HabEx Error Budget Definition and STOP Modeling

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Executive Summary

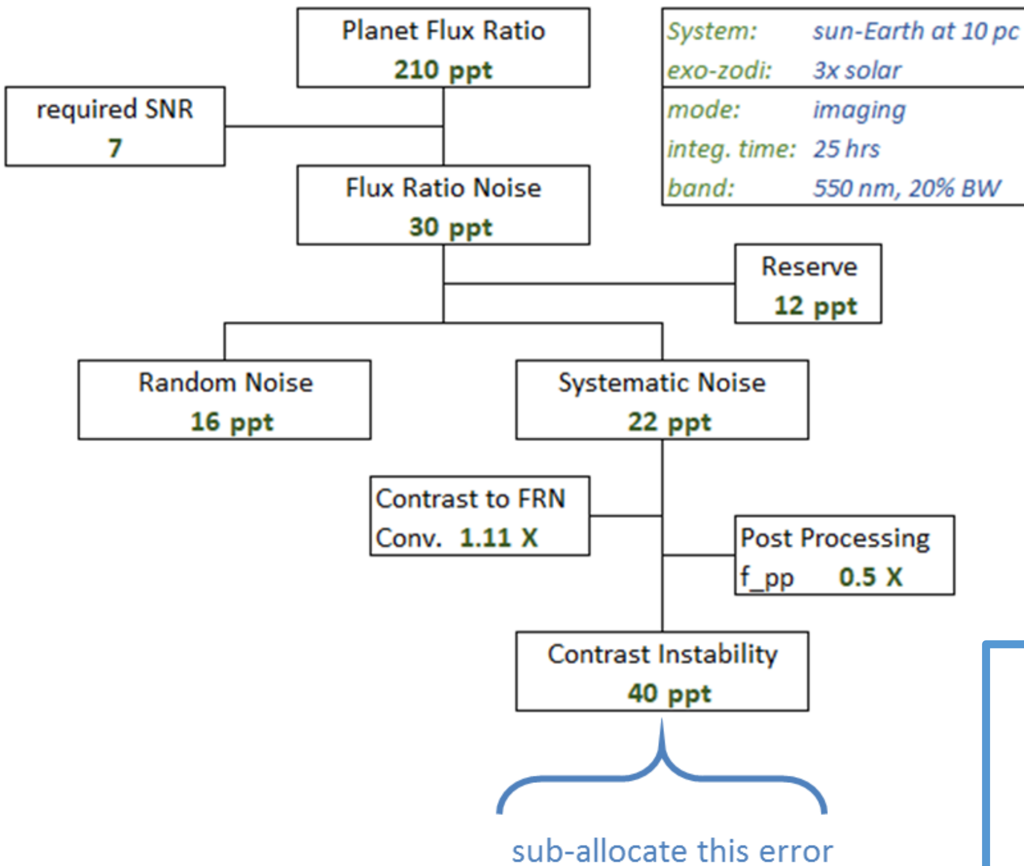
HabEx Baseline Architecture-A Optical Telescope Design Closes

The HabEx Optical Telescope Assembly (OTA) design team is using Science Driven Systems Engineering.

Because HabEx Science Performance depends on the spatial frequency content of the Wavefront Error Stability, a Zernike Polynomial Error Budget has been established and is used to define OTA engineering specification.

WFE Stability Error Budget

Starting with allowable Starlight Leakage through Coronagraph, derive tolerances for 48 (X,Y) Zernikes or 27 (R,θ) Zernikes.



allocation tolerance

$$\epsilon_i = \left(\frac{\partial \epsilon}{\partial x_i}\right) \cdot \delta x_i$$

sensitivity

WFE Stability Error Budget

Derive Tolerance for Zernike polynomials

- Sensitivities per Zernike are Fixed by Coronagraph
- Allocation Adjusted to ‘balance’ errors

$$\epsilon_i = \left(\frac{\partial \epsilon}{\partial x_i}\right) \cdot \delta x_i$$

allocation (ϵ_i), sensitivity ($\frac{\partial \epsilon}{\partial x_i}$), tolerance ($\delta x_i$)

Order				VVC-4 Sensitivity	40 ppt Allocation	VVC-4 Tolerance	PV to RMS	VVC-4 Tolerance
K	N	M	Aberration	[ppt/pm]	[ppt]	[pm PV]		[pm rms]
			TOTAL RMS		40.02	3062.6		1628.4
1	1	1	Tilt	1.96E-04	0.47	2385.6	2.00	1192.8
2	2	0	Power (Defocus)	2.44E-04	0.47	1920.1	1.73	1108.6
3	2	2	Pri Astigmatism	0.730	6.84	9.4	2.45	3.8
4	3	1	Pri Coma	0.789	7.38	9.4	2.83	3.3
5	3	3	Pri Trefoil	0.539	5.04	9.4	2.83	3.3
6	4	0	Pri Spherical	1.291	8.89	6.9	2.24	3.1
7	4	2	Sec Astigmatism	0.506	4.94	9.7	3.16	3.1
8	4	4	Pri Tetrafoil	0.527	4.94	9.4	3.16	3.0
9	5	1	Sec Coma	0.774	7.25	9.4	3.46	2.7
10	5	3	Sec Trefoil	0.547	5.12	9.4	3.46	2.7
11	5	5	Pri Pentafoil	0.680	6.37	9.4	3.46	2.7
12	6	0	Sec Spherical	1.244	8.89	7.1	2.65	2.7
13	6	2	Ter Astigmatism	1.151	8.89	7.7	3.74	2.1
14	6	4	Sec Tetrafoil	0.863	8.10	9.4	3.74	2.5
15	6	6	Pri Hexafoil	0.795	7.44	9.4	3.74	2.5
16	7	1	Ter Coma	1.577	8.89	5.6	4.00	1.4
17	7	3	Ter Trefoil	1.353	8.89	6.6	4.00	1.6
18	7	5	Sec Pentafoil	1.393	8.89	6.4	4.00	1.6
19	7	7	Pri Septafoil	1.246	8.89	7.1	4.00	1.8
20	8	0	Ter Spherical	4.338	8.89	2.0	3.00	0.7
21	8	2	Qua Astigmatism	2.078	8.89	4.3	4.24	1.0
22	8	4	Ter Tetrafoil	1.723	8.89	5.2	4.24	1.2
23	8	6	Sec Hexafoil	1.461	8.89	6.1	4.24	1.4
24	8	8	Pri Octafoil	1.533	8.89	5.8	4.24	1.4
25	9	1	Qua Coma	2.182	8.89	4.1	4.47	0.9
26	10	0	Qua Spherical	2.344	8.89	3.8	3.32	1.1
27	12	0	Qin Spherical	1.263	8.89	7.0	3.61	2.0

VVC-4 is insensitive to Tip/Tilt and Power

Sub-Allocation of Error Budget

Each Zernike term is sub-allocated to LOS, Inertial & Thermal

			RSS Allocation	100%	50%	70%	50%	10%
Order				VVC-4 Tolerance	LOS	Inertial	Thermal	Reserve
K	N	M	Aberration	[pm rms]	[pm rms]	[pm rms]	[pm rms]	[pm rms]
			TOTAL RMS	1628.4	814	1140	814	163
1	1	1	Tilt	1192.8	596.40	834.95	596.40	119.28
2	2	0	Power (Defocus)	1108.6	554.29	776.00	554.29	110.86
3	2	2	Pri Astigmatism	3.8	1.91	2.67	1.91	0.38
4	3	1	Pri Coma	3.3	1.65	2.32	1.65	0.33
5	3	3	Pri Trefoil	3.3	1.65	2.32	1.65	0.33
6	4	0	Pri Spherical	3.1	1.54	2.16	1.54	0.31
7	4	2	Sec Astigmatism	3.1	1.54	2.16	1.54	0.31
8	4	4	Pri Tetrafoil	3.0	1.48	2.07	1.48	0.30
9	5	1	Sec Coma	2.7	1.35	1.89	1.35	0.27
10	5	3	Sec Trefoil	2.7	1.35	1.89	1.35	0.27
11	5	5	Pri Pentafoil	2.7	1.35	1.89	1.35	0.27
12	6	0	Sec Spherical	2.7	1.35	1.89	1.35	0.27
13	6	2	Ter Astigmatism	2.1	1.03	1.45	1.03	0.21
14	6	4	Sec Tetrafoil	2.5	1.25	1.76	1.25	0.25
15	6	6	Pri Hexafoil	2.5	1.25	1.75	1.25	0.25
16	7	1	Ter Coma	1.4	0.70	0.99	0.70	0.14
17	7	3	Ter Trefoil	1.6	0.82	1.15	0.82	0.16
18	7	5	Sec Pentafoil	1.6	0.80	1.12	0.80	0.16
19	7	7	Pri Septafoil	1.8	0.89	1.25	0.89	0.18
20	8	0	Ter Spherical	0.7	0.34	0.48	0.34	0.07
21	8	2	Qua Astigmatism	1.0	0.50	0.71	0.50	0.10
22	8	4	Ter Tetrafoil	1.2	0.61	0.85	0.61	0.12
23	8	6	Sec Hexafoil	1.4	0.72	1.00	0.72	0.14
24	8	8	Pri Octafoil	1.4	0.68	0.96	0.68	0.14
25	9	1	Qua Coma	0.9	0.46	0.64	0.46	0.09
26	10	0	Qua Spherical	1.1	0.57	0.80	0.57	0.11
27	12	0	Qin Spherical	2.0	0.98	1.37	0.98	0.20

Line of Sight Tolerance

LOS Jitter causes beam-shear WFE and PSF smear.

LOS Jitter is residual error after active correction. It is assumed that laser-truss or low-order wavefront-sensor (LOWFS) systems can sense and correct LOS drift/vibration at frequencies below 10 Hz.

LOS Stability = Rigid Body Tolerances

System LOS Jitter Specification is < 0.7 mas (56 mas at FSM)

Using Zemax alignment sensitivity analysis, optical component rigid body motion allocation that meets LOS Spec.

Specification				56.00	mas
				ALLOCATION (one sided PV)	
Alignment	ZEMAX	Tolerance	units	RSS	Units
PM X-Decenter	DX	**10**	nanometer	17.20	mas
PM Y-Decenter	DY	**10**	nanometer	16.70	mas
PM Z-Despace	DZ	10	nanometer	4.30	mas
PM Y-Tilt	TX	0.5	nano-radian	17.32	mas
PM X-Tilt	TY	0.5	nano-radian	17.05	mas
PM Z-Rotation	TZ	0.5	nano-radian	2.15	mas
SM X-Decenter	DX	20	nanometer	30.60	mas
SM Y-Decenter	DY	20	nanometer	29.60	mas
SM Z-Despace	DZ	20	nanometer	8.60	mas
SM Y-Tilt	TX	1	nano-radian	3.05	mas
SM X-Tilt	TY	1	nano-radian	3.00	mas
SM Z-Rotation	TZ	1	nano-radian	0.33	mas
TM X-Decenter	DX	10	nanometer	1.90	mas
TM Y-Decenter	DY	10	nanometer	1.90	mas
TM Z-Despace	DZ	1000	nanometer	0.00	mas
TM Y-Tilt	TX	10	nano-radian	4.17	mas
TM X-Tilt	TY	10	nano-radian	4.17	mas
TM Z-Rotation	TZ	1000	nano-radian	0.74	mas
RSS LOS Error				56.00	mas

WFE Stability LOS Error

Rigid body motion also causes WFE due to wavefront shear.

WFE produced by rigid body motions that meet LOS Jitter Spec do not meet the WFE Stability Tolerance for VVC4.

Order				Allocation LOS		LOS
K	N	M	Aberration	[pm rms]	MARGIN	RSS WFE (pm rms)
			TOTAL RMS	814	5.41	150.5078
1	1	1	Tilt	596.40	27.91	21.3665
2	2	0	Power (Defocus)	554.29	3.82	145.1984
3	2	2	Pri Astigmatism	1.91	0.06	32.5080
4	3	1	Pri Coma	1.65	0.22	7.5136
5	3	3	Pri Trefoil	1.65	4.72	0.3505
6	4	0	Pri Spherical	1.54	4.08	0.3775
7	4	2	Sec Astigmatism	1.54	11.37	0.1355
8	4	4	Pri Tetrafoil	1.48	365.93	0.0040
9	5	1	Sec Coma	1.35	60.79	0.0222
10	5	3	Sec Trefoil	1.35	735.26	0.0018
11	5	5	Pri Pentafoil	1.35	27556.76	0.0000
12	6	0	Sec Spherical	1.35	1359.22	0.0010
13	6	2	Ter Astigmatism	1.03	2140.91	0.0005
14	6	4	Sec Tetrafoil	1.25	28299.58	0.0000
15	6	6	Pri Hexafoil	1.25	88310.79	0.0000
16	7	1	Ter Coma	0.70	11880.47	0.0001
17	7	3	Ter Trefoil	0.82	23453.55	0.0000
18	7	5	Sec Pentafoil	0.80	53809.89	0.0000
19	7	7	Pri Septafoil	0.89	52529.41	0.0000
20	8	0	Ter Spherical	0.34	28407.55	0.0000
21	8	2	Qua Astigmatism	0.50		
22	8	4	Ter Tetrafoil	0.61		
23	8	6	Sec Hexafoil	0.72		
24	8	8	Pri Octafoil	0.68		
25	9	1	Qua Coma	0.46		
26	10	0	Qua Spherical	0.57		
27	12	0	Qin Spherical	0.98		

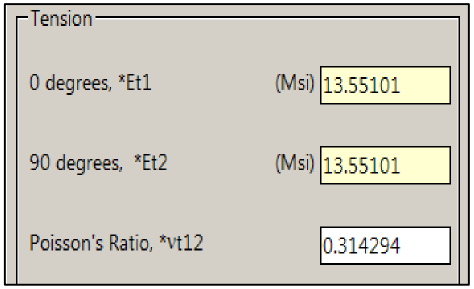
But, non-compliance is only Astig & Coma.

