

Habitable-zone exoplanet observatory (HabEx) baseline 4-m telescope design and predicted performance

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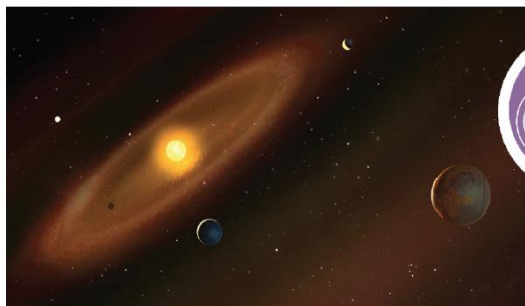


EXPLORING PLANETARY SYSTEMS AROUND NEARBY SUNLIKE STARS AND ENABLING OBSERVATORY SCIENCE FROM THE UV THROUGH NEAR-IR



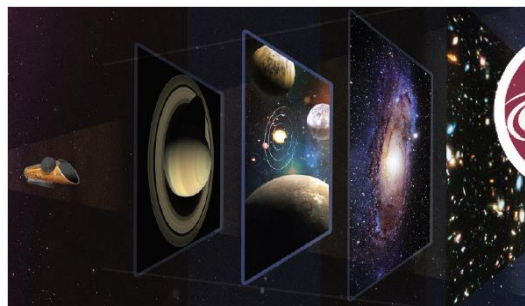
GOAL 1

To seek out nearby worlds and explore their habitability, *HabEx* will search for habitable zone Earth-like planets around sunlike stars using direct imaging and will spectrally characterize promising candidates for signs of habitability and life.



GOAL 2

To map out nearby planetary systems and understand the diversity of the worlds they contain, *HabEx* will take the first “family portraits” of nearby planetary systems, detecting and characterizing both inner and outer planets, as well as searching for dust and debris disks.



GOAL 3

To carry out observations that open up new windows on the universe from the UV through near-IR, *HabEx* will have a community driven, competed Guest Observer program to undertake revolutionary science with a large-aperture, ultra-stable UV through near-IR space telescope.

from HabEx interim
report URS273294



The HabEx STDT chose these parameters for Architecture A:

Telescope with a 4m aperture

72-m diameter, formation flying external Starshade occulter

Four instruments:

Coronagraph Instrument for Exoplanet Imaging

Starshade Instrument for Exoplanet Imaging

UV– Near-IR Imaging Multi-object Slit Spectrograph for General Observatory Science

High Resolution UV Spectrograph for General Observatory Science

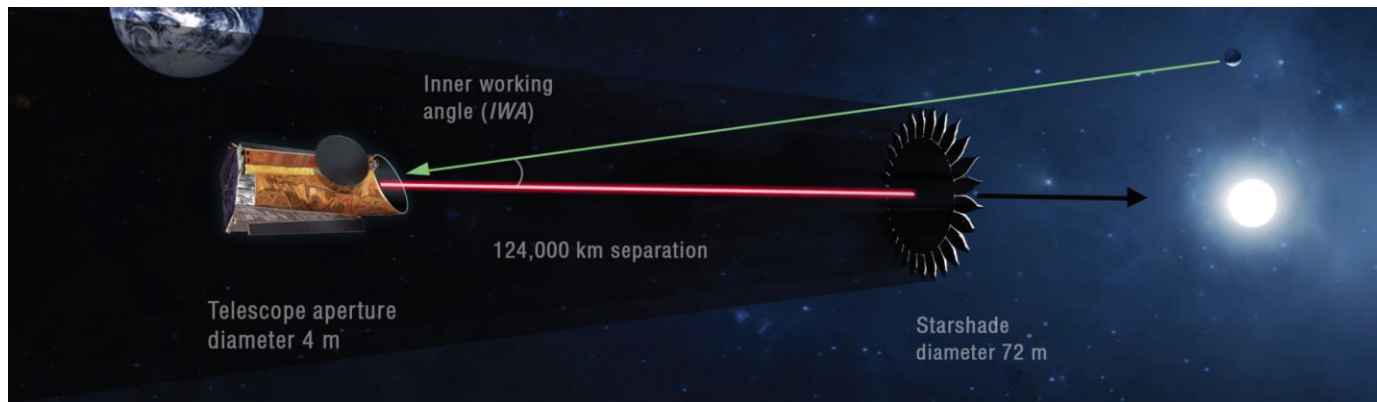


Image from HabEx
interim report
URS273294



The HabEx Baseline Telescope Design ‘Closes’.

It meets the specifications for LOS Jitter and WFE Stability.

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.



