Telescope Technology Needs for HabEx and LUVOIR

H. Philip Stahl
NASA MSFC
Huntsville, AL 35812

Matt Bolcar
NASA GSFC
Greenbelt, MD 20771

Rhonda Morgan
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

David Redding
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109
**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.
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 Science
  - High Resolution UV Spectrograph for General Observatory Science
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.
Architecture: Unobscured Off-Axis F/2.5 TMA

Aperture Dia: 4-meters Monolithic (Minimum)

LOS Stability: < 2.5 mas on-sky jitter (< 10 Hz) for astrophysics & starshade
< 0.3 mas on-sky jitter (> 10 Hz) for coronagraph

Diffraction Limit: 400 nm

Wavefront Error: 30 nm rms Total

Primary Mirror: Total SFE < 5.6 nm rms
Low-Order (< 30 cpd) < 4.3 nm rms
Mid-Spatial (30 to 100 cpd) < 3.3 nm rms
High-Spatial (>100 cpd) < 1.5 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.
HabEx Baseline Telescope

Science Driven Systems Engineering
‘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.

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
IWA and Core Throughput

The greater the core throughput at the smallest possible IWA, the larger the number of habitable zones that can be searched.

IWA is driven by

- **PSF Size**
- **PSF Stability**
- **Aperture Diameter & Off-Axis Architecture**
- **LOS Jitter and WFE Stability Specification**
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)  
Expoplanet 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 = $1.22 \, \lambda/D$.

83% of the energy is in the central lobe.

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

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

Diffraction Limited Performance

Diffraction limited performance (in addition to aperture) drives PSF size:

- General Astrophysics Resolution
- Coronagraphy Inner Working Angle

Diffraction limit drives transmitted wavefront error (WFE).

Primary Mirror requirements flow from transmitted WFE.

- Telescope: 30 nm rms wavefront
  - Primary Mirror: 20 nm rms
  - Secondary Mirror: 15 nm rms
  - Tertiary Mirror: 15 nm rms
  - Alignment: 7 nm rms
Primary Mirror Total Surface Figure Requirement

PM must have < 10 nm rms surface.

PM Specification depends on thermal behavior & mounting

PM must be very smooth.

Mid-spatial frequency errors move light from core into ‘hole’

DM moves that light back into the core.

High-spatial errors (3X OWA) ‘fold’ or ‘scatter’ light into ‘hole’

Errors above DM range produce speckles whose amplitude varies as $1/\lambda^2$
Spatial Frequency vs Science

Low spatial frequency specification is driven by General Astrophysics (not Exoplanet) science.

Exoplanet instruments have deformable mirrors to correct low-spatial errors and General Astrophysics instruments typically do not.

Mid/High spatial frequency specification is driven by Exoplanet because of ‘leakage’ or ‘frequency folding’.

For exoplanet, the spatial band is from the inner working angle (IWA) to approximately 3X the outer working angle (OWA).

Theoretically, a 64 x 64 DM can correct spatial frequencies up to 32 cycles per diameter (N/2), therefore, the maximum mid-spatial frequency of interest is ~ 90 cycles.

Since mirrors are smooth & DM controllability rolls-off near N/2 limit, a conservative lower limit is ~N/3 or ~20 cycles.
Risks to Diffraction Limited Performance

Assuming that mirrors are made to their prescription, biggest potential WFE source is ability to align mirrors and maintain that alignment on-orbit.

- Mitigate risk by designing hexapod actuators range.
- Mitigate risk by using laser position metrology system.

Another potentially error source is ability to quantify and back-out gravity effects.

Because mirrors are made in 1-G and operated in 0-G, G-release is a risk.

- Mitigate risk by active mirror control with actuator placement optimized to control most likely error modes.
Line of Sight (LOS) In-Stability

LOS in-stability causes PSF smear and beam-shear WFE.

LOS in-stability 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.
Wavefront In-Stability

WFE Drift cause speckles which can produce a false exoplanet measurement or mask a true signal.

Spatial frequency of that error is important.

Three sources of WFE in-stability:

• LOS: Rigid body motions of optical components on their mounts causes beam-shear – this is mostly low-order.

• Inertial: Shape change of primary or secondary mirror reacting against its mount due to mechanical accelerations.

• Thermal: Shape changes of telescope structure or individual optical components due to thermal environment.
Wavefront In-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.
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.

![Mirror Design Diagram]
Wavefront In-Stability: Thermal

Thermal WFE instability occurs when the primary mirror’s bulk temperature or temperature gradient changes.

If the mirror’s coefficient of thermal expansion (CTE) is completely homogeneous and constant, then a bulk temperature should only result in a defocus error.

But any inhomogeneity in the mirror’s CTE will result in a temperature dependent WFE.

Additionally, because CTE is itself temperature dependent, any change in the mirror’s thermal gradient will also result in a WFE.