LOS Jitter Spec may meet VVC6 Tolerance.

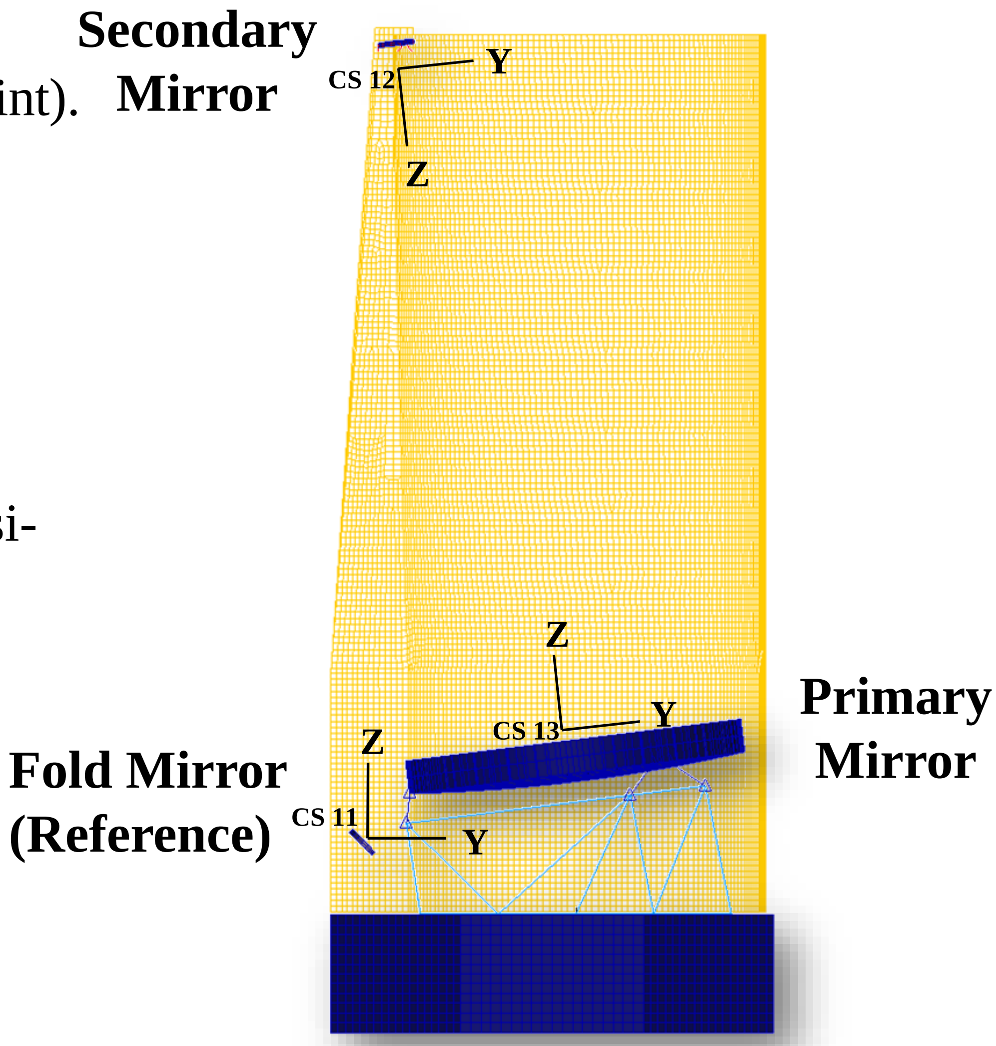
What is actual predicted LOS Performance for Micro-Thrusters?

Calculating Predicted PM/SM Rigid Body Motion

- 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)

Micro-Thruster Disturbance

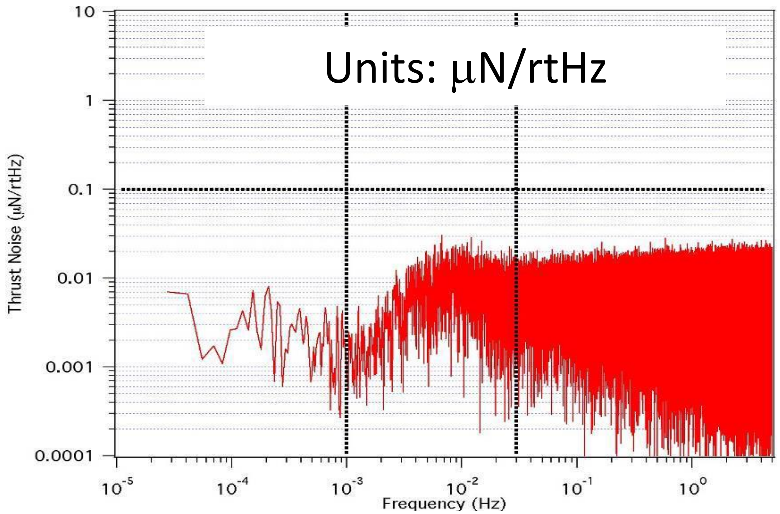
Micro-thruster noise excites modes in primary mirror & telescope

Spacecraft has 4 forward thruster pods' and 4 aft pods.

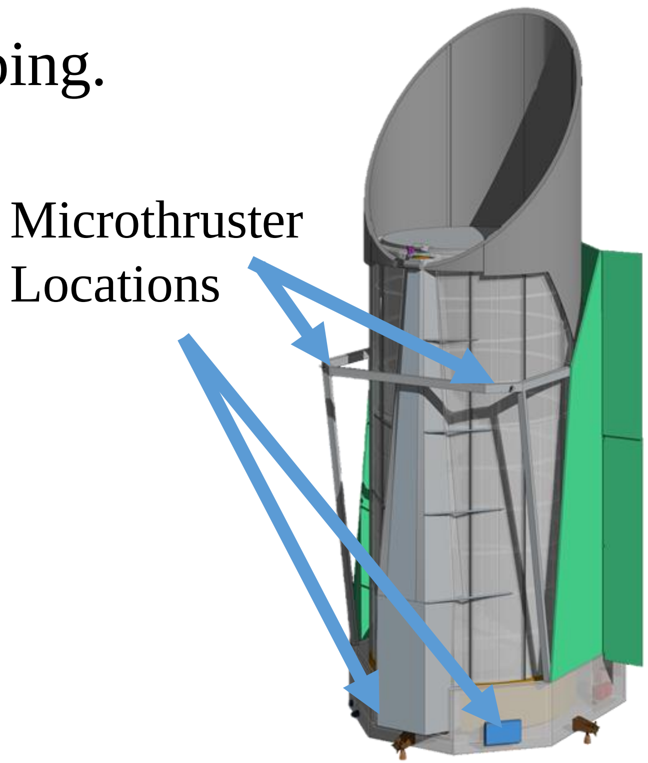
Forward pods have 4 thruster-heads. Aft pods have 8 heads.

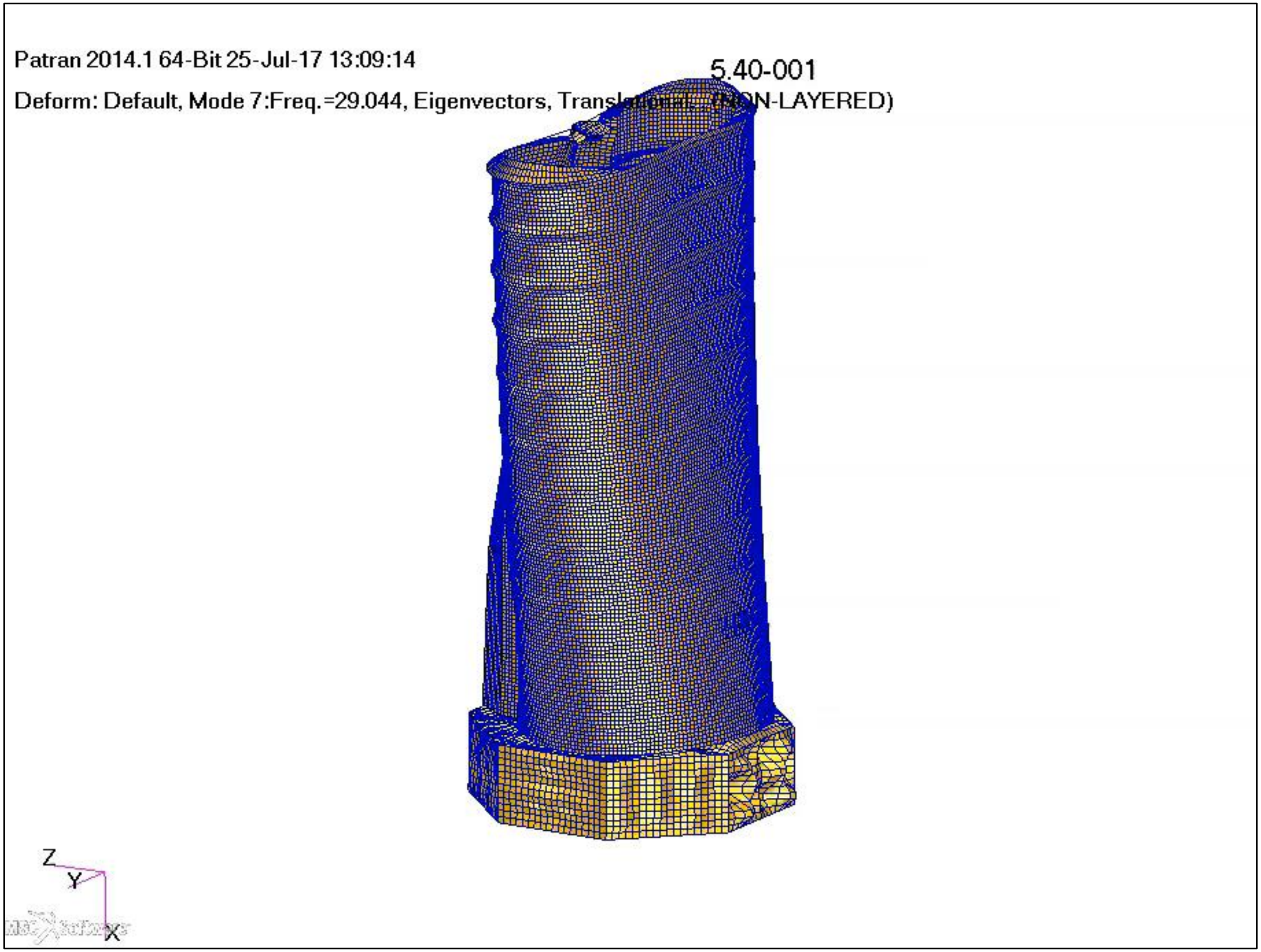
Analysis assumes that each head has a flat 0.1 micro-Newton noise spectrum.

Analysis assumes 0.0005% critical damping.



Thruster noise PSD plot for colloidal microthrusters. Max noise above 10^{-3} is likely due to thrust-balance sensor noise limits. (ref: *"Colloid Micro-Newton Thrusters For Precision Attitude Control", John Ziemer, et. al, April 2017, CL#17-2067)*

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5.40-001
Z
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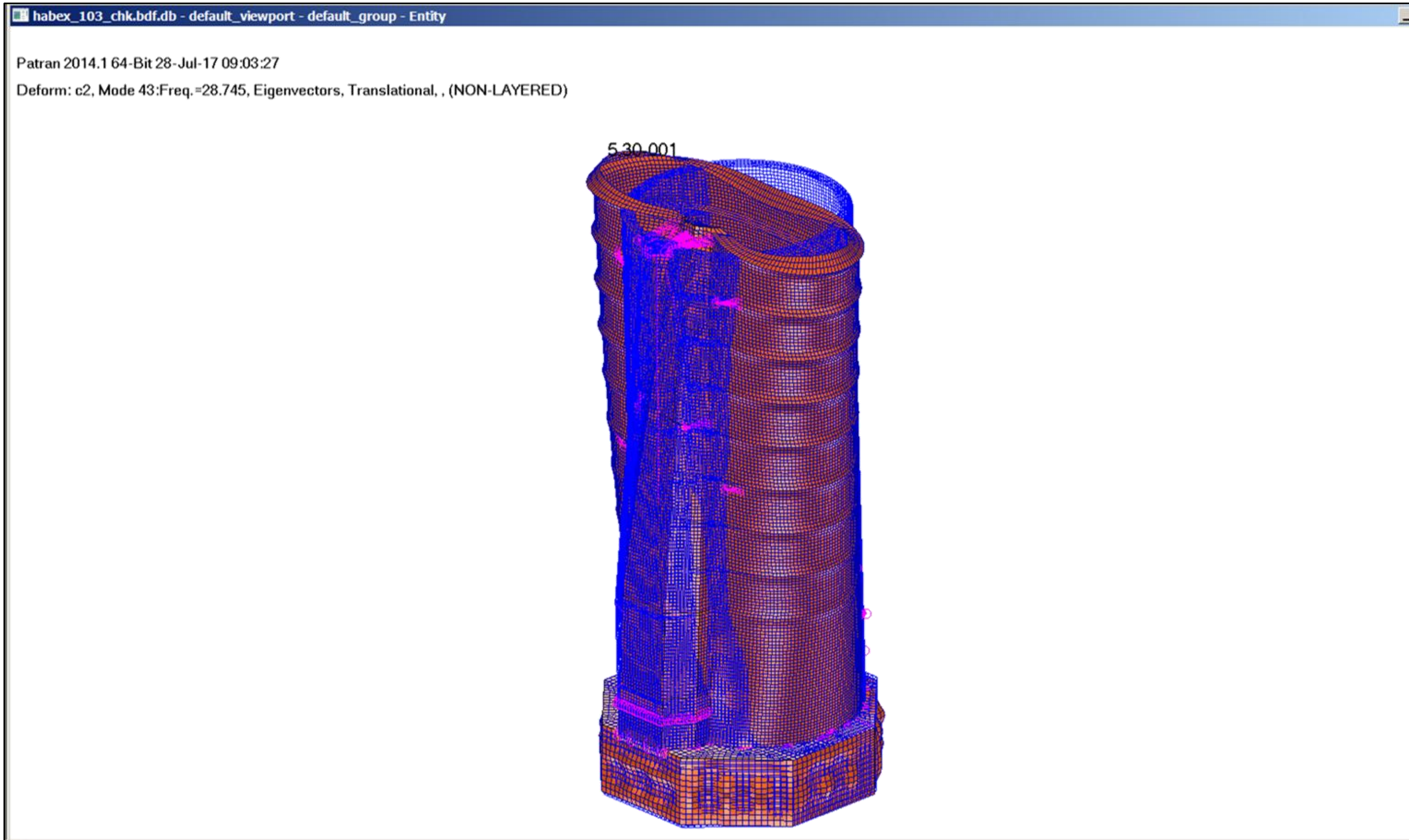

