HabEx

Habitable-zone Exoplanet Observatory (HabEx) Telescope: Systems Engineering and STOP Modeling

H. Philip Stahl
NASA
MSFC, AL 35812

HabEx

Contributors

JPL
- Gary Kuan
- Velibor Cormarkovic
- Scott Howe
- Stefan Martin
- Navtej Saini
- Juan Villalvazo
- Keith Warfield

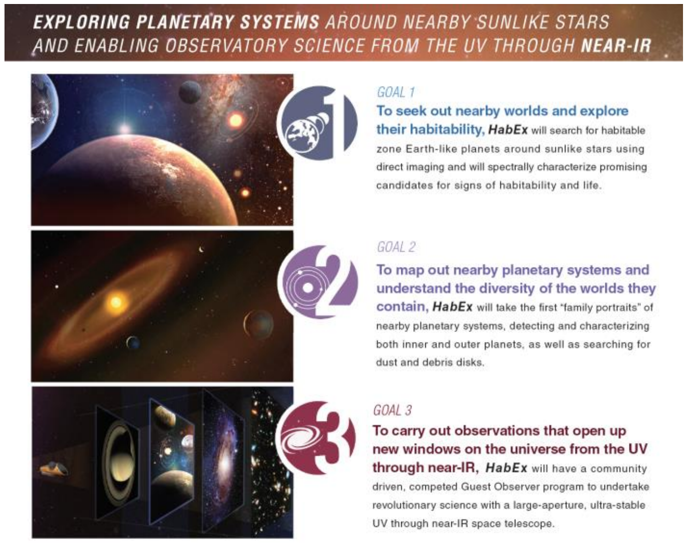
MSFC
- Thomas Brooks, NASA
- Jacqueline Davis, NASA
- Brent Knight, NASA

AI Solutions
- William Arnold,

ESSA
- Mike Baysinger
- Jay Garcia

Interns
- Jonathon Gaskin, UNCC
- Jonathan McCready, NCSU
- Hao Tang, Univ of MI

Purpose of HabEx



from HabEx interim report URS273294

Architecture A Concept

The HabEx STDT chose these parameters for Architecture A:

- Telescope with a 4m aperture
- 52-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

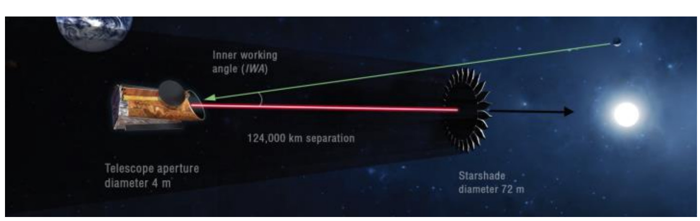


Image from HabEx interim report URS273294

HabEx

Executive Summary

Telescope Design Team used Science-Driven Systems-Engineering:
- Performance Specifications derived from Science Requirements.

Coronagraphy requires an ultra-stable wavefront.

Able to achieve Ultra-Stable Telescope using standard engineering practices because of:
- 8-m fairing volume provided by SLS
- Low mechanical disturbance provided by micro-thrusters.

STOP Modeling indicates that HabEx Baseline Telescope Design achieves its specified LOS Jitter and Wavefront stability.

HabEx

Science Driven Systems Engineering

HabEx — Systems Engineering

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**
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

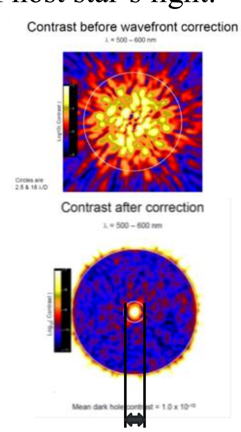
HabEx — 'The' System Challenge: Dark Hole

Imaging an 'exo-Earth' requires blocking 10^{10} of host star's light.

Internal coronagraph (with deformable mirrors) can create a 'dark hole' with $< 10^{-10}$ contrast.

Once established, the dark hole's instantaneous (not averaged over integration time) speckle intensity must be stable to $\sim 10^{-11}$ contrast between science exposures.

This requires that the corrected wavefront phase must be kept stable to within a few picometers rms between science exposures – either passively or via active control.