The best mitigation strategy is to actively control the mirror’s thermal stability.
PM Thermal Stability

Thermal WFE stability depends on the primary mirror’s thermal sensitivity and the thermal system’s controllability.

Rate at which the PM’s RMS WFE changes depends on CTE, mass and specific heat ($c_p$):

$$\frac{\delta SFE}{\delta t} \sim \frac{CTE}{M c_p}$$

The larger a mirror’s mass and smaller it’s CTE, the smaller and slower its thermal response.

Thus want a zero CTE material.

Also want zero CTE homogeneity.
Wavefront In-Stability: Thermal

CTE homogeneity causes WFE as a function of thermal variation. Again, this WFE is minimized by thermal control. BUT, the required control precision is proportional to CTE homogeneity. The more homogeneous, the less precise the required control.

AMTD tested a 1.2m Zerodur mirror and determined that its CTE homogeneity is approx. +/- 5 ppb/K. This mirror would meet WFE stability with ~2 mK thermal stability.
TRL Assessment
Technology Readiness Level (TRL)

NASA requires that the technology to manufacture and test the HabEx primary mirror must be:

- TRL-5 before start of Phase A
- TRL-6 before by PDR & start of Phase C.

<table>
<thead>
<tr>
<th>TRL</th>
<th>Abridged definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported</td>
</tr>
<tr>
<td>2</td>
<td>Concept and/or application formulated</td>
</tr>
<tr>
<td>3</td>
<td>Proof of concept hardware or model validation; critical properties demonstrated</td>
</tr>
<tr>
<td>4</td>
<td>Low-fidelity component or breadboard in lab demonstrates functionality and validates models that predicts performance in relevant environment</td>
</tr>
<tr>
<td>5</td>
<td>Medium fidelity component or breadboard demonstrate overall performance in relevant environment</td>
</tr>
<tr>
<td>6</td>
<td>High fidelity system/subsystem demonstrates critical performance in operational environment; scaling is understood</td>
</tr>
<tr>
<td>7</td>
<td>High fidelity engineering unit demonstrates performance in operational environment</td>
</tr>
<tr>
<td>8</td>
<td>System is flight qualified</td>
</tr>
<tr>
<td>9</td>
<td>System flight performance successful</td>
</tr>
</tbody>
</table>
Assessed TRL assessment to identify Enabling Technology Gaps (i.e. < TRL4):

- **Star-Shade**
  - Petal Position Accuracy and Stability
  - Petal Shape Accuracy and Stability
  - Contrast Model Validation

- **Large Mirror Fabrication**

- **Large Mirror Coating Uniformity**

- **Coronagraph Architecture**

- **Zernike Wavefront Sensing & Control**

- **Deformable Mirrors**

- **Detectors**

- **Micro-Thrusters**
Primary Mirror TRL Assessment

HabEx assesses that the technology to manufacture a 4-m class flight mirror is currently TRL-4 because of 3 key technologies:

- Ability to Certify that Zerodur Blank has CTE Homogeneity
- Ability to Certify that Mirror has Wavefront Error
- Ability to Certify that Mirror will achieve Wavefront Stability

### Large Mirror Fabrication

<table>
<thead>
<tr>
<th>Technology</th>
<th>Need</th>
<th>State of the Art</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Substrate Diameter</td>
<td>4.04 meter</td>
<td>Schott Corp manufactures blanks that are 4.2 m diameter x 420 mm thick</td>
<td>6</td>
</tr>
<tr>
<td>Mirror Substrate CTE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Bulk CTE</td>
<td>0 at 270 K</td>
<td>Schott Corp can tune CTE to be 0 at a specific temperature.</td>
<td>6</td>
</tr>
<tr>
<td>• CTE Homogeneity</td>
<td>&lt; +/- 5 ppb/K over 100 x 100 spatial sampling</td>
<td>Schott Corp demonstrated &lt; +/- 3 ppb/K over limited spatial sampling on DKIST</td>
<td>4</td>
</tr>
<tr>
<td>Substrate Machining</td>
<td>3–4 mm ribs, 14 mm facesheet, and pocket depth of 290 mm for 400 mm thick blank</td>
<td>Schott Corp demonstrated computer-controlled-machine lightweighting to pocket depth of 340 mm, 4 mm rib thickness on E-ELT M5 and 240 mm deep/2 mm thick rib on Schott 700 mm diameter test unit</td>
<td>6</td>
</tr>
<tr>
<td>Areal Density</td>
<td>110 kg.m²</td>
<td>State-of-the-practice lightweighting has made large glass mirrors with aerial density of 70 kg/m²</td>
<td>6</td>
</tr>
<tr>
<td>First Mode Frequency</td>
<td>≥ 60 Hz</td>
<td>By design, if the baseline Zerodur® mirror substrate can be machined to its specified dimensions using demonstrated Schott Corp machining capability, it will achieve the required first mode frequency. Also, sub-scale WFIRST 2.4-m Primary Mirror has ~ 200 Hz first mode.</td>
<td>6</td>
</tr>
<tr>
<td>Wavefront Error</td>
<td>0-7 cy/D: 6.9 nm RMS</td>
<td>Demonstrated on sub-scale WFIRST 2.4-m Primary Mirror</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>7-100 cy/D: 6.0 nm RMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;100 cy/D: 0.8 nm RMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavefront Stability</td>
<td>1 to 100 pm rms</td>
<td>By design, baseline Zerodur® mirror will achieve required wavefront stability with active zonal thermal control stability of &lt; 5-mK. Sub-scale active thermal control has been demonstrated by Harris Corp to TRL-9 on 1.1-m Spaceview™</td>
<td>4</td>
</tr>
</tbody>
</table>
Mirror Material