First Tube Mode

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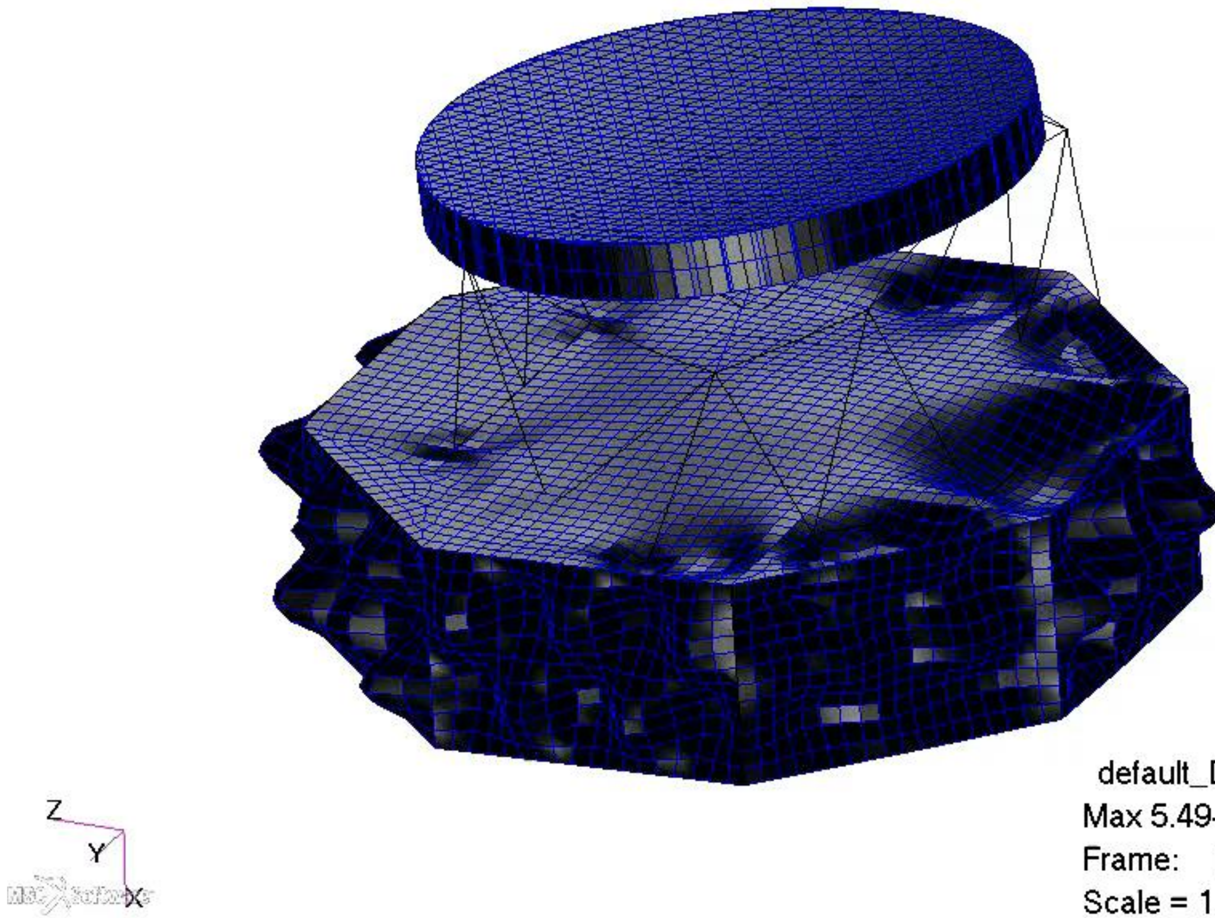

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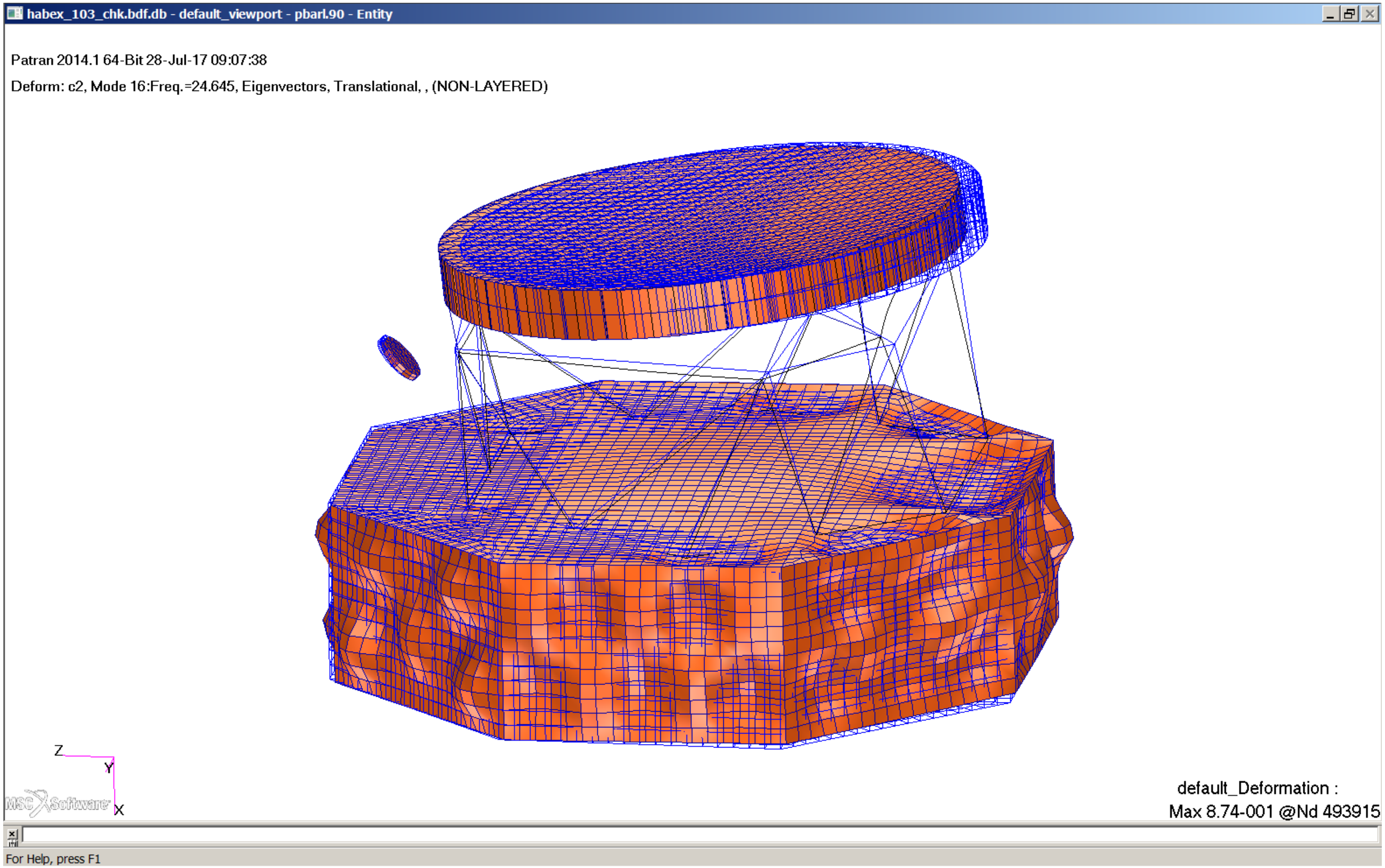
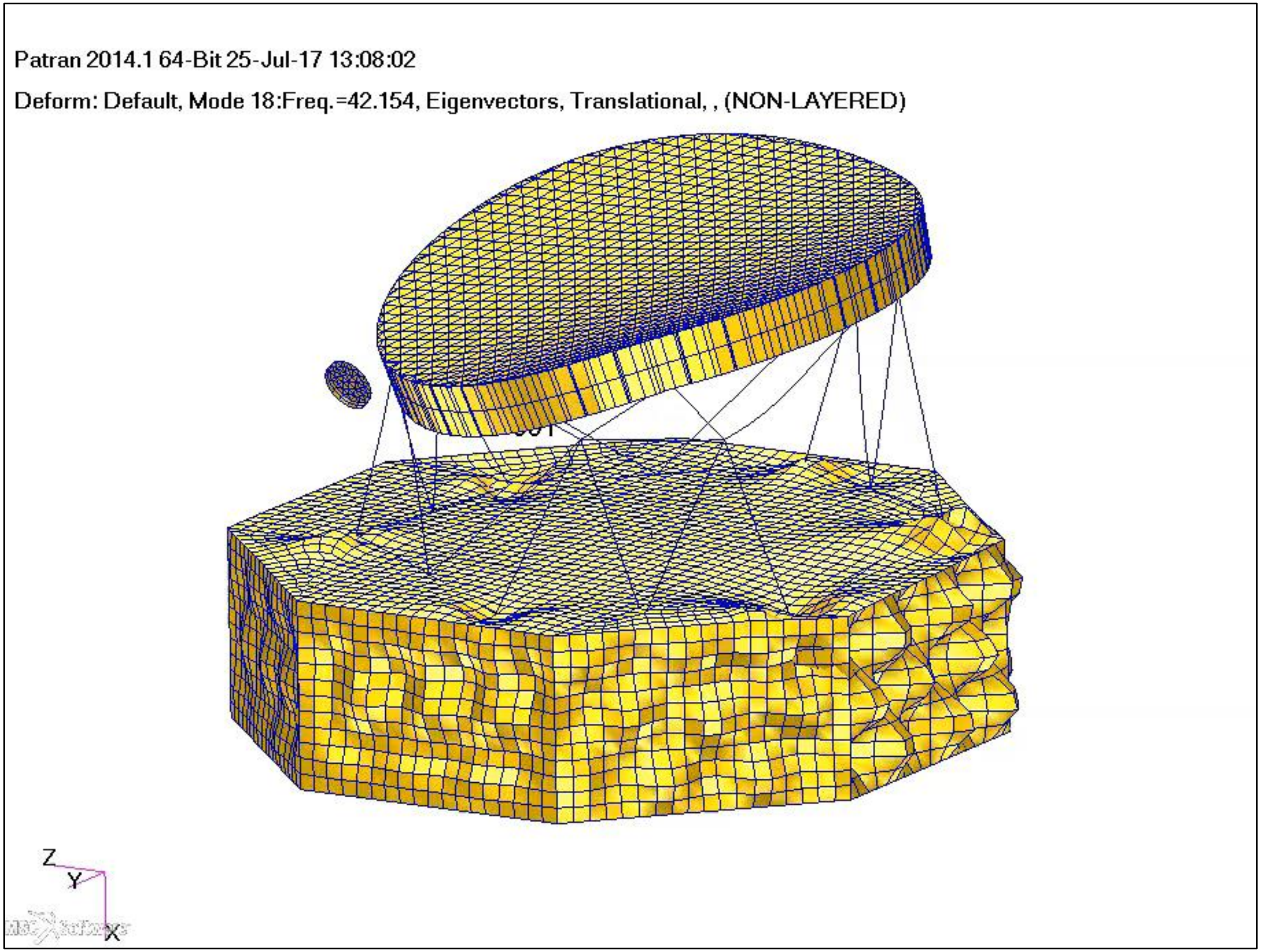


