Habitable-Zone Exoplanet (HabEx) Observatory Architecture-A Telescope Specification and Design Overview

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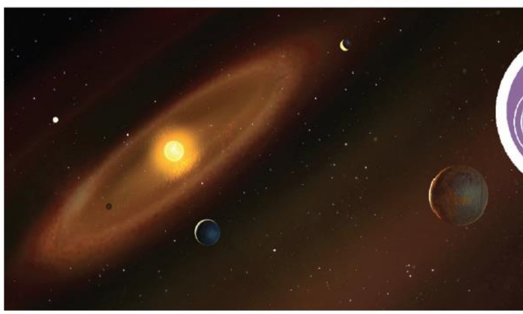
Purpose of HabEx

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

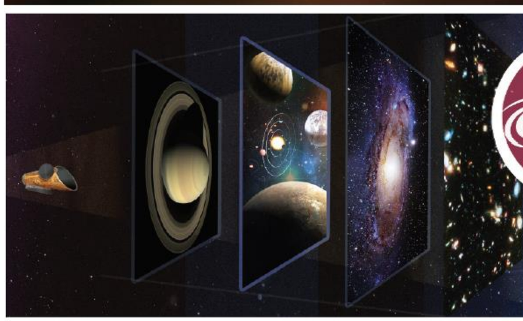
GOAL 1

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

Architecture A Concept

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

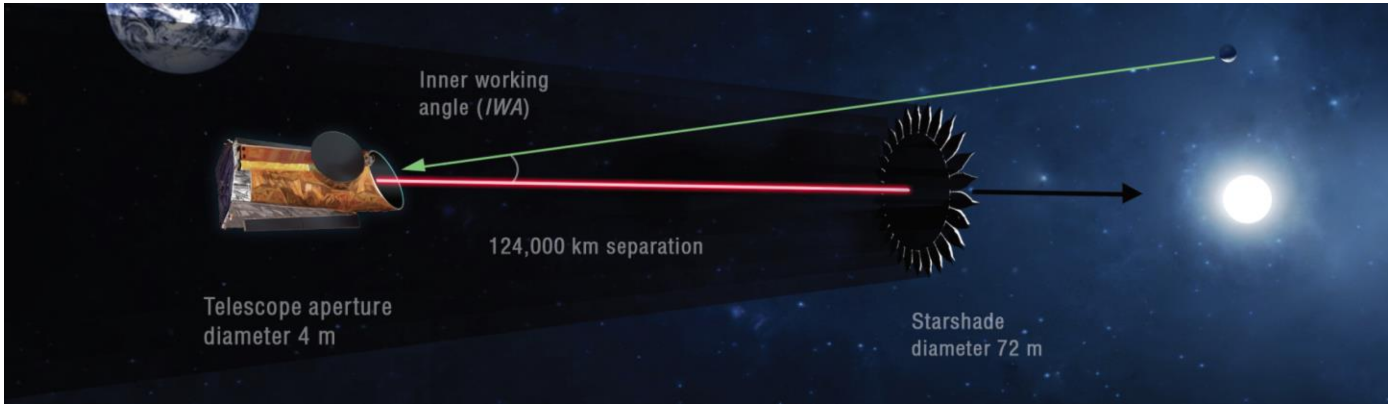


Image from HabEx interim report URS273294

HabEx Baseline Telescope

Specification

Science Requirement to Engineering Specification

General Astrophysics & Exoplanet Requirements & Launch Vehicle Constraints define different Engineering Specifications

Science Requirements → Engineering Specifications

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

OTA Specifications

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

Primary Mirror Specification

Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:

- **Observatory** *40 nm rms*
  - **Instruments** *15 nm rms*
  - **Telescope** *36 nm rms*
  - **Pointing Control** *10 nm rms*

Then flowing Telescope Requirements to major Sub-Systems

- **Telescope** *36 nm rms*
  - **PMA** *20 nm rms*
  - **SMA** *16 nm rms*
  - **Stability** *20 nm rms*
  - **Assemble, Align** *16 nm rms*

- **Monolithic PMA** *10 nm rms surface*
  - **Thermal** *5 nm rms*
  - **Polishing** *7.1 nm rms*
  - **Gravity/Mount** *5 nm rms*

Spatial Frequency Specification

Mid & High errors are important for Exoplanet Science. They can produce errors in the Dark Hole.

Thus, need a PSD Specification.

