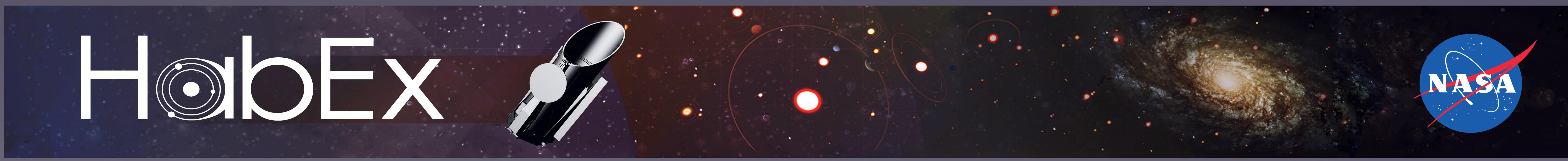

Baseline Telescope: Design & Performance Analysis

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and the HabEx MSFC/JPL Design Team and the HabEx Science and Technology Definition Team

STOP Modeling indicates Baseline Telescope has ultra-stable wavefront for coronagraphy

HABITABLE EXOPLANET MISSION

HabEx is one of four missions under study for 2020 Astrophysics Decadal Survey. It will directly image and spectroscopically characterize planetary systems in the habitable zone of Sun-like stars. Additionally, HabEx will perform a broad range of general astrophysics science enabled by 115 to 2500 nm spectral range and 3 x 3 arc-minute FOV.

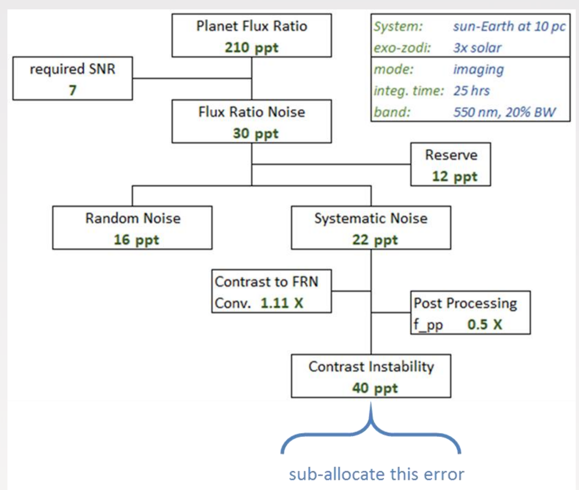
Baseline Telescope design & performance specifications derive from science requirements

- Diameter > 4 meters unobscured
- Primary Mirror F/# 2.5 (driven by Polarization)
- Diffraction Limit 400 nm
- LOS Stability (per axis on sky) < 0.5 mas rms
- WFE Stability < 1 to 250 pm rms

Wavefront Stability is critical for internal coronagraphy.

To derive WFE stability specification:

- Start with allowable Starlight Leakage through Coronagraph,
- Calculate Contrast Leakage Sensitivities for each Zernike polynomial
- Sub-Allocate allowable Contrast Leakage between Zernike polynomials
- Then partition allowable Zernike errors between Line-of-Sight (LOS) jitter, Inertial WFE and Thermal WFE (see Conclusion).

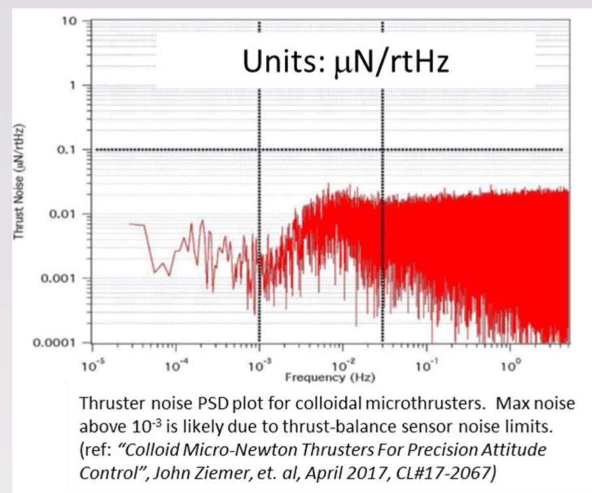


allocation, tolerance, sensitivity:

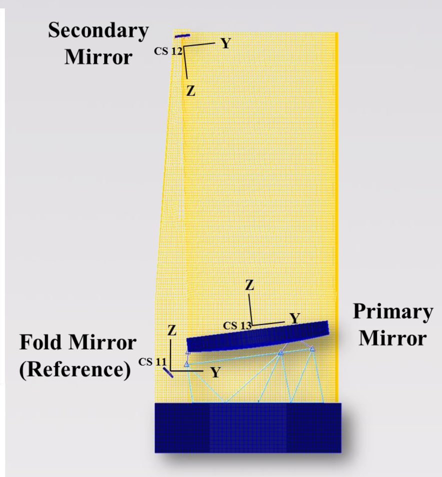
$$\epsilon_i = \left(\frac{\partial e}{\partial x_i}\right)\cdot \delta x_i$$

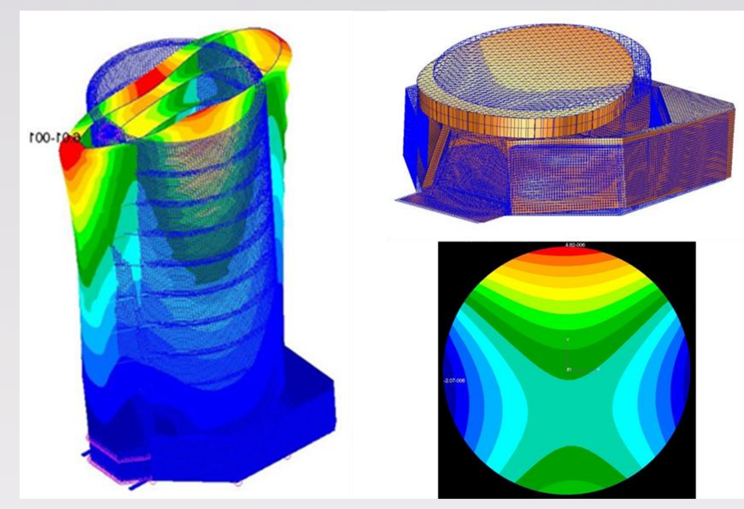
MECHANICAL STABILITY

Micro-thruster noise can excite telescope modes – causing LOS jitter and WFE instability. Dynamic STOP analysis determined rigid body motion between primary, secondary and tertiary mirrors. And inertial bending of primary mirror on its mount. Analysis assumes that each head has a flat 0.1 micro-Newton noise spectrum and telescope has 0.0005% critical damping.

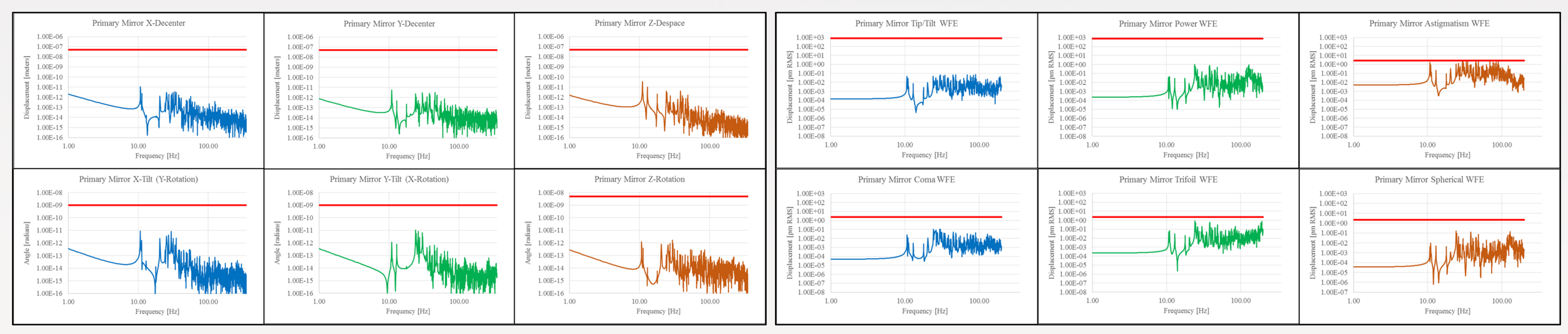


Thruster noise PSD plot for colloidal microthrusters. Max noise above 10^{-3} is likely due to thrust-balance sensor noise limits. (ref: *"Colloid Micro-Newton Thrusters For Precision Attitude Control", John Ziemer, et. al, April 2017, CL#17-2067*)





