HabEx Optical Telescope Assembly

H. Philip Stahl

Purpose

• Introduce candidate optical telescope assembly (OTA) architectures
• Illustrate design/analysis process

Agenda

• Definitions, Specification & Assumptions
• 4-meter Monolithic Mirror Concept
• 6.5-meter Segmented Mirror Concept
Definitions, Specifications & Assumptions

Optical Telescope Assembly (OTA)

Optical Telescope Assembly (OTA) is defined to consist of:

- Primary Mirror Assembly
  - Primary Mirror Substrate
  - Primary Mirror Struts
  - Primary Mirror Truss Structure

- Secondary Mirror Assembly
  - Secondary Mirror Substrate
  - Secondary Mirror Struts
  - Secondary Mirror Truss Structure

- OTA Structure
  Connects PMA to SMA and houses Science Instruments (SI).

- OTA Light Tube Baffle
OTA Specification

Science Requirements
Launch Vehicle Capacity
Programmatic Constraints

Engineering Specifications

Exoplanet
- Habitable Zone Size
- Contrast
- Contrast
- Star Size
- Architecture
Minimum Telescope Diameter
Mid/High-Spatial Wavefront Error
WFE Stability
Line of Sight Stability
Unobscured (off-axis)

General Astrophysics
- Diffraction Limit
- Spatial Resolution
Low/Mid-Spatial Wavefront Error
Line of Sight Stability

Launch Vehicle
- Up-Mass Capacity
- Fairing Size
Mass Budget
Architecture (monolithic/segmented)

Programmatic
- Budget
Maximum Telescope Diameter

Design Assumptions

Mission will have an Internal Coronagraph which requires:
- Unobscured Aperture – off-axis
- Stable Wavefront.

General Astrophysics:
- 500 nm diffraction limit requires no development effort

Launch Vehicle
- SLS will exist. Therefore, for ‘baseline’ design mass and volume constraints are secondary to wavefront stability.
- ‘Backup’ designs will be considered for EELV.

The Most important Design Constraints are:
- Line of Sight Stability
- Wavefront Stability
# DRAFT OTA Specifications

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Unobscured Off-Axis F/2.5 TMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter</td>
<td>4-meters Monolithic (Minimum)</td>
</tr>
<tr>
<td></td>
<td>6.5-meters Segmented (Maximum)</td>
</tr>
<tr>
<td>Mass Budget</td>
<td>&lt; 10,000 kg (nominal – assumed met)</td>
</tr>
<tr>
<td>Line of Sight Stability</td>
<td>&lt; ~5 milli-arc-second</td>
</tr>
<tr>
<td>Diffraction Limit</td>
<td>500 nm (assumed to be achievable)</td>
</tr>
<tr>
<td>Wavefront Error</td>
<td>36 nm rms Total (assumed achievable)</td>
</tr>
<tr>
<td>Primary Mirror (cpd = cycles/diameter)</td>
<td>Total SFE &lt; 8.0 nm rms</td>
</tr>
<tr>
<td></td>
<td>Low-Order (&lt; 3 cpd) &lt; 5.6 nm rms</td>
</tr>
<tr>
<td></td>
<td>Mid-Spatial (3 to 60 cpd) &lt; 5.6 nm rms</td>
</tr>
<tr>
<td></td>
<td>High-Spatial (&gt;60 cpd) &lt; 0.6 nm rms</td>
</tr>
<tr>
<td></td>
<td>Roughness &lt; 0.2 nm rms</td>
</tr>
<tr>
<td>Wavefront Stability</td>
<td>Architecture and Coronagraph Specific</td>
</tr>
</tbody>
</table>

## DRAFT OTA Line of Sight Stability

PSF (2.44\(\lambda/D\) full-angle) at 500 nm

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Wavefront Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-m</td>
<td>~300 nano-radian ~ 60 mas</td>
</tr>
<tr>
<td>6.5-m</td>
<td>~200 nano-radian ~ 40 mas</td>
</tr>
</tbody>
</table>

LOS Jitter < 5 mas (1/8\(^{th}\) of 40 mas)
DRAFT OTA Wavefront Stability

From Garreth Ruane and Dimitri Mawet, RMS wavefront tolerances for vector vortex coronagraphs over 2.5-3.5 \( \lambda/D \).