A key metric for selecting the HabEx primary mirror material is coefficient of thermal expansion (CTE).

- CTE and CTE homogeneity are important because they determine how the mirror’s shape deforms as a function of bulk temperature or thermal gradient changes.
- Such deformations impacts the telescopes ability to meet its diffraction limited performance and wavefront stability specifications.

Typical approaches for mitigating this risk are
- Select a material with zero CTE and extreme homogeneity.
- Measure the mirror’s shape change between its manufacture and operational temperatures and ‘cryo-null figure’ the mirror
- Actively control the mirror’s on-orbit shape or its thermal environment.
Mirror Material

Both Zerodur® and ULE® are TRL-9 with multiple mirrors flying.

Both Schott and Corning can tailor their material’s zero CTE temperature.

And both claim similar CTE homogeneity (i.e. +/- 5 ppb).

Thus, a mirror manufactured from either material should have similar thermal performance.
Mirror Material

A significant difference between ULE® and Zerodur® is the design architecture enabled by each.

As a glass, ULE® can be assembled to enable closed-back mirror architectures. Such mirrors are stiffer.

As a ceramic, Zerodur® must be machined from a single blank. Thus, Zerodur® mirrors required an open-back architecture.

However, because Zerodur® mirrors are machined from a single boule, they may have a smoother and more homogeneous CTE.
Primary Mirror Material Selection

Zerodur® was selected as the baseline HabEx primary mirror material because Schott has demonstrated a routine ability to manufacture 4-m class mirror blanks.

This demonstrated capability enables HabEx to assess the ability to make 4-m class mirror blanks to be TRL-6.
Machining high-fidelity sub-scale mirrors has capability at TRL-6

0.7-m diameter, 200 mm thick mirror with 2 mm machined walls.

1.2-m diameter, 125-mm thick mirror with 2 mm machined walls.
Polishing Infrastructure

Multiple organizations have existing infrastructure to grind and polish 4-m class substrates into space mirrors, including: Collins Aerospace, L3/Brashears, Harris Cor., Arizona Optical Systems, University of Arizona, and REOSC.
Wavefront Stability

Schott’s ability to provide a 4-m substrate with $< \pm 5$ ppb/K CTE homogeneity is assessed at TRL-4 because they do not have a non-destructive process for validating CTE homogeneity on a 4-m class mirror over 100 x 100 spatial sampling.
Schott Corp has a dilatometer process that can measured CTE of test samples with a reproducibility of ~ +/- 1 ppb/K.

Since 20010, Schott has produced seven 4-m mirror substrates with CTE homogeneity < 10 ppb/K. And one with 3 ppb/K.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dimension [mm]</th>
<th>Number of Samples</th>
<th>CTE (0°; 50°) absolute value [ppb / K]</th>
<th>CTE (0°; 50°) homogeneity [ppb / K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Specification</td>
<td>Achieved</td>
</tr>
<tr>
<td>2003</td>
<td>4100 x 171</td>
<td>18</td>
<td>+/-  50</td>
<td>66</td>
</tr>
<tr>
<td>2005</td>
<td>3610 x 370</td>
<td>12</td>
<td>+/- 100</td>
<td>80</td>
</tr>
<tr>
<td>2009</td>
<td>3700 x 163</td>
<td>36</td>
<td>+/- 150</td>
<td>54</td>
</tr>
<tr>
<td>2010</td>
<td>3400 x 180</td>
<td>12</td>
<td>+/- 100</td>
<td>42</td>
</tr>
<tr>
<td>2012</td>
<td>4250 x 350</td>
<td>16</td>
<td>+/-  50</td>
<td>60</td>
</tr>
<tr>
<td>2014</td>
<td>4250 x 350</td>
<td>16</td>
<td>+/-  50</td>
<td>0</td>
</tr>
<tr>
<td>2016</td>
<td>4060 x 103</td>
<td>16</td>
<td>+/- 150</td>
<td>15</td>
</tr>
<tr>
<td>2016</td>
<td>4000 x 100</td>
<td>12</td>
<td>+/- 20*</td>
<td>-9*</td>
</tr>
<tr>
<td>2019</td>
<td>4250 x 100</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


But, because acquiring CTE samples is destructive, data sampling is limited to perimeters and holes.

