocus
SFE = 977 nm PV; 288 nm RMS



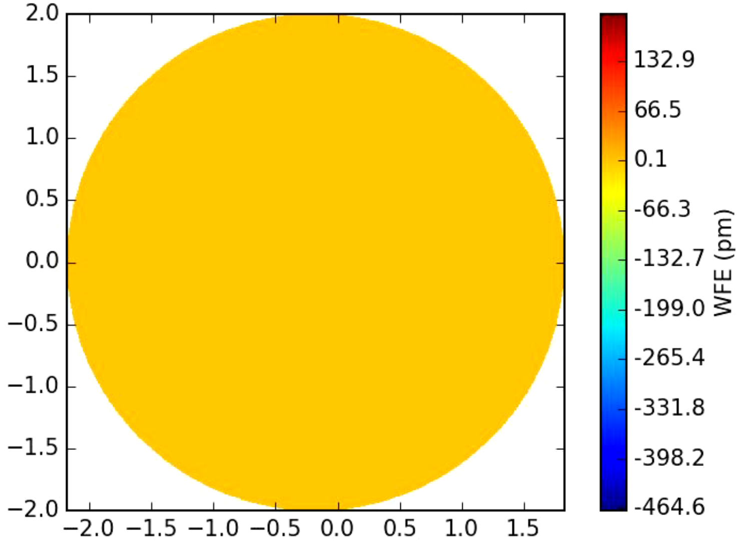
SFE from with defocus removed
SFE = 128 nm PV; 24 nm RMS

Dynamic Thermal WFE Video

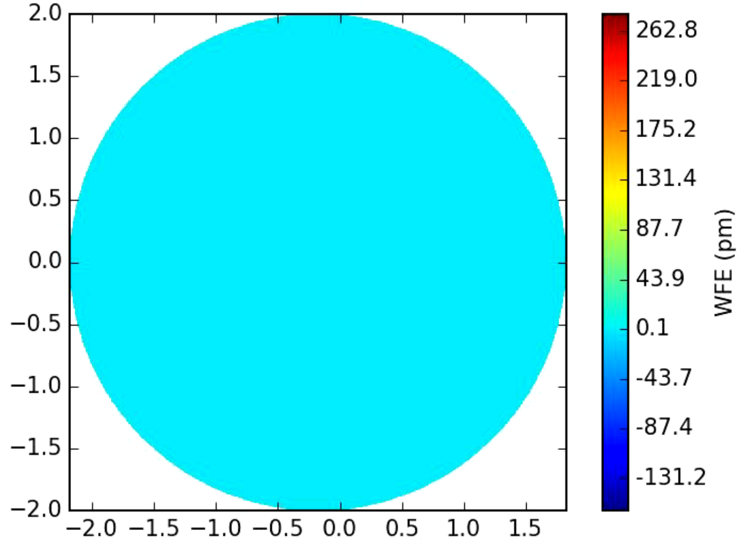
Passive Wavefront Error from 1 hour exposure.

Sun angle changes by 0.0411 degree per hour.

All Errors



Power Removed



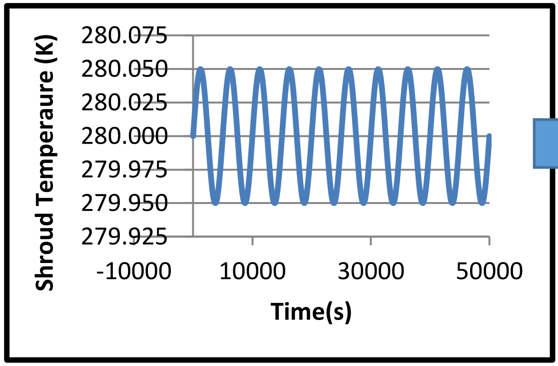
WFE/1-hour = 233 pm PV
WFE/20-min = 28 pm

