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

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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.
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
HabEx Baseline Telescope

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

Science Requirements → Engineering Specifications

**Exoplanet**
- Habitable Zone Size
- Contrast
- Contrast
- Star Size
- Telescope Diameter
- Mid/High Spatial Error
- WFE Stability
- Line of Sight Stability

**General Astrophysics**
- Diffraction Limit
- Wavefront Error (Low/Mid)

**Launch Vehicle**
- Up-Mass Capacity
- Fairing Size
- Mass Budget
- Architecture (monolithic/segmented)
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Architecture</strong></td>
<td>Unobscured Off-Axis F/2.5 TMA</td>
</tr>
<tr>
<td><strong>Aperture Dia</strong></td>
<td>4-meters Monolithic (Minimum)</td>
</tr>
<tr>
<td><strong>Mass Budget</strong></td>
<td>&lt; 10,000 kg (excluding science instruments &amp; spacecraft)</td>
</tr>
<tr>
<td><strong>Diffraction Limit</strong></td>
<td>400 nm (assumed to be achievable)</td>
</tr>
<tr>
<td><strong>Wavefront Error</strong></td>
<td>30 nm rms Total (assumed to be achievable)</td>
</tr>
<tr>
<td><strong>Primary Mirror</strong></td>
<td>Total SFE &lt; 7 nm rms</td>
</tr>
<tr>
<td>(cpd = cycles/diameter)</td>
<td>Low-Order (&lt; 30 cpd) &lt; 5 nm rms</td>
</tr>
<tr>
<td></td>
<td>Mid-Spatial (30 to 90 cpd) &lt; 4 nm rms</td>
</tr>
<tr>
<td></td>
<td>High-Spatial (&gt;90 cpd) &lt; 2 nm rms</td>
</tr>
<tr>
<td></td>
<td>Roughness &lt; 1 nm rms</td>
</tr>
<tr>
<td><strong>LOS Stability</strong></td>
<td>&lt; 2 mas on-sky jitter (astrophysics and starshade)</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.7 milli-arc-second on-sky jitter (coronagraph)</td>
</tr>
<tr>
<td><strong>WFE Stability</strong></td>
<td>&lt; 5 nm rms (astrophysics and starshade)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 to 200 pm rms per spatial frequency (coronagraph)</td>
</tr>
</tbody>
</table>
Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:

Then flowing Telescope Requirements to major Sub-Systems

Observatory
40 nm rms

Instruments
15 nm rms

Telescope
36 nm rms

Pointing Control
10 nm rms

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

Thus, need a PSD Specification.

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.

<table>
<thead>
<tr>
<th>Temporal Frequency</th>
<th>On-Sky LOS Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 Hz</td>
<td>&lt; 1 mas rms per axis</td>
</tr>
<tr>
<td>&gt; 10 Hz</td>
<td>&lt; 0.5 mas rms per axis</td>
</tr>
</tbody>
</table>

(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)
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.

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

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

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Indices</th>
<th>Allowable RMS wavefront error (nm) per mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$m$</td>
</tr>
<tr>
<td>Tip-tilt</td>
<td>1</td>
<td>±1</td>
</tr>
<tr>
<td>Defocus</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>2</td>
<td>±2</td>
</tr>
<tr>
<td>Coma</td>
<td>3</td>
<td>±1</td>
</tr>
<tr>
<td>Spherical</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Trefoil</td>
<td>3</td>
<td>±3</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Astig.</td>
<td>4</td>
<td>±2</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Coma</td>
<td>5</td>
<td>±1</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Spher.</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Quadrafoil</td>
<td>4</td>
<td>±4</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Trefoil</td>
<td>5</td>
<td>±3</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Astig.</td>
<td>6</td>
<td>±2</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Coma</td>
<td>7</td>
<td>±1</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Spher.</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Garreth Ruane, June 2017
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 sources of Temporal Wavefront Error:

- Thermal Environment
- Mechanical Environment
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.
• 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.

  ![Graphs showing JWST Observatory LOS V3 Specification 4 mas and JWST WFE Specification 13 nm rms](image)

• 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.