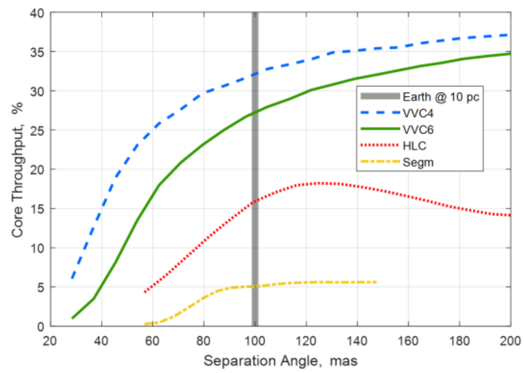
Inner Working Angle
(John Krist, JPL)

Krist, Trauger, Unwin and Traub, "End-to-end coronagraphic modeling including a low-order wavefront sensor", SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

Shaklan, Green and Palacios, "TPFC Optical Surface Requirements", SPIE 626511-12, 2006.

HabEx ‘The’ System Challenge: Dark Hole

- Dark hole must have 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.

HabEx Line of Sight (LOS) Stability

LOS instability causes PSF smear and beam-shear WFE.

LOS instability has two causes:

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

Specification of < 0.3 mas rms per axis is uncorrectable Jitter and residual Drift after correction by Laser-truss system.

Specification establishes rigid-body motion error budget.

LOS instability also causes WFE instability due to beam shear.

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

HabEx

Wavefront Stability

WFE instability causes 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 drivers for Temporal Wavefront Error:

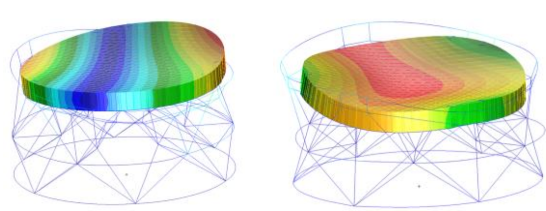
- Thermal Environment – telescope slews relative to sun
- Mechanical Environment – vibration disturbance sources

HabEx

Wavefront Stability: Inertial

A potentially less familiar source of WFE instability is 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:

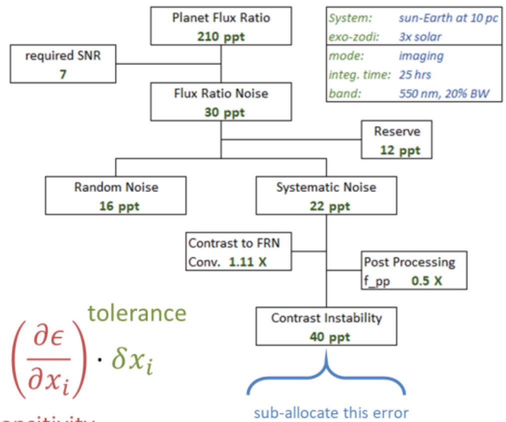
- Design the PM Substrate to be as stiff as possible
- Consider the Mount stiffness and location.

NOTE: Inertial WFE is not caused by resonant motion.

HabEx Wavefront Stability Error Budget

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

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



allocation — tolerance

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

sensitivity

HabEx 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%
				30				
Index			VVC-6 Sensitivity	Contrast Allocation	VVC-6 Tolerance	LOS	Inertial	Thermal
N	M	Aberration	[ppt/pm]	[ppt]	[pm rms]	[pm rms]	[pm rms]	[pm rms]
		TOTAL RMS		30.00	4381.1	2528	2528	2528
1	1	Tilt	2.13E-04	1.00	2342.6	1351.83	1351.83	1351.83
2	0	Power (Defocus)	3.30E-04	1.00	1751.9	1010.98	1010.98	1010.98
2	2	Astigmatism	1.92E-04	1.00	2121.2	1224.08	1224.08	1224.08
3	1	Coma	1.87E-04	1.00	1888.2	1089.60	1089.60	1089.60
4	0	Spherical	2.79E-04	1.00	1603.7	925.42	925.42	925.42
3	3	Trefoil	1.00	8.00	2.8	1.63	1.63	1.63
4	2	Sec Astigmatism	1.650	8.00	1.5	0.88	0.88	0.88
5	1	Sec Coma	1.665	8.00	1.4	0.80	0.80	0.80
6	0	Sec Spherical	2.890	8.00	1.0	0.60	0.60	0.60
4	4	Tetrafoil	0.931	8.00	2.7	1.57	1.57	1.57
5	3	Sec Trefoil	1.820	8.00	1.3	0.73	0.73	0.73
6	2	Ter Astigmatism	2.722	8.00	0.8	0.45	0.45	0.45
7	1	Ter Coma	3.061	8.00	0.7	0.38	0.38	0.38
5	5	Pentafoil	2.441	8.00	0.9	0.55	0.55	0.55
6	4	Sec Tetrafoil	2.205	8.00	1.0	0.56	0.56	0.56
7	3	Ter Trefoil	2.795	8.00	0.7	0.41	0.41	0.41
6	6	Hexafoil	3.167	8.00	0.7	0.39	0.39	0.39
7	5	Sec Pentafoil	3.069	8.00	0.7	0.38	0.38	0.38
7	7	Septafoil	2.651	8.00	0.8	0.44	0.44	0.44