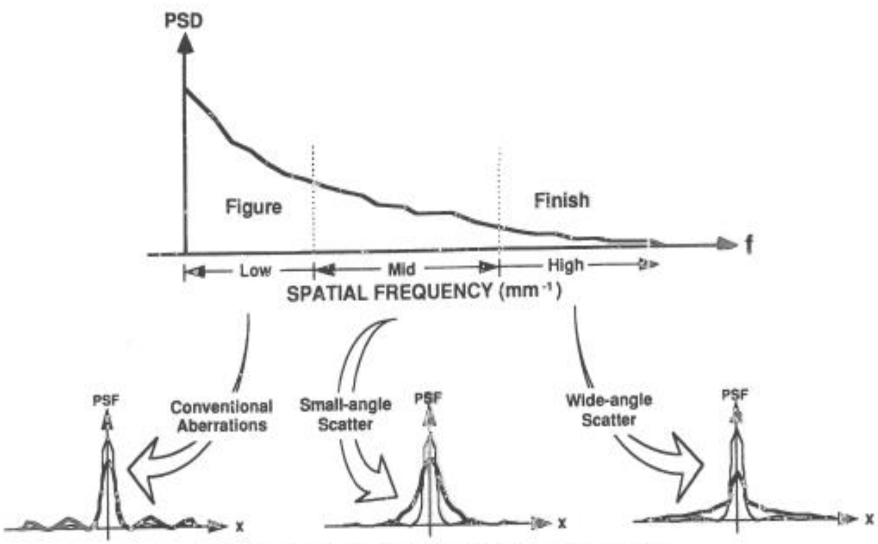
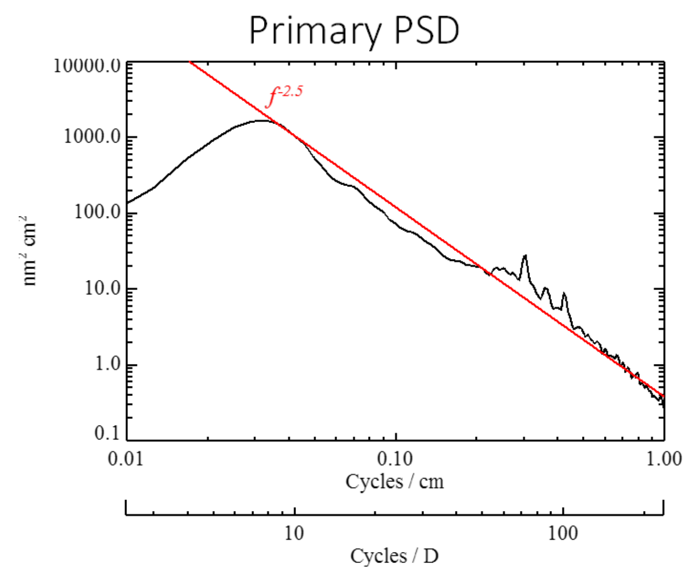


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

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



Line of Sight (LOS) Jitter

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.

Temporal Frequency	On-Sky LOS Stability
< 10 Hz	< 1 mas rms per axis
> 10 Hz	< 0.5 mas rms per axis (only required for internal coronagraph)

Notes:

- For Baseline Optical Design, 0.5 mas on-sky = 40 mas at FSM.
- LOWFS/FSM reduces 2.5 mas LOS motion of frequency < ~10 Hz to < 0.5 mas.
- Astrophysics Instruments don't have FSM and requires LOS < 1/10th of PSF radius.
- For 4-m telescope, PSF (1.22λ/D half-angle) at 400 nm is ~122 n-radian (~ 25 mas)
- For 6-m telescope, PSF (1.22λ/D half-angle) at 400 nm is ~ 80 n-radian (~ 16 mas)

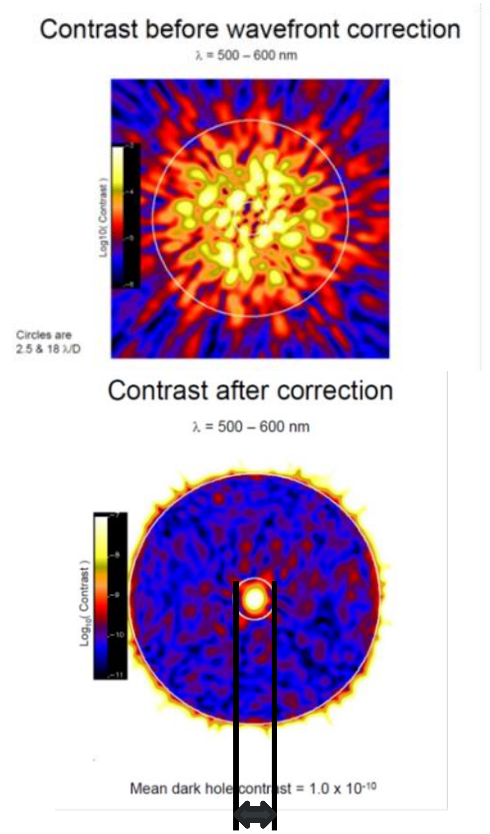
Wavefront Stability

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 ~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.

VVC Spatial Error Tolerance

The Vector Vortex Coronagrph (VVC) has varying sensitivities to different Zernike polynomial modes.

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

Garreth Ruane, June 2017

not rejected
first-order rejection
> first-order rejection

Wavefront Stability

Important WFE stability sources include:

Rigid body motions of optical components on their mounts causing relative misalignment between optical components,

Shape changes of individual optical components,

Shape changes of telescope structure that misalign or change shape of optical components.