![Wavefront Tolerances Table]

From Stahl, Stahl and Shaklan, PV wavefront tolerances for a 4th order radial coronagraph over 1.5-2.5 \( \lambda/D \).

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Tolerance</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip/Tilt</td>
<td>9.6</td>
<td>nm</td>
</tr>
<tr>
<td>Power</td>
<td>1.1</td>
<td>nm</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>6.8</td>
<td>nm</td>
</tr>
<tr>
<td>Seidel Coma</td>
<td>0.84</td>
<td>nm</td>
</tr>
<tr>
<td>Spherical</td>
<td>0.3</td>
<td>nm</td>
</tr>
<tr>
<td>Trefoil</td>
<td>6.0</td>
<td>nm</td>
</tr>
<tr>
<td>Hexafoil</td>
<td>9.6</td>
<td>nm</td>
</tr>
</tbody>
</table>

Design for Stability

Wavefront and Line of Sight Stability has design consequences.

- **Mechanical**
  - Secondary Mirror Support Structure Dynamic Response
  - Primary Mirror Dynamic Response
  - Passive/Active Vibration Isolation
  - Passive/Active Dampening/Control

- **Thermal**
  - PM & SM Mirror CTE
  - Structure CTE
  - Passive Thermal Isolation
  - Active Thermal Control
BACKUP: Diffraction Limit WFE

Diffraction Limit of 500 requires total system WFE ~ 38 nm ms

4-meter Monolithic Concept

Concept
Tolerances
Structural Design
Primary Mirror Design
HabEx 4-m Off-Axis Concept

Observatory = OTA (PM/SM/Tube) & Science Instruments.

Observatory attaches to Spacecraft.

Solar Panels on Sunshade attach to Spacecraft.

Wide field imager
Chronograph
Multi image spectrometer
Launch Configuration – no deployments

Launch Configuration – Star-Shade below
Deployed Forward Scarf

Spacecraft & Sun Shade / Solar Panels
Tolerances

LOS & WFE Stability drive Mechanical Tolerances

Wavefront Stability

From Garreth Ruane and Dimitri Mawet, RMS wavefront tolerances for vector vortex coronagraphs over 2.5-3.5 \( \lambda/D \).

From Stahl, Stahl and Shaklan, PV wavefront tolerances for a 4\(^{th}\) order radial coronagraph over 1.5-2.5 \( \lambda/D \).

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<td>nm</td>
</tr>
<tr>
<td>Spherical</td>
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<td>nm</td>
</tr>
<tr>
<td>Trefoil</td>
<td>6.0</td>
<td>nm</td>
</tr>
<tr>
<td>Hexafoil</td>
<td>0.96</td>
<td>nm</td>
</tr>
</tbody>
</table>
Wavefront Stability is driven by Coronagraph Contrast Leakage.

Wavefront Errors (WFE) are caused by:

- OTA response to mechanical disturbances
- OTA response to thermal perturbation.

Following the definitions and methodology published by:

Contrast leakage decomposed into radial & azimuthal components

- Photometric Noise – time and spatial averaged radial
- Systematic Noise – azimuthal varying error

For Monolithic Aperture, the primary WFEs in response to mechanical stimuli are:

- Alignment Error from motion of PM relative to SM
  - Lateral Displacement produces Seidel Coma (Zernike Coma & Tilt)
  - Longitudinal Displacement produce Power and Spherical
- Bending of PM reacting against its mount - Trefoil
BACKUP: Coronagraph Contrast Leakage at 1.5-2.5 λ/D