HabEx Baseline Telescope

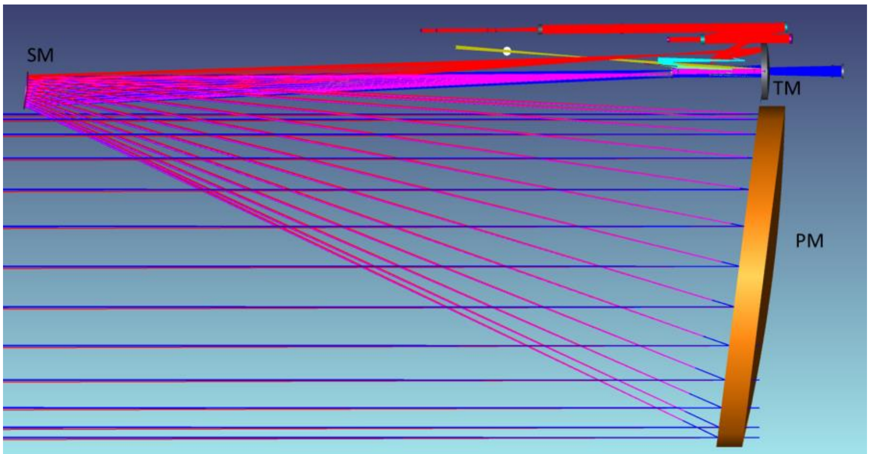
Design Overview

Optical Telescope Assembly (OTA) Specifications

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)	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

HabEx telescope optical design is off-axis TMA.



HabEx — Why Off-Axis

Science depends on the telescope Point Spread Function (PSF) and the angular size of the 80% Encircled Energy (EE) circle:

- Inner Working Angle (IWA) Expolanet Science
- Angular Resolution General Astrophysics

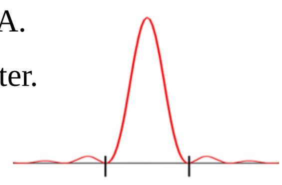
IWA is how close to a host star the coronagraph can detect an exo-planet – based on its ability to block light from the host star.

The more compact the PSF, the smaller the IWA.

PSF size depends on Telescope aperture diameter.

PSF central lobe angular radius = 1.22 λ/D.

83% of the energy is in the central lobe.



The larger the telescope aperture, the smaller the PSF and IWA.

HabEx — Why Off-Axis

But, PSF is also affected by central obscuration and spiders.

Diffraction from central obscuration and spiders broaden the PSF and move energy out of the central core.

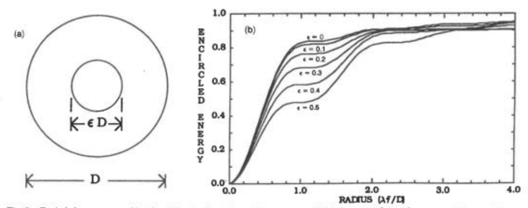


Fig. 6. Encircled energy caused by the diffraction-limited annular apertures. This figure can be used as a set of characteristic curves from which to obtain values of $EE_{annulus}(r)$, which are necessary when the empirical equation is applied to various aperture configurations.

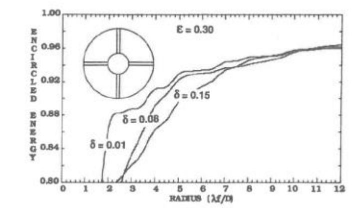


Fig. 13. Corresponding fractional encircled energy curves providing insight into the image-degradation effects of secondary mirror spiders of varying widths.