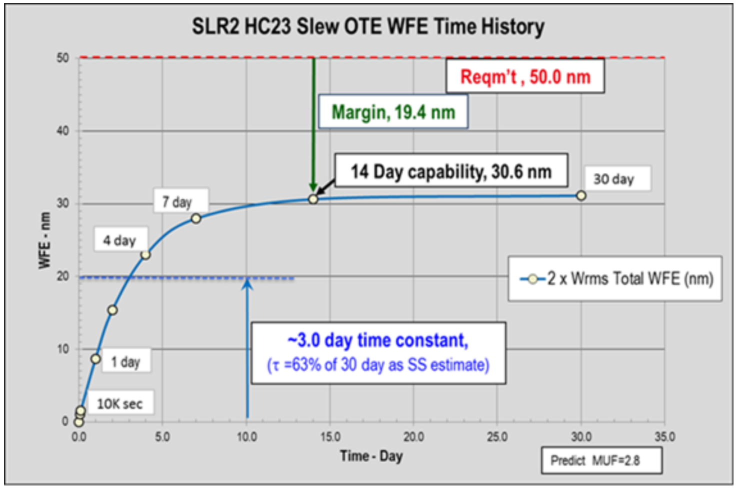
There are 2 primary source of Temporal Wavefront Error:

Thermal Environment

Mechanical Environment

Wavefront Stability - Thermal

As illustrated by JWST Prediction, Changes in orientation relative to Sun changes system thermal load. These changes can increase (or decrease) the average temperature and introduce thermal gradients.



In response to temperature changes, variations in the Coefficient of Thermal Expansion (CTE) distribution cause wavefront errors.

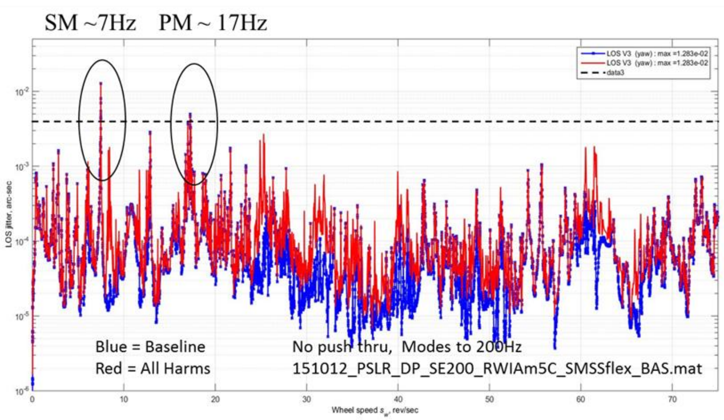
Stability depend on the temporal response (thermal time constant) of the mirror system to the thermal change.

13-JWST-0207 F, 2013

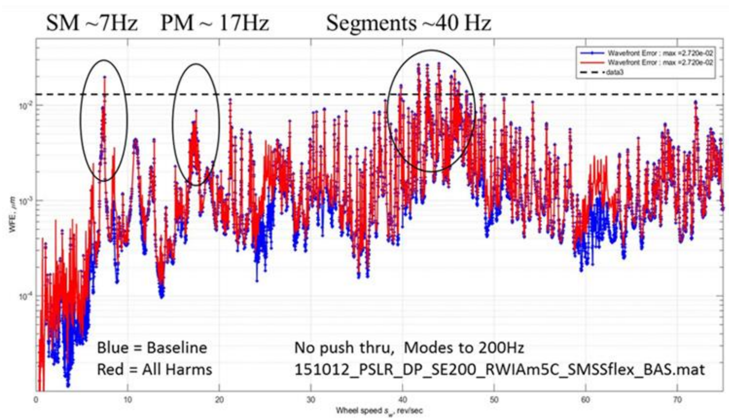
Wavefront Stability - Mechanical

- Mechanical disturbances cause LOS Jitter and WFE Instability by forcing inertial motion and exciting vibrational modes in optical components and structure.
- For example, JWST LOS & WFE impacted by SM & PM.

JWST Observatory LOS V3 Specification 4 mas



JWST WFE Specification 13 nm rms



- Because mechanical vibration tends to be fast, i.e. many cycles per second, it is difficult to control actively.
- Best solution is to eliminate or isolate mechanical noise.
- If motion is periodic, it may be removable by calibration.

Mosier, Gary, “Isolation Requirement”, AMTD Report, 2014

Primary Mirror Inertial WFE

Inertial Error is 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
- Consider the Mount stiffness and location.

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

- If Trefoil Gravity sag is 60 micrometers.
- And, if Coronagraph requires < 6 pm of Trefoil
- Then mirror acceleration must remain < 0.1 μG.

