Advanced Mirror Technology Development (AMTD) for Future Large Space Telescopes

H. Philip Stahl, MSFC

Introduction

AMTD

Advanced Mirror Technology Development (AMTD) is a multi-year effort to systematically mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

To accomplish our objective,
- We use a science-driven systems engineering approach.
- We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system.

The Challenge

Most future space telescope missions require mirror technology. Just as JWST’s architecture was driven by launch vehicle, future mission’s architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures. To provide the science community with options, we must pursue multiple technology paths.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:
- Very Smooth Surfaces < 10 nm rms
- Thermal Stability Low CTE Material
- Mechanical Stability High Stiffness Mirror Substrates

Critical Technologies

Space telescopes require advances in 6 inter-linked technologies:
- Large-Aperture, Low Areal Density, High Stiffness Mirrors: 4 - 8 m monolithic & 8 - 16 m segmented primary mirrors require larger, thicker, stiffer substrates.
- Support System: Large-aperture mirrors require large support systems to ensure they survive launch and deploy on orbit in a stress-free and undistorted shape.
- Mid/High Spatial Frequency Figure Error: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.
- Segment Edges: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.
- Segment-to-Segment Gap Phasing: Segment phasing is critical for producing a high-quality temporally stable PSF.

Simultaneous Maturation

Pursuing technology maturation in all 6 critical technologies simultaneously because all are required to make a primary mirror assembly (PMA); AND, it is the PMA’s on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.
Science & Engineering work collaboratively to insure that we mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

- derive engineering specifications for monolithic & segmented mirrors which provide on-orbit science performance needs AND satisfy implementation constraints
- identify technical challenges in meeting these specifications,
- iterate between science needs and engineering specifications to mitigate the challenges, and
- prioritize technology development which yields greatest on-orbit performance for lowest cost and risk.

STOP (structural, thermal, optical performance) models are used to help predict on-orbit performance & assist in trade studies.

To meet our goals, we need to derive engineering specifications for future monolithic or segmented space telescope based on science needs & implementation constraints.

We use a science-driven systems engineering approach:

Science Requirements → Engineering Specifications

The purpose of this effort is NOT to design a specific telescope for a specific mission or to work with a specific instrument. We are not producing an optical design or prescription. We are producing a set of primary mirror engineering specifications which will enable the on-orbit telescope performance required to enable the desired science.

Our philosophy is to define a set of specifications which ‘envelop’ the most demanding requirements of all potential science. If the PM meets these specifications, it should work with most potential science instrument.

Future is to integrate these PM specifications into a telescope. Also, right now, Coatings are out of scope. And, this presentation is a sub-set of our work.

**Science Requirements**

- Habitability Zone Size
- Contrast
- Star Size
- Diffraction Limit
- Mass Capacity
- Faring Size

**Engineering Specifications**

- Telescope Diameter
- Mid/High Spatial Error
- WFE Stability
- Line of Sight Stability
- Wavefront Error (Low/Mid)
- Mass Budget
- Architecture (monolithic/segmented)
Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions (2010)

<table>
<thead>
<tr>
<th>Science Question</th>
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<th>Measurements Needed</th>
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<tbody>
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<td>Discover exoplanets with Earth-like planets (V = 14 mag stars)</td>
<td>High contrast (ΔMag&gt;25 mag) SNR=10 broadband (R=5) imaging with IWA ~40 mas for ~100 target stars.</td>
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<td>Exoplanet characterization places the most challenging demands on a future UVOIR space telescope.</td>
<td>Detect at least 10 Earth-like planets in HZ with 95% confidence if n_Earth = 0.15</td>
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**Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope**

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**Exploration Measurement Capability**

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**Aperture Size Specification**

| Exoplanet Measurement Capability | Detect the presence of habitability and bio-signatures in the spectra of Earth-like HZ planets | High contrast (ΔMag>25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~40 mas. Exposure times <500 ksec. |
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Aperture Size vs $\eta_{\text{Earth}}$

Number of stars needed to find Exo-Earths depends on $\eta_{\text{Earth}}$
(probability of an Exo-Earth in a given star system)

Kepler indicates $\eta_{\text{Earth}}$ lies in the range [0.03, 0.30]