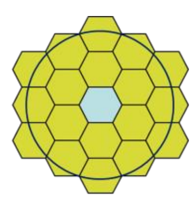
Thus, an off-axis unobscured aperture has a smaller IWA than an on-axis centrally obscured aperture.

Harvey, James E. and Christ Ftaclas, "Diffraction effects of telescope secondary mirror spiders on various image-quality criteria", Applied Optics, Vol.34, No.28, p.6337, 1 Oct 1995.

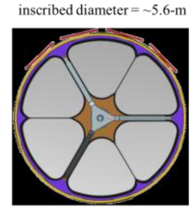
HabEx — Why Off-Axis

For an on-axis aperture to achieve the same angular resolution as an off-axis aperture, it needs to be larger.

Obscuration Ratio [%]	80% EE Radius [λ/D]	Aperture [m]
0	0.9	4.0
10%	1.0	4.4
20%	1.6	6.4
30%	1.7	6.8
40%	1.8	7.2
50%	1.9	7.6
75%	4.5	18



JWST is 20% obscured; inscribed diameter = ~5.6-m



Proposed HabEx Lite is 40% obscured.

To achieve same IWA as Baseline 4-m off-axis:

- At 20% obscured a JWST style aperture would need a point to point size of ~7.2m
- At 40%, proposed HabEx Lite also needs ~7.2m

Harvey, James E. and Christ Ftaclas, "Diffraction effects of telescope secondary mirror spiders on various image-quality criteria", Applied Optics, Vol.34, No.28, p.6337, 1 Oct 1995.
Baliga, J.V. and B.D. Cohn, "Simplified method for calculating encircled energy", SPIE Proc.892, p.152, 1988.
Redding et. al., "HabEx Lite: a Starshade-only Habitable Exoplanet Imager Alternative", SPIE, 2018

HabEx — Why Off-Axis

Finally, diffraction from Segment Gaps and Struts also removes energy from the PSF core and can significantly increase radius to achieve 80% EE.

Potentially doubling the required aperture diameter to achieve the same IWA for a centrally obscured aperture without struts. (Or nearly 4X that of an off-axis unobscured aperture.)

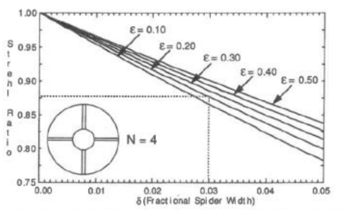


Fig. 3. Parametric plot of the ratio of the peak irradiance in the diffraction-limited PSF produced by an annular aperture of obscuration ratio ε and four spiders of width δD divided by that produced by an annular aperture without spiders.

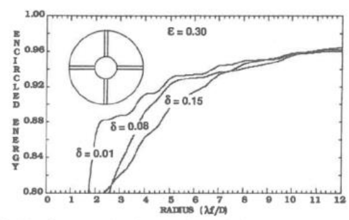


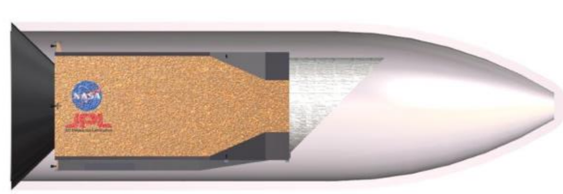
Fig. 13. Corresponding fractional encircled energy curves providing insight into the image-degradation effects of secondary mirror spiders of varying widths.

Harvey, James E. and Christ Ftaclas, "Diffraction effects of telescope secondary mirror spiders on various image-quality criteria", Applied Optics, Vol.34, No.28, p.6337, 1 Oct 1995.