Wavefront Stability - Mechanical

Mechanical disturbances

from spacecraft such as reaction wheels or mechanisms, or

from the solar wind

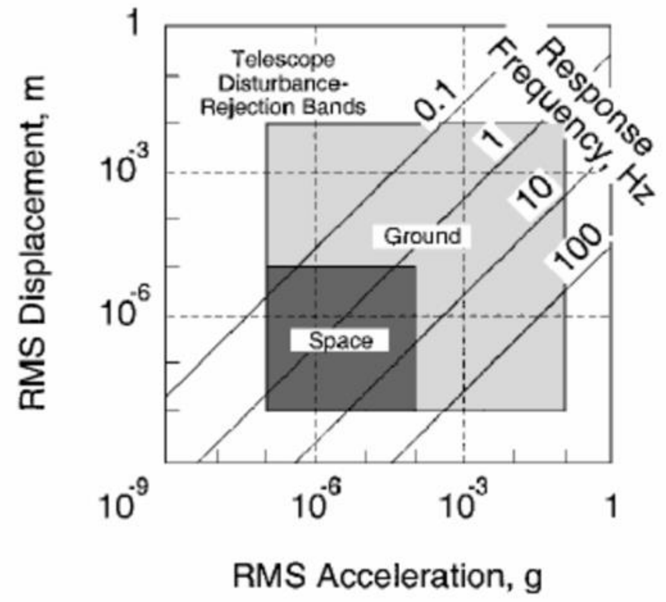
can excite modal vibration modes.

Per Lake, rms wavefront error is proportional to rms magnitude of the applied inertial acceleration (a_{rms}) divided by square of the structure's first mode frequency (f_0)

$$WFE_{rms} \sim a_{rms}/f_0^2$$

To achieve < 10 pm rms requires

First Mode Frequency	RMS Acceleration
10 HZ	< 10^-9 g
100 HZ	< 10^-7 g



Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

Design for Stability

Wavefront and Line of Sight Stability has design consequences.

Mechanical

- Secondary Mirror Support Structure Dynamic Response – make higher
- Primary Mirror Dynamic Response – make higher
- Passive/Active Vibration Isolation – lower acceleration/better isolation
- Passive/Active Dampening/Control – mass damping

First Order Scaling

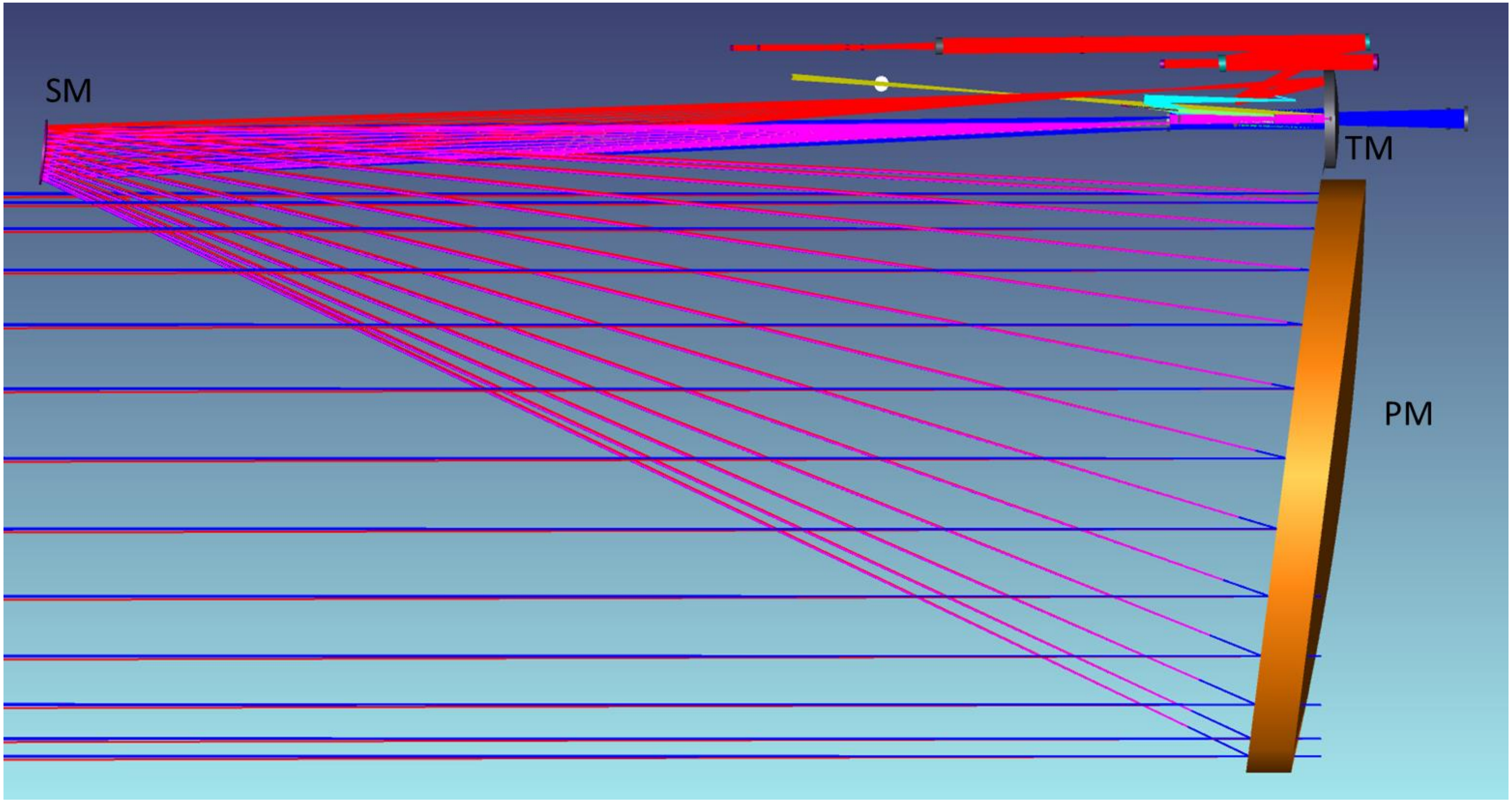
- WFE & LOS Stability is proportional to frequency^2.
  - 3.3X increase in frequency response = 10X improvement in stability
- WFE & LOS Stability is proportional to acceleration.
  - 1X decrease in acceleration force = 1X improvement in stability
- WFE & LOS Stability is proportional to mass. (Mass Dampening)
  - 1X increase in mass = 1X improvement in stability