HabEx Baseline Telescope

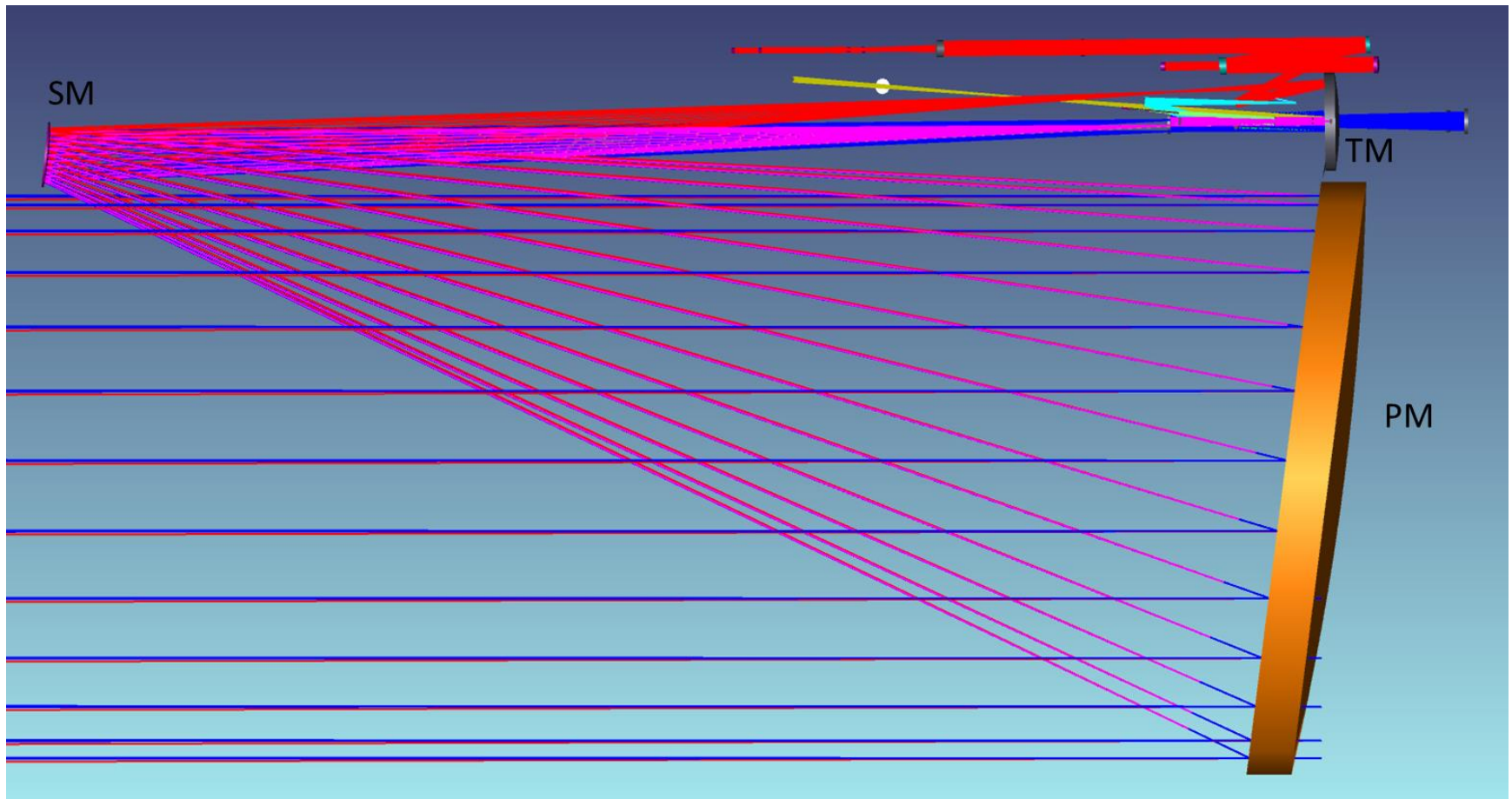
Design Overview



Architecture	Unobscured Off-Axis F/2.5 TMA										
Aperture Dia	4-meters Monolithic (Minimum) 6.5-meters Segmented or Monolithic (Maximum)										
Mass Budget	< 10,000 kg (excluding science instruments & spacecraft)										
LOS Stability	< 2 mas on-sky jitter (astrophysics and starshade) < 0.7 milli-arc-second on-sky jitter (coronagraph)										
Diffraction Limit	400 nm (assumed to be achievable)										
Wavefront Error	30 nm rms Total (assumed achievable)										
Primary Mirror (cpd = cycles/diameter)	<table> <tr> <td>Total SFE</td><td>< 7 nm rms</td></tr> <tr> <td>Low-Order (< 30 cpd)</td><td>< 5 nm rms</td></tr> <tr> <td>Mid-Spatial (30 to 90 cpd)</td><td>< 4 nm rms</td></tr> <tr> <td>High-Spatial (>90 cpd)</td><td>< 2 nm rms</td></tr> <tr> <td>Roughness</td><td>< 1 nm rms</td></tr> </table>	Total SFE	< 7 nm rms	Low-Order (< 30 cpd)	< 5 nm rms	Mid-Spatial (30 to 90 cpd)	< 4 nm rms	High-Spatial (>90 cpd)	< 2 nm rms	Roughness	< 1 nm rms
Total SFE	< 7 nm rms										
Low-Order (< 30 cpd)	< 5 nm rms										
Mid-Spatial (30 to 90 cpd)	< 4 nm rms										
High-Spatial (>90 cpd)	< 2 nm rms										
Roughness	< 1 nm rms										
WFE Stability	< 5 nm rms (astrophysics and starshade) < 1 to 200 pm rms per spatial frequency (coronagraph)										



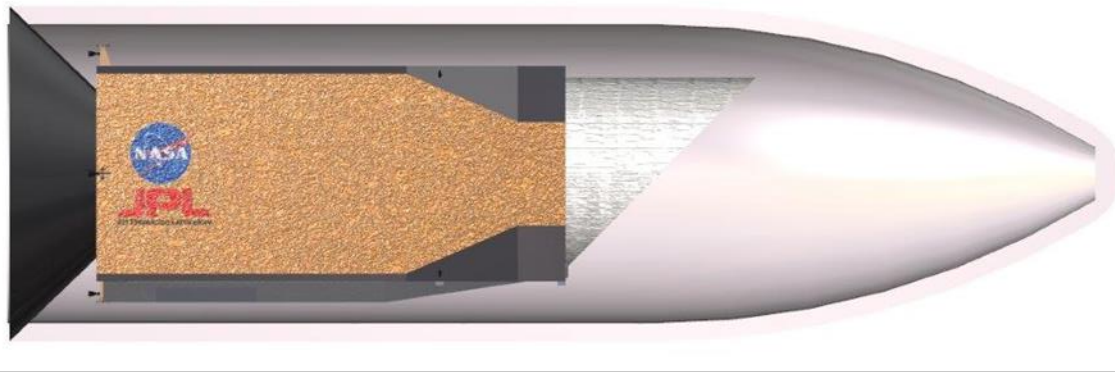
HabEx telescope optical design is off-axis TMA.





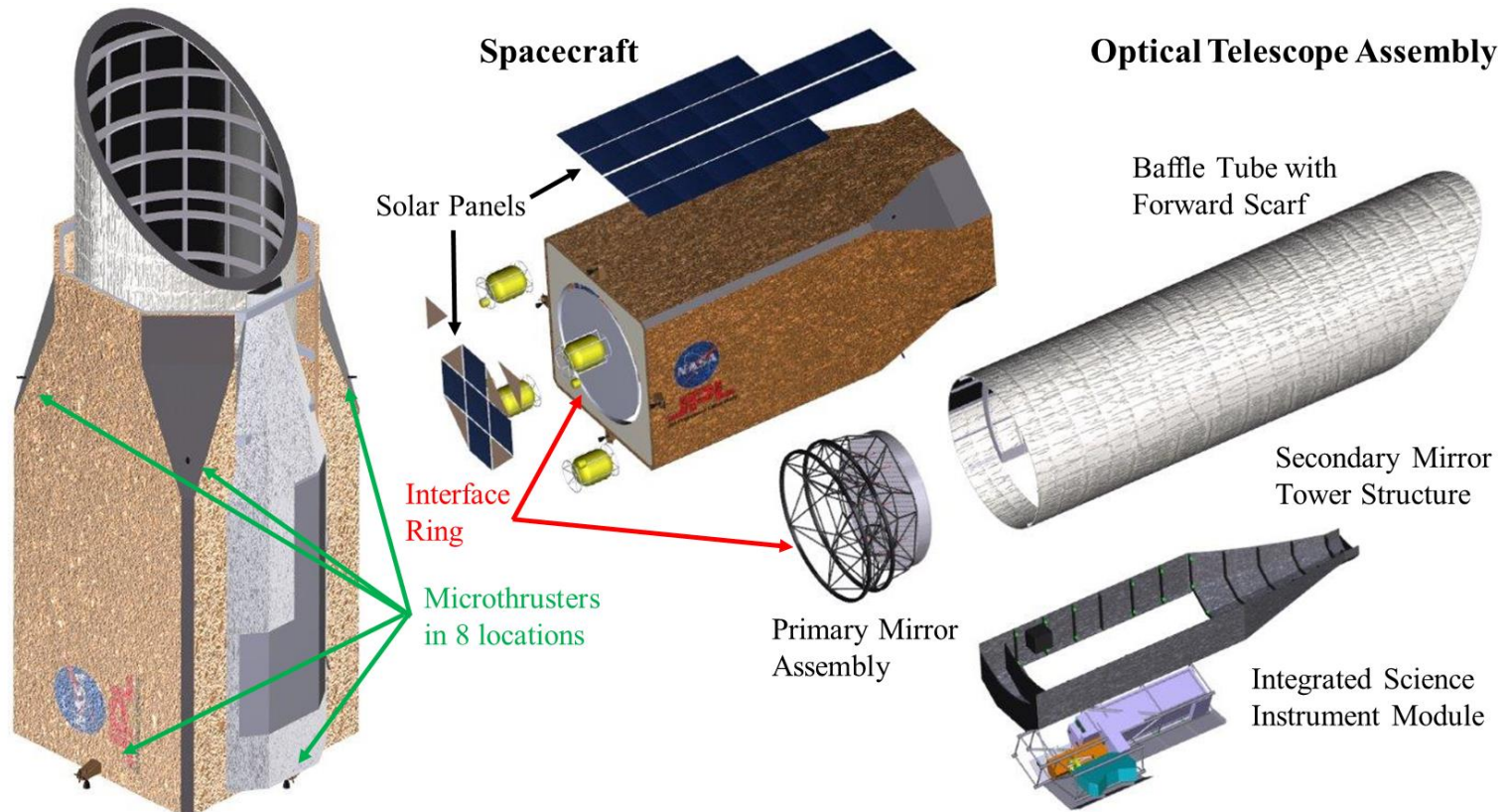
Baseline takes advantage of SLS Volume and Mass Capacities.

Can be launched with significant mass margin and without the need for complex deployments.





Baseline Observatory is Telescope surrounded by Spacecraft.
Only connection between two is Interface Ring.
Interface Ring is also where Observatory attaches to SLS PAF.