HabEx — Designed for the SLS

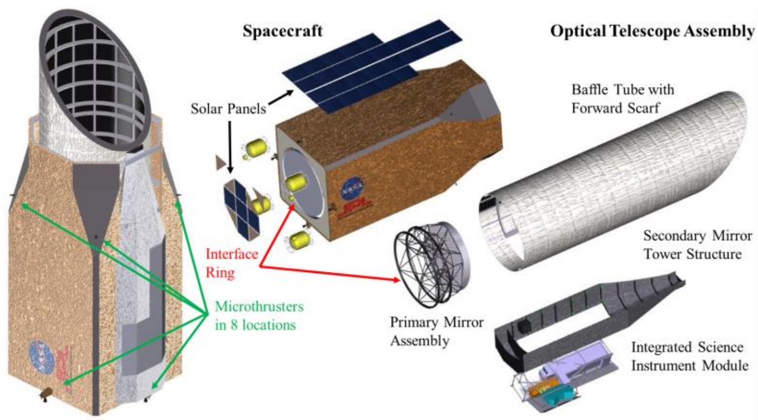
Baseline takes advantage of SLS Volume and Mass Capacities.

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



HabEx — Baseline Design

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



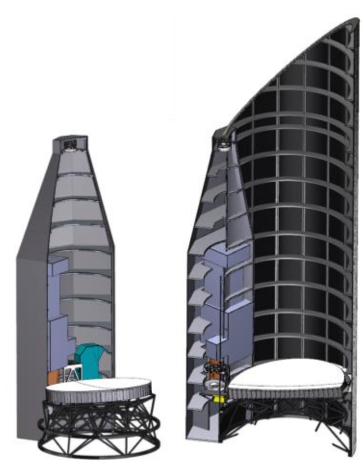
HabEx — Tower and Tube Structure

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.



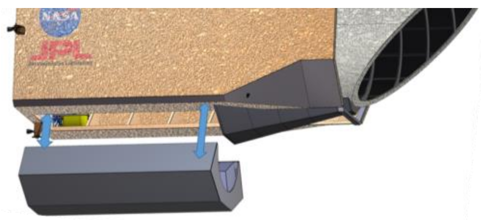
HabEx Science Instrument Module

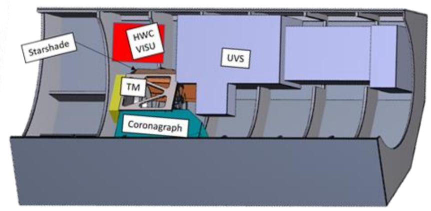
Science Instruments are in Integrated Science Instrument Module.

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.



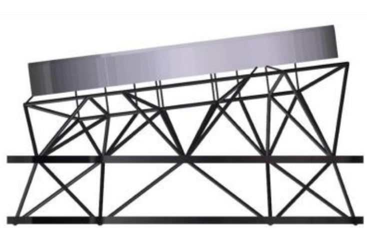


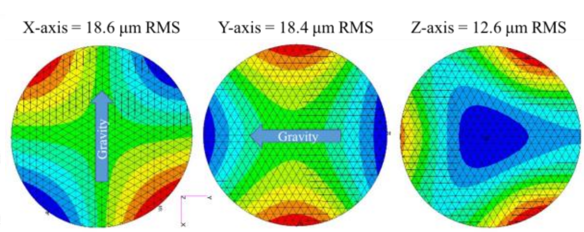
HabEx Primary Mirror Assembly

Dozens of Zerodur® and ULE® mirror designs were considered.

Baseline Zerodur® mirror design balances mass and stiffness.

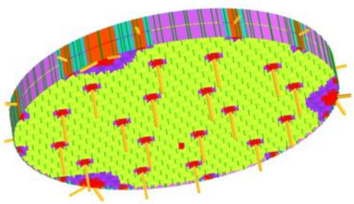
- Substrate has a flat-back geometry with a 42 cm edge thickness and mass of approximately 1400 kg.
- The mirror's free-free first mode frequency is 88 Hz. And, its mounted first mode frequency is 70 Hz.
- The mirror is locally stiffened to minimize gravity sag.



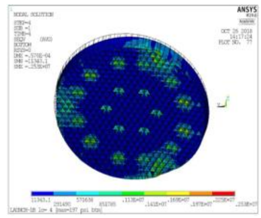


HabEx PM Launch Constraint System

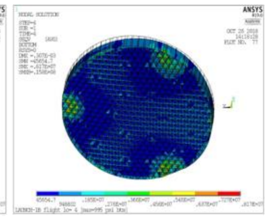
While Zerodur® can survive loads as high as 17,400 psi, the launch constraint system keeps launch stress at ~100 psi.