HabEx Baseline Telescope

Design Overview

Telescope Optical Design

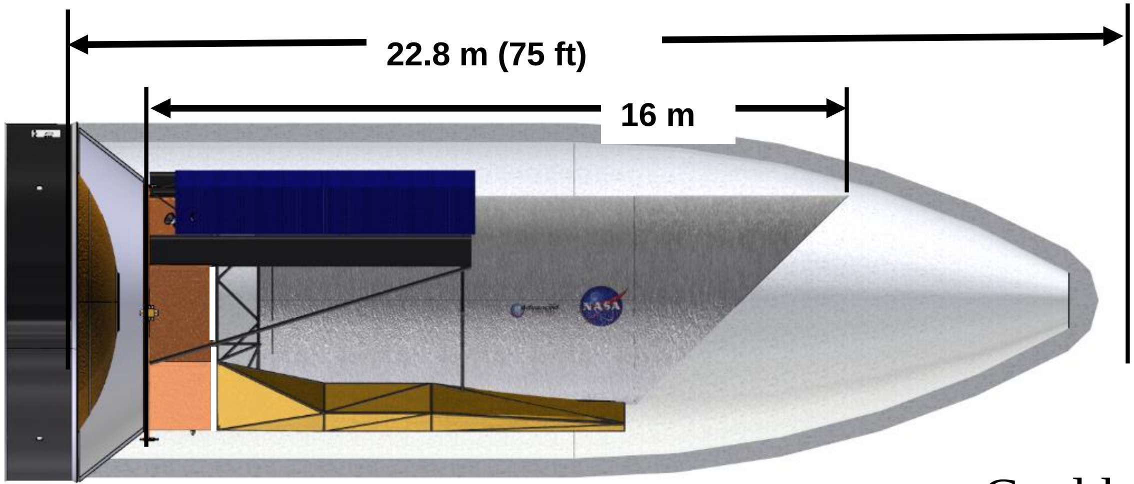
HabEx telescope optical design is off-axis TMA.



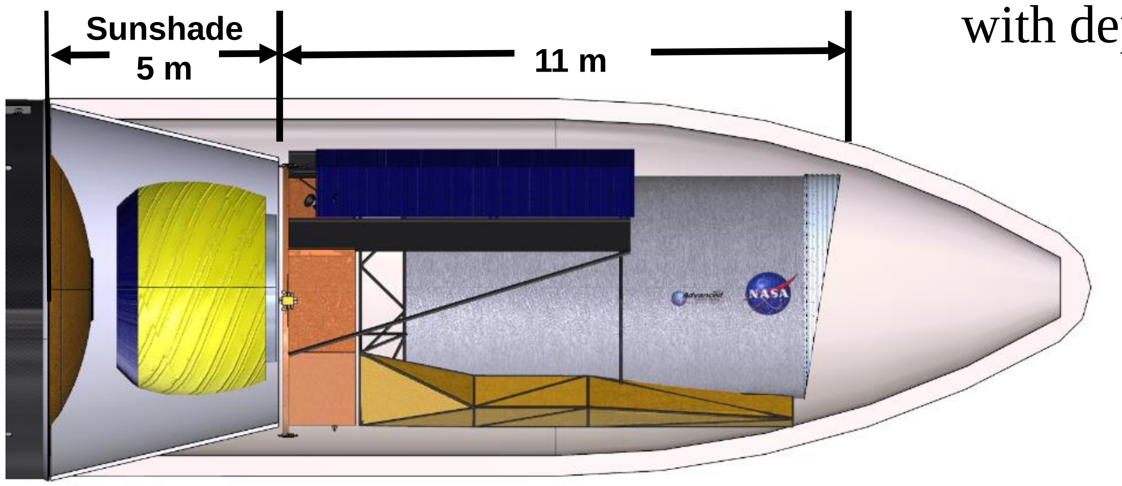
Baseline is designed to take advantage of SLS Volume and Mass Capacities.