Thus, HabEx requires a ‘validated’ non-destructive process to certify CTE homogeneity of the primary mirror blank over at least a 100 x 100 spatial sampling as part of the primary mirror blank acceptance process.

Tony Hull Private Communication
CTE Homogeneity Characterization

Schott has mapped CTE homogeneity of meter class blanks, but this mapping has not been correlated with Cryo-Deformation.
Surface Figure Error

Polishing mirrors to required specification at 2.4-m is TRL-9. HabEx specification is same as WFIRST’s current surface.

The primary risk is the ability to quantify and back-out gravity induced self-weight deflection to ~ 4 nm rms over a 100 x 100 spatial sampling is assessed to be at TRL-4.
Gravity Deformation State of Practice

Gravity-sag characterization and mitigation have been studied extensively since the 1960s.

Mitigation approaches:

• Minimize Gravity Sag by making the mirror as stiff as possible and optimizing its mounting
• Off-load Gravity during fabrication and test
• Analytically removed Gravity Sag during test
• Actively correct mirror shape on-orbit
Minimize Gravity Sag

Design the mirror to be as stiff as possible

\[ 1G \text{ Gravity Sag} \sim C_{SP} \left( \frac{D^4}{t^3} \right) \rho_{AD} \sim \frac{1}{(2\pi f)^2} \]

And optimize its mounting

Yields Baseline Zerodur® mirror designed to minimize gravity sag

<table>
<thead>
<tr>
<th>Support Constant</th>
<th>C_{sp}</th>
<th>Factor of Reduced Deflection Compared to 3- Pt Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring at 68% of Diameter</td>
<td>0.028</td>
<td>11</td>
</tr>
<tr>
<td>6 Points Equal Spaced at 68.1% of Diameter</td>
<td>0.041</td>
<td>8</td>
</tr>
<tr>
<td>Edge Clamped</td>
<td>0.187</td>
<td>1.5</td>
</tr>
<tr>
<td>3 Points, Equal Spaced at 64.5% of Diameter</td>
<td>0.316</td>
<td>-</td>
</tr>
<tr>
<td>3 Points, Equal Spaced at 66.7% of Diameter</td>
<td>0.323</td>
<td>-1</td>
</tr>
<tr>
<td>3 Points, Equal Spaced at 70.7% of Diameter</td>
<td>0.359</td>
<td>0.9</td>
</tr>
<tr>
<td>Edge Simply Supported</td>
<td>0.828</td>
<td>1/3</td>
</tr>
<tr>
<td>Continuous Support along the Diameter</td>
<td>0.943</td>
<td>1/3</td>
</tr>
<tr>
<td>&quot;Central Support&quot; (Mushroom or Stalke Mount; ( r ) = radius of stalk)</td>
<td>1.206</td>
<td>1/4</td>
</tr>
<tr>
<td>3 Points Equal Spaced at Edge</td>
<td>1.356</td>
<td>1/4</td>
</tr>
</tbody>
</table>

Gravity Off-Loading

Gravity off-loading is typically done via:

• Multipoint Mount
• Air Bag Support

Hubble PM’s 7.6 micrometer G-sag was characterized to an accuracy of 1.4 nm rms using a 135 point metrology mount.

Analytical Removal

Gravity Sag can be estimated via an orientation test:

• Face-up/Face-down Test
• Horizontal Rotation Test

JWST segments were tested using rotation test to < 10 nm rms.
Kepler Gravity Sag

Kepler primary mirror was tested using an air bag, a 108 point metrology mount, and a face-up/face-down orientation test. Air bag was estimated to off-load gravity sag to 5.6 nm rms. Difference between air bag & multi-point mount was 16.4 nm rms. Difference between air bag & face-up/face-down was 18.4 nm rms. Largest component of difference was spherical aberration. By inference, difference between multipoint mount and up/down test should be 8.3 nm rms.

Thermal Control System TRL

Baseline HabEx thermal control system is assessed to be TRL-4.

System is scale-up of TRL-9 system built by Harris Corp.

- 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.

Analysis indicates that, because of PM thermal mass, system with 0.5-Hz, 50-mK sensors will keep PM stable to ~1-mK.
## Primary Mirror Coating TRL Assessment

HabEx assesses that to:

- Achieve TRL-5 requires demonstrated on coupons, representing a 4-m diameter mirror, ability to coat with required reflectivity and uniformity.
- Achieve TRL-6 requires a full-scale 4-m mirror demonstration.