18-Axial Launch Locks
12-Radial Launch Locks



With Launch Locks
Launch Stress = ~ 200 psi



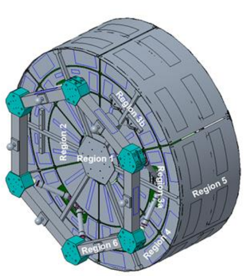
Without Launch Locks
Launch Stress = ~ 1000 psi

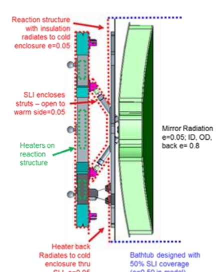
Launch constraint system has 18 axial and 12 radial launch locks.

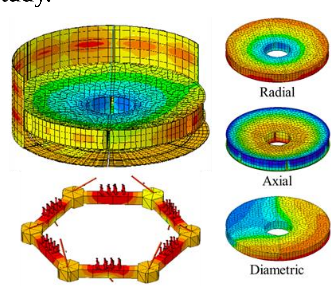
HabEx PM Thermal Control System

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.

HabEx Mission Mass Estimate

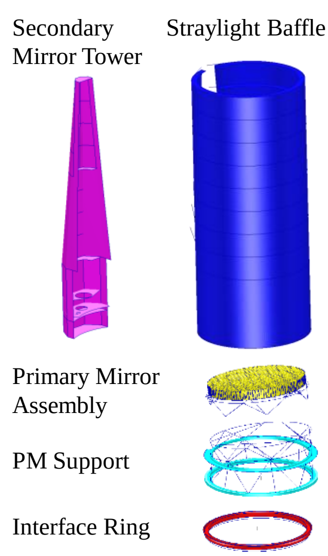
Baseline mission mass with 30% margin is well within the 44 mt SLS mass capacity (only uses ~ 33%).

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

HabEx OTA Mass Estimate

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

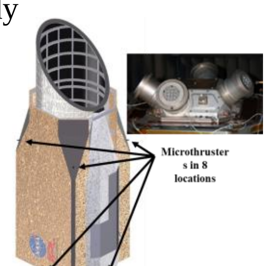


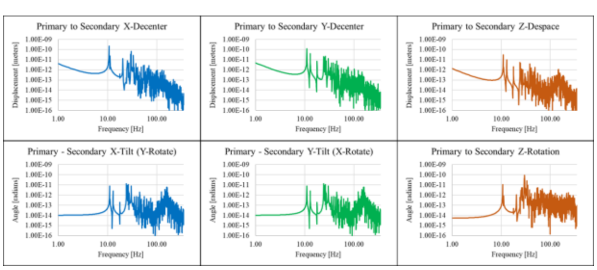
HabEx Baseline Telescope

Performance Predictions

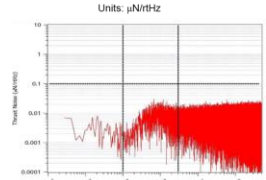
Predicted LOS Stability: Jitter

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.





Units: µN/rtHz

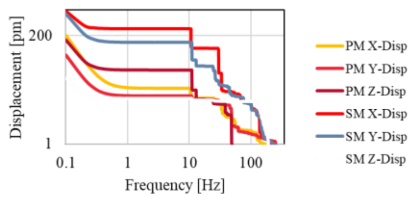


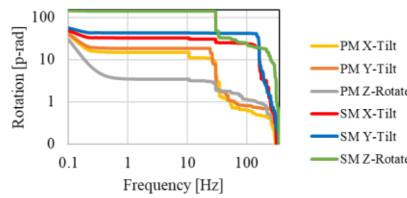
Thruster noise PSD plot for colloidal microthrusters. Max noise above 10^{-3} is likely due to thrust-balance sensor noise limits.

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

Predicted LOS Stability: Jitter (> 10 Hz)

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.





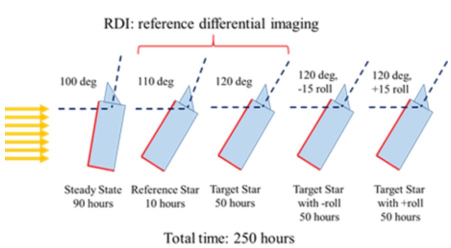
Total rigid-body motion yields < 0.03 mas jitter (10X margin) against 0.3 mas (> 10 Hz) specification.