Complete characterization requires multiple observations

<table>
<thead>
<tr>
<th>Number of Earth-like Planets to Detect</th>
<th>$\eta_{\text{Earth}}$</th>
<th>Number of Stars one needs to Survey</th>
<th>Minimum Telescope Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.03</td>
<td>67</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>0.30</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0.03</td>
<td>167</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>33</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>17</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>0.03</td>
<td>333</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>0.15</td>
<td>67</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
<td>33</td>
<td>8</td>
</tr>
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Wavefront & Surface Figure Error Specification

WFE vs 500 nm Diffraction Limit

Total system WFE is derived from PSF requirement using Diameter, Strehl ratio ($S$) & wavelength ($\lambda$):

$$\text{PSF FWHM (mas)} = \left(\frac{0.2063}{S}\right) \times \frac{\lambda \text{ (nm)}}{D \text{ (meters)}}$$

$$S \approx \exp\left(-\frac{2\pi \times \text{WFE}/\lambda}{3}ight)$$

$$\text{WFE} = \left(\frac{\lambda}{2n}\right) \times \sqrt{-\ln S}$$

Diffraction limited performance requires $S \approx 0.80$.

At $\lambda = 500 \text{ nm}$, this requires total system WFE of $\approx 38 \text{ nm}$.

Aperture Size Recommendation

Based on the analysis, the Science Advisory Team recommends a
space telescope in the range of 4 meters to 8 meters.

<table>
<thead>
<tr>
<th>Telescope Diameter</th>
<th>Mirror Segmentation</th>
<th>Secondary Mirror Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>None – Monolithic</td>
<td>On-Axis or Off-Axis</td>
</tr>
<tr>
<td>8</td>
<td>Segmented</td>
<td>On-Axis or Partially Off-Axis</td>
</tr>
<tr>
<td>8</td>
<td>None - Monolithic</td>
<td>On-Axis or Off-Axis</td>
</tr>
</tbody>
</table>

Wavefront Error

Total system wavefront error (WFE) is driven by:

- 500 nm Diffraction Limited Performance
- Dark Hole Speckle

Exoplanet science driven specifications include:

- Line of Sight Pointing Stability
- Total Wavefront Error Stability

Primary Mirror Total Surface Figure Requirement

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
Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or segmented,

PM must have < 10 nm rms surface.

And, if segmented, it must have a ‘phased’ wavefront which as same performance as a monolithic aperture.

PM Specification depends on thermal behavior & mounting uncertainty, leaving < ~8 nm rms for total manufactured SFE.

Next question is how to partition the PM SFE error.

PM Manufacturing Specification

Define band-limited or spatial frequency specifications

<table>
<thead>
<tr>
<th>Figure/Low</th>
<th>Mid Spatial</th>
<th>High Spatial</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1 to 5 cycles/aperture)</td>
<td>(5 to 10 cycles/aperture)</td>
<td>(10 cycles to &lt; 1 micrometer)</td>
</tr>
</tbody>
</table>

Roughness

<table>
<thead>
<tr>
<th>Spatial Frequency (cycles/mm)</th>
<th>Surface Figure (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>1.E-11</td>
</tr>
<tr>
<td>0.001</td>
<td>1.E-09</td>
</tr>
<tr>
<td>0.01</td>
<td>1.E-07</td>
</tr>
<tr>
<td>0.1</td>
<td>1.E-05</td>
</tr>
<tr>
<td>1</td>
<td>1.E-03</td>
</tr>
<tr>
<td>10</td>
<td>1.E-01</td>
</tr>
<tr>
<td>100</td>
<td>1.E+01</td>
</tr>
<tr>
<td>1000</td>
<td>1.E+03</td>
</tr>
</tbody>
</table>

Also, what is proper PSD Slope

Spatial Frequency Specification

There is no precise definition for the boundary between

- Figure/Low and Mid-Spatial Frequency
- Mid and High-Spatial Frequency

Harvey defines Figure/Low errors as removing energy from core without changing shape of core, Mid errors as changing the shape of the core, and High errors scattering light.

Mid & High errors are important for Exoplanet Science.

PM SFE Spatial Frequency Specification

Shaklan shows that a UVOIR mirror similar to Hubble (6.4 nm rms) or VLT (7.8 nm rms) can meet the requirements needed to provide a < 10^{-10} contrast ‘dark hole’.