<table>
<thead>
<tr>
<th>Description</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>TRL 2019</th>
<th>2023 TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror coating with high spatial uniformity over the visible spectrum</td>
<td>• Reflectance uniformity &lt;0.5% of protected Ag on 2.5 m TPF Technology Demo Mirror</td>
<td>• Reflectance uniformity &lt;1% over 0.45–1.0 μm</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>• IUE, HST, and GALEX used MgF$_2$ on Al to obtain &gt;70% reflectivity from 0.115 to 2.5 μm</td>
<td>• Reflectivity compared to HST:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
|                                                                            | • Operational life: >28 yrs on HST                                                 |   ▪ 0.115–0.3 μm: ≥70 %  
   ▪ 0.3 – 0.45 μm: ≥88 %  
   ▪ 0.45 – 1.0 μm: ≥85 %  
   ▪ 1.0 - 1.8 μm: ≥90 %  |          |          |
|                                                                            | • Operational life >10 years                                                       | • Operational life >10 years                                                                  |          |          |
## Deformable Mirror TRL Assessment

<table>
<thead>
<tr>
<th>Description</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>TRL 2019</th>
<th>2023 TRL</th>
</tr>
</thead>
</table>
| Flight-qualified large-format deformable mirror                            | • Micro-electromechanical DMs available up to 64 × 64 actuators, 400 µm pitch with 6 nm RMS flattened WFE;  
                                • 3.3 nm RMS demonstrated on 32 × 32 DM  
                                • 16 bit resolution drive electronics                                             | • > 64 × 64 actuators                                      | 4        | 5        |
### Zernike Wavefront Sense & Control TRL Assessment

<table>
<thead>
<tr>
<th>Description</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>TRL 2019</th>
<th>2023 TRL</th>
</tr>
</thead>
</table>
| Sensing & control low-order wavefront drift; monitoring of higher order Zernike modes | • <0.36 mas rms per axis LoS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs on Mv = 5 equivalent source; ~26 pm rms sensitivity of focus (WFIRST Coronagraph Instrument Testbed)  
  • WFE stability of 25 nm/orbit in low Earth orbit (HST). Higher low-order modes sensed to 10–100 nm WFE rms on ground-based telescopes | • LoS error <0.2 mas rms per axis  
  • Wavefront stability: ≤~100 pm rms over 1 second for vortex  
  • WFE <0.76 nm rms | 4 | 6 |
Path to TRL-6

HabEx Study has roadmap to mature technology gaps to TRL-6. But opportunity exists for SBIR contributions.
Star-Shade Only Option
**HabEx Starshade-Only Architectures**

**HabEx mission goals**

*Seek out nearby worlds* and explore their habitability.

*Map out nearby planetary systems* and understand the diversity of the worlds they contain.

*Open up new windows on the universe* from the UV through near-IR.

### Key Mission Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>3.2 to 4 meter</td>
</tr>
<tr>
<td>Bandpass</td>
<td>115–1,700 nm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>≥270K</td>
</tr>
<tr>
<td>Diffraction limit wavelength</td>
<td>400 nm</td>
</tr>
<tr>
<td>Wavefront error, total</td>
<td>≤30 nm rms</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>2 mas/axis</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>2 mas/axis</td>
</tr>
<tr>
<td>Raw contrast</td>
<td>≤10^-10 from IWA</td>
</tr>
<tr>
<td>Inner Working Angle (IWA)</td>
<td>&lt;74 mas</td>
</tr>
<tr>
<td>Spectroscopy resolution</td>
<td>R ≥ 7 (300–450 nm)</td>
</tr>
<tr>
<td></td>
<td>R ≥ 140 (450–1,000 nm)</td>
</tr>
<tr>
<td></td>
<td>R ≥ 40 (1,000–1,800 nm)</td>
</tr>
<tr>
<td><strong>Exoplanet</strong></td>
<td></td>
</tr>
<tr>
<td>Waveband, imaging</td>
<td>150–1,700 nm</td>
</tr>
<tr>
<td>Waveband, spectroscopy</td>
<td>350–1,400 nm</td>
</tr>
<tr>
<td>Field of View</td>
<td>3x3 amin</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>R ≥2,000</td>
</tr>
<tr>
<td><strong>Workhorse Camera</strong></td>
<td></td>
</tr>
<tr>
<td>Waveband</td>
<td>115–300 nm</td>
</tr>
<tr>
<td>Field of View</td>
<td>2.5x2.5 amin</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>R = 1 to 60,000</td>
</tr>
<tr>
<td><strong>UV Spectrograph</strong></td>
<td></td>
</tr>
<tr>
<td>Waveband, imaging</td>
<td>300–1,700 nm</td>
</tr>
<tr>
<td>Waveband, spectroscopy</td>
<td>300–1,700 nm</td>
</tr>
<tr>
<td>Field of View</td>
<td>8x8 asec</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>R ≥2,000</td>
</tr>
</tbody>
</table>
Active Optics Telescope