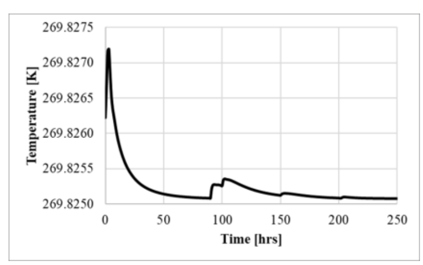
Table 6: Predicted maximum 'jitter' motion of PM and SM from Microthruster Noise

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 (< 10 Hz)

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

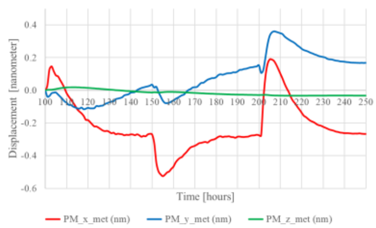


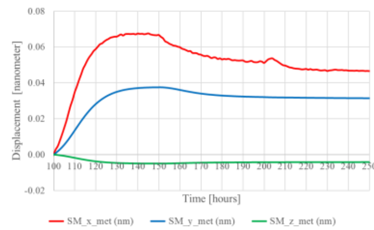


Drift is the 'residual' the rigid-body motion of the primary and secondary mirrors relative to the tertiary mirror that is not corrected by the laser metrology system that senses and controls the optical alignment of the primary and secondary mirrors.

Predicted LOS Stability: Thermal Drift (< 10 Hz)

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 (12.5X margin) against 2.5 mas (< 10 Hz) specification

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 errors are Power & Astigmatism, but VVC-6 is insensitive

Most important error is Trefoil, but it still has 140X margin.

Index N	M	Aberration	Allocation LOS [pm rms]	MARGIN	LOS RSS WFE (pm rms)
		TOTAL RMS	2528	1430	1.767
1	1	Tilt	1351.83	1984	0.681
2	0	Power (Defocus)	1010.98	837	1.208
2	2	Astigmatism	1224.08	1145	1.069
3	1	Coma	1089.60	4547	0.240
4	0	Spherical	925.42	212904	0.004
3	3	Trefoil	1.63	141	0.012
4	2	Sec Astigmatism	0.88	201	0.004
5	1	Sec Coma	0.80	1179	0.001
6	0	Sec Spherical	0.60	42835	0.000
4	4	Tetrafoil	1.57	11780	0.000
5	3	Sec Trefoil	0.73	12189	0.000
6	2	Ter Astigmatism	0.45	29360	0.000
7	1	Ter Coma	0.38	229124	0.000
5	5	Pri Pentafoil	0.55	356736	0.000
6	4	Sec Tetrafoil	0.56	740369	0.000
7	3	Ter Trefoil	0.41	1376489	0.000
6	6	Hexafoil	0.39	3944935	0.000
7	5	Sec Pentafoil	0.38	4982996	0.000
7	7	Pri Septafoil	0.44	6511622	0.000

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.

Trefoil is the most important error with only a 1.6X predicted margin.

Additional margin can be gained by reallocating the error budget.

Or, 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	1.63	1.6	1.039
4	2	Sec Astigmatism	0.88	5.0	0.178
5	1	Sec Coma	0.80	30.8	0.026
6	0	Sec Spherical	0.60	21.5	0.028
4	4	Tetrafoil	1.57	7.9	0.198
5	3	Sec Trefoil	0.73	6.5	0.112
6	2	Ter Astigmatism	0.45	21.6	0.021
7	1	Ter Coma	0.38	11.4	0.033
5	5	Pentafoil	0.55	7.4	0.074
6	4	Sec Tetrafoil	0.56	19.3	0.029
7	3	Ter Trefoil	0.41	27.5	0.015
6	6	Hexafoil	0.39	15.0	0.026
7	5	Sec Pentafoil	0.38	25.1	0.015
7	7	Septafoil	0.44	43.5	0.010

Wavefront Stability: Thermal

Thermal WFE instability occurs when PM temperature changes.

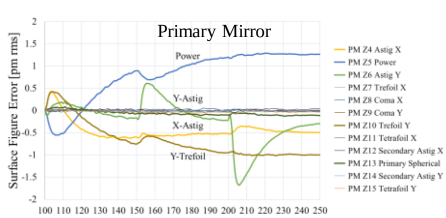
PM CTE homogeneity produces a temperature dependent WFE.