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Random</th>
<th>Static</th>
<th>Sinusoidal</th>
<th>units</th>
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</thead>
<tbody>
<tr>
<td>Zernike Tip/Tilt</td>
<td>9,600</td>
<td>9,600</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Seidel Power</td>
<td>1,100</td>
<td>190</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Zernike Astigmatism</td>
<td>6,800</td>
<td>6,800</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Seidel Coma</td>
<td>840</td>
<td>260</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Seidel Spherical</td>
<td>300</td>
<td>73</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Zernike Trefoil</td>
<td>6,000</td>
<td>6,800</td>
<td></td>
<td>pm</td>
</tr>
<tr>
<td>Zernike Hexafoil</td>
<td>9,600</td>
<td>11,000</td>
<td></td>
<td>pm</td>
</tr>
</tbody>
</table>

Wavefront Error (WFE) Stability Specification

Optical Design WFE Alignment Sensitivity

Alignment specification to achieve WFE Stability

4th order Radial tolerance driven by coma and defocus sensitivity.
VVC tolerances driven by astigmatism sensitivity
Line of Sight (LOS) Specification

Optical Design LOS Alignment Sensitivity

<table>
<thead>
<tr>
<th>Alignment</th>
<th>Tolerance</th>
<th>Units</th>
<th>F/2.5</th>
<th>F/2</th>
<th>F/1.5</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM X-Tilt</td>
<td>1</td>
<td>micro-degree</td>
<td>35.2</td>
<td>35.4</td>
<td>35.6</td>
<td>nano-radian</td>
</tr>
<tr>
<td>PM Y-Tilt</td>
<td>1</td>
<td>micro-degree</td>
<td>34.6</td>
<td>34.5</td>
<td>34.2</td>
<td>nano-radian</td>
</tr>
<tr>
<td>SM X-Tilt</td>
<td>1</td>
<td>micro-degree</td>
<td>3.93</td>
<td>4.48</td>
<td>5.54</td>
<td>nano-radian</td>
</tr>
<tr>
<td>SM Y-Tilt</td>
<td>1</td>
<td>micro-degree</td>
<td>2.87</td>
<td>2.85</td>
<td>2.79</td>
<td>nano-radian</td>
</tr>
<tr>
<td>SM X-Decenter</td>
<td>10</td>
<td>nanometer</td>
<td>0.91</td>
<td>1.11</td>
<td>1.45</td>
<td>nano-radian</td>
</tr>
<tr>
<td>SM Y-Decenter</td>
<td>10</td>
<td>nanometer</td>
<td>0.89</td>
<td>1.11</td>
<td>1.45</td>
<td>nano-radian</td>
</tr>
</tbody>
</table>

Alignment specification to achieve LOS < 5 mas (24 nrad)

Multiple potential distribution of tolerances

<table>
<thead>
<tr>
<th>Line of Sight Stability</th>
<th>2</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>mas</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM X-Tilt</td>
<td>2.5</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>nano-radians</td>
</tr>
<tr>
<td>PM Y-Tilt</td>
<td>2.5</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>nano-radians</td>
</tr>
<tr>
<td>SM X-Tilt</td>
<td>7</td>
<td>20</td>
<td>16</td>
<td>15</td>
<td>nano-radians</td>
</tr>
<tr>
<td>SM Y-Tilt</td>
<td>7</td>
<td>20</td>
<td>16</td>
<td>15</td>
<td>nano-radians</td>
</tr>
<tr>
<td>SM X-Decenter</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>nanometers</td>
</tr>
<tr>
<td>SM Y-Decenter</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>nanometers</td>
</tr>
</tbody>
</table>

5 mas LOS Stability is more difficult than WFE Stability

Structure Dynamic Analysis

To determine PM/SM Rigid Body motions, apply at the OTA/Spacecraft interface:

- JWST Reaction Wheel Vibration Specification
- JWST Passive Vibration Isolation

Key Unknowns that impact analysis

1) Dimensions of Interface between OTA and Spacecraft
2) Amplitude and Location of Science Instrument Mass
Secondary Mirror Support Structure Stability

Studied Four Design Concepts
- Free-Standing Tower (~ 10 Hz)
- Tower Attached to Baffle Tube (~20 Hz)
- Tower Attached to Baffle Tube with Struts (~30 Hz)
- HST style Truss Structure

30 Hz Secondary Mirror Structure Dynamic Response

Apply JWST Reaction Wheel Assembly Disturbance Specification at 4 locations in the Spacecraft and calculate rigid body motions of the Primary and Secondary Mirrors with 1% dampening

<table>
<thead>
<tr>
<th>Rigid Body Alignment Motion</th>
<th>DOF</th>
<th>RWA Disturbance Only</th>
<th>RWA Disturbance &amp; Isolation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM/SM Y-Rotation</td>
<td>54</td>
<td></td>
<td>n-rad</td>
<td></td>
</tr>
<tr>
<td>PM/SM X-Rotation</td>
<td>44</td>
<td>n-rad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM/SM X-Despace</td>
<td>910</td>
<td>nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM/SM Y-Despace</td>
<td>2490</td>
<td>nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM/SM Z-Despace</td>
<td>1000</td>
<td>nm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Passive Isolation Required to meet SM Rigid Body Motion Specification

<table>
<thead>
<tr>
<th>Alignment</th>
<th>LOS</th>
<th>4'h Radial</th>
<th>VVC6</th>
<th>VVC8</th>
<th>VVC10</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM/SM Y-Rotation</td>
<td>6X</td>
<td>0.4X</td>
<td>0.7X</td>
<td>0.2X</td>
<td>0.1X</td>
<td>nano-radians</td>
</tr>
<tr>
<td>PM/SM X-Rotation</td>
<td>5X</td>
<td>0.5X</td>
<td>1X</td>
<td>0.2X</td>
<td>0.1X</td>
<td>nano-radians</td>
</tr>
<tr>
<td>PM/SM X-Despace</td>
<td>12X</td>
<td>10X</td>
<td>10X</td>
<td>4X</td>
<td>1X</td>
<td>nanometers</td>
</tr>
<tr>
<td>PM/SM Y-Despace</td>
<td>35X</td>
<td>25X</td>
<td>25X</td>
<td>10X</td>
<td>2.5X</td>
<td>nanometers</td>
</tr>
<tr>
<td>PM/SM Z-Despace</td>
<td>NA</td>
<td>40X</td>
<td>2X</td>
<td>1X</td>
<td>1X</td>
<td>nanometers</td>
</tr>
</tbody>
</table>
BACKUP: Tower Attached to Baffle Tube (~20 Hz)

RWA Vibration only, no Passive Isolation, 1% dampening.

<table>
<thead>
<tr>
<th>Relative Mirror Motion</th>
<th>Max</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (meters)</td>
<td>3.78E-06</td>
<td>De-Center</td>
</tr>
<tr>
<td>Y (meters)</td>
<td>1.37E-06</td>
<td>Vector Components</td>
</tr>
<tr>
<td>Z (meters)</td>
<td>1.92E-06</td>
<td>De-Space</td>
</tr>
<tr>
<td>RX (Radians)</td>
<td>2.52E-08</td>
<td>Net De-Center</td>
</tr>
<tr>
<td>RY (Radians)</td>
<td>1.15E-07</td>
<td>LOS Delta</td>
</tr>
<tr>
<td>RZ (Radians)</td>
<td>1.15E-07</td>
<td>Net LOS Delta</td>
</tr>
</tbody>
</table>