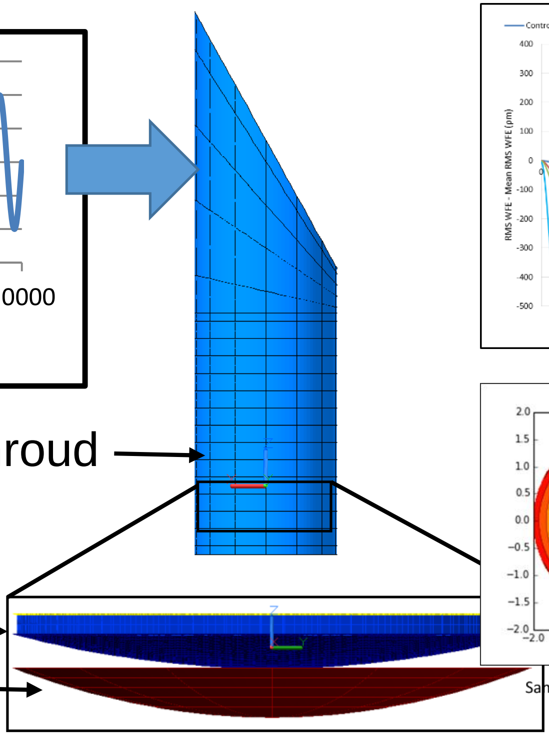
WFE/1-hour = 101 pm PV
WFE/20-min = 13 pm

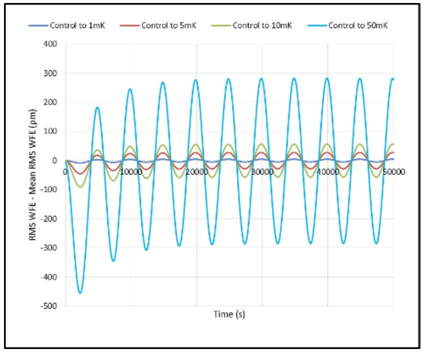
Dynamic Thermal WFE

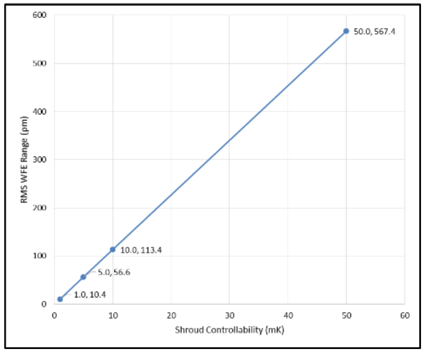
Primary mirror responds to dynamic external thermal load

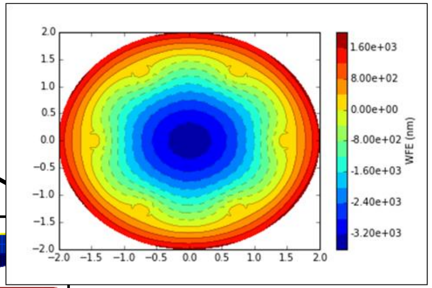
Required stability (10 pm per 10 min) can be achieved by controlling the telescope thermal environment.