Initial Concept

SLS 8.4m fairing accommodates a 4-m Observatory with a straylight baffle tube with no deployments.



Could scale-up to 6-m with deployed Scarf.

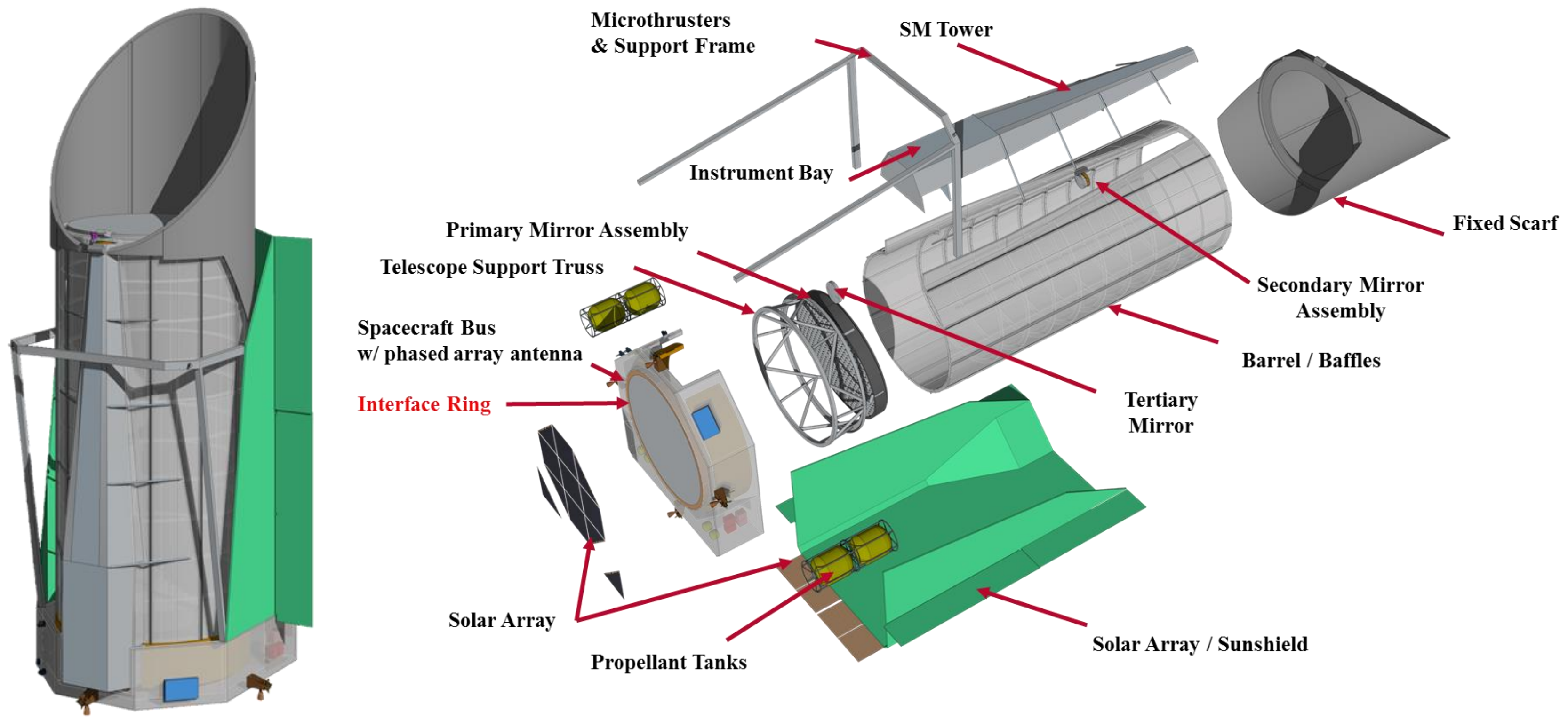


Baseline Design

Baseline Observatory is Telescope surrounded by Spacecraft.

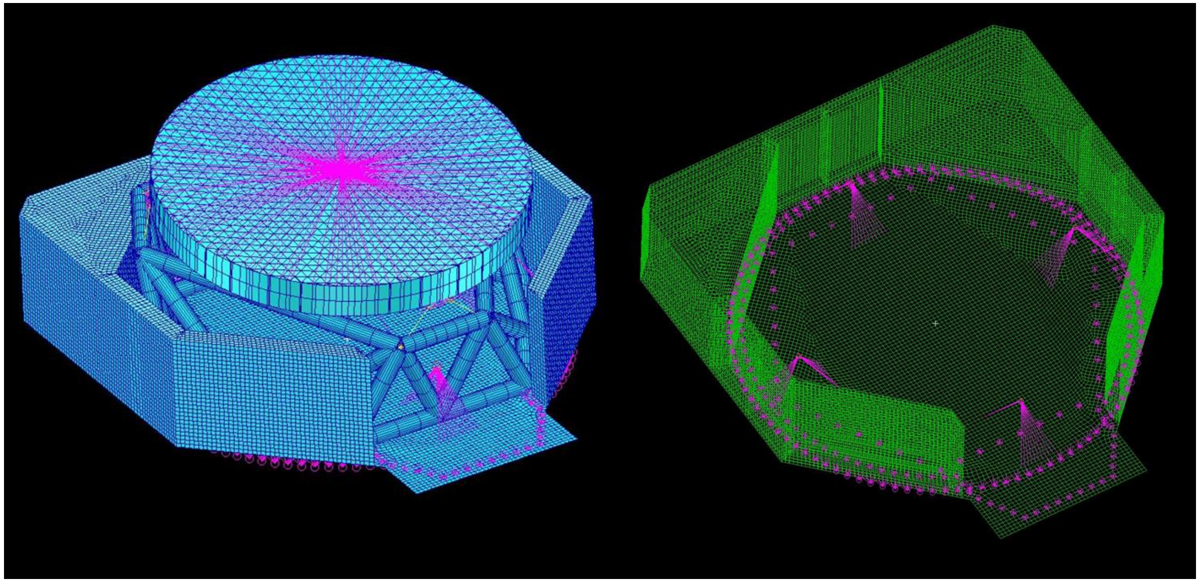
Only connection between two is Interface Ring.