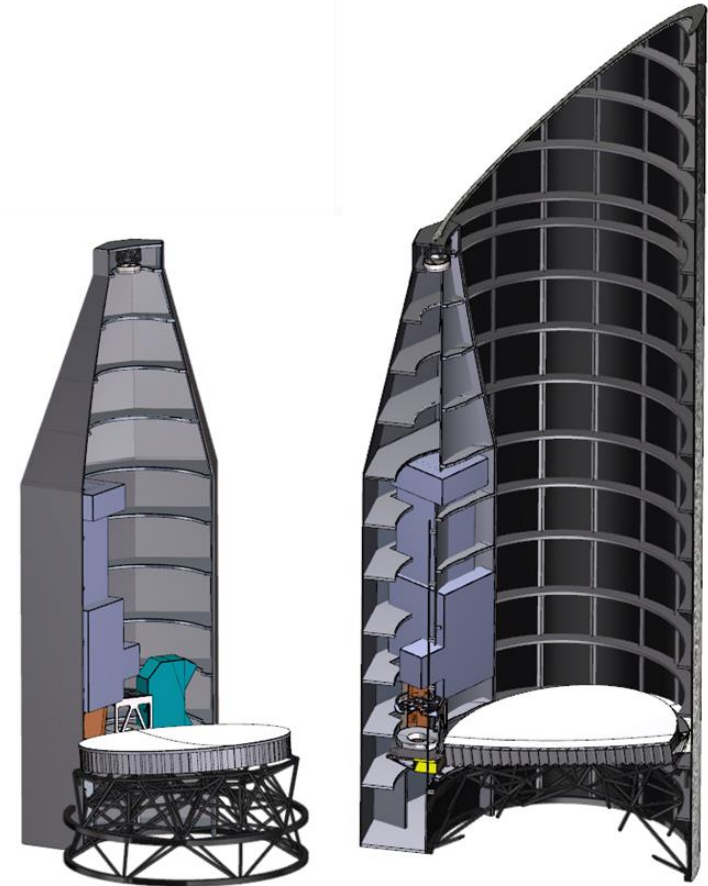


A key element of the structural design is connecting the secondary mirror tower and straylight baffle.

In addition to straylight suppression, baffles provide stiffness.

Because optical design is off-axis, baffles are not continuous, gussets in the tower structure span the baffle gaps.

Gussets eliminated need for a truss structure – reducing mass and opening the space for instruments.



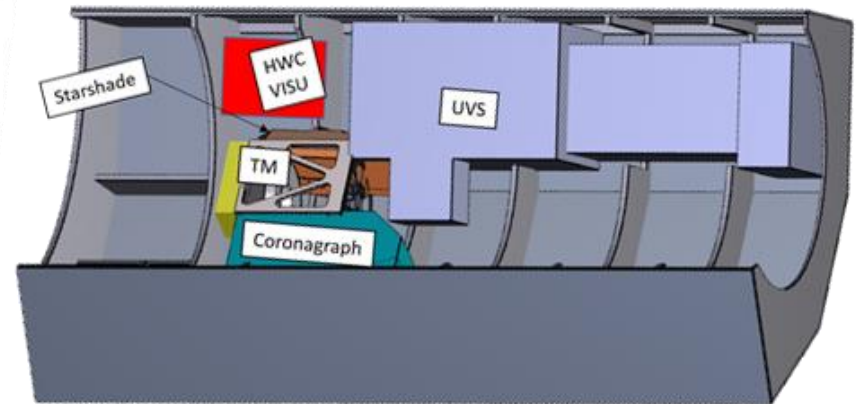
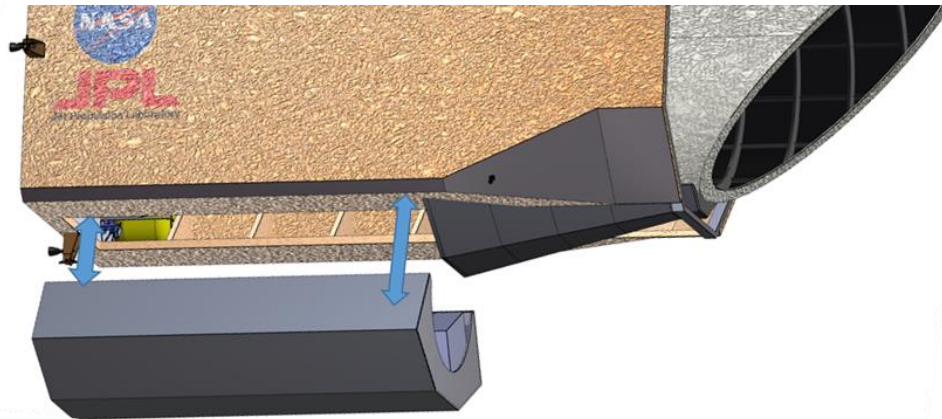


Science Instruments are in Integrated Science Instrument Module.

ISIM is a structural element of the secondary mirror tower.

ISIM is removable from tower for servicing.

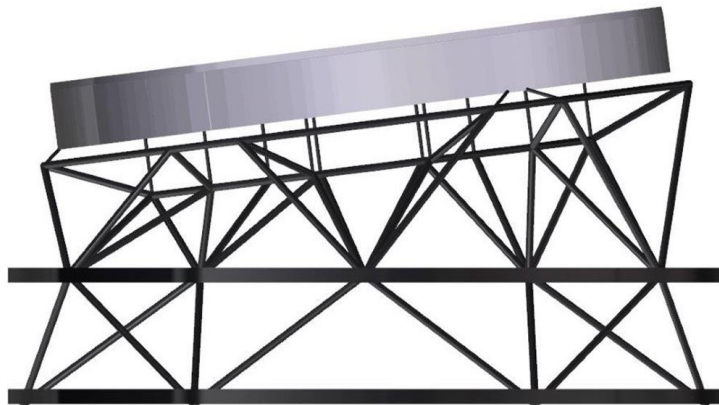
Individual SIs are removable from ISIM for servicing.



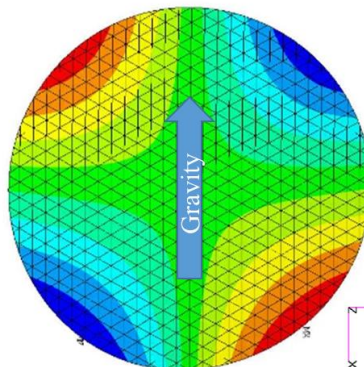


Dozens of Zerodur[®] and ULE[®] mirror designs were considered. Baseline Zerodur[®] mirror design balances mass and stiffness.

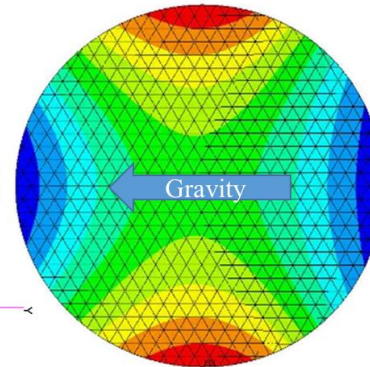
- Substrate has a flat-back geometry with a 42 cm edge thickness and mass of approximately 1400 kg.
- The mirror's free-free first mode frequency is 88 Hz. And, its mounted first mode frequency is 70 Hz.
- The mirror is locally stiffened to minimize gravity sag.