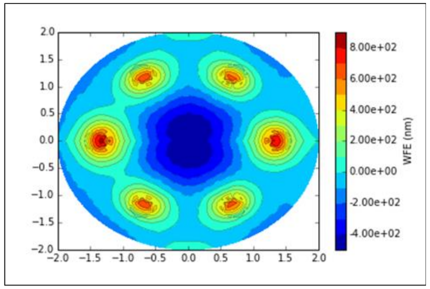






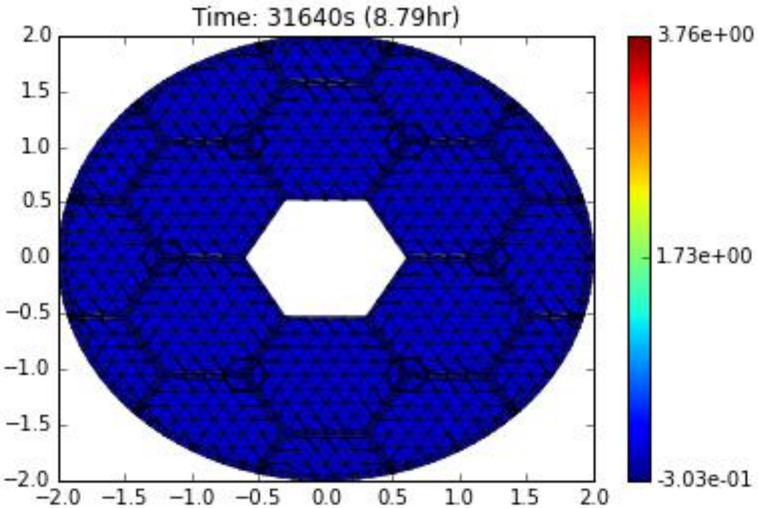


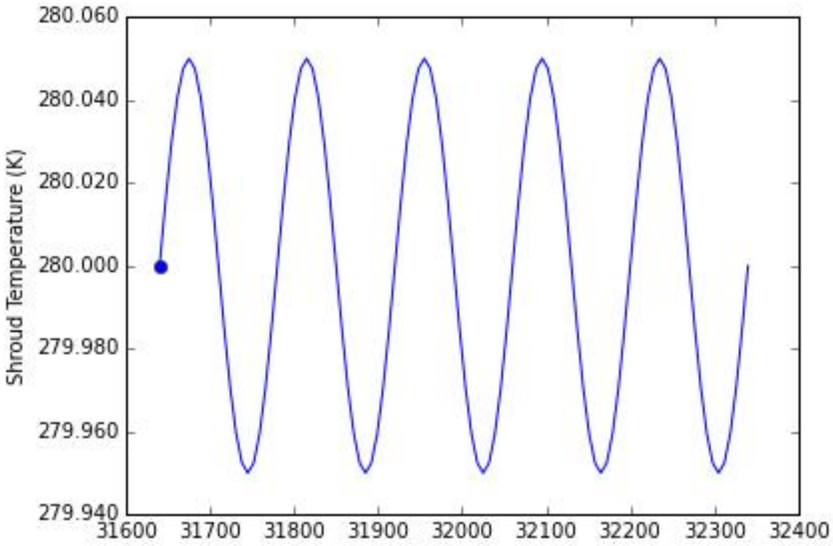
Sample WFE Contour Plot (50mK, 140s Period)



Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)