Passive Isolation Required to meet SM Rigid Body Motion Specification

<table>
<thead>
<tr>
<th>Alignment</th>
<th>LOS</th>
<th>4th Radial</th>
<th>VVC6</th>
<th>VVC8</th>
<th>VVC10</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM X-Tilt</td>
<td>12X</td>
<td>0.3X</td>
<td>0.4X</td>
<td>0.1X</td>
<td>0.05X</td>
<td>nano-radians</td>
</tr>
<tr>
<td>SM Y-Tilt</td>
<td>3X</td>
<td>1.2X</td>
<td>2X</td>
<td>0.5X</td>
<td>0.2X</td>
<td>nano-radians</td>
</tr>
<tr>
<td>SM X-Decenter</td>
<td>50X</td>
<td>40X</td>
<td>40X</td>
<td>15X</td>
<td>4X</td>
<td>nanometers</td>
</tr>
<tr>
<td>SM Y-Decenter</td>
<td>20X</td>
<td>15X</td>
<td>15X</td>
<td>6X</td>
<td>1.5X</td>
<td>nanometers</td>
</tr>
<tr>
<td>SM Z-Despace</td>
<td>NA</td>
<td>80X</td>
<td>4X</td>
<td>2X</td>
<td>2X</td>
<td>nanometers</td>
</tr>
</tbody>
</table>

BACKUP: Reaction Wheel Assemblies

Reaction Wheel Assemblies (RWA) in common pyramid arrangement providing three axis control with redundancy.

RWA disturbance forces and moments applied locally at grids.

RWA radial force and radial moment disturbances are swept through the 360 degree wheel rotation in order to calculate maximum relative displacement between primary and secondary mirror due to each wheel.

Enveloped disturbances from each RWA are linearly combined to produce the overall maximum relative displacement between the primary and secondary mirror during three axis control.
BACKUP: Reaction Wheel Assembly Disturbance

Modal solution is provided by NASTRAN
Boundary conditions to the spacecraft are unconstrained (Free-Free)
Radial force and moment are applied in 10 degree increments around the wheel rotation axis. This results in 144 load cases.
Critical Damping is set at 1%

BACKUP: JWST Passive Vibration Isolation

RWA Spec Vib Level from Scott Knight, BATC
Tower Attached to Baffle Tube with Struts (~30 Hz)

Structural Material assumed to be M55J.

Secondary Support Tower

Exoskeleton provide stiffness without obscuration.
Primary Mirror Dynamic Wavefront Error

Dynamic PM WFE arises from two sources:

- Thermal
- Mechanical

Thermal changes produce structural and component motions as a result of material response (bulk CTE and CTE homogeneity)

Mechanical Vibrations have a temporal spectrum:

- Specific vibration frequencies induce harmonic modal response.
- All other vibration frequencies cause inertial response.

These responses produce structural motions that cause:

- Optical mis-alignment aberrations
- Optical component bending and deformations from mount stress

Static Thermal WFE

0.5 m thick closed-back ULE mirror
Radial Gradient depends on view factor and side insulation.

Temperature gradient
Keeping Front Surface > 273K
20°C Axial; 10°C Radial

SFE from isothermal with defocus
SFE = 977 nm PV; 288 nm RMS

SFE from with defocus removed
SFE = 128 nm PV; 24 nm RMS
Dynamic Thermal WFE Video

Passive Wavefront Error from 1 hour exposure.
Sun angle changes by 0.0411 degree per hour.

All Errors

Power Removed

WFE/1-hour = 233 pm PV
WFE/20-min = 28 pm

WFE/1-hour = 101 pm PV
WFE/20-min = 13 pm

Dynamic Thermal WFE

Primary mirror responds to dynamic external thermal load
Required stability (10 pm per 10 min) can be achieved by controlling the telescope thermal environment.
4m Aperture Transient WFE Video

Thermal Stability

The ability to achieve any required wavefront stability depends on:

- Mirror Substrate Properties: CTE, Thermal Mass, Conductivity, etc.
- Thermal Environment Controllability
- Control Period.