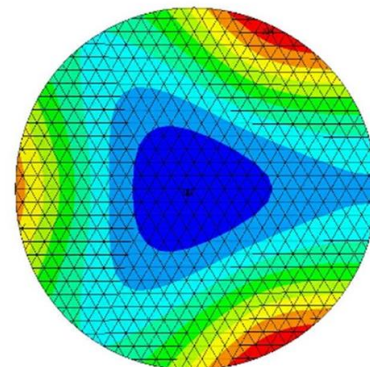
X-axis = 18.6 μm RMS



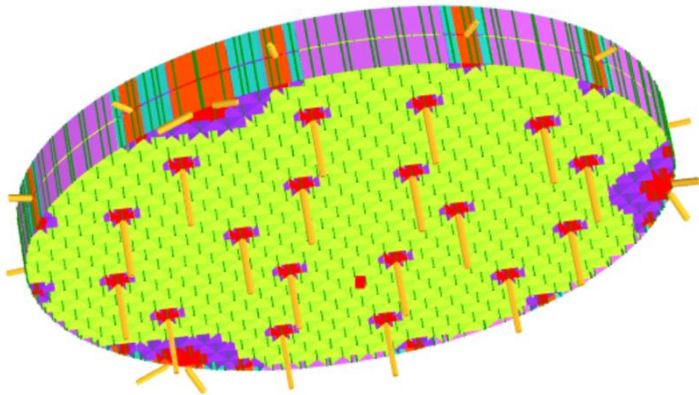
Y-axis = 18.4 μm RMS



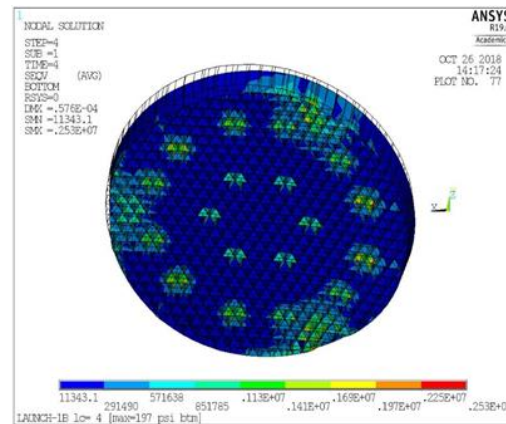
Z-axis = 12.6 μm RMS



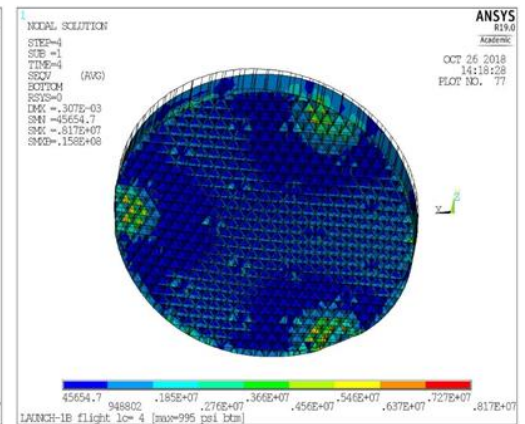
While Zerodur® can survive loads as high as 17,400 psi, the launch constraint system keeps launch stress at ~100 psi.



18-Axial Launch Locks
12-Radial Launch Locks



With Launch Locks
Launch Stress = ~ 200 psi



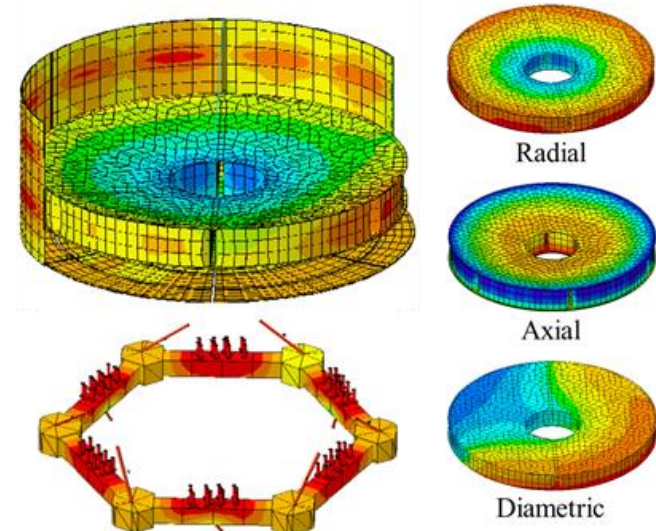
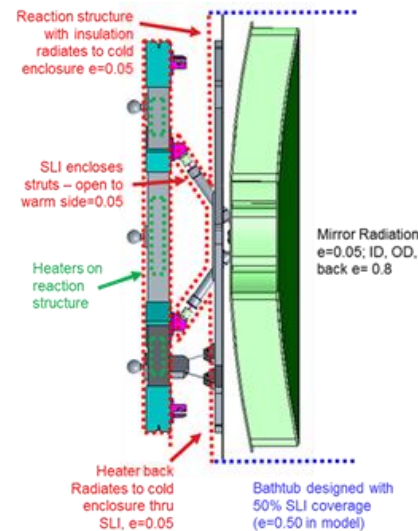
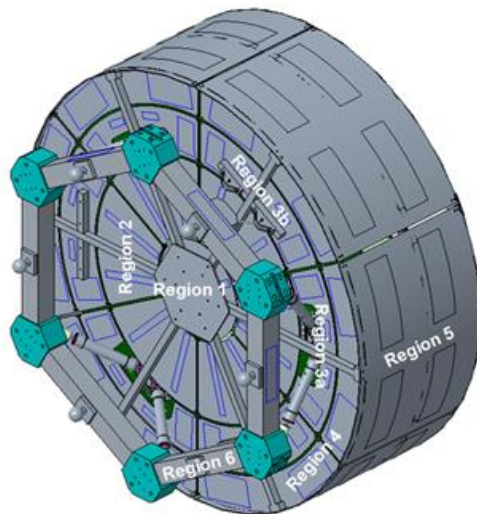
Without Launch Locks
Launch Stress = ~ 1000 psi

Launch constraint system has 18 axial and 12 radial launch locks.



Baseline HabEx active zonal thermal control concept is scale-up of systems built by the Harris Corporation.

- Harris is flying 0.7 & 1.1-m systems on its Spaceview™ telescopes.
- Harris built 1.5-m system built with 37 thermal control zones for MSFC Predictive Thermal Control Study.



Because of PM thermal mass, such a system with 0.5-Hz, 50-mK sensors will keep PM temperature stable to ~1-mK.



Baseline mission mass with 30% margin is well within the 44 mt SLS mass capacity (only uses ~ 33%).

HabEx Mission Mass Estimate			
Component	CBE [kg]	30% [kg]	Total [kg]
Telescope	3431	1029	4460
Science Instruments	1164	499	1663
Spacecraft	4500	1350	5850
Interface Ring	210	63	273
PAF	TBE		
Mission Dry Mass	9305	2941	12246
Propellant	1700		1700
Mission Wet Mass	11005		13946



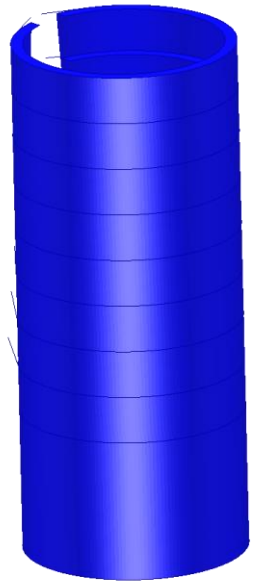
Detailed FEM for OTA Mass Estimate

Description	CBE Mass (kg)
Primary Mirror Assembly	1453
Primary Mirror Support	865
Secondary Mirror Assembly	11
Secondary Tower & Baffle Tube	982
Tertiary Mirror Assembly	65
Forward Door	55
HabEx OTA Assembly	3431

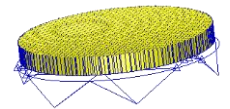
Secondary Mirror Tower



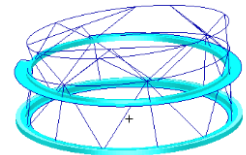
Straylight Baffle



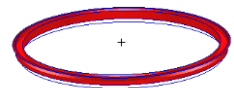
Primary Mirror Assembly



PM Support



Interface Ring



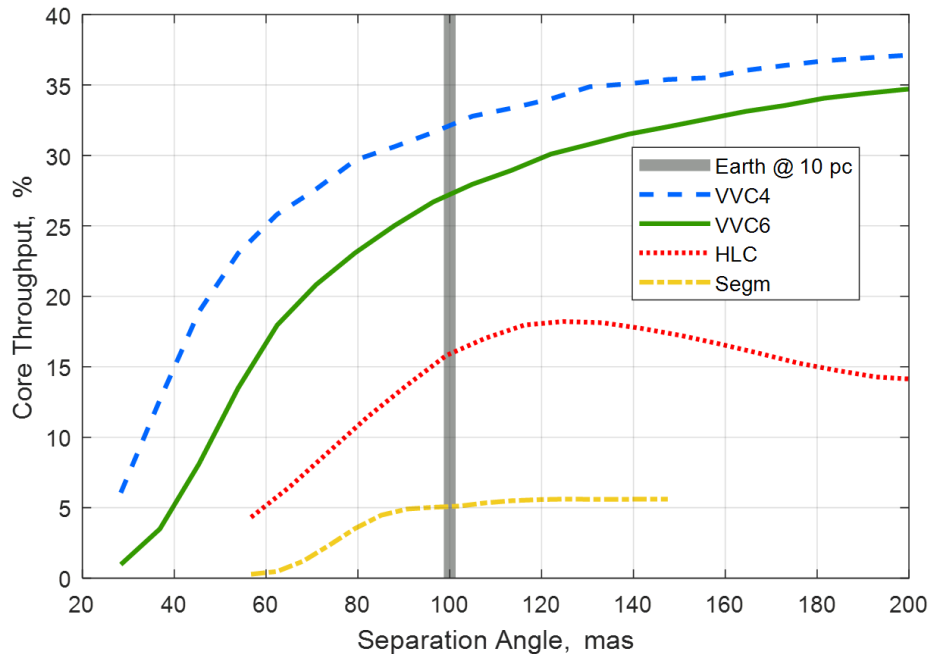


HabEx Baseline Telescope

Performance Predictions

‘The’ System Challenge: Dark Hole

Imaging an exo-Earth requires a telescope/coronagraph system that produces a 10^{-10} dark-hole with as small of an inner working angle (IWA) as possible and as large of a throughput as possible.