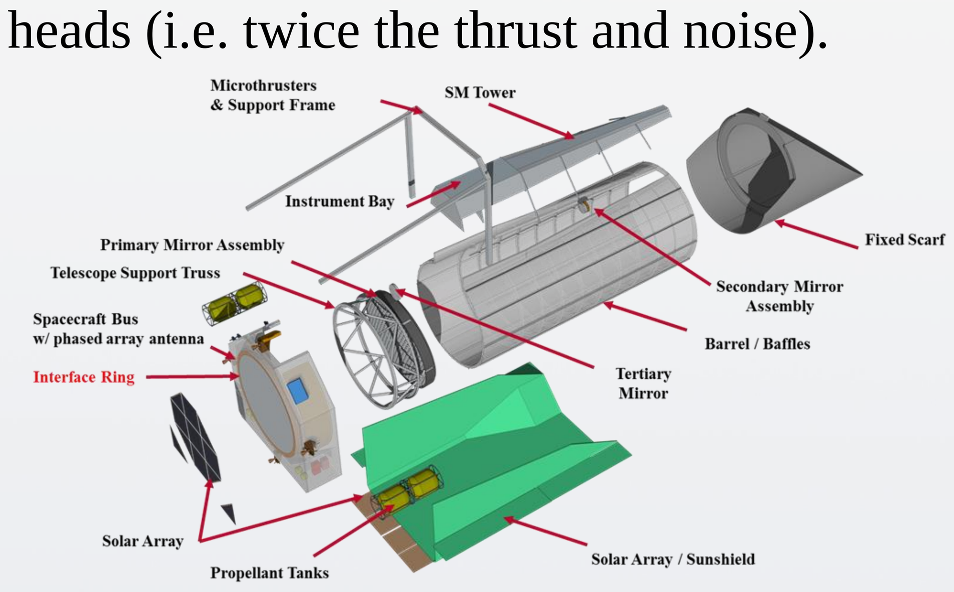
Predicted rigid body motion (with 4X MUF) caused by micro-thruster noise is several orders of magnitude below LOS Jitter Specification (left) and has margin against Primary Mirror Inertial WFE Specification (right). Actual micro-thruster performance is 2X lower than specification.

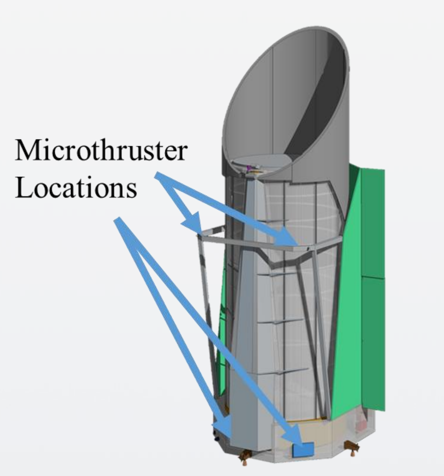


DESIGN CONCEPT

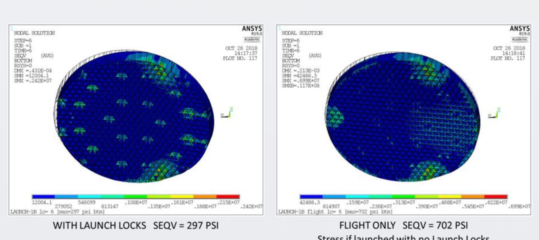
Baseline telescope is a 4-meter off-axis unobscured TMA with a scarfed straylight baffle tube. Spacecraft surrounds telescope providing thermal isolation. For mechanical isolation, the two are connected only at a common interface ring.

Micro-thrusters provide pointing control during science observations. Spacecraft has 4 forward thruster pods' and 4 aft pods. Forward pods have 4 heads. Aft pods have 8 heads (i.e. twice the thrust and noise).



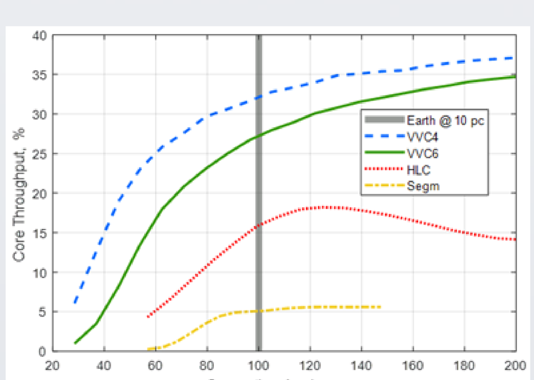


Primary Mirror designed to have sufficient stiffness and thermal mass to provide required WFE stability, survive launch and be easily manufactured.

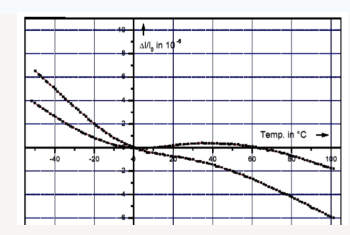


PM Launch Lock system keeps launch stress < 300 psi.