4m Aperture Transient WFE Video

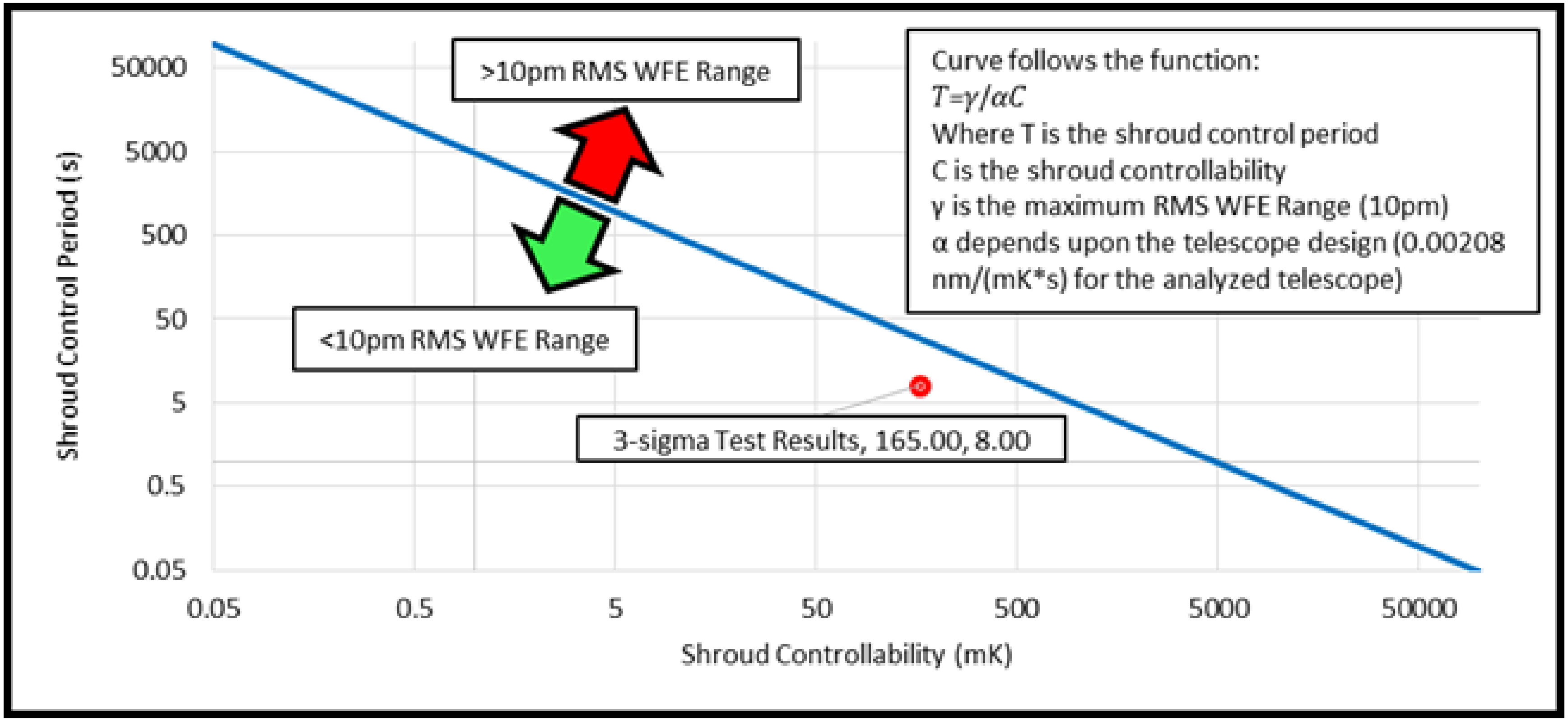




Thermal Stability

The ability to achieve any required wavefont stability depends on:

- Mirror Substrate Properties: CTE, Thermal Mass, Conductivity, etc.
- Thermal Environment Controllability
- Control Period.



Conclusions

Conclusions

HabEx requires an OTA with unprecedented stability.

Baseline Design Closes for LOS Stability using TRL9 technology

Baseline Design enhanced via active isolation or micro-thrusters

Design Philosophy – Passive First, then Active as Required.

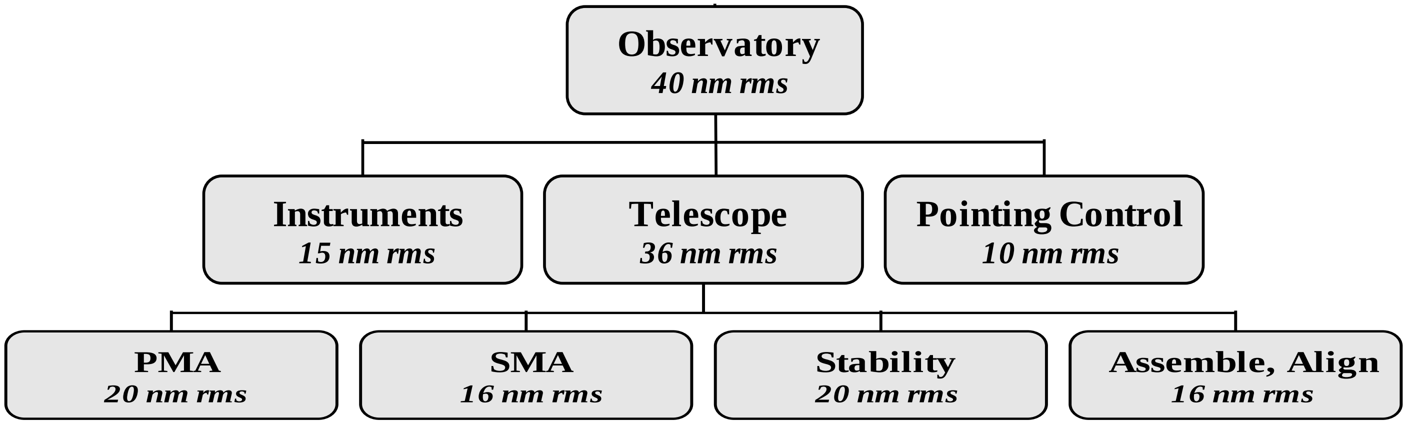
Baseline Design may require Predictive Thermal Control

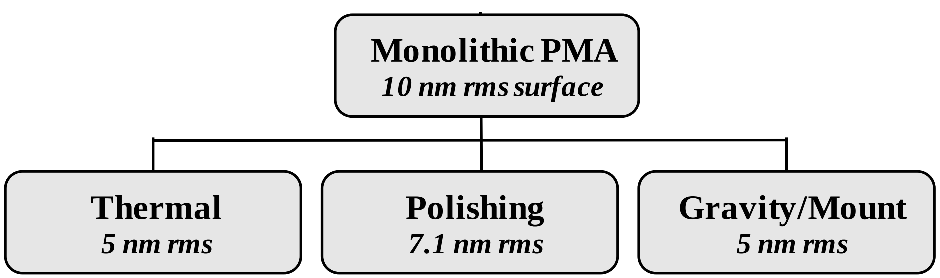
Because of the optical designs sensitivity to LOS over WFE, to verify Baseline Design – may not need to measure picometers of WFE – instead measure 5 mas LOS stability (LOFS ~ 0.2 mas).