First Mirror Mode



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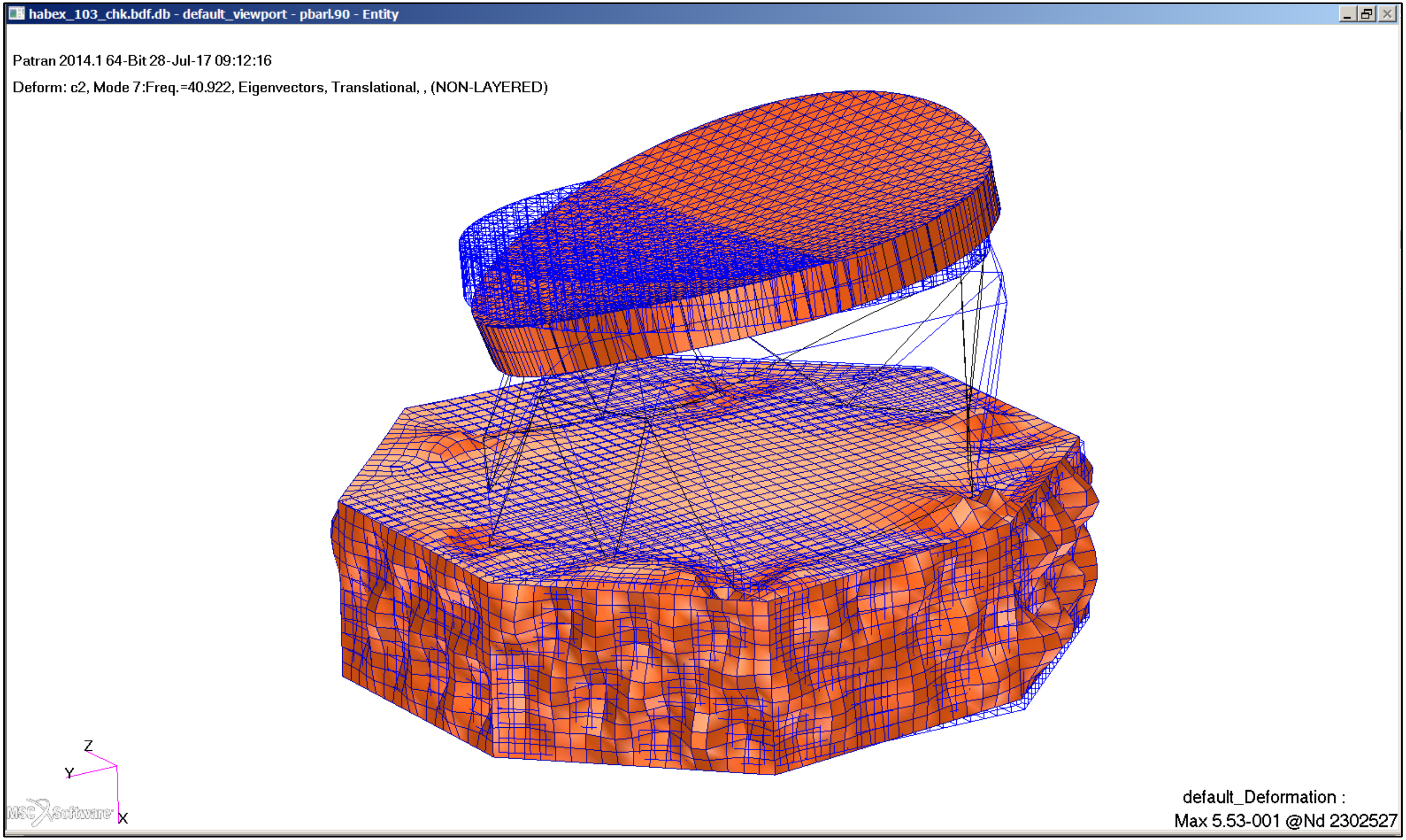
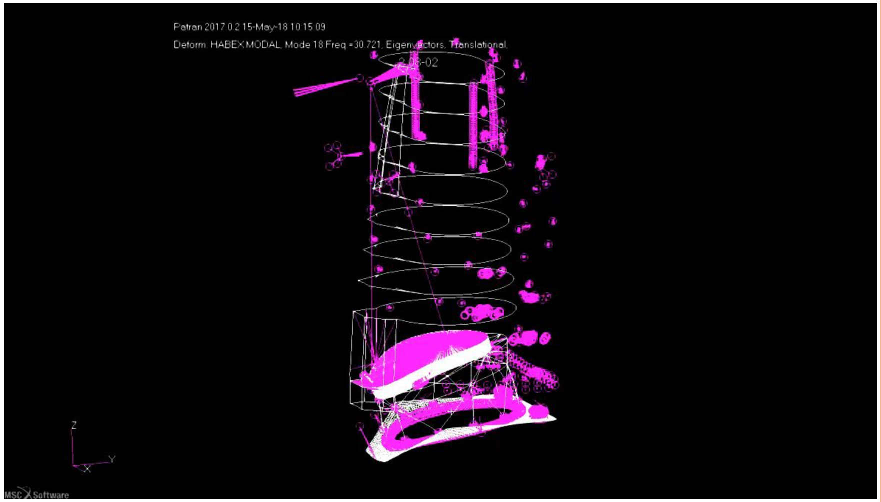
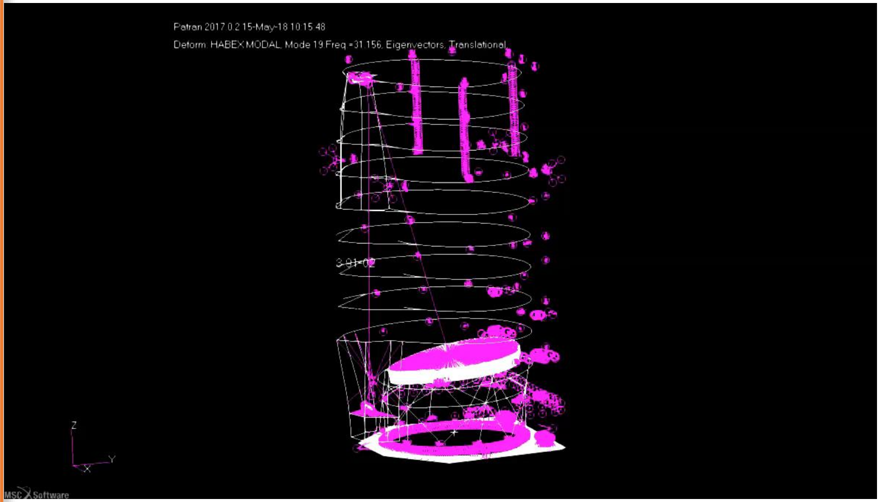
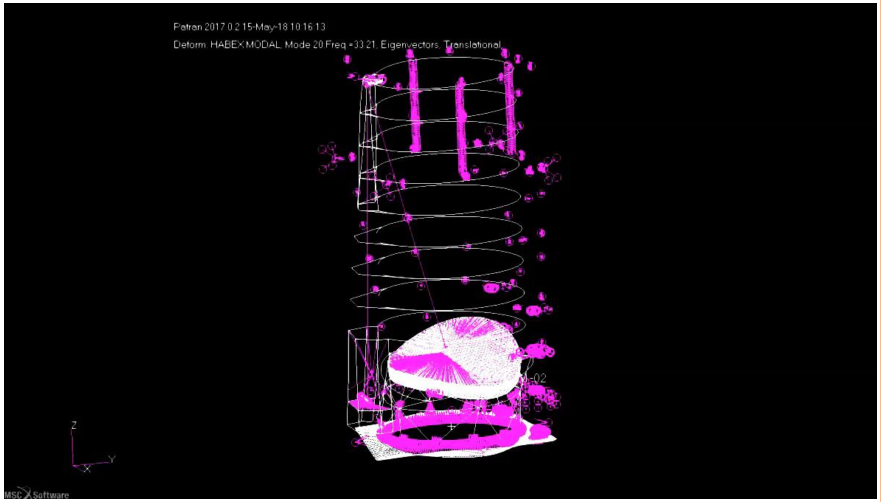


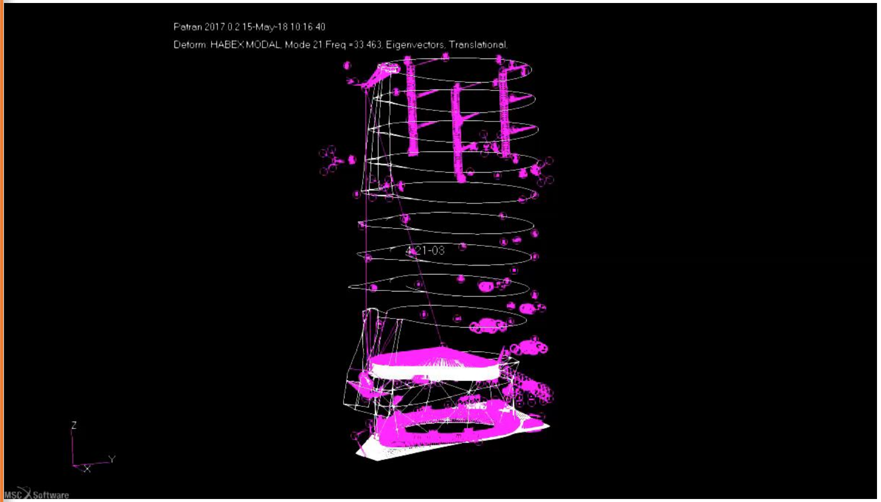
Second Mirror Mode

Structure Modes



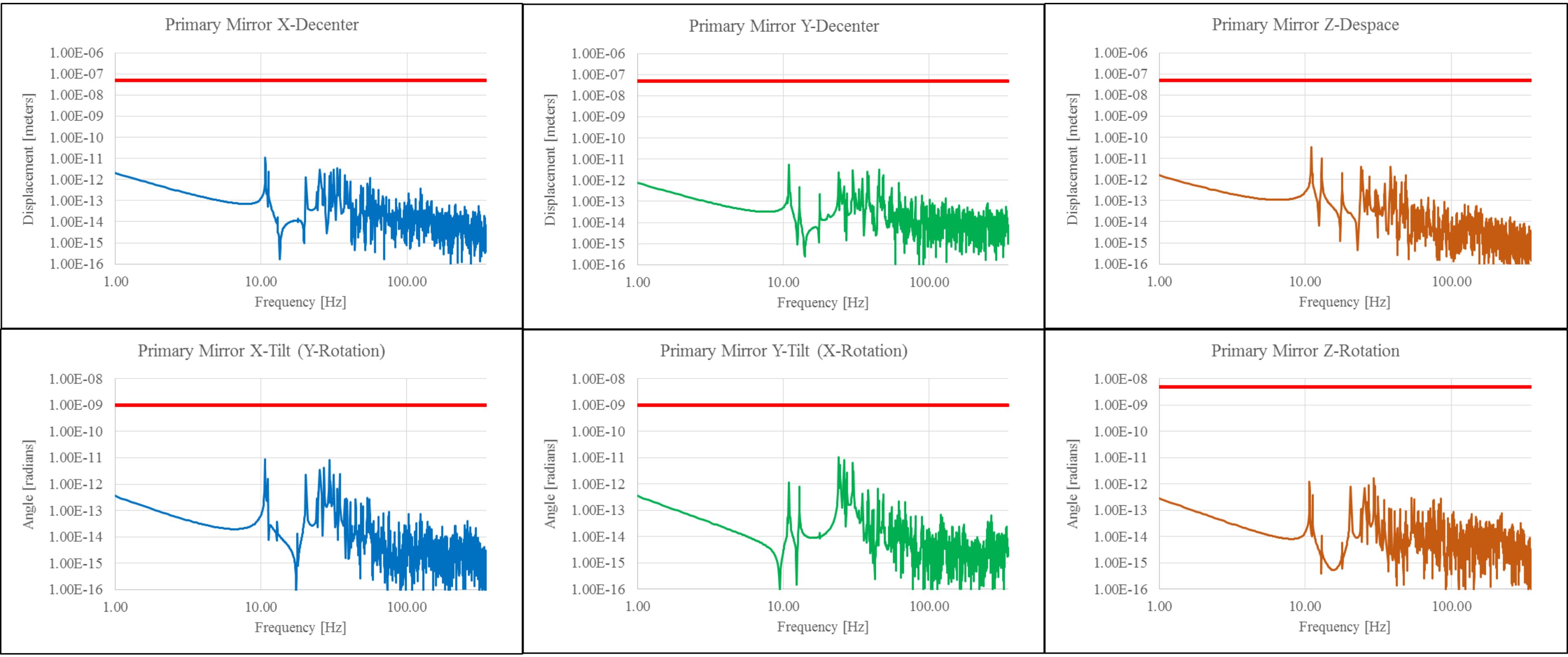






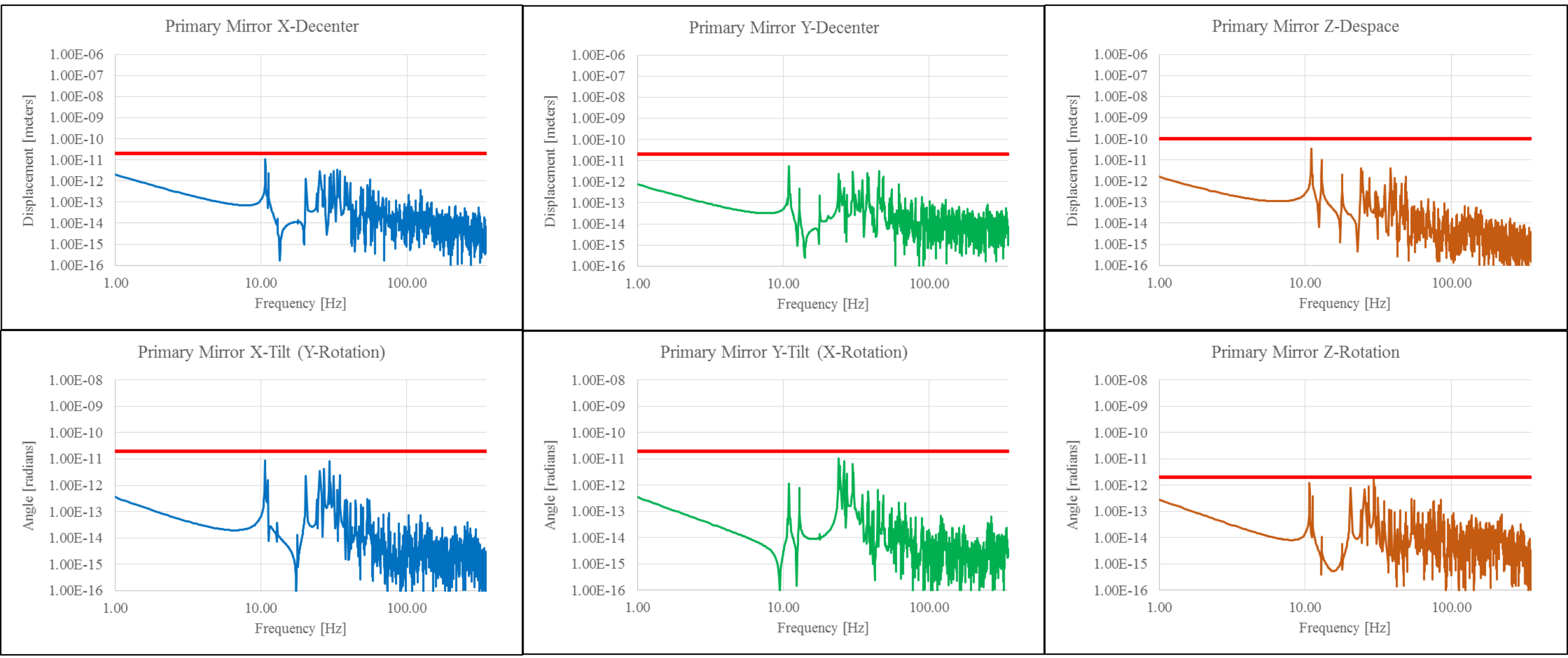
Predicted Primary Mirror Motion

Predicted primary mirror rigid body motion (with 4X MUF) caused by the micro-thruster noise is several orders of magnitude below the tolerance that meets the LOS Jitter Specification.