LOS Jitter & Drift impacts IWA by making PSF broader.

WFE Stability impacts noise floor.

Line of Sight (LOS) Stability

LOS Stability causes PSF smear and beam-shear WFE.

LOS Stability has two causes:

- Jitter – response of structure to mechanical accelerations
- Drift – response of structure to changes in thermal environment

Specification of < 0.5 mas rms per axis is uncorrectable Jitter and residual Drift after correction by Laser-truss system.

Specification establishes rigid-body motion error budget.

Specification				56.0	mas
			ALLOCATION (one sided PV)		
Alignment	ZEMAX	Tolerance	units	RSS	Units
PM X-Decenter	DX	5.0	nanometer	8.6	mas
PM Y-Decenter	DY	5.0	nanometer	8.4	mas
PM Z-Despace	DZ	5.0	nanometer	2.2	mas
PM Y-Tilt	TX	0.5	nano-radian	17.7	mas
PM X-Tilt	TY	0.5	nano-radian	17.4	mas
PM Z-Rotation	TZ	0.5	nano-radian	2.2	mas
SM X-Decenter	DX	25.0	nanometer	38.3	mas
SM Y-Decenter	DY	20.0	nanometer	29.6	mas
SM Z-Despace	DZ	5.0	nanometer	2.2	mas
SM Y-Tilt	TX	1.0	nano-radian	3.1	mas
SM X-Tilt	TY	1.0	nano-radian	3.0	mas
SM Z-Rotation	TZ	5.0	nano-radian	1.7	mas
				56.0	mas

Wavefront Stability

Imaging an exo-Earth also requires a telescope/coronagraph system with a stable transmitted wavefront.

Drift in WFE may result in speckles which can produce a false exoplanet measurement or mask a true signal.

Spatial frequency of that error is important.

Important WFE stability sources include:

- Rigid body motions of optical components on their mounts causing relative misalignment between optical components (beam-shear),
- Shape changes of individual optical components,
- Shape changes of telescope structure that misalign or change shape of optical components.

There are 2 primary source of Temporal Wavefront Error:

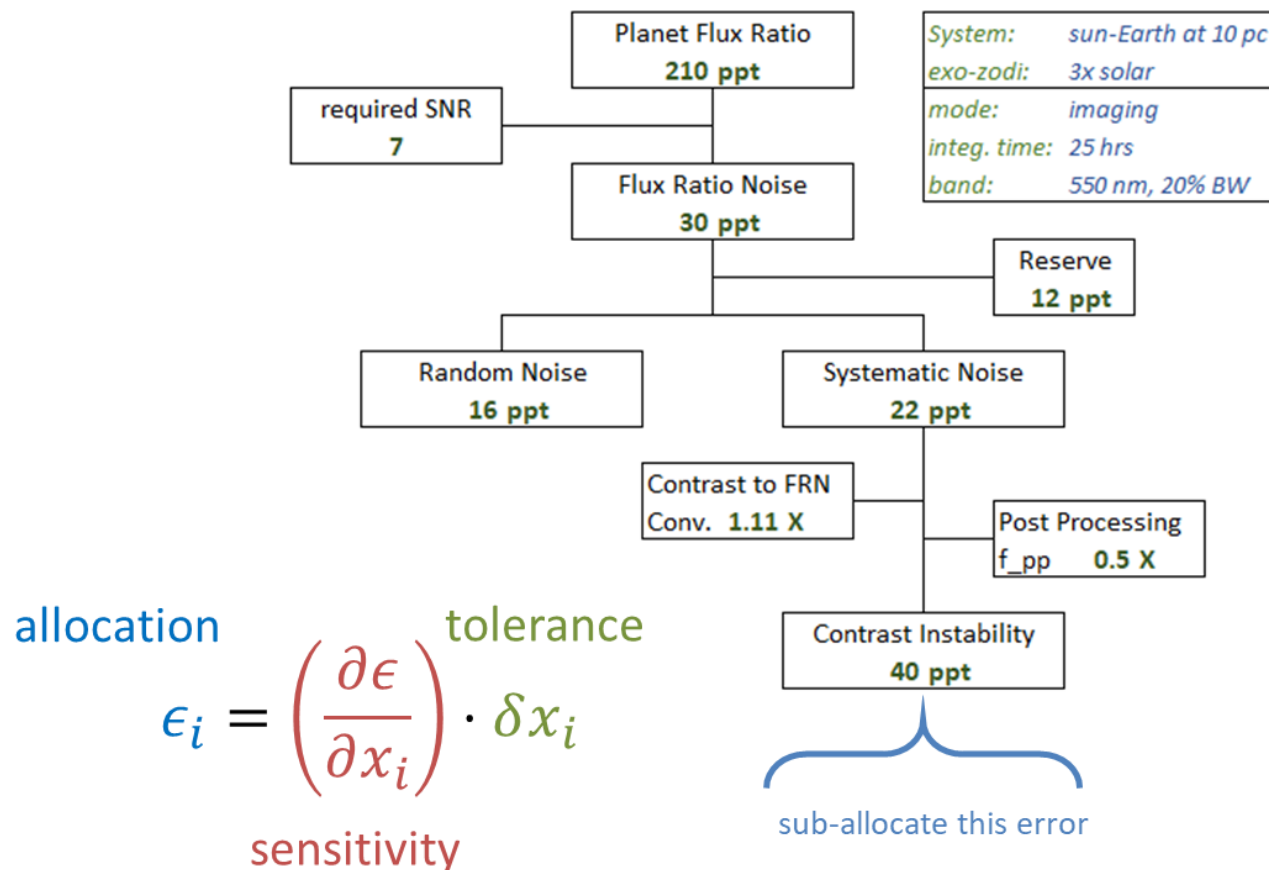
Thermal Environment

Mechanical Environment

Wavefront Stability Error Budget

Observing an exo-Earth requires contrast instability < 40 ppt.

Noise Equivalent Contrast Ratio (NECR) allocates instability based on coronagraph sensitivity.