- Wavefront Sensing and Control establishes initial 30 nm RMS WF error
  - Rigid-body control of PM segments and SM phase and collimate the telescope
  - PM segment figure control assures performance while relaxing fabrication reqts.
- Laser Metrology is used to continuously maintain optical alignments

- Corrects optical errors on-orbit
- Mirror fabrication within current state of practice

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Nominal</th>
<th>Corrected</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0 nm rms WFE</td>
<td>18.0</td>
<td>10.0</td>
<td>8</td>
</tr>
<tr>
<td>Segment Figure</td>
<td>56.0</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>Mounting Errors</td>
<td>26.0</td>
<td>10.0</td>
<td></td>
</tr>
</tbody>
</table>

Includes effects of bonding mounts and devices, material creep, desorption, etc.
ULE Mirrors: Demonstrated Performance

• MMSD low mass: 10 kg/m²
  • Prefer 20 kg/m² for HabEx B
• WF error:
  • 15 nm RMS WFE stand-alone, with backouts
  • 8 nm WFE RMS post-actuation predicted
• Survivability tested to high level
  • Random vibe and shock
**Harris Capture Range Replication**

- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for mirror fabrication, saving time and cost

*CRR mirror finished under IRAD funding*
Maintaining Alignments

- Laser Metrology (MET) measures SM-PM-Instrument Bench alignments in real time
- Rigid Body Actuators move the SM and PM segments to preserve alignments

**Laser Distance Gauge measures distance to <1 nm accuracy**

- Probe beam from the beam launcher is reflected by corner cube
- Returning probe beam mixes with a reference beam within the beam launcher
- Phasemeter electronics measure phase between the reference and return beams

**Laser Truss combines gauges to measure 6DOF alignment of all optics wrt corner cubes on the SM**

- MET technology originally developed for Space Interferometry Mission
- Elements flown on LISA Pathfinder and GRACE Follow-On

**Requires:**
- Laser frequency stability to <1 MHz
- Temperature control of all optical elements to <0.2C
- RBA precision <5 nm
Passive Thermal Design

Passive thermal system design is similar to HabEx 4H Baseline

- Heat pipes in isolated routing manifolds channel excess heat from instrument detectors, electronics and structures to the radiator
- Three radiator stages operate at 240K, 130K and 55K, providing purely passive cooling for instrument electronics and detectors
- Heaters in thermal cans stabilize PM segments and the SM at 270K

Radiator panel sets A and D are equivalent to each other. Both sets consist of two stacked radiator panels that will be used to cool instruments of operating temperatures of 273K and 150K.

Radiator panel sets B and C are equivalent to each other. Both sets consist of three stacked radiator panels. The panel closest to space will be used to cool instruments of operating temperatures of 77K. The panels stacked behind are used as insulators from the hot barrel.
Exotic Worlds

The Search for Life

Our Dynamic Solar System

Cosmic Origins & the Ultra-Faint Universe
Signature science cases span Astro2020 science

1. Finding habitable planet candidates
2. Searching for biosignatures and confirming habitability
3. The search for habitable worlds in the solar system
4. Comparative atmospheres
5. The formation of planetary systems
6. Small bodies in the solar system
7. Connecting the smallest scales across cosmic time
8. Constraining dark matter using high precision astrometry
9. Tracing ionizing light over cosmic time
10. The cycles of galactic matter
11. The multi-scale assembly of galaxies
12. Stars as engines of galactic feedback

Mapping to Science Panels
Exoplanets, Astrobiology, and the Solar System
Interstellar Medium and Star and Planet Formation
Cosmology
Galaxies
Stars, the Sun, and Stellar Populations
Compact Objects and Energetic Phenomena

11/5/2019
The LUVOIR Mission

Launch in 2039 aboard an SLS Block 1B/2
SpaceX Starship and Blue Origin New Glenn
are viable alternatives

5-year primary mission, designed to be serviceable for a 25+ year lifetime

Operate in Sun-Earth L2 orbit

Can view entire sky except for a 45° cone about the sun-spacecraft axis
  • 3° / min slew rate
  • 60 arcsec / sec tracking rate
One Architecture, Two Concepts

Single *scalable* architecture responds to future uncertainties:

- Available launch vehicles
- Budget constraints
- Infrastructure availability
- Technological capability

Two LUVOIR concepts bracket a range of scientific capability, cost, and risk.
LUVOIR-A

15-m, on-axis telescope
- 120 segments, 1.223-m flat-to-flat
- 155 m² collecting area

Four instruments
- Extreme Coronagraph for Living Planetary Systems (ECLIPS)
- LUVOIR UV Multi-object Spectrograph (LUMOS)
- High Definition Imager (HDI)
- Pollux (CNES-contributed instrument design)
LUVOIR-B

8-m, off-axis telescope
- 55 segments, 0.955-m flat-to-flat
- 43.4 m² collecting area

Three instruments
- Extreme Coronagraph for Living Planetary Systems (ECLIPS)
- LUVOIR UV Multi-object Spectrograph (LUMOS)
- High Definition Imager (HDI)
Technology Development

Technologies are organized into three technology systems:

- High-Contrast Coronagraph Instrument
- Ultra-stable Segmented Telescope
- Ultra-violet Instrumentation

Three development paths mature each of the technologies at the system level.