Predicted Primary Mirror Motion

Thus allowing significantly tighter rigid-body motion tolerances.



New LOS Jitter Prediction

Micro-thruster OTA has predicted on-sky LOS Jitter of 0.018 mas and WFE Stability with 2.5X Astig margin for VVC4.

LOS RSS Error			Specification	56.00	mas
				ALLOCATION (one sided P	
Alignment	ZEMAX	Tolerance	units	RSS	Units
PM X-Decenter	DX	0.02	nanometer	0.03	mas
PM Y-Decenter	DY	0.02	nanometer	0.03	mas
PM Z-Despace	DZ	0.10	nanometer	0.04	mas
PM Y-Tilt	TX	0.02	nano-radian	0.69	mas
PM X-Tilt	TY	0.02	nano-radian	0.68	mas
PM Z-Rotation	TZ	0.002	nano-radian	0.01	mas
SM X-Decenter	DX	0.50	nanometer	0.77	mas
SM Y-Decenter	DY	0.50	nanometer	0.74	mas
SM Z-Despace	DZ	0.01	nanometer	0.00	mas
SM Y-Tilt	TX	0.02	nano-radian	0.06	mas
SM X-Tilt	TY	0.02	nano-radian	0.06	mas
SM Z-Rotation	TZ	0.20	nano-radian	0.07	mas
TM X-Decenter	DX	0.10	nanometer	0.02	mas
TM Y-Decenter	DY	0.10	nanometer	0.02	mas
TM Z-Despace	DZ	0.10	nanometer	0.00	mas
TM Y-Tilt	TX	0.01	nano-radian	0.00	mas
TM X-Tilt	TY	0.01	nano-radian	0.00	mas
TM Z-Rotation	TZ	0.01	nano-radian	0.00	mas
RSS LOS Error				1.45	mas

Order				Allocation LOS			LOS RSS WFE
K	N	M	Aberration	[pm rms]		MARGIN	(pm rms)
			TOTAL RMS	814		640.98	1.2703
1	1	1	Tilt	596.40		1251.51	0.4765
2	2	0	Power (Defocus)	554.29		623.99	0.8883
3	2	2	Pri Astigmatism	1.91		2.53	0.7545
4	3	1	Pri Coma	1.65		9.87	0.1676
5	3	3	Pri Trefoil	1.65		203.32	0.0081
6	4	0	Pri Spherical	1.54		458.99	0.0034
7	4	2	Sec Astigmatism	1.54		497.39	0.0031
8	4	4	Pri Tetrafoil	1.48		15756.44	0.0001
9	5	1	Sec Coma	1.35		2872.33	0.0005
10	5	3	Sec Trefoil	1.35		31963.42	0.0000
11	5	5	Pri Pentafoil	1.35		1251062.38	0.0000
12	6	0	Sec Spherical	1.35		121850.21	0.0000
13	6	2	Ter Astigmatism	1.03		95757.25	0.0000
14	6	4	Sec Tetrafoil	1.25		2352446.64	0.0000
15	6	6	Pri Hexafoil	1.25		20917403.44	0.0000
16	7	1	Ter Coma	0.70		625089.60	0.0000
17	7	3	Ter Trefoil	0.82		3719658.50	0.0000
18	7	5	Sec Pentafoil	0.80		17228267.14	0.0000
19	7	7	Pri Septafoil	0.89		18000287.24	0.0000
20	8	0	Ter Spherical	0.34		8063896.81	0.0000
21	8	2	Qua Astigmatism	0.50			
22	8	4	Ter Tetrafoil	0.61			
23	8	6	Sec Hexafoil	0.72			
24	8	8	Pri Octafoil	0.68			
25	9	1	Qua Coma	0.46			
26	10	0	Qua Spherical	0.57			
27	12	0	Qin Spherical	0.98			

Inertial WFE Stability

Inertial WFE Stability is bending of the mirror as it reacts against its mount when exposed to a noise acceleration.

Primary Mirror Inertial WFE

Inertial WFE is <u>not</u> a resonant mode. It is response to acceleration.

Inertial Error may be proportional to Gravity Sag.

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

To minimize Inertial WFE:

- Design the PM Substrate to be as stiff as possible. The stiffer the mirror the smaller the Gravity Sag.
- Consider the Mount stiffness and location.
- If Astigmatism 1G sag is 50 micrometers surface.
- And, if Coronagraph requires < 2 pm wavefront
- Then mirror acceleration must remain < 0.02 μG.

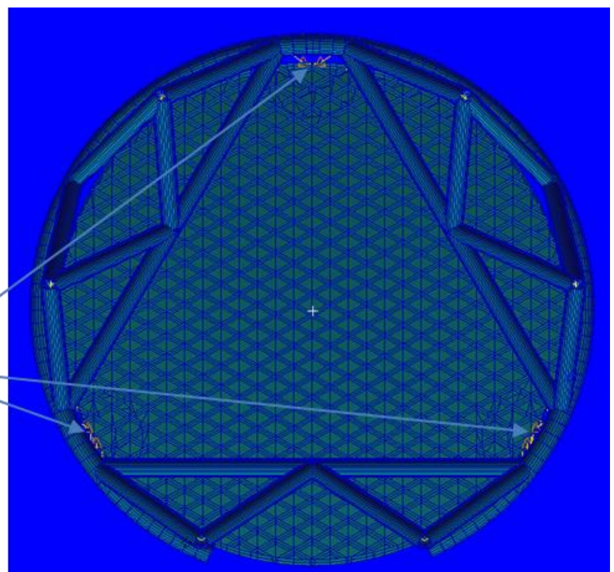
Predicted Acceleration at Primary Mirror

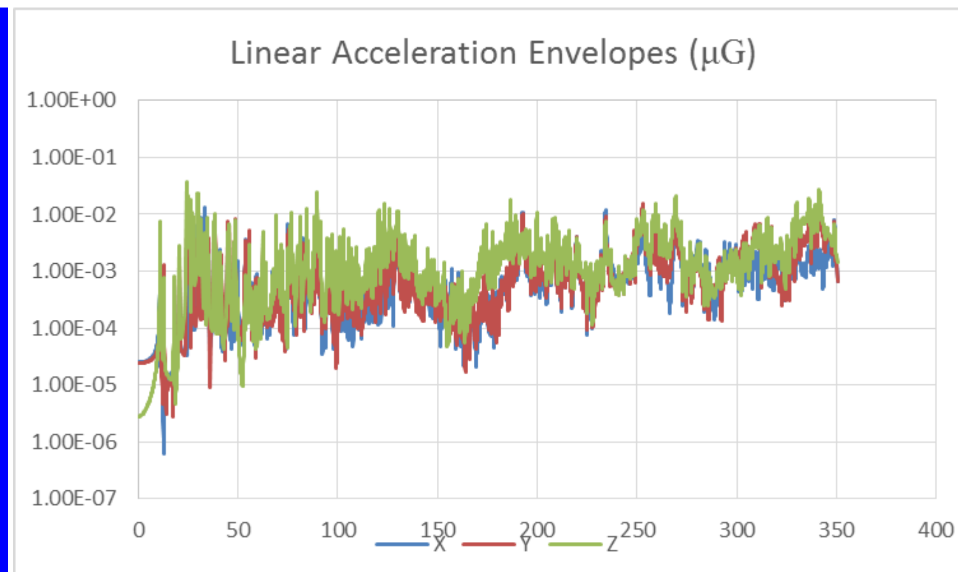
Micro-Thruster noise propagates through Spacecraft Structure, through Interface Ring to the OTA and through the PM Truss Structure to the 3 Primary Mirror Mount Interfaces.

Acceleration at PM Mount Interfaces:

	X	X	Z	RSS	
RMS	0.001	0.002	0.003	0.003	µG
MAX	0.013	0.016	0.037	0.037	µG

3 interfaces at 3 locations

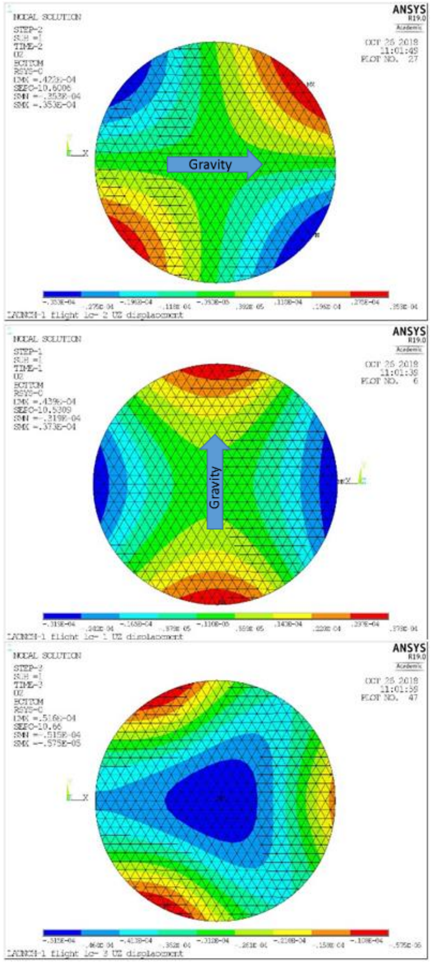




Primary Mirror Inertial Deformation

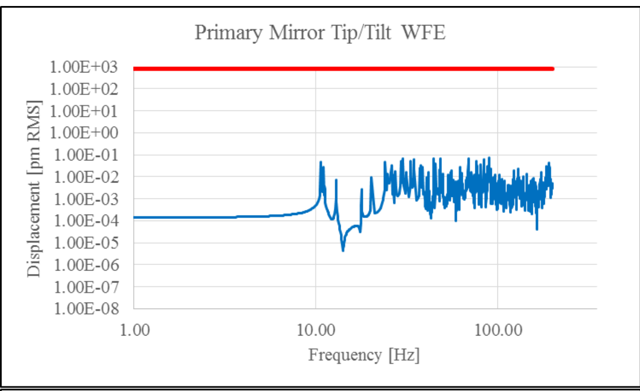
Primary Mirror has sufficient stiffness (86 Hz free-free) that its predicted Micro-Thruster noise gravity deflection has 2X Astigmatism margin for the VVC4.

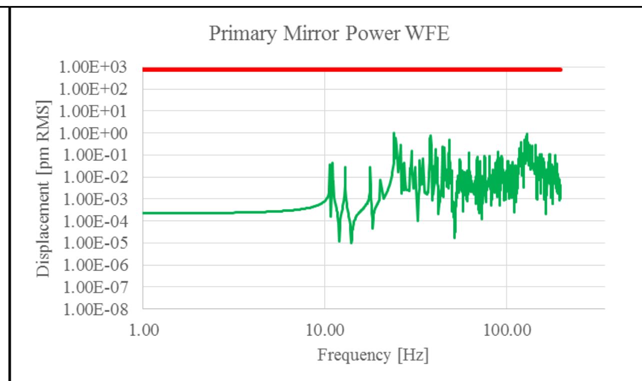
			Inertial WFE Stability					Scaled G-Sag Zernikes		
					Acceleration [µG]	0.024	µG	0.01	0.01	0.02
				Allocation		RSS-Zernikes		X-Zern	Y-Zern	Z-Zern
Order				Inertial	MARGIN	[pm rms]		[pm rms]	[pm rms]	[pm rms]
K	N	M	Aberration	[pm rms]						
			TOTAL RMS	1139.91		1.425		0.743	0.736	1.007
1	1	1	Tilt	834.95	5714.58	0.146		0.11	0.092	0.028
2	2	0	Power (Defocus)	776.00	1308.40	0.593		0.036	0	0.592
3	2	2	Pri Astigmatism	2.67	2.56	1.047		0.728	0.725	0.2
4	3	1	Pri Coma	2.32	162.98	0.014		0.003	0.007	0.012
5	3	3	Pri Trefoil	2.32	3.21	0.722		0.047	0.001	0.72
6	4	0	Pri Spherical	2.16	29.04	0.074		0.006	0	0.074
7	4	2	Sec Astigmatism	2.16	40.20	0.054		0.037	0.037	0.012
8	4	4	Pri Tetrafoil	2.07	23.15	0.090		0.062	0.062	0.018
9	5	1	Sec Coma	1.89	845.83	0.002		0	0.001	0.002
10	5	3	Sec Trefoil	1.89	16.55	0.114		0.008	0	0.114
11	5	5	Pri Pentafoil	1.89	34.78	0.054		0.037	0.038	0.012
12	6	0	Sec Spherical	1.89	472.62	0.004		0	0	0.004
13	6	2	Ter Astigmatism	1.45	417.34	0.003		0.002	0.002	0.002
14	6	4	Sec Tetrafoil	1.76	187.09	0.009		0.006	0.006	0.004
15	6	6	Pri Hexafoil	1.75	41.59	0.042		0.003	0	0.042
16	7	1	Ter Coma	0.99	493.29	0.002		0	0	0.002
17	7	3	Ter Trefoil	1.15	52.21	0.022		0.001	0	0.022
18	7	5	Sec Pentafoil	1.12	128.13	0.009		0.006	0.006	0.002
19	7	7	Pri Septafoil	1.25	61.85	0.020		0.014	0.014	0.004
20	8	0	Ter Spherical	0.48	5.83	0.082		0.002	0	0.082
21	8	2	Qua Astigmatism	0.71	352.98	0.002		0	0	0.002
22	8	4	Ter Tetrafoil	0.85		0.000		0	0	0
23	8	6	Sec Hexafoil	1.00	41.69	0.024		0.002	0	0.024
24	8	8	Pri Octafoil	0.96	109.75	0.009		0.006	0.006	0.002
25	9	1	Qua Coma	0.64		0.000		0	0	0
26	10	0	Qua Spherical	0.80	4.71	0.170		0.004	0	0.17
27	12	0	Qin Spherical	1.37	6.27	0.218		0.005	0	0.218