Wavefront Stability Error Budget

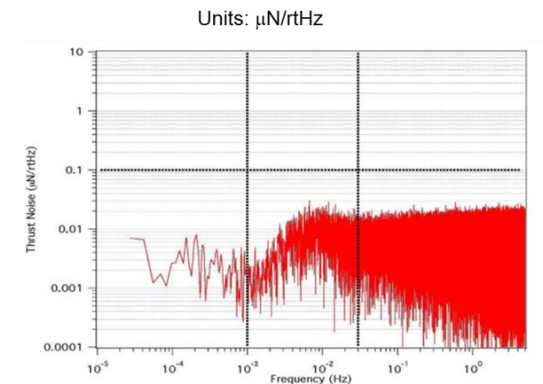
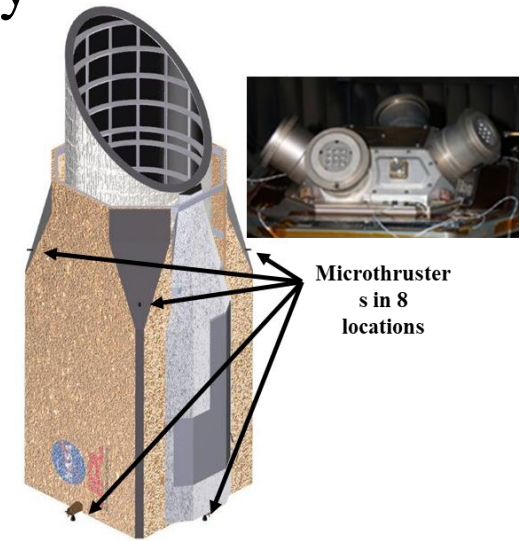
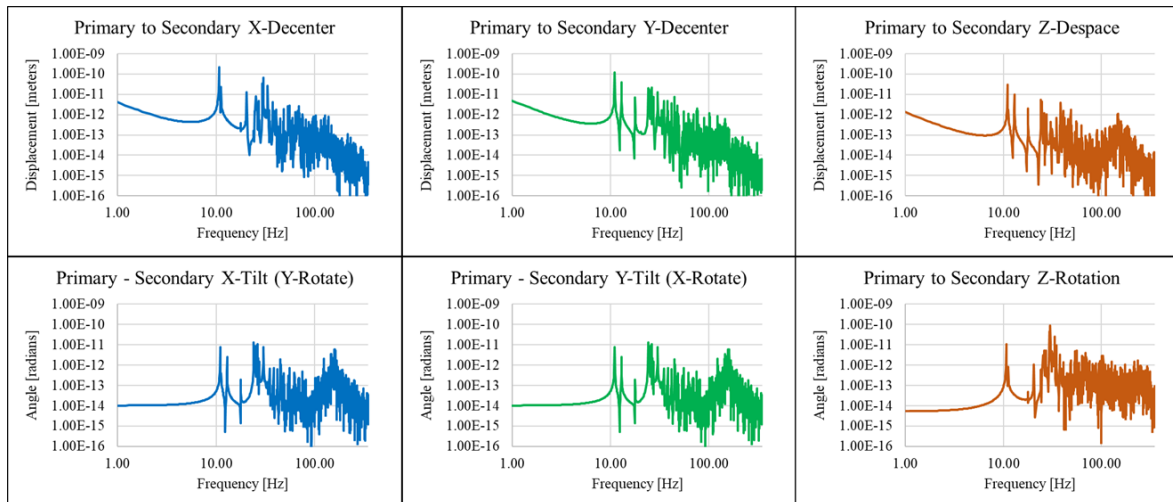
Create 'initial' Zernike polynomial WFE Stability Error Budget:

- Allocating 1-ppt to tilt, power, astigmatism, coma and spherical. And, the balance is divide between the higher order terms.
- Sub-allocate 33% each to LOS, inertial and thermal sources.

		Allocation	100%	33%	33%	33%
Index			VVC-6 Tolerance	LOS	Inertial	Thermal
N	M	Aberration	[pm rms]	[pm rms]	[pm rms]	[pm rms]
		TOTAL RMS	4381.1	2528	2528	2528
1	1	Tilt	2342.6	1351.83	1351.83	1351.83
2	0	Power (Defocus)	1751.9	1010.98	1010.98	1010.98
2	2	Astigmatism	2121.2	1224.08	1224.08	1224.08
3	1	Coma	1888.2	1089.60	1089.60	1089.60
4	0	Spherical	1603.7	925.42	925.42	925.42
3	3	Trefoil	0.9	0.51	0.51	0.51
4	2	Sec Astigmatism	0.5	0.28	0.28	0.28
5	1	Sec Coma	0.4	0.25	0.25	0.25
6	0	Sec Spherical	0.3	0.19	0.19	0.19
4	4	Tetrafoil	0.8	0.49	0.49	0.49
5	3	Sec Trefoil	0.4	0.23	0.23	0.23
6	2	Ter Astigmatism	0.2	0.14	0.14	0.14
7	1	Ter Coma	0.2	0.12	0.12	0.12
5	5	Pentafoil	0.3	0.17	0.17	0.17
6	4	Sec Tetrafoil	0.3	0.17	0.17	0.17
7	3	Ter Trefoil	0.2	0.13	0.13	0.13
6	6	Hexafoil	0.2	0.12	0.12	0.12
7	5	Sec Pentafoil	0.2	0.12	0.12	0.12
7	7	Septafoil	0.2	0.14	0.14	0.14

Predicted LOS Stability: Jitter

LOS jitter was calculated by modeling rigid-body motion of the primary and secondary mirrors relative to the tertiary mirror as a result of the structure's response from 0 to 350 Hz to the micro-thruster noise specification applied to the structure from 0 to 10 Hz.

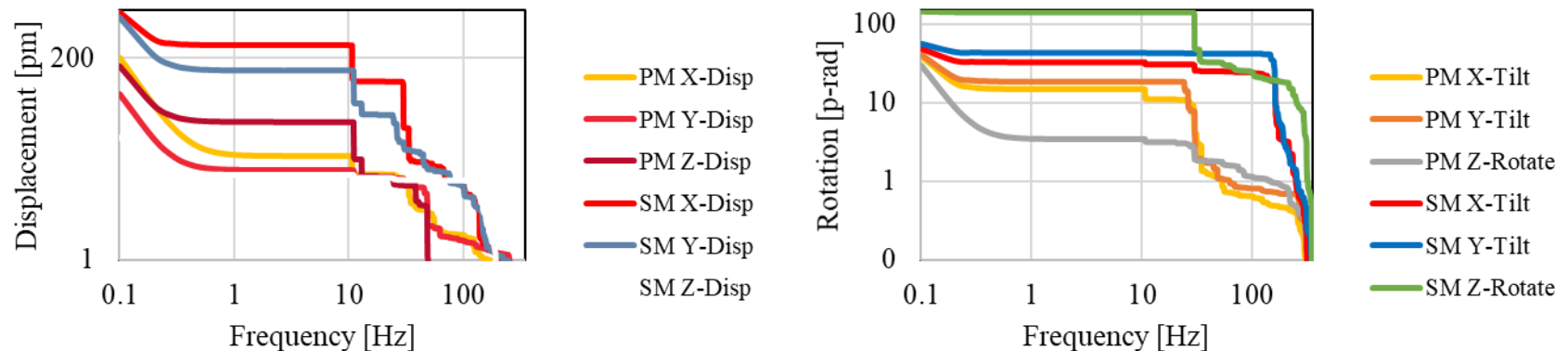


Thruster noise PSD plot for colloidal microthrusters. Max noise above 10^{-3} is likely due to thrust-balance sensor noise limits.

(ref. "Colloid Micro-Newton Thrusters For Precision Attitude Control", John Ziemer, et. al, April 2017, CL#17-2067)

Predicted LOS Stability: Jitter

Because HabEx is using microthrusters, which are always on and simultaneously excite the structure over the entire frequency range, it is necessary to take an extra step and RSS the individual components into a running sum to get the total rigid-body motion.

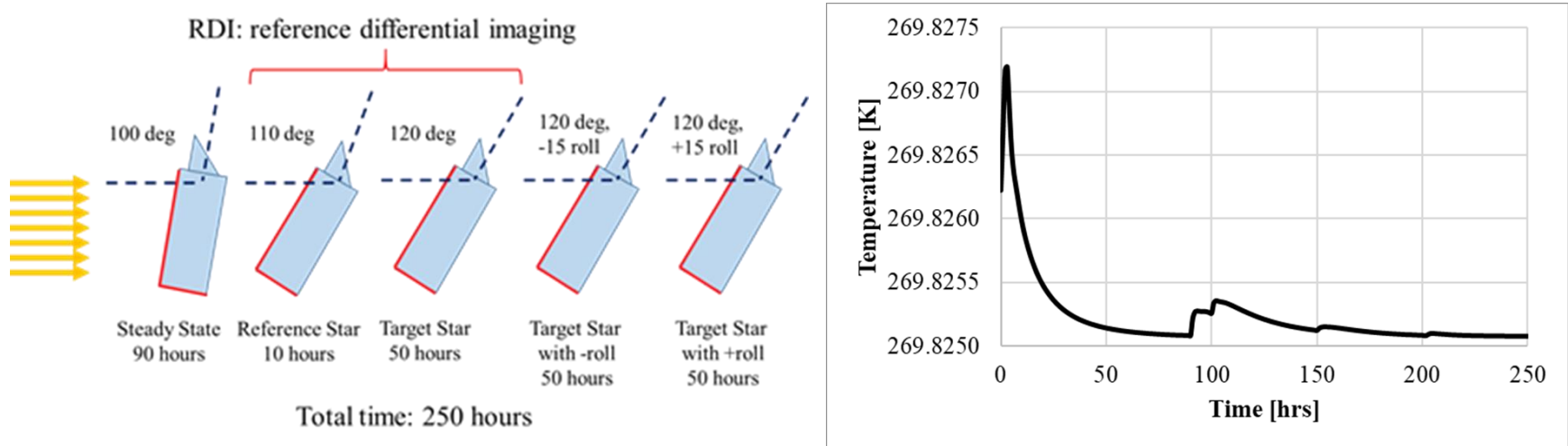


Total rigid-body motion yields < 0.2 mas jitter (40X margin)