Interface Ring is also where Observatory attaches to SLS PAF.



Spacecraft

By using microthruster instead of reaction wheels, it is possible to integrate the spacecraft bus around the primary mirror assembly allowing for a shorter total payload height



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	4250	1275	5525
Science Instruments	1500	450	1950
Spacecraft	4500	1350	5850
Interface Ring	210	63	273
PAF	tbd		
Mission Dry Mass	10460		13598
Propellant	1700		1700
Mission Wet Mass	12160		15298

SLS mass capacity is sufficient to dual launch a star-shade.

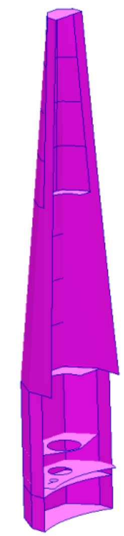
OTA Mass Estimate

Detailed FEM for OTA Mass Estimate

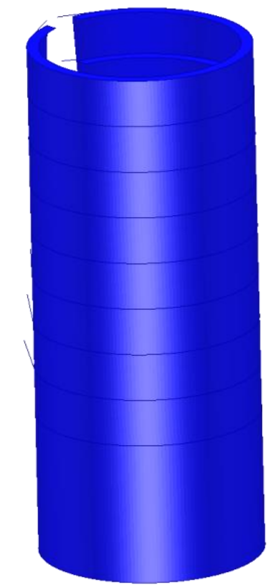
Description	Mass (kg)
Stray-light Baffle Tube	1536.3
Primary Mirror Assembly	1297.4
Primary Mirror Support	1000.9
Secondary Mirror Assembly	10.5
Secondary Mirror Tower	376.2
Tertiary Mirror	20.4
HabEx MSFC Assembly	4241.7
Interface ring	209.5

PMA Mass with Launch Locks is 1454 kg.