Curve follows the function:

\[ T = \frac{\gamma}{\alpha C} \]

Where \( T \) is the shroud control period
\( \gamma \) is the maximum RMS WFE Range (10pm)
\( \alpha \) depends upon the telescope design (0.00208 nm/(mKs) for the analyzed telescope)

3-sigma Test Results, 165.00, 8.00
1.2m Zerodur Predicted vs Measured Thermal WFE

Predicted SFE: 9.55 nm RMS
Measured: 9.4 nm RMS

1.5m ULE Predicted Lateral Thermal WFE

Primary Mirror Dynamic Wavefront Error

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Primary Mirror Dynamic WFE

Dynamic WFE depends on the mirror’s mounted self-weight deflection (G-sag) and its inertial response function.

G-sag defines the maximum possible WFE for a 1G driving force and a unity response function.

G-sag depends on stiffness of mirror substrate and how it is mounted.

For example, JWST’s 220-Hz open-back beryllium primary mirror segments on a 3-point mount have a static horizontal G-sag of approximately 200 nm.

When driven at 87.3 Hz, they have a dynamic Astigmatic WFE of 220 nm per G of driving force.


Primary Mirror Dynamic WFE

To minimize PM Dynamic WFE:

• Design the PM Substrate to be as stiff as possible
• Consider the Mount stiffness and location.
ULE 4-m Mirror Trade Studies

MSFC explored range of higher mass, more robust designs. Harris Corporation explored lower limit of mass.

JWST total mass of primary mirror segment assemblies (PMSA) is 700 kg. Total PM Assembly mass is 1250 kg. Individual JWST PM substrates are 220 Hz. Individual PMSA are 40 Hz. Total PMA is 16 Hz.

ULE PM Trade Study: Substrate Stiffness

ULE mirrors can be Closed-Back Architectures.

State of Practice Thickness is 35 cm, SOA is 40 cm, 60-cm is developmental.

<table>
<thead>
<tr>
<th>depth (m)</th>
<th>0.45</th>
<th>0.6</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass (kg)</td>
<td>1388</td>
<td>1707</td>
<td>1835</td>
</tr>
<tr>
<td>cell size (m)</td>
<td>0.167</td>
<td>0.167</td>
<td>0.167</td>
</tr>
<tr>
<td>front fs (m)</td>
<td>0.0277</td>
<td>0.0277</td>
<td>0.0277</td>
</tr>
<tr>
<td>back fs (m)</td>
<td>0.0231</td>
<td>0.0231</td>
<td>0.0231</td>
</tr>
<tr>
<td>1st mode (Hz)</td>
<td>180</td>
<td>215</td>
<td>245</td>
</tr>
</tbody>
</table>

Gravity Sag:
- Stiffer mirror less G-Sag
- More Mount Points less G-Sag
ULE PM Trade Study: Dynamic WFE

Dynamic WFE for 4-m off-axis 180-Hz 1388-kg Mirror as a function of mount support system when excited at 49.9-Hz.

Dynamic WFE amplitude is similar to gravity sag.

<table>
<thead>
<tr>
<th></th>
<th>3 POINT</th>
<th>6 POINT</th>
<th>9 POINT</th>
<th>18 POINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ST MOUNTED MODAL (HZ)</td>
<td>47.2</td>
<td>50.4</td>
<td>54.1</td>
<td>55.4</td>
</tr>
<tr>
<td>HARMONIC PV (M)</td>
<td>1.16E-01</td>
<td>9.37E-01</td>
<td>1.71E-01</td>
<td>9.84E-01</td>
</tr>
<tr>
<td>AT FREQUENCY (HZ)</td>
<td>49.9</td>
<td>49.9</td>
<td>49.9</td>
<td>49.8</td>
</tr>
<tr>
<td>GRAVITY PV (M)</td>
<td>8.83E-06</td>
<td>2.81E-06</td>
<td>2.59E-06</td>
<td>7.10E-07</td>
</tr>
<tr>
<td>SCALE</td>
<td>2.45E-05</td>
<td>6.86E-05</td>
<td>6.61E-05</td>
<td>1.38E-04</td>
</tr>
</tbody>
</table>

Dynamic WFE amplitude goes down with support points.