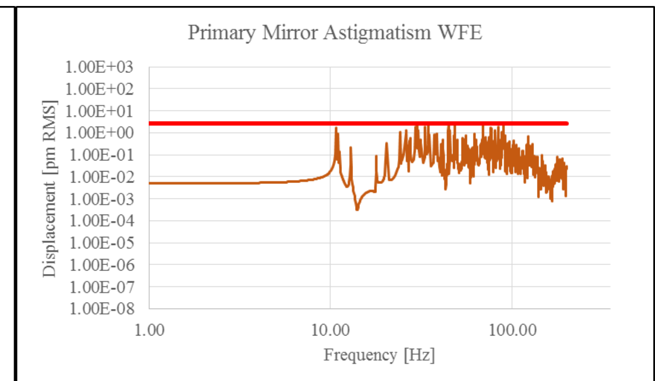


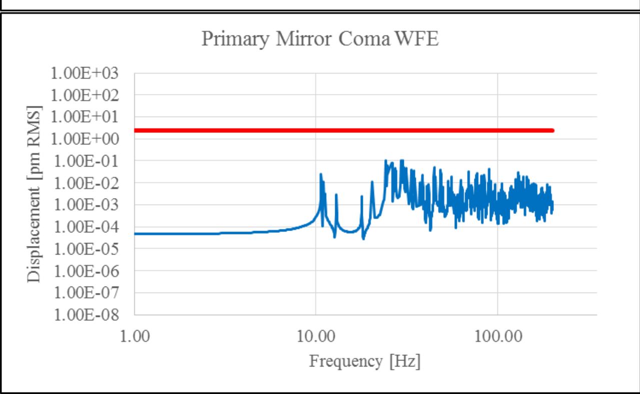
Predicted Primary Mirror Inertial Bending

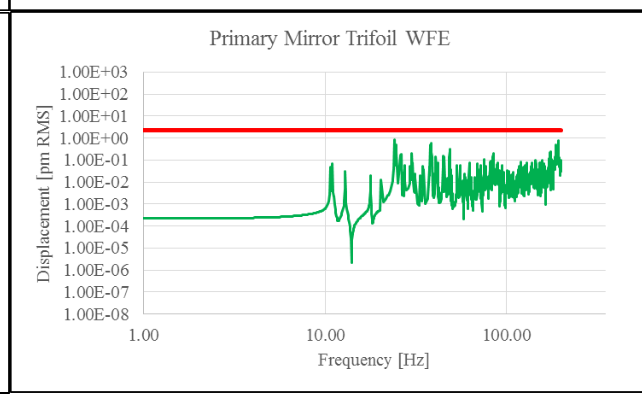
- SigFit and NASTRAN used to determine Zernike decomposition.
- Predicted primary mirror inertial bending (with 4X MUF) caused by the micro-thruster noise specification of 0.1 µN broad band is below the error budget tolerance (red line).
- Micro-thruster noise roll off at higher frequencies will reduce error.
- Tolerance for Astig, Coma & Spherical is higher for VVC6.

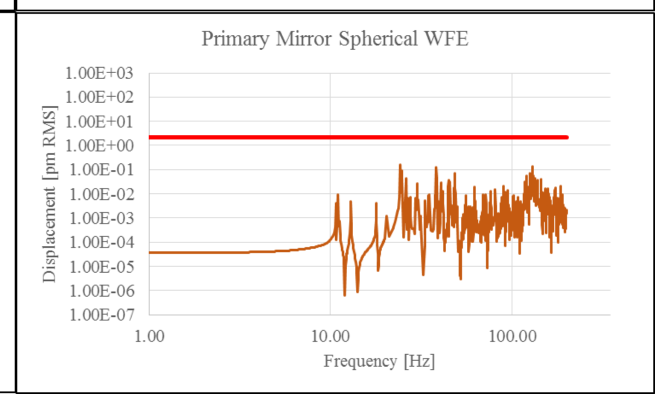












Inertial Deformation Cross Check

Inertial WFE was calculated by two methods:

- Linear Scaling of Gravity Sag
  - Scale from (1,1,1) G to (0.01, 0.01, 0.02) μG
- Dynamic Deformation Analysis vis SigFit and NASTRAN
  - Calculate RMS of Zernike term from 1 to 200 Hz and multiply by 4

Zernike Term	0.024 μG Scaled G-Sag	Dynamic Analysis
Tip/Tilt	0.156 pm rms	0.038 pm rms
Power	0.593 pm rms	0.465 pm rms
Astigmatism	1.047 pmrms	1.151 pm rms
Coma	0.014 pm rms	0.031 pm rms
Trefoil	0.772 pm rms	0.344 pm rms
Spherical	0.074 pm rms	0.069 pm rms

Thermal WFE Stability

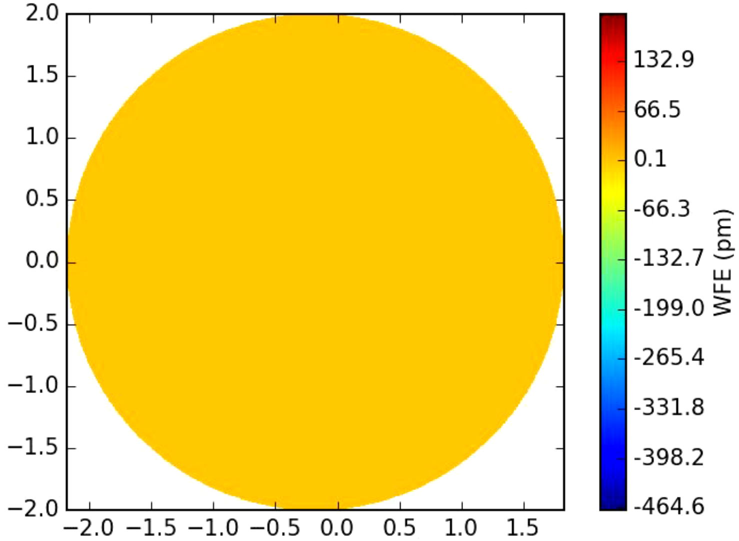
Temperature changes result in WFE caused by CTE and CTE homogeneity.

Initial Concept - Dynamic Thermal WFE Video

Passive Wavefront Error from 1 hour exposure.

Sun angle changes by 0.0411 degree per hour.

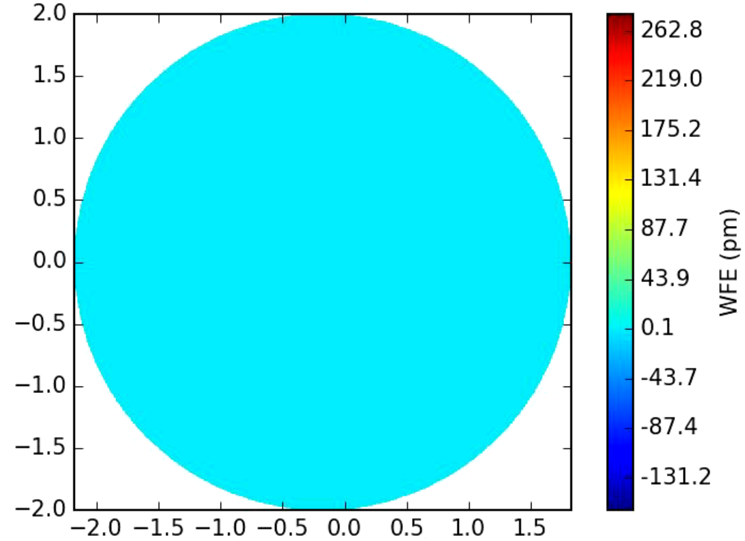
All Errors



WFE/1-hour = 233 pm PV

WFE/20-min = 28 pm

Power Removed



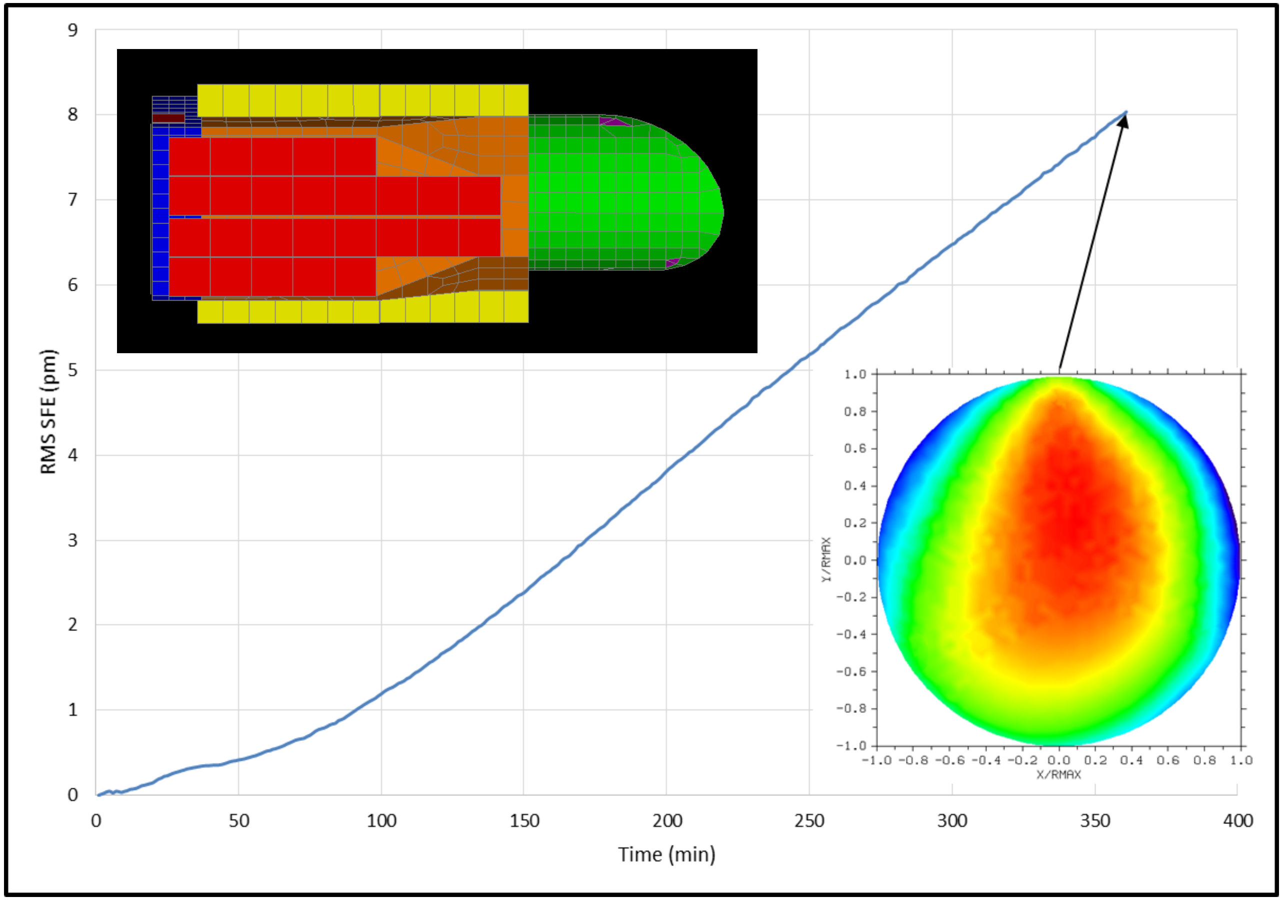
WFE/1-hour = 101 pm PV

WFE/20-min = 13 pm

Thermal WFE Stability Analysis – Passive

Baseline 4m telescope (with open-back Zerodur mirror, sun-shield, MLI) thermal WFE stability analysis for a 20 deg slew.