BACKUP: WFE Specification

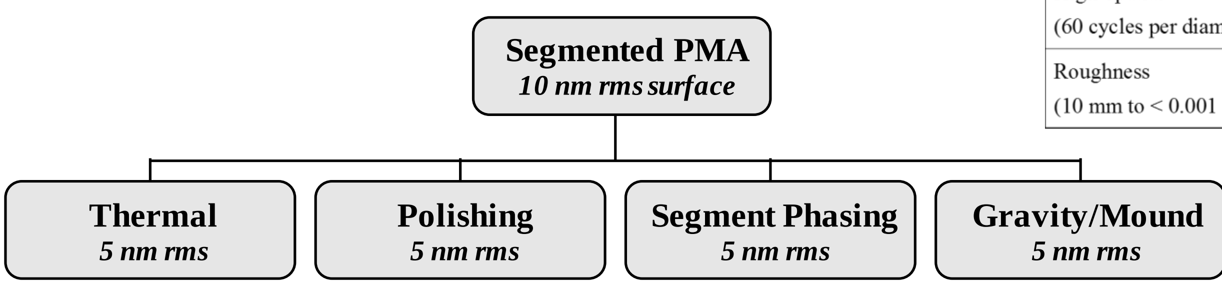
Diffraction Limit WFE

Diffraction Limit of 500 requires total system WFE ~ 38 nm ms





Spatial Frequency Band Limited Primary Mirror Surface Specification			
PSD Slope	- 2.0	- 2.25	- 2.5
Total Surface Error	8.0 nm rms	8.0 nm rms	8.0 nm rms
Figure/Low Spatial (1 to 4 cycles per diameter)	5.2 nm rms	5.5 nm rms	5.8 nm rms
Mid Spatial (4 to 60 cycles per diameter)	5.8 nm rms	5.6 nm rms	5.4 nm rms
High Spatial (60 cycles per diameter to 10 mm)	1.4 nm rms	1.0 nm rms	0.7 nm rms
Roughness (10 mm to < 0.001 mm)	0.6 nm rms	0.3 nm rms	0.2 nm rms



PM SFE Spatial Frequency Specification

Shaklan shows that a UVOIR mirror similar to Hubble (6.4 nm rms) or VLT (7.8 nm rms) can meet the requirements needed to provide a < 10^{-10} contrast 'dark hole'.

- If PM is conjugate with the DM, then PM low-order errors are compensated by DM.
- Recommends < 4 nm rms above 40 cycles
- Both HST & VLT surface figure error is so small enough that there is negligible Contrast reduction from frequency folding
- Because VLT is larger, stiffer and not light-weighted, it is actually smoother at frequencies of concern

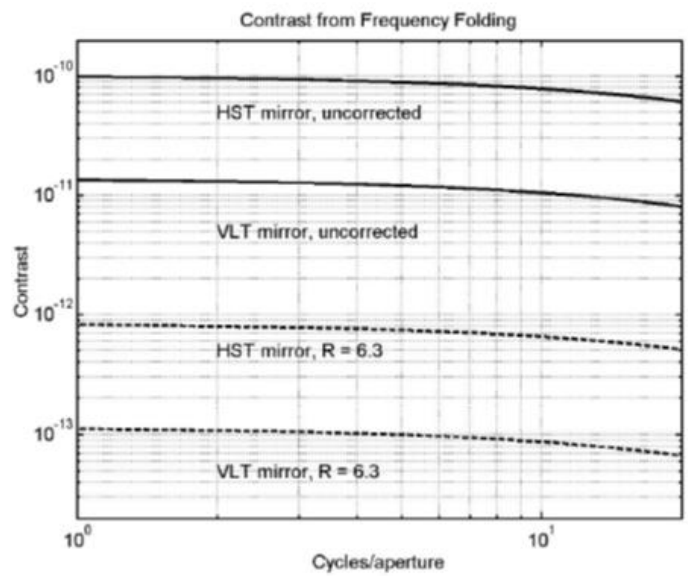


Figure 7. Contrast from frequency folding for spatial frequencies above 48 cycles per aperture, for an 8-m VLT primary and the 2.4 m HST primary. The uncompensated effect is above the required level of 10^{-12} for both mirrors. The sequential DM configuration provides about ~100x reduction of the contrast when it compensates the center of a 100 nm bandpass centered at 633 nm. Both mirrors are acceptable after compensation. The frequency folding effect can be perfectly compensated by the Michelson configuration and is not present in the Visible Nuller.