Table 6: Predicted maximum ‘jitter’ motion of PM and SM from Microthruster Noise						
DOF	Δx (nm)	Δy (nm)	Δz (nm)	Θx (nrad)	Θy (nrad)	Θz (nrad)
Primary	0.20	0.08	0.16	0.04	0.04	0.03
Secondary	0.67	0.58	0.03	0.05	0.06	0.15

Predicted LOS Stability: Thermal Drift

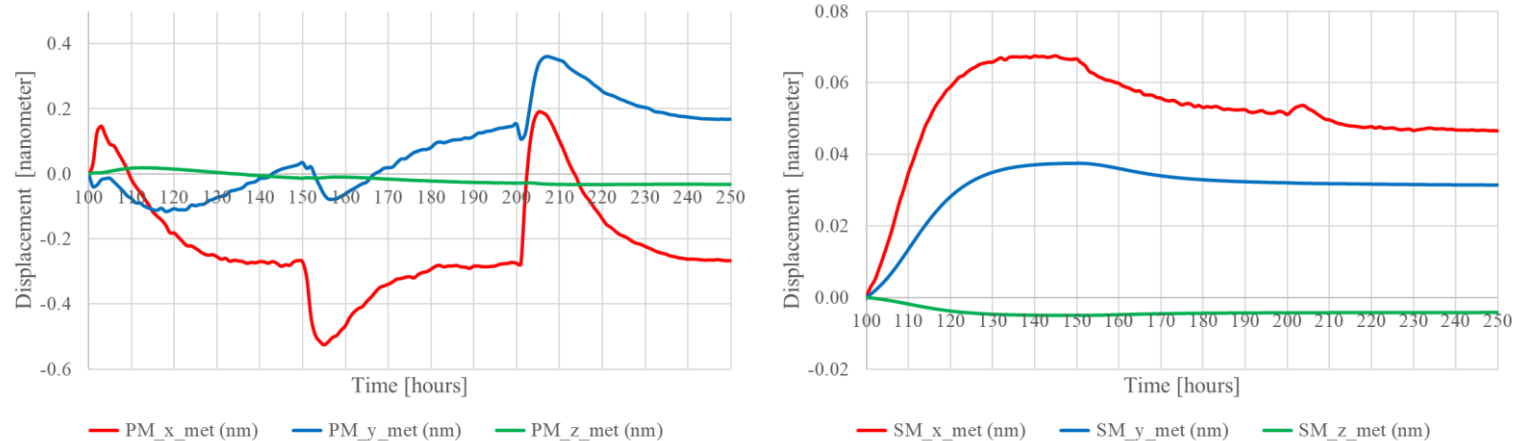
Thermal drift was calculated by modeling the telescope structure's response to a 250-hr DRM.



Drift is the ‘residual’ the rigid-body motion of the primary and secondary mirrors relative to the tertiary mirror that is not corrected by the laser metrology system that senses and controls the optical alignment of the primary and secondary mirrors.

Predicted LOS Stability: Thermal Drift

Thermal Drift is ‘residual’ rigid-body motion of primary and secondary mirrors not corrected by laser metrology system.



Total rigid-body motion yields < 0.2 mas drift (3.5X margin)

Table 7: Predicted maximum rigid body motion of PM and SM for a Design Reference Mission

DOF	Δx (nm)	Δy (nm)	Δz (nm)	Θx (nrad)	Θy (nrad)	Θz (nrad)
Primary	0.71	0.48	0.05	0.25	0.38	0.39
Secondary	0.07	0.04	0.01	0.01	0.04	0.29

Residual Thermal Drift = Total LOS Instability

Wavefront Stability: LOS

LOS instability causes wavefront error caused by beam-shear on the secondary and tertiary mirrors.

Each rigid body motion produces different Zernike errors.

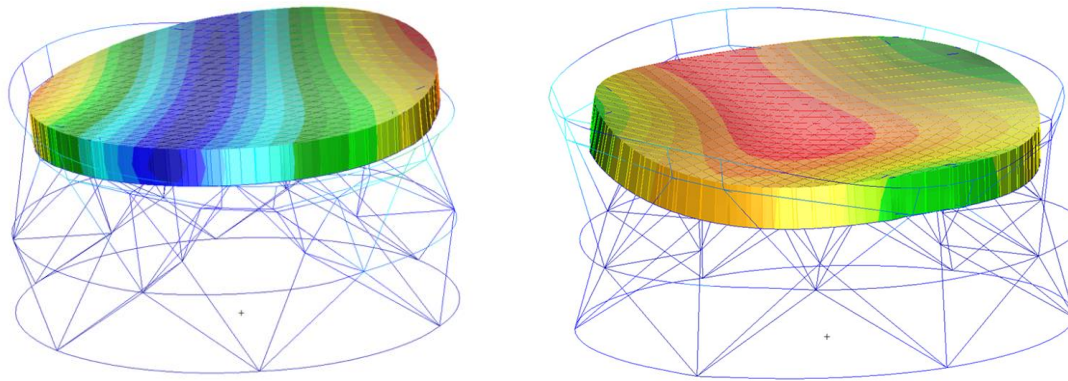
Largest error is Astigmatism, but VVC-6 is insensitive.

Most important error is Trefoil, but it still has 10X margin.

				LOS	
Index		Aberration	Allocation LOS [pm rms]	MARGIN	RSS WFE
N	M				(pm rms)
		TOTAL RMS	2528	423	5.982
1	1	Tilt	1351.83	436	3.100
2	0	Power (Defocus)	1010.98	717	1.411
2	2	Astigmatism	1224.08	255	4.795
3	1	Coma	1089.60	999	1.090
4	0	Spherical	925.42	134014	0.007
3	3	Trefoil	0.51	10	0.052
4	2	Sec Astigmatism	0.28	14	0.020
5	1	Sec Coma	0.25	80	0.003
6	0	Sec Spherical	0.19	6229	0.000
4	4	Tetrafoil	0.49	822	0.001
5	3	Sec Trefoil	0.23	845	0.000
6	2	Ter Astigmatism	0.14	2015	0.000
7	1	Ter Coma	0.12	15487	0.000
5	5	Pri Pentafoil	0.17	24802	0.000
6	4	Sec Tetrafoil	0.17	49528	0.000
7	3	Ter Trefoil	0.13	107071	0.000
6	6	Hexafoil	0.12	406765	0.000
7	5	Sec Pentafoil	0.12	297466	0.000
7	7	Pri Septafoil	0.14	582541	0.000

Wavefront Stability: Inertial

Inertial WFE is caused by the Primary Mirror reacting against its mount (i.e. rocking or bouncing) in response to accelerations (i.e. from the microthrusters).



To minimize Inertial WFE:

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

NOTE: Inertial WFE is not caused by resonant motion.

Wavefront Stability: Inertial

To predict inertial WFE:

- NASTRAN calculated PM surface displacement from 0 to 350 Hz for micro-thruster noise applied to structure from 0 to 10 HZ.
- WFE was fit to Zernike polynomials using SigFig.

While trefoil is 2X higher than its initial error budget allocation, this is not a problem.

It is easily remedied by reallocating the error budget.

Additional margin can be obtained by adding passive or active vibration isolation.

		Inertial WFE Stability			
			Allocation		Zernikes
Index			Inertial	MARGIN	[pm rms]
N	M	Aberration	[pm rms]		
		TOTAL RMS	891.94		3.994
1	1	Tilt	1351.83	10990.5	0.123
2	0	Power (Defocus)	1010.98	707.0	1.430
2	2	Astigmatism	1224.08	343.9	3.559
3	1	Coma	1089.60	11006.1	0.099
4	0	Spherical	925.42	4344.7	0.213
3	3	Trefoil	0.51	0.5	1.039
4	2	Sec Astigmatism	0.28	1.6	0.178
5	1	Sec Coma	0.25	9.6	0.026
6	0	Sec Spherical	0.19	6.7	0.028
4	4	Tetrafoil	0.49	2.5	0.198
5	3	Sec Trefoil	0.23	2.0	0.112
6	2	Ter Astigmatism	0.14	6.7	0.021
7	1	Ter Coma	0.12	3.6	0.033
5	5	Pentafoil	0.17	2.3	0.074
6	4	Sec Tetrafoil	0.17	6.0	0.029
7	3	Ter Trefoil	0.13	8.6	0.015
6	6	Hexafoil	0.12	4.7	0.026
7	5	Sec Pentafoil	0.12	7.8	0.015
7	7	Septafoil	0.14	13.6	0.010

Wavefront Stability: Thermal

Thermal WFE instability occurs when PM temperature changes.