- If PM is conjugate with the DM, then PM low-order errors are compensated by DM.
- Recommends < 4 nm rms above 40 cycles
- Both HST & VLT surface figure error is so small enough that there is negligible Contrast reduction from frequency folding
- Because VLT is larger, stiffer and not light-weighted, it is actually smoother at frequencies of concern

Spatial Frequency vs Exoplanet Science

Exoplanet Science requires a Deformable Mirror (DM) to correct wavefront errors and create a ‘Dark Hole’ for the coronagraph.

To image an exoplanet, ‘dark hole’ needs to be below 10^{-10}

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/λ^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.
Primary Mirror Spatial Frequency Specification

Manufacturing processes typically range from -2.0 to -2.5 (in special cases to -3.0). Different slopes result in different allocations of PM spatial frequency surface figure error.

<table>
<thead>
<tr>
<th>Spatial Frequency Band Limited Primary Mirror Surface Specification</th>
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<tbody>
<tr>
<td>PSD Slope</td>
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<tr>
<td>Total Surface Error</td>
</tr>
<tr>
<td>Figure/Low Spatial (1 to 4 cycles per diameter)</td>
</tr>
<tr>
<td>Mid Spatial (4 to 60 cycles per diameter)</td>
</tr>
<tr>
<td>High Spatial (60 cycles per diameter to 10 mm)</td>
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<tr>
<td>Roughness (10 mm to &lt; 0.001 mm)</td>
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Wavefront Error Stability Specification

Per Krist, once a $10^{-10}$ contrast dark hole has been created, the corrected wavefront phase must be kept stable to within a few picometers rms between science exposures to maintain the instantaneous (not averaged over integration time) speckle intensity to within $10^{-11}$ contrast.

Any drift in WFE can result in speckles which can produce a false exoplanet measurement or mask a true signal.

WFE can vary with time due to the response of optics, structure and mounts to mechanical and thermal stimuli.

- Vibrations can be excited from reaction wheels, gyros, etc.
- Thermal drift can occur from slew changes relative to Sun

Key issue is how long does it take to sense and correct the temporal wavefront error.

Constraining factors include:
- Aperture Diameter of Telescope
- ‘Brightness’ of Star used to sense WFE
- Spectral Bandwidth of Sensing
- Spatial Frequency Degrees of Freedom being Sensed
- Wavefront Control ‘Overhead’ and ‘Efficacy’

Another factor is the difference between systematic, harmonic and random temporal WFE.

Primary Mirror Surface Figure Error Stability

If the telescope system cannot be designed near zero stability, then the WFE must be actively controlled.

Assuming that DMs can perfectly ‘correct’ WFE error once every ‘control period’, then the Telescope must have a WFE change less than the required ‘few’ picometers between corrections.


Primary Mirror SFE Stability Specification

Telescope and PM must be stable < 10 pm for periods longer than the control loop period.

Ignoring the issue of what magnitude star is used for the control loop, a conservative specification for the primary mirror surface figure error stability might be:
- < 10 picometers rms per 800 seconds for 4-m telescope
- < 10 picometers rms per 200 seconds for 8-m telescope

If PM SFE changes less than this rate, then coronagraph control system should be able to maintain $10^{-11}$ contrast.

This specifies how the PM SFE can change as a function of:
- Thermal environment from slews or rolls relative to the sun, etc.
- Mechanical stimuli such as reaction wheels, solar wind, etc.
Segmented Aperture

Primary Mirror Total Surface Figure Error

Regardless of whether PM is monolithic or segmented, it must have < 10 nm rms surface.

Segmenting increases complexity and redistributes errors.

Polishing specification is for individual segments.
Phasing specification is how well individual segments can be aligned before correction by a segmented deformable mirror.

Monolithic vs Segmented Aperture

Segmented apertures have many challenges:

- Segmentation Pattern results in secondary peaks
- Segmentation Gaps redistribute energy
- Rolled Edges redistribute energy
- Segment Co-Phasing Absolute Accuracy
- Segment Co-Phasing Stability

There are many different segmentation schemes, ranging from hexagonal segments to pie segments to large circular mirrors.

Selection and analysis of potential segmentation patterns is beyond the scope of this effort.

For this analysis, we assume hexagonal.

Hexagonally Segmented Aperture

Point Spread Function for Hexagonal Segmented Aperture:

$$PSF_{TP}(\rho) = \left( \frac{A W}{\lambda x} \right)^2 \cdot PSF_{TP}(\rho) \cdot Grid