Shaklan, Green and Palacios, "TPFC Optical Surface Requirements", SPIE 626511-12, 2006.
Shaklan & Green, "Reflectivity and optical surface height requirements in a coronagraph", Applied Optics, 2006

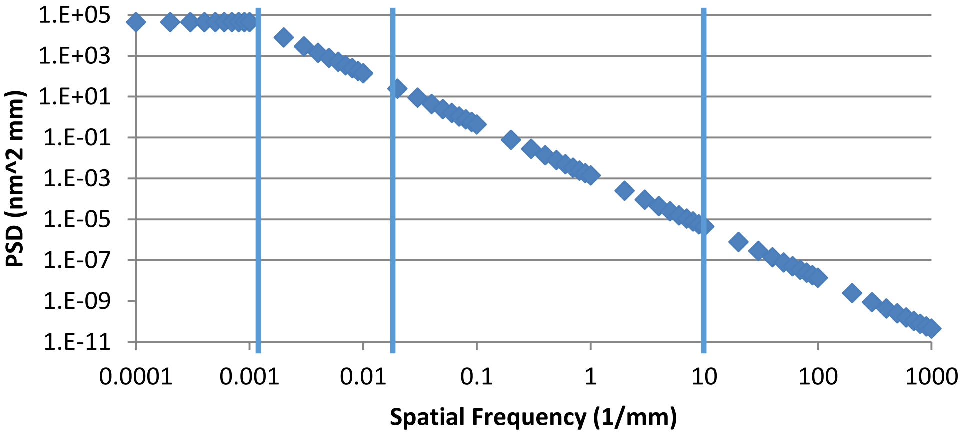
PM Manufacturing Specification

Define band-limited or spatial frequency specifications

Figure/Low	(1 to SF1 cycles/aperture)
Mid Spatial	(SF1 to SF2 cycles/aperture)
High Spatial	(SF2 cycles/aperture to 10 mm)
Roughness	(10 mm to < 1 micrometer)

Assume that Figure/Low Frequency Error is Constant

Key questions is how to define SF1 and SF2



Also, what is proper PSD Slope

Low/Mid Spatial Frequency Specification

To best of my knowledge, there is no precise definition for the boundary between Figure/Low and Mid-Spatial Frequency.

Have seen values ranging from 4 cycles to 10 cycle.

Many assert that Zernike Polynomial Set defines Figure/Low

Harvey defines Figure/Low errors as removing energy from core without changing shape of core, and Mid errors as changing the shape of the core:

We choose 4 cycles

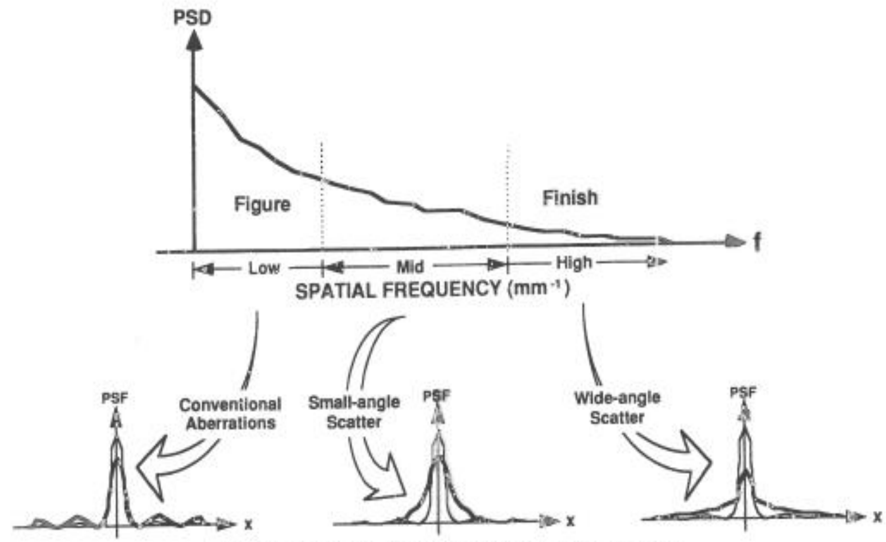


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

Harvey, Lewotsky and Kotha, "Effects of surface scatter on the optical performance of x-ray synchrotron beam-line mirrors", Applied Optics, Vol. 34, No. 16, pp.3024, 1995.