Technologies are identified at component level, and validated in assembly-, sub-system-, and system-level demonstrations.

Technology systems are coupled, and must be developed in parallel with cross-validation.
# High-Contrast Coronagraphy - Components

<table>
<thead>
<tr>
<th>Technology Component</th>
<th>Implementation Options</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>FY19 TRL</th>
<th>In LUVOIR Baseline?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apodized Pupil Lyot Coronagraph (APLC)</td>
<td>6.3x10^-6 over 6% bandpass in air. Validated models with WFIRST CGI SPC demonstrations</td>
<td>1x10^-10 raw contrast &gt;10% bandpass</td>
<td>4</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Vortex Coronagraph (VC)</td>
<td>8.5x10^-8 contrast over 10% band with unobscured pupil. SCDA modelling for unobscured, segmented pupil</td>
<td>&lt;4 λ/D inner working angle</td>
<td>3</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Phase-Induced Amplitude Apodization (PIAA)</td>
<td>SCDA modeling results for unobscured, segmented pupil</td>
<td>128 λ/D outer working angle</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid-Lyot Coronagraph (HLC)</td>
<td>3.6x10^-10 contrast over 10% band in DST. SCDA modeling for unobscured segmented pupil</td>
<td>Robust to stellar diameter and jitter</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nulling Coronagraph (NC)</td>
<td>5x10^-9 narrowband at 2.5 λ/D</td>
<td>Minimum 64 x 64 actuators (&gt;100 x 100 actuators is enhancing)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformable Mirrors</td>
<td>Micro-Electro-Mechanical Systems (MEMS)</td>
<td>Available up to 64 x 64 actuators; 8.5x10^-9 contrast demonstrated with 32 x 32 actuators</td>
<td>Wavefront stability ~10 pm RMS</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td>Lead-Magnesium-Niobate (PMN) Macro-scale</td>
<td>&lt;1x10^-5 contrast demonstrated with 48 x 48 actuator Xerics DMs (WFIRST CGI Testbed)</td>
<td>~1 Hz bandwidth with Mv &lt; 9 source</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavefront Sensing</td>
<td>Out-of-band Wavefront Sensing</td>
<td>Model predicting &lt;10 pm residual error with nonlinear ZWFS, Mv = 5 source</td>
<td>Able to capture wavefront spatial frequencies on the order of segment-to-segment drift and DM actuators</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td>Low-order Wavefront Sensing</td>
<td>&lt;0.36 mas RMS line-of-sight residual error; &lt;30 pm RMS focus, Mv = 5 source (WFIRST CGI Testbed)</td>
<td>Concept study for guide star spacecraft and wavefront sensing control loop completed.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial Guide Star</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV/VIS Low-noise Detector</td>
<td>Electron-Multiplying CCD</td>
<td>1k x 1k WFIRST Detector: 7x10^-5 e/pix/s dark current 0 e- read noise 2.3x10^-3 CIC</td>
<td>3x10^-5 e/pix/s dark current 0 e- read noise 1.3x10^-3 e/pix CIC</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td>Hole-Multiplying CCD</td>
<td>Prototype devices fabricated with gains &gt; 10x (&gt;20x in at least one device)</td>
<td>&gt;80% QE at all detection wavelengths</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIR Low-noise Detector</td>
<td>HgCdTe Photodiode Array</td>
<td>H4RG-10 currently meets needed capability @ 170 K</td>
<td>4k x 4k array size</td>
<td>5</td>
<td>✓</td>
</tr>
<tr>
<td>HgCdTe Avalanche Photodiode</td>
<td>1.5x10^-3 e/pix/s dark current &lt; 1 e- read noise 320 x 256 array size Requires &lt; 100 K temperatures</td>
<td>&lt; 1x10^-3 e/pix/s dark current &lt; 3e- read noise 4k x 4k array size</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Ultra-stable Segmented Telescope - Components