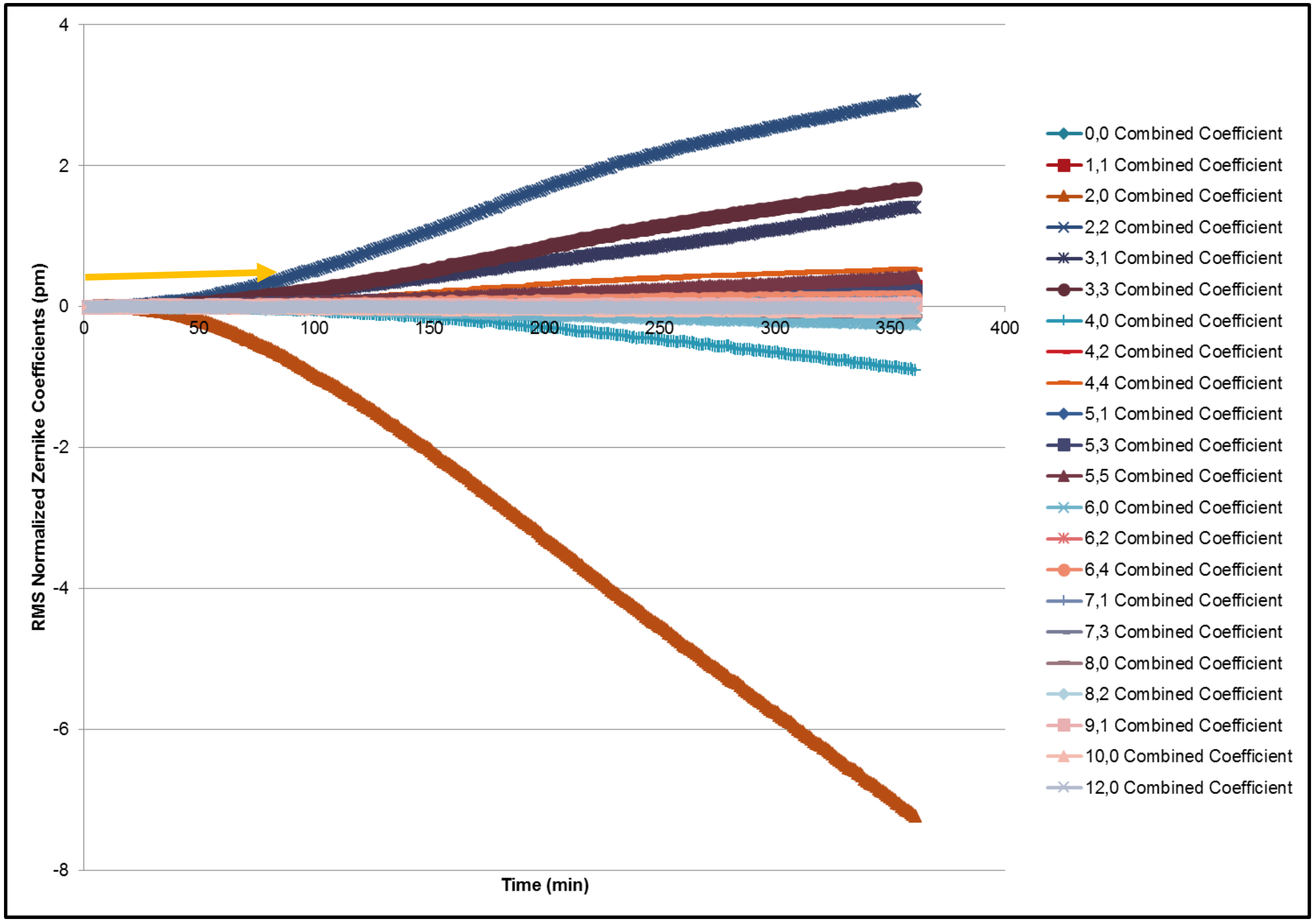
WFE changes by less than 1 pm rms over 90 minutes.



Thermal WFE Stability Analysis

Dominant error is Power.

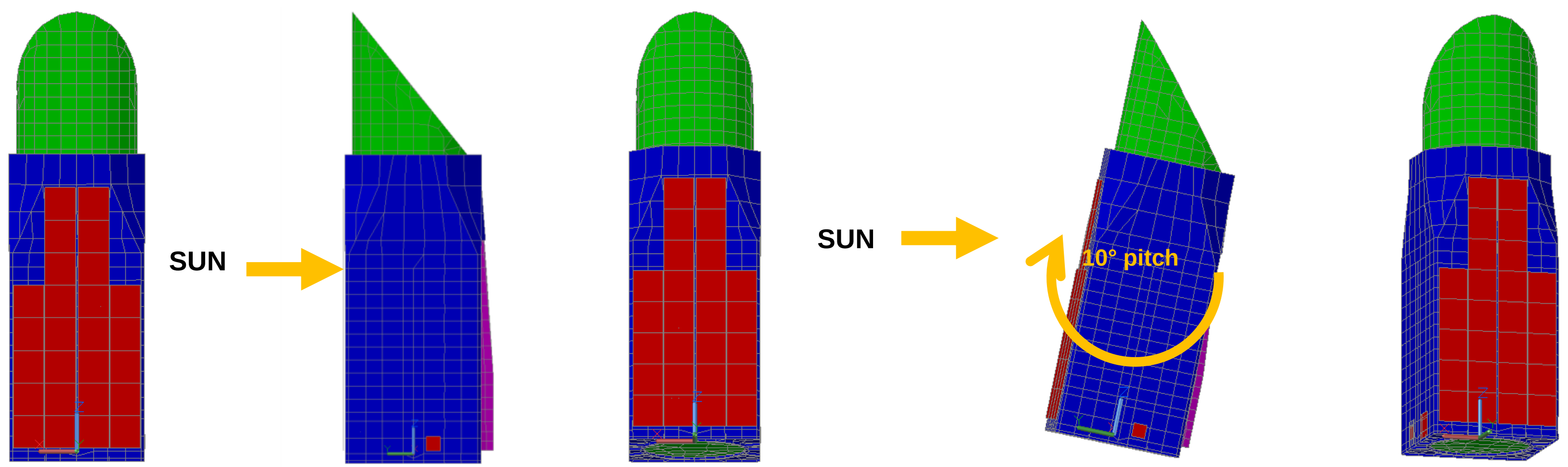
Trefoil 0.5 pm allocation is achieved in approx. 90 minutes.



HabEx

Observing Strategy

1. Telescope points at a Reference Star to dig a dark hole in the coronagraph and reaches a steady state in this orientation.
2. After reaching steady state the telescope performs a 10° pitch to point at the Target Star and stays at this position for 50hrs
3. For Speckle Subtraction, Telescope performs a 15° roll and stays at this position for 50hrs



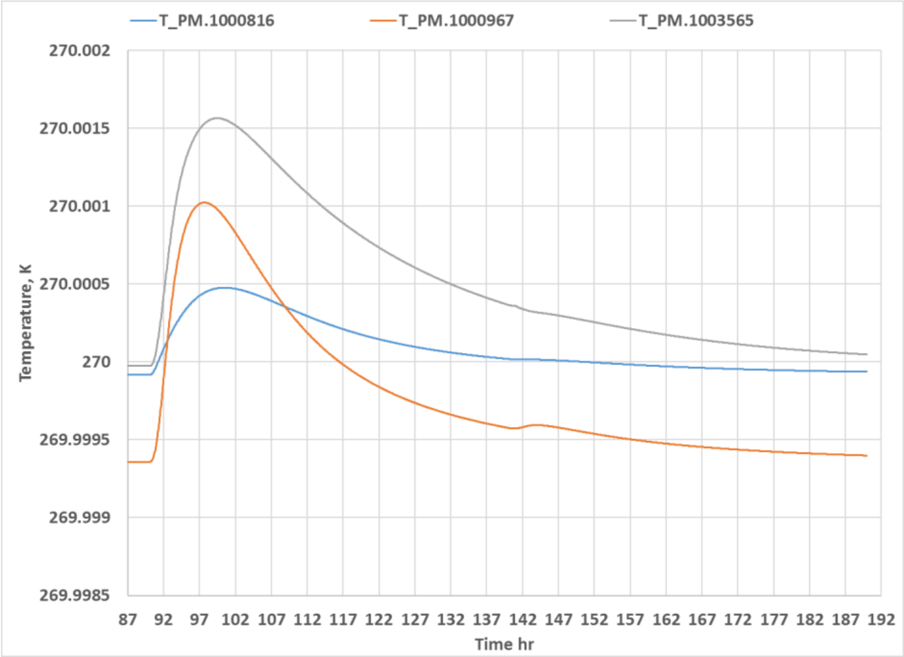
"ReferenceStar"
View from the sun

"After pitch 10° pitch"
View from the sun

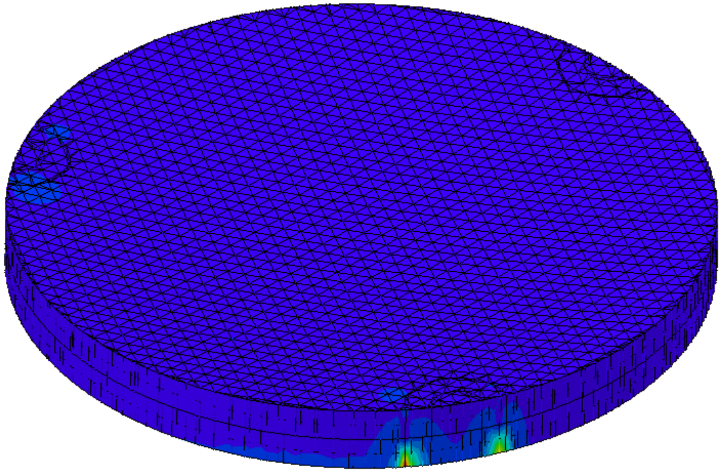
"After 15° Roll"
View from the sun

PM Temperature Stability

10 deg pitch causes maximum 1.6 mK change to the Primary Mirror at the hexapod strut mount locations – indicating need to heat struts.



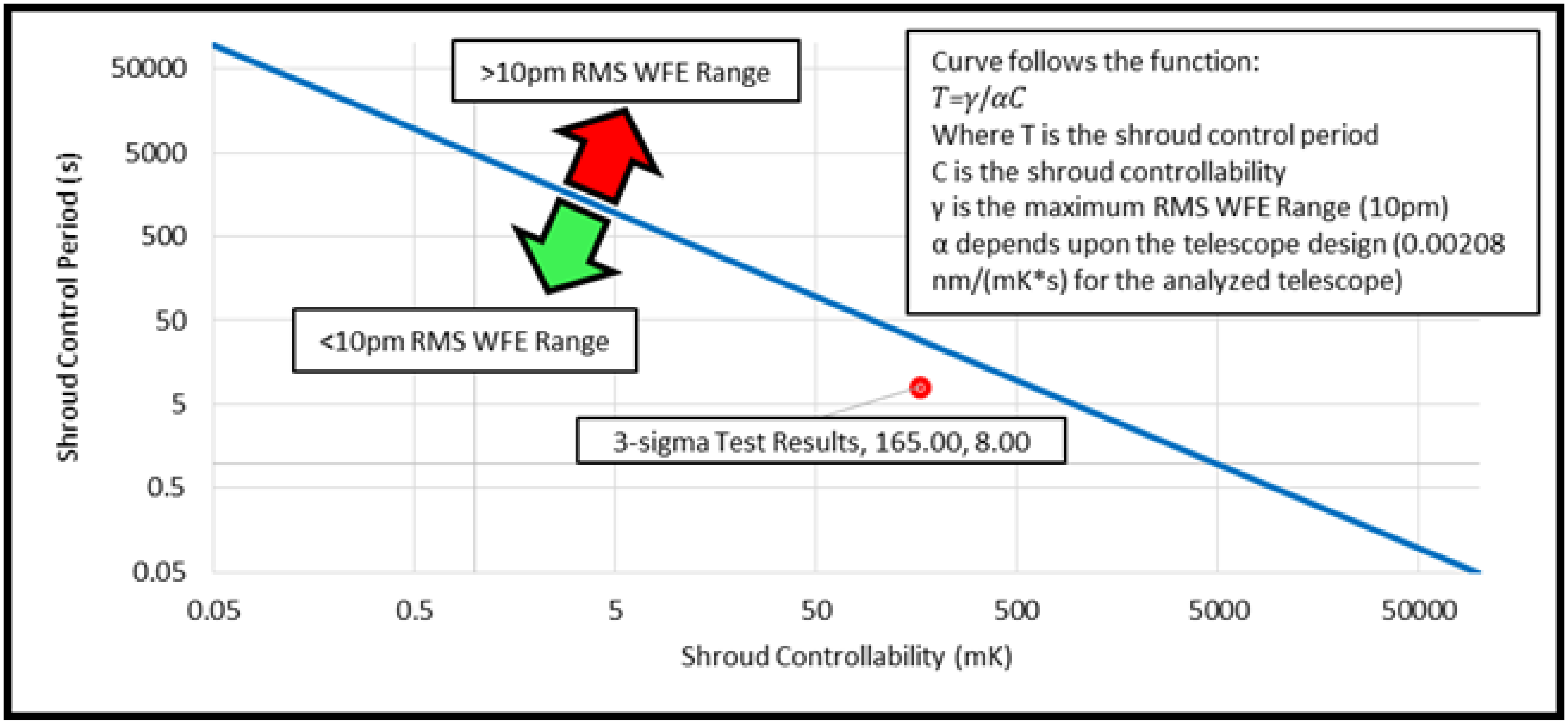
Max Delta T from reference star after pitch maneuver
Average ΔT 1.6mK



Active Thermal Stability

The ability to achieve any required wavefont stability depends on:

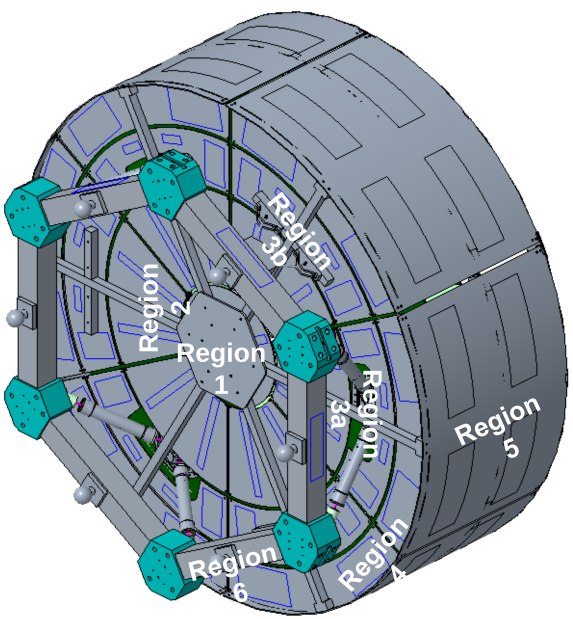
- Mirror Substrate Properties: CTE, Thermal Mass, Conductivity, etc.
- Thermal Environment Controllability
- Control Period.