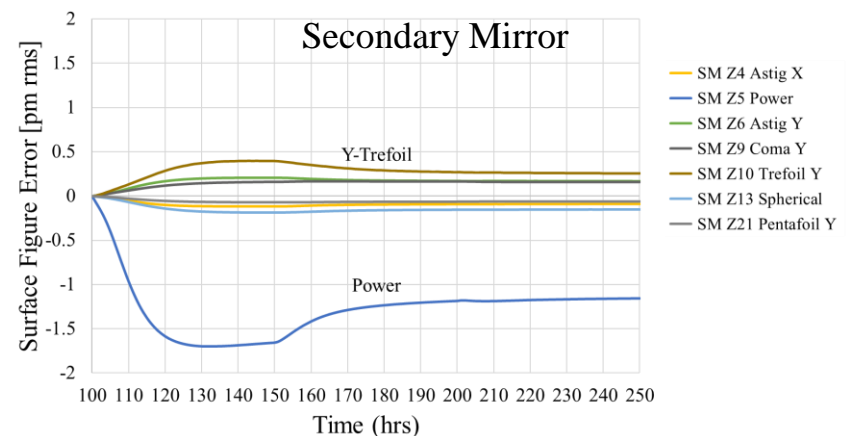
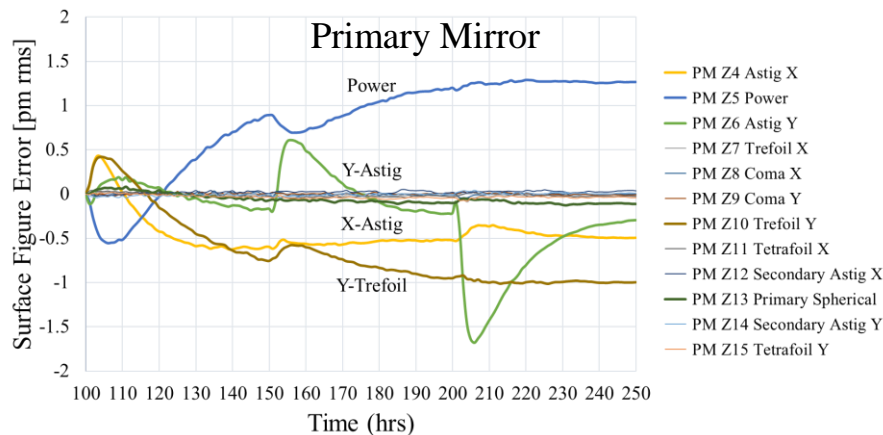
PM CTE homogeneity produces a temperature dependent WFE.

Thermal WFE instability as a function of time was calculated using Thermal Desktop, NASTRAN and SigFit.

Symmetric errors change with pitch angle

Asymmetric errors change with roll.

SM is insensitive to roll.



Wavefront Stability: Thermal

Total DRM wavefront error was calculated by RSSing the primary and secondary mirror Zernike terms as a function of time and selecting the maximum amplitude for each.

Trefoil is a problem, but again the error budget can be reallocated.

And, additional margin can be obtained by adding passive or active vibration isolation.

Please note: Thermal STOP analysis pipeline does not evaluate as many of the higher order Zernike terms as the Opto-Mechanical STOP analysis pipeline.

Thermal WFE Stability					
Index			Allocation	MARGIN	Zernike
N	M	Aberration	Thermal [pm rms]		[pm rms]
		TOTAL RMS	2528.15		5.565
1	1	Tilt	1351.83	51993.3	0.026
2	0	Power (Defocus)	1010.98	268.9	3.759
2	2	Astigmatism	1224.08	353.5	3.463
3	1	Coma	1089.60	3158.3	0.345
4	0	Spherical	925.42	2285.0	0.405
3	3	Trefoil	0.51	0.2	2.098
4	2	Sec Astigmatism	0.28	2.6	0.108
5	1	Sec Coma	0.25	2.4	0.105
6	0	Sec Spherical	0.19		
4	4	Tetrafoil	0.49	2.6	0.189
5	3	Sec Trefoil	0.23	1.0	0.233
6	2	Ter Astigmatism	0.14		
7	1	Ter Coma	0.12		
5	5	Pentafoil	0.17	0.8	0.217
6	4	Sec Tetrafoil	0.17		
7	3	Ter Trefoil	0.13		
6	6	Hexafoil	0.12		
7	5	Sec Pentafoil	0.12		
7	7	Septafoil	0.14		

Baseline Telescope Error Budget Optimized for VVC-6

Because some Zernike terms are more likely to occur than others, it is permissible to reallocate contrast leakage from the less likely terms to the more likely terms, i.e. Trefoil, and have 2.7X margin.

Index		Aberration	Predicted Performance Amplitude [pm rms]			Total WFE [pm rms]	VVC-6 Sensitivity [ppt/pm PV]	Raw Contrast [ppt]	Allocation [ppt]	WFE Tolerance [pm RMS]	Margin
N	M		LOS	Inertial	Thermal						
		TOTAL RMS	5.982	3.994	5.565	9.094		14.569	40.000	24.969	
1	1	Tilt	3.100	0.123	0.026	3.103	0.0002	0.001	0.004	8.519	2.7
2	0	Power (Defocus)	1.411	1.430	3.759	4.262	0.0003	0.002	0.007	11.702	2.7
2	2	Astigmatism	4.795	3.559	3.463	6.903	0.0002	0.003	0.009	18.952	2.7
3	1	Coma	1.090	0.099	0.345	1.148	0.0002	0.001	0.002	3.152	2.7
4	0	Spherical	0.007	0.213	0.405	0.458	0.0003	0.000	0.001	1.257	2.7
3	3	Trefoil	0.052	1.039	2.098	2.342	1.0016	6.634	18.215	6.430	2.7
4	2	Sec Astigmatism	0.020	0.178	0.108	0.209	1.6495	1.091	2.995	0.574	2.7
5	1	Sec Coma	0.003	0.026	0.105	0.108	1.6645	0.624	1.713	0.297	2.7
6	0	Sec Spherical	0.000	0.028	0.000	0.028	2.8902	0.214	0.588	0.077	2.7
4	4	Tetrafoil	0.001	0.198	0.189	0.274	0.9312	0.806	2.213	0.752	2.7
5	3	Sec Trefoil	0.000	0.112	0.233	0.259	1.8200	1.630	4.475	0.710	2.7
6	2	Ter Astigmatism	0.000	0.021	0.000	0.021	2.7219	0.214	0.587	0.058	2.7
7	1	Ter Coma	0.000	0.033	0.000	0.033	3.0608	0.404	1.109	0.091	2.7
5	5	Pentafoil	0.000	0.074	0.217	0.229	2.4409	1.939	5.323	0.629	2.7
6	4	Sec Tetrafoil	0.000	0.029	0.000	0.029	2.2050	0.239	0.657	0.080	2.7
7	3	Ter Trefoil	0.000	0.015	0.000	0.015	2.7946	0.168	0.460	0.041	2.7
6	6	Hexafoil	0.000	0.026	0.000	0.026	3.1667	0.308	0.846	0.071	2.7
7	5	Sec Pentafoil	0.000	0.015	0.000	0.015	3.0694	0.184	0.506	0.041	2.7
7	7	Septafoil	0.000	0.010	0.000	0.010	2.6510	0.106	0.291	0.027	2.7

Please note: this error budget is ONLY for the baseline PMA.
And, error budget can be adjusted for ‘actual’ performance.

Conclusions

The HabEx Baseline Telescope Design ‘Closes’.

It meets the specifications for LOS Jitter and WFE Stability.

The design uses standard engineering practice.

Baseline design is enabled by two capabilities:

- SLS volume and mass capacity.
- Low mechanical disturbance provided by micro-thrusters.