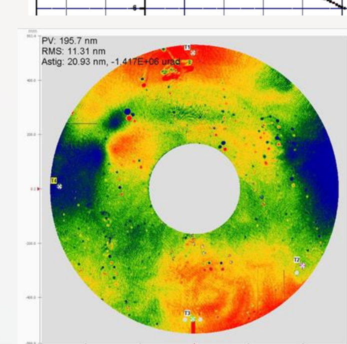
Baseline Coronagraph is Vector Vortex. Both Charge 4 and Charge 6 provide excellent Core Throughput and small Inner Working Angle.



THERMAL STABILITY



Zerodur® is baseline for primary mirror because its ±5 ppb/C homogeneous CTE can be tailored to near 'zero' over operating temperature range – minimizing thermal WFE instability.

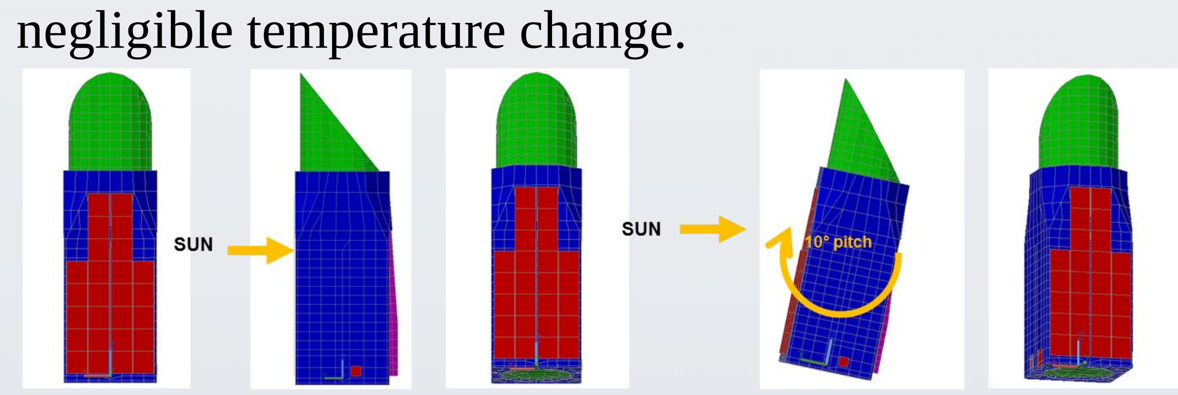


Analysis of measured Zerodur mirror thermal performance indicates that Error Budget Thermal WFE allocation can be achieved if primary mirror stability is < 2 mK.

Stability is provided by primary mirror's mass, passive thermal isolation and active 'predictive' thermal control of the primary mirror and structure.

STOP Analysis indicates that science observations can proceed without interruption for anti-sun pitch of up to 45 degree and 15 degree roll (for speckle subtraction)

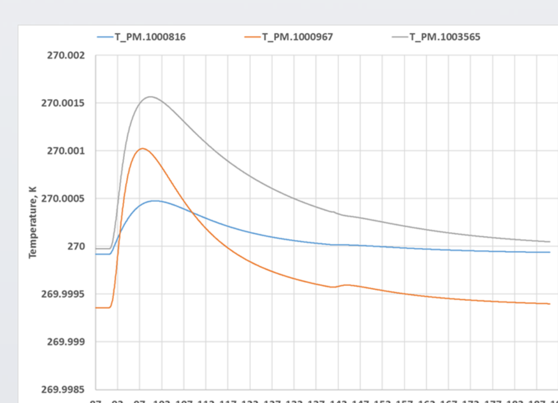
Plot on right shows Maximum Temperature change of 1.6 mK for a 15 degree anti-sun pitch after 50 hours 'digging' the dark hole. (45 deg pitch produces max temp change of 1.9 mK.) 15 degree roll after another 50 hours shows negligible temperature change.



"ReferenceStar" View from the sun

"After pitch 10° pitch" View from the sun

"After 15° Roll" View from the sun



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CONCLUSION

STOP Analysis indicates that HabEx's Baseline 4-m off-axis telescope design has mechanical & thermal stability required to perform coronagraphy with at least a VVC-6 and maybe a VVC-4.

Micro-Thrusters are enabling.

K	N	M	Aberration	VVC-4 Tolerance [pm rms]	LOS [pm rms]	Inertial [pm rms]	Thermal [pm rms]	Reserve [pm rms]	Predicted Performance Margin LOS	Predicted Performance Margin Inertial [uG]	Predicted Performance Margin Thermal [mK]
			RSS Allocation	100%	50%	70%	50%	10%		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