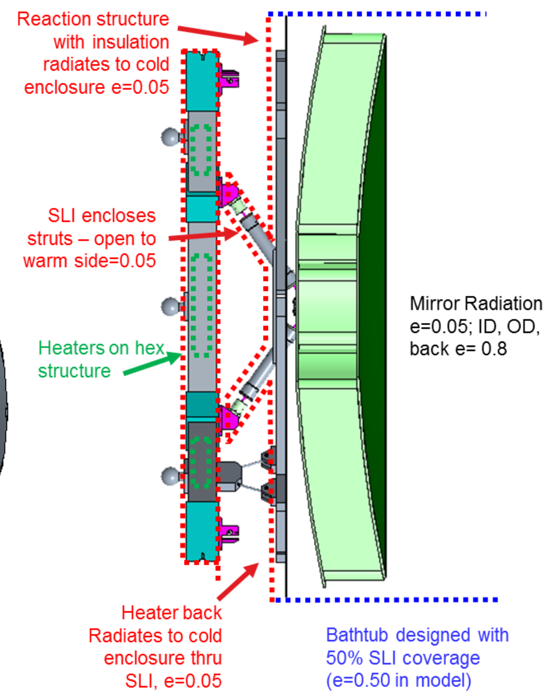


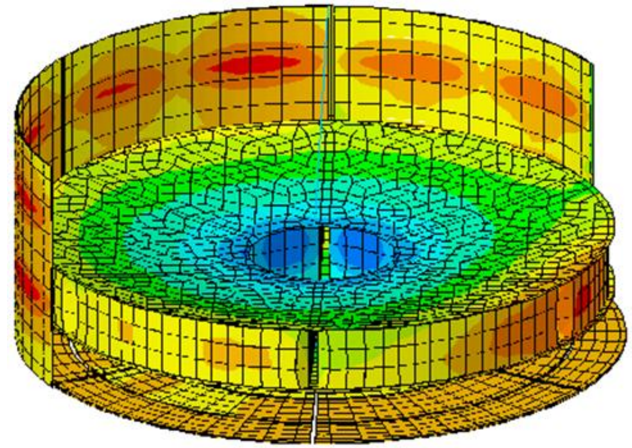
Predictive Thermal Control

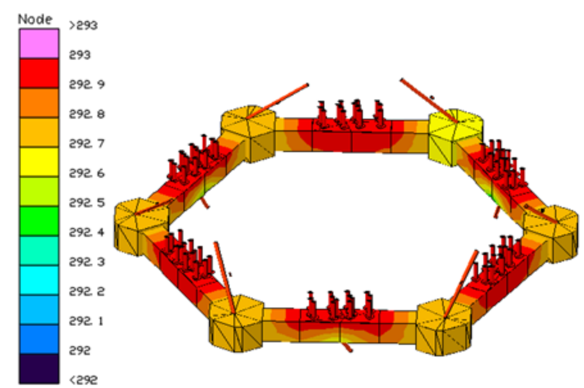
Additional Stability can be achieved using active thermal control.

Heater zones behind, surrounding & in front of mirror



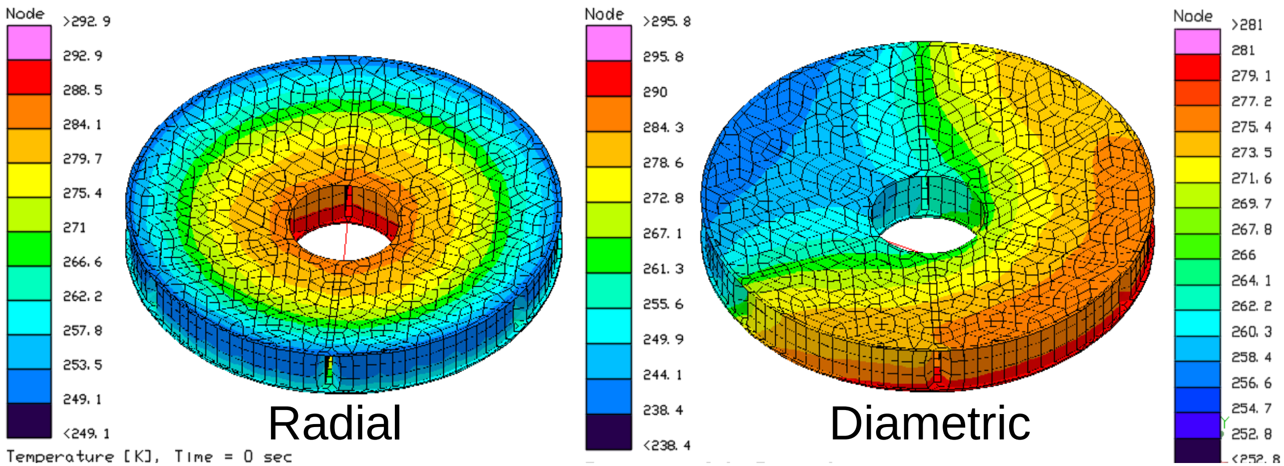






Steady State Gradients

Heater design induces gradients to compensate thermal environment

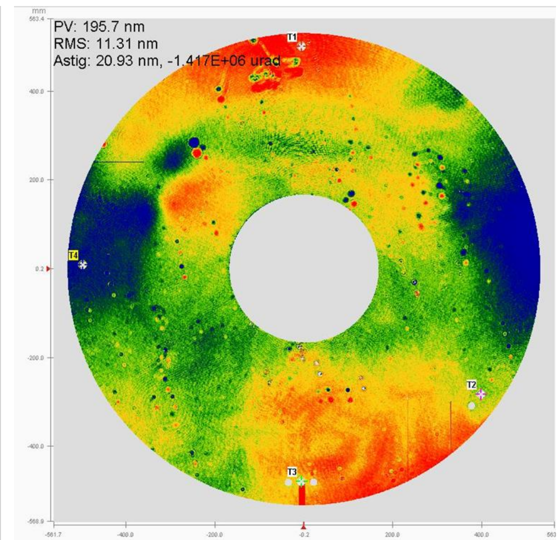


Predicted Thermal Performance

For HabEx we are assuming a linear scaling of the measured 11.3 nm rms per 62K cryo-deformation performance of a 1.2-meter Zerodur mirror owned by Schott decomposed into Zernikes.

Mirror achieves 2X Astig margin for ~2 mK thermal stability.

			Delta Temperature			62000.0	mK					
			Thermal Stability			2.0	mK					
										Measured Delta-SFE 292-230K		
							WFE/dT			Zernike Coefficient [nm] RMS Surface		
				Allocation		Zernikes	RMS-Zern			RMS-Zern	X-Zern	Y-Zern
Order				Thermal	MARGIN	Thermal WFE	[pm rms / mK]			[nm rms]	[nm rms]	[nm rms]
K	N	M	Aberration	[pm rms]		RMS pm/mK		N	M			
			TOTAL RMS	814.22		0.822				26.016	nm rms	
1	1	1	Tilt	596.40	195503.42	0.003	0.002	1	1	0.095	0.055	0.077
2	2	0	Power (Defocus)	554.29	41266.52	0.013	0.007	2	0	0.416	0.416	
3	2	2	Pri Astigmatism	1.91	2.83	0.675	0.338	2	2	20.940	-19.960	-6.330
4	3	1	Pri Coma	1.65	20.18	0.082	0.041	3	1	2.541	-2.539	0.109
5	3	3	Pri Trefoil	1.65	8.42	0.196	0.098	3	3	6.089	-3.970	-4.617
6	4	0	Pri Spherical	1.54	79.67	0.019	0.010	4	0	0.599	0.599	
7	4	2	Sec Astigmatism	1.54	20.93	0.074	0.037	4	2	2.283	-2.046	-1.012
8	4	4	Pri Tetrafoil	1.48	8.39	0.176	0.088	4	4	5.471	-3.683	4.046
9	5	1	Sec Coma	1.35	16.16	0.084	0.042	5	1	2.591	-1.050	2.369
10	5	3	Sec Trefoil	1.35	8.70	0.155	0.078	5	3	4.811	0.912	-4.724
11	5	5	Pri Pentafoil	1.35	22.78	0.059	0.030	5	5	1.838	1.713	-0.666
12	6	0	Sec Spherical	1.35	39.23	0.034	0.017	6	0	1.067	1.067	
13	6	2	Ter Astigmatism	1.03	9.24	0.112	0.056	6	2	3.465	3.341	-0.918
14	6	4	Sec Tetrafoil	1.25	35.69	0.035	0.018	6	4	1.089	-0.647	0.876
15	6	6	Pri Hexafoil	1.25	8.13	0.154	0.077	6	6	4.772	-4.569	-1.376
16	7	1	Ter Coma	0.70	7.11	0.099	0.050	7	1	3.073	0.786	-2.971
17	7	3	Ter Trefoil	0.82	3.71	0.221	0.111	7	3	6.863	-1.165	6.763
18	7	5	Sec Pentafoil	0.80	12.67	0.063	0.031	7	5	1.953	-0.487	1.891
19	7	7	Pri Septafoil	0.89			0.000					
20	8	0	Ter Spherical	0.34	14.54	0.024	0.012	8	0	0.729	-0.729	
21	8	2	Qua Astigmatism	0.50	91.63	0.006	0.003	8	2	0.171	-0.091	-0.144
22	8	4	Ter Tetrafoil	0.61	9.43	0.064	0.032	8	4	1.999	1.262	-1.550
23	8	6	Sec Hexafoil	0.72			0.000					
24	8	8	Pri Octafoil	0.68			0.000					
25	9	1	Qua Coma	0.46	3.86	0.118	0.059	9	1	3.659	3.220	-1.738
26	10	0	Qua Spherical	0.57	9.41	0.061	0.030	10	0	1.883	-1.883	
27	12	0	Qin Spherical	0.98	11.49	0.085	0.043	12	0	2.635	2.635	



Conclusions

Error Budget Closes for LOS, Inertial & Thermal

Error budget closes for VVC4. VVC6 relaxes Astig and Coma.

			RSS Allocation	100%	50%	70%	50%	10%			
									Predicted Performance Margin		
Order				VVC-4 Tolerance	LOS	Inertial	Thermal	Reserve	LOS	Inertial [uG]	Thermal [mK]
K	N	M	Aberration	[pm rms]	[pm rms]	[pm rms]	[pm rms]	[pm rms]		0.02	2
			TOTAL RMS	1628.4	814	1140	814	163			
1	1	1	Tilt	1192.8	596.40	834.95	596.40	119.28	1251.51	5714.58	195503.42
2	2	0	Power (Defocus)	1108.6	554.29	776.00	554.29	110.86	623.99	1308.40	41266.52
3	2	2	Pri Astigmatism	3.8	1.91	2.67	1.91	0.38	2.53	2.56	2.83
4	3	1	Pri Coma	3.3	1.65	2.32	1.65	0.33	9.87	162.98	20.18
5	3	3	Pri Trefoil	3.3	1.65	2.32	1.65	0.33	203.32	3.21	8.42
6	4	0	Pri Spherical	3.1	1.54	2.16	1.54	0.31	458.99	29.04	79.67
7	4	2	Sec Astigmatism	3.1	1.54	2.16	1.54	0.31	497.39	40.20	20.93
8	4	4	Pri Tetrafoil	3.0	1.48	2.07	1.48	0.30	15756.44	23.15	8.39
9	5	1	Sec Coma	2.7	1.35	1.89	1.35	0.27	2872.33	845.83	16.16
10	5	3	Sec Trefoil	2.7	1.35	1.89	1.35	0.27	31963.42	16.55	8.70
11	5	5	Pri Pentafoil	2.7	1.35	1.89	1.35	0.27	1251062.38	34.78	22.78
12	6	0	Sec Spherical	2.7	1.35	1.89	1.35	0.27	121850.21	472.62	39.23
13	6	2	Ter Astigmatism	2.1	1.03	1.45	1.03	0.21	95757.25	417.34	9.24
14	6	4	Sec Tetrafoil	2.5	1.25	1.76	1.25	0.25	2352446.64	187.09	35.69
15	6	6	Pri Hexafoil	2.5	1.25	1.75	1.25	0.25	20917403.44	41.59	8.13
16	7	1	Ter Coma	1.4	0.70	0.99	0.70	0.14	625089.60	493.29	7.11
17	7	3	Ter Trefoil	1.6	0.82	1.15	0.82	0.16	3719658.50	52.21	3.71
18	7	5	Sec Pentafoil	1.6	0.80	1.12	0.80	0.16	17228267.14	128.13	12.67
19	7	7	Pri Septafoil	1.8	0.89	1.25	0.89	0.18	18000287.24	61.85	
20	8	0	Ter Spherical	0.7	0.34	0.48	0.34	0.07	8063896.81	5.83	14.54
21	8	2	Qua Astigmatism	1.0	0.50	0.71	0.50	0.10	0.00	352.98	91.63
22	8	4	Ter Tetrafoil	1.2	0.61	0.85	0.61	0.12	0.00	0.00	9.43
23	8	6	Sec Hexafoil	1.4	0.72	1.00	0.72	0.14	0.00	41.69	
24	8	8	Pri Octafoil	1.4	0.68	0.96	0.68	0.14	0.00	109.75	
25	9	1	Qua Coma	0.9	0.46	0.64	0.46	0.09	0.00	0.00	3.86
26	10	0	Qua Spherical	1.1	0.57	0.80	0.57	0.11	0.00	4.71	9.41
27	12	0	Qin Spherical	2.0	0.98	1.37	0.98	0.20	0.00	6.27	11.49

Conclusions

The HabEx Baseline Telescope Design ‘Closes’.

It meets the WFE Stability Error Budget

The design uses standard engineering practice.

Baseline design is enabled by two capabilities:

- 8-m fairing volume provided by SLS
- Low mechanical disturbance provided by micro-thrusters.