Inertial Error is proportional to Gravity Sag.

\[
\begin{align*}
1 \text{ G acceleration} & = 1 \text{ Gravity Sag} \\
1 \mu\text{G acceleration} & = 1 \mu\text{ Gravity Sag}
\end{align*}
\]

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 \mu G.
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 ($a_{\text{rms}}$) divided by square of the structure’s first mode frequency ($f_0$)

$$\text{WFE}_{\text{rms}} \sim \frac{a_{\text{rms}}}{f_0^2}$$

To achieve $< 10 \text{ pm}$ rms requires

<table>
<thead>
<tr>
<th>First Mode Frequency</th>
<th>RMS Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 HZ</td>
<td>$&lt; 10^{-9}$ g</td>
</tr>
<tr>
<td>100 HZ</td>
<td>$&lt; 10^{-7}$ g</td>
</tr>
</tbody>
</table>

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
HabEx telescope optical design is off-axis TMA.
Baseline is designed to take advantage of SLS Volume and Mass Capacities.
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 Observatory is Telescope surrounded by Spacecraft. Only connection between two is Interface Ring. Interface Ring is also where Observatory attaches to SLS PAF.
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.
Baseline mission mass with 30% margin is well within the 44 mt SLS mass capacity (only uses ~ 33%).

<table>
<thead>
<tr>
<th>HabEx Mission Mass Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Component</strong></td>
</tr>
<tr>
<td>Telescope</td>
</tr>
<tr>
<td>Science Instruments</td>
</tr>
<tr>
<td>Spacecraft</td>
</tr>
<tr>
<td>Interface Ring</td>
</tr>
<tr>
<td>PAF</td>
</tr>
<tr>
<td><strong>Mission Dry Mass</strong></td>
</tr>
<tr>
<td><strong>Propellant</strong></td>
</tr>
<tr>
<td><strong>Mission Wet Mass</strong></td>
</tr>
</tbody>
</table>

SLS mass capacity is sufficient to dual launch a star-shade.
### Detailed FEM for OTA Mass Estimate

<table>
<thead>
<tr>
<th>Description</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stray-light Baffle Tube</td>
<td>1536.3</td>
</tr>
<tr>
<td>Primary Mirror Assembly</td>
<td>1297.4</td>
</tr>
<tr>
<td>Primary Mirror Support</td>
<td>1000.9</td>
</tr>
<tr>
<td>Secondary Mirror Assembly</td>
<td>10.5</td>
</tr>
<tr>
<td>Secondary Mirror Tower</td>
<td>376.2</td>
</tr>
<tr>
<td>Tertiary Mirror</td>
<td>20.4</td>
</tr>
<tr>
<td>HabEx MSFC Assembly</td>
<td>4241.7</td>
</tr>
<tr>
<td>Interface ring</td>
<td>209.5</td>
</tr>
</tbody>
</table>

PMA Mass with Launch Locks is 1454 kg.
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

Max Launch Stress without Launch Locks would be < 1000 psi
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.
Itemized MEL and refined FEM will help improve the agreement.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant Tanks [t=2mm]</td>
<td>Ti-6AL_4V</td>
<td>141</td>
<td>141</td>
<td></td>
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<tr>
<td>Sun Shade</td>
<td>M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td>1575</td>
<td>1575</td>
<td></td>
</tr>
<tr>
<td>Sun Shade Frame</td>
<td>M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td>957</td>
<td>953</td>
<td></td>
</tr>
<tr>
<td>Bulkhead HoneyComb</td>
<td>Top Sheet: M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td></td>
<td>5846</td>
<td>308</td>
</tr>
<tr>
<td></td>
<td>Core: Honeycomb (AL 3/8-5056-2.3) = 240.0 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bottom Sheet: M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propellant Tank Frame 1</td>
<td>AL-6061_T6_A_basis</td>
<td>37</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Propellant Tank Frame 2</td>
<td>AL-6061_T6_A_basis</td>
<td>197</td>
<td>256</td>
<td></td>
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<tr>
<td>Space Craft Wall</td>
<td>M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td>430</td>
<td>492</td>
<td></td>
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<tr>
<td>Ribs</td>
<td>M46J Composite (Quasi-Isotropic Layup) t=5.08 mm</td>
<td>336</td>
<td>336</td>
<td></td>
</tr>
<tr>
<td>Non_StructuralMass</td>
<td>mass spread on the bulk head mass</td>
<td>(1596)*</td>
<td>1574</td>
<td>1586</td>
</tr>
<tr>
<td>(Attitude Control, Command &amp; Data,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power, Propulsion-electrospray,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabling, Telecom, Thermal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propellant Mass</td>
<td></td>
<td>1653</td>
<td>1688</td>
<td>1688</td>
</tr>
<tr>
<td>Number of Component:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of Model:</td>
<td></td>
<td>7498</td>
<td>7243</td>
<td>7432</td>
</tr>
<tr>
<td>Percent Difference [%]</td>
<td></td>
<td>-3.4</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td>Telescope and Barrel (MSFC Strucure)</td>
<td></td>
<td>TBD</td>
<td>4435</td>
<td>4435</td>
</tr>
</tbody>
</table>

* Mass is included into 5846 kg (CBE+30% Uncertainty)
**spacecraft height increased to accommodate propellant tanks
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.