Mid/High Spatial Frequency Specification

Exo-Planet Science requires a Deformable Mirror to correct wavefront errors and create a ‘Dark Hole’ for the coronagraph.

A 64 x 64 DM can theoretically correct spatial frequencies up to 32 cycles per diameter to create the ‘dark hole’ but in practice, the limit is approx 20 cycles per diameter.

3X aliasing can cause spatial frequency errors to put energy into the ‘dark hole’; need smooth WFE up to 60 cycles/diameter.

Higher spatial frequencies scatter energy outside of ‘dark hole’.

We will use 60 cycles as the Mid/High boundary.

HabEx is planning to use 96 x 96 DM (or larger) to get as large of an OWA as possible. Thus, PM must be smooth to maybe 100 cycles per diameter.

Intuition Cross-Check

JWST WFE Stability spec < 13 nm rms

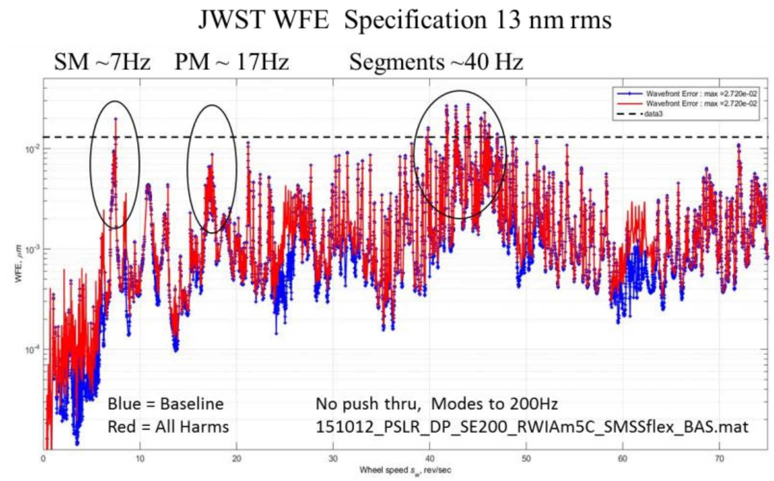
Because of dampening, a warm JWST may have WFE < 2 nm rms.

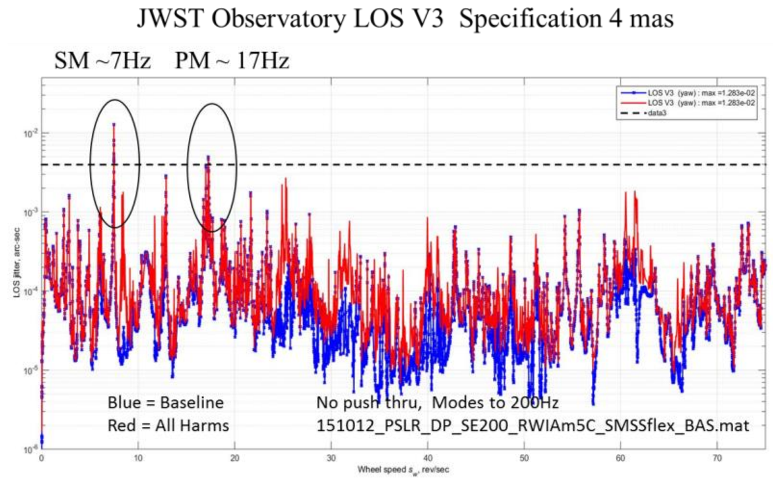
HabEx Design SM Tower is ~28 Hz or ~4X higher frequency and ~16X lower amplitude than JWST.

Mass dampening gives 2X reduction.

Total SM WFE ~ 25 pm rms (coma)

JWST PM is 17 Hz, HabEx PM is 120 Hz (Zerodur) to 180 Hz (ULE) or 7X to 10X higher frequency and 50X to 100X lower amplitude.





Feinberg, et. al., “A Cost-effective and Serviceable ATLAST 9.2m Telescope Architecture”, *Proc. SPIE*. 9143. (August 02, 2014) doi: 10.1117/12.2054915