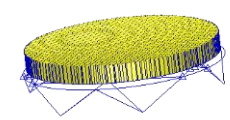
Secondary Mirror Tower



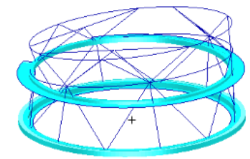
Straylight Baffle



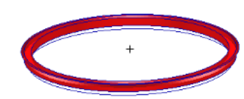
Primary Mirror Assembly



PM Support



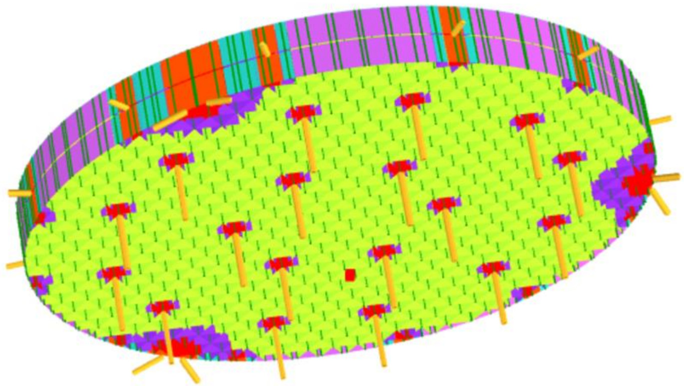
Interface Ring

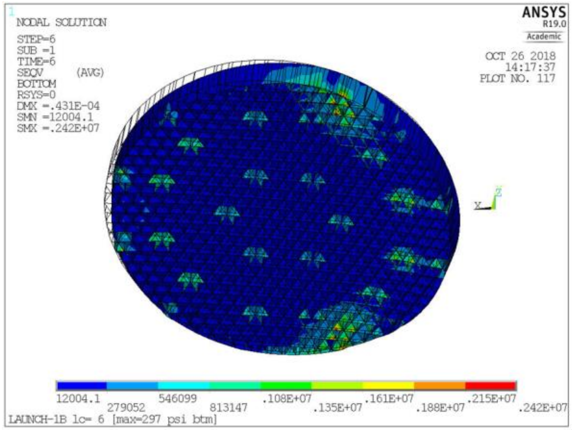


Primary Mirror

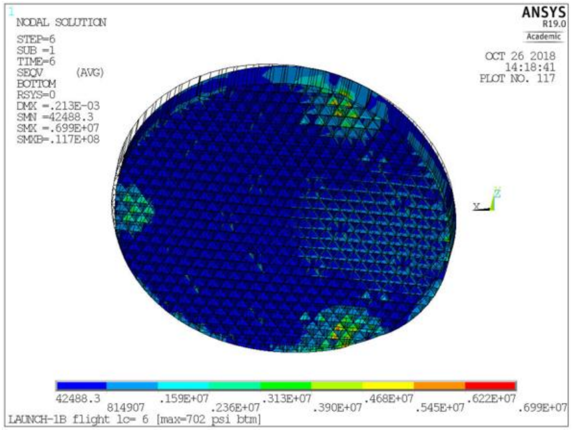
Baseline Primary Mirror (26 Oct 2018) is 4-meter Zerodur.

- Total Mass with Launch System and Struts = 1454 kg.
- First Mode Frequency
  - Free-Free = 86 Hz
  - Mounted = 69 Hz
  - Launch Lock = 163 Hz
- Max Launch Stress is < 300 psi





WITH LAUNCH LOCKS SEQV = 297 PSI



FLIGHT ONLY SEQV = 702 PSI
Stress if launched with no Launch Locks

Max Launch Stress without Launch Locks would be < 1000 psi

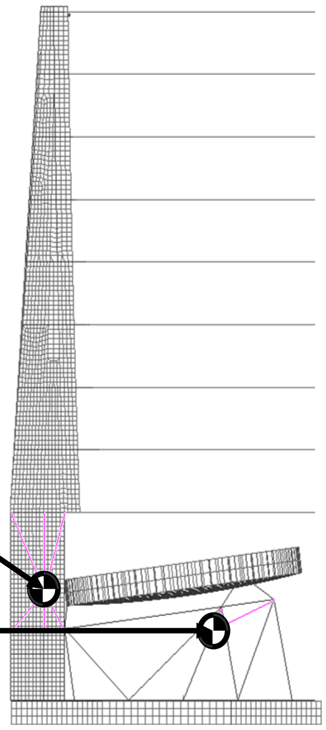
Science Instrument

Science Instrument Mass provided by JPL Team X = 1464 kg

Inserted into FEM as lump mass

Instruments
UV Spectrometer = 274 kg
Coronagraph = 650 kg
Wide Field Imager = 230 kg
Star Shade Camera = 210 kg

UV Spectrometer Focal Plane & Electronics = 100 kg



Analysis indicates that Science Instrument mass has negligible effect on dynamic performance.

HabEx Mass and Materials Table

	In Ref. MEL: Option 2 Telescope MEL - 02152018.xlsx	CBE + 30% Uncertainty In Ref. MEL: Option 2 Telescope MEL - 02152018.xlsx	FEM Baseline	FEM Rev. #1 (4 Prop. Tanks st Spacecraft Corners)	
Component	**Material**	**Mass [kg]**	**Mass [kg]**	**Mass [kg]**	
Propellant Tanks [t=2mm]	Ti-6AL_4V		141	141	
Sun Shade	M46J Composite (Quasi-Isotropic Layup) t=5.08 mm		1575	1575	
Sun Shade Frame	M46J Composite (Quasi-Isotropic Layup) t=5.08 mm		957	953	
Bulkhead HoneyComb	Top Sheet: M46J Composite (Quasi-Isotropic Layup) t=5.08 mm Core: Honeycomb (AL 3/8-5056-2.3) = 240.0 mm Bottom Sheet: M46J Composite (Quasi-Isotropic Layup) t=5.08 mm	5846	308	368	
Propellant Tank Frame 1	AL-6061_T6_A_basis		37	37	
Propellant Tank Frame 2	AL-6061_T6_A_basis		197	256	
Space Craft Wall	M46J Composite (Quasi-Isotropic Layup) t=5.08 mm		430	492	
Ribs	M46J Composite (Quasi-Isotropic Layup) t=5.08 mm		336	336	
Non_StructuralMass (Attitude Control, Command & Data, Power, Propulsion-electrospray, Cabling, Telecom, Thermal)	mass spread on the bulk head mass	(1596)*	1574	1586	
Propellant Mass		1653	1688	1688	
Number of Component:			13	13	
Mass of Model:		7498	7243	7432	**
Percent Difference [%]			-3.4	-0.9	
Telescope and Barrel (MSFC Strucure)		TBD	4435	4435	

*** Mass is included into 5846 kg (CBE+30% Uncertainty)**

****spacecraft height increased to accommodate propellant tanks**

Itemized MEL and refined FEM will help improve the agreement

Summary

The HabEx Baseline Architecture-A Telescope Design Specification is derived from Science Requirements.

Robust design uses standard engineering practice.

Design is enabled by two capabilities:

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