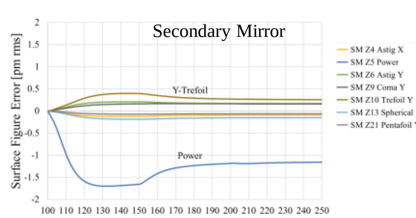
Thermal WFE instability as a function of time was calculated using Thermal Desktop, NASTRAN and SigFit.

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.

Index			Thermal WFE Stability		
			Allocation		Zernike
			Thermal	MARGIN	[pm rms]
N	M	Aberration	[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	1.63	0.8	2.098
4	2	Sec Astigmatism	0.88	8.2	0.108
5	1	Sec Coma	0.80	7.6	0.105
6	0	Sec Spherical	0.60		
4	4	Tetrafoil	1.57	8.3	0.189
5	3	Sec Trefoil	0.73	3.1	0.233
6	2	Ter Astigmatism	0.45		
7	1	Ter Coma	0.38		
5	5	Pentafoil	0.55	2.5	0.217
6	4	Sec Tetrafoil	0.56		

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

Baseline Telescope Error Budget Optimized for VVC-6

Because some Zernike terms are more likely to occur than others, reallocate contrast leakage from the less likely terms to the more likely terms, i.e. Trefoil, to give every error mode a 4.1X margin.

Index			Predicted Performance Amplitude [pm rms]			Total WFE	VVC-6 Sensitivity	Raw Contrast	Allocation	WFE Tolerance	Margin
N	M	Aberration	LOS	Inertial	Thermal	[pm rms]	[ppt/pm PV]	[ppt]	[ppt]	[pm RMS]	
		TOTAL RMS	5.715	3.994	5.565	8.921		7.289	30.000	36.715	
1	1	Tilt	3.025	0.123	0.026	3.027	0.0002	0.001	0.005	12.459	4.1
2	0	Power (Defocus)	0.728	1.430	3.759	4.087	0.0003	0.002	0.010	16.821	4.1
2	2	Astigmatism	4.674	3.559	3.463	6.819	0.0002	0.003	0.013	28.066	4.1
3	1	Coma	1.064	0.099	0.345	1.123	0.0002	0.001	0.002	4.620	4.1
4	0	Spherical	0.005	0.213	0.405	0.458	0.0003	0.000	0.001	1.883	4.1
3	3	Trefoil	0.050	1.039	2.098	2.342	1.0016	6.634	27.303	9.638	4.1
4	2	Sec Astigmatism	0.019	0.178	0.108	0.209	1.6495	1.091	4.489	0.861	4.1
5	1	Sec Coma	0.003	0.026	0.105	0.108	1.6645	0.624	2.568	0.445	4.1
6	0	Sec Spherical	0.000	0.028	0.000	0.028	2.8902	0.214	0.881	0.115	4.1
4	4	Tetrafoil	0.001	0.198	0.189	0.274	0.9312	0.806	3.317	1.127	4.1
5	3	Sec Trefoil	0.000	0.112	0.233	0.259	1.8200	1.630	6.708	1.064	4.1
6	2	Ter Astigmatism	0.000	0.021	0.000	0.021	2.7219	0.214	0.880	0.086	4.1
7	1	Ter Coma	0.000	0.033	0.000	0.033	3.0608	0.404	1.663	0.136	4.1
5	5	Pentafoil	0.000	0.074	0.217	0.229	2.4409	1.939	7.979	0.944	4.1
6	4	Sec Tetrafoil	0.000	0.029	0.000	0.029	2.2050	0.239	0.985	0.119	4.1
7	3	Ter Trefoil	0.000	0.015	0.000	0.015	2.7946	0.168	0.690	0.062	4.1
6	6	Hexafoil	0.000	0.026	0.000	0.026	3.1667	0.308	1.268	0.107	4.1
7	5	Sec Pentafoil	0.000	0.015	0.000	0.015	3.0694	0.184	0.758	0.062	4.1
7	7	Septafoil	0.000	0.010	0.000	0.010	2.6510	0.106	0.436	0.041	4.1

Please note: this error budget is ONLY for the baseline PMA.

Conclusions

HabEx telescope design team followed a science-driven systems-engineering process to produce a design that ‘Closes’

Baseline telescope meets specifications for LOS Jitter & 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.