<table>
<thead>
<tr>
<th>Technology Component</th>
<th>Implementation Options</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>FY19 TRL</th>
<th>In LUVOIR Baseline?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Substrate</td>
<td>Closed-back ULE (rigid body actuated)</td>
<td>7.5 nm RMS surface figure area with no actuated figure correction</td>
<td>~5 nm RMS surface figure error</td>
<td>5</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Closed-back ULE (surface figure actuated)</td>
<td>&lt; 200 Hz first free mode</td>
<td>&gt; 400 Hz first free mode</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open-back Zerodur (rigid body actuated)</td>
<td>~10 kg/m² areal density</td>
<td>19 kg/m² areal density</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Meets wavefront error requirement, but first mode and areal density are challenges</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td>Combined piezo/mechanical</td>
<td>JWST mechanical actuators; Off-the-shelf PZT actuator with 5 pm resolution</td>
<td>&gt; 10 mm stroke</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>All-piezo</td>
<td>20 mm travel with 5 nm coarse resolution and 5 pm fine resolution</td>
<td>&lt; 10 pm resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 1 pm / 10min creep</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Long lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge Sensors</td>
<td>Capacitive</td>
<td>5 pm in gap dimension, 60 Hz readout</td>
<td>&lt;4 pm sensitivity at 50-100 Hz rate (control bandwidth of 5-10 Hz)</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Inductive</td>
<td>1 nm / sqrt(Hz) for 1-100 Hz in shear; 100 nm / sqrt(Hz) for 1-10 Hz in gap</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optical</td>
<td>20 pm / sqrt(Hz) up to 100 Hz</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High-speed Speckle Interferometry</td>
<td>&lt; 5 pm RMS at kHz rates; requires center-of-curvature location and high-speed computing</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Laser Metrology</td>
<td>Laser truss with phasemeter electronics</td>
<td>Planar lightwave circuit; 0.1 nm gauge error; LISA-Pathfinder heritage laser</td>
<td>&lt; 100 pm sensitivity at 10 Hz rate (control bandwidth of 1 Hz)</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td>Vibration Isolation</td>
<td>Non-contact Isolation System</td>
<td>&gt; 40 dB transmissibility isolation &gt; 1 Hz; Requires electronics development and performance validation</td>
<td>&gt; 40 dB transmissibility isolation &gt; 1 Hz</td>
<td>4</td>
<td>✓</td>
</tr>
</tbody>
</table>
## UV Instrumentation - Components

<table>
<thead>
<tr>
<th>Technology Component</th>
<th>Implementation Options</th>
<th>State of the Art</th>
<th>Capability Needed</th>
<th>FY19 TRL</th>
<th>In LUVOIR Baseline?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far-UV Broadband Coating</td>
<td>Al + eLiF + MgF₂</td>
<td>Meets performance requirements, but requires demonstration on meter-class optics; requires validation of uniformity, repeatability, environmental stability</td>
<td>&gt;50% reflectivity (100-115 nm) &gt;80% reflectivity (115-200 nm) &gt;88% reflectivity (200-850 nm) &gt;96% reflectivity (&gt; 850 nm)</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Al + eLiF + AlF₃</td>
<td></td>
<td>&lt;1% reflectance nonuniformity (over entire primary mirror) over coronograph bandpass (200 - 2000 nm)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al + eLiF</td>
<td>Meets performance requirements, but is environmentally unstable</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Microshutter Arrays</td>
<td>Next-gen Electrostatic Microshutter Arrays</td>
<td>840 x 420 prototype demonstrated, but requires development survive vibe and acoustic testing</td>
<td>840 x 420 array format, two-side buttatable</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td>Large-format Microchannel Plates</td>
<td>CsI</td>
<td>Meets requirements for 100-150 nm</td>
<td></td>
<td>6</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>GaN</td>
<td>Meet requirements for 150-200 nm range; requires development for large tile size and integration with cross-strip readout. GaN has better solar blind performance.</td>
<td>200 mm x 200 mm tile size &gt;30% QE between 100 - 200 nm</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Bi-alkali</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Funnel microchannels</td>
<td>Demonstrated 50% improved quantum efficiency with CsI photocathode</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-format High-resolution Focal Plane Arrays</td>
<td>8k x 8k CMOS</td>
<td>4k x 4k devices exist, require development for 8k x 8k and readout optimization</td>
<td>8k x 8k format, &lt;7 micron pixels, three-side butttable ~1 e⁻ read noise ~1x10⁻⁴ e⁻/pix/s dark current at 170 K</td>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>4k x 4k CCD</td>
<td>8k x 8k devices exist with 18 micron pixels; lacks programmable high-speed region-of-interest readout for guiding capability</td>
<td></td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Path to TRL 6

Following slides show the technology development plans for each technology system

Includes associated manufacturing and engineering developments that will also enable LUVIOR

- Technology Development
- Engineering Development
- Manufacturing Development
Ultra-stable Segmented Telescope – Path to TRL 6

2020

System-level Model Development & Validation

Thermal Sensing and Control Development

Composite Material Process Development and Optimization

Parallelized Mirror Fabrication Process

Technology Component: Mirror Substrate

Technology Component: Mirror Actuators

Technology Component: Edge Sensor

Technology Component: Laser Metrology

Technology Component: Vibration Isolation

Assembly Demonstration: Full-scale Mirror Segment Assembly

Sub-system Demonstration: Metrology & Control Sub-system

Technology System Demonstration: Segmented Telescope System

11/5/2019
For more detailed information, see our Final Report at www.luvoirtelescope.org

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