ZERODUR PM Trade Study: Substrate Stiffness

ZERODUR mirrors are constrained to Open-Back architectures with a maximum thickness of 42 cm.

Trade Studies:

#1: Isogrid (triangular) Pockets
- First mode ~ 70 Hz.
- Mass ~ 2600 kg

#2: Hex Pockets with T-back
- First mode ~ 120 Hz.
- Mass ~ 1800 kg

#3: SOFIA Style
- First mode ~ 125 Hz.
- Mass ~ 1350 kg
## ZERODUR PM Trade Study: Multiple Designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Face</th>
<th>Cell</th>
<th>Web</th>
<th>Mass</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Mode</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>250</td>
<td>372</td>
<td>26</td>
<td>2313</td>
<td>71</td>
<td>322</td>
</tr>
<tr>
<td>2.5</td>
<td>250</td>
<td>372</td>
<td>50</td>
<td>2893</td>
<td>69</td>
<td>110</td>
</tr>
<tr>
<td>2.5</td>
<td>250</td>
<td>372</td>
<td>10</td>
<td>1373</td>
<td>71</td>
<td>322</td>
</tr>
<tr>
<td>2.5</td>
<td>250</td>
<td>372</td>
<td>25</td>
<td>3373</td>
<td>71</td>
<td>322</td>
</tr>
<tr>
<td>1.5</td>
<td>315</td>
<td>173</td>
<td>15</td>
<td>1421</td>
<td>75</td>
<td>121</td>
</tr>
<tr>
<td>1.5</td>
<td>315</td>
<td>173</td>
<td>31</td>
<td>4321</td>
<td>75</td>
<td>121</td>
</tr>
</tbody>
</table>

### Support trade studies

**Static Response**

- **Lp (mm)**: 25, 345, 195, 20
- **Depth (mm)**: 37.5, 345, 195, 20
- **Cell (mm)**: 50, 365, 195, 20
- **Face (mm)**: 60, 365, 195, 20

**Harmonic Response**

- **Lp (mm)**: 75, 365, 195, 20
- **Depth (mm)**: 350, 365, 195, 20
- **Cell (mm)**: 60, 365, 195, 18
- **Face (mm)**: 60, 365, 195, 22
Suspension system consists of beam elements with the desired stiffness and geometry.

Mirror and Mount system assumes 0.5% dampening give a Q (amplification factor) about 100X on transmissibility.
UTAS 4-m Zerodur Mirror Design

Milled Open-Back Zerodur Mirror
- Diameter: 4.2 meters
- Mass: 1200 kg
- First Mode: 120 Hz Mounted

Primary Mirror Assembly

Mirror Substrate is 180 Hz.
Assembly is 45 Hz before attachment to Secondary Tower
Primary Mirror Dynamic WFE

Primary Mirror Dynamic Trefoil Specification is defined by Coronagraph Contrast Leakage Sensitivity

<table>
<thead>
<tr>
<th>PV Trefoil Tolerance for Primary Mirror</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>from 1.5 to 2.5 λ/D</td>
<td></td>
</tr>
<tr>
<td>from 2.5 to 3.5 λ/D</td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td></td>
</tr>
<tr>
<td>4th Order Radial</td>
<td>VVC6</td>
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<tr>
<td>Trefoil</td>
<td>6 PV</td>
</tr>
<tr>
<td></td>
<td>0.0184 PV</td>
</tr>
</tbody>
</table>

We have not yet analyzed the dynamic WFE for our primary mirror candidates.
6.5-meter Segmented Concept

Concept ONLY
No Analysis

Conceptual Deployment Movie
Fairing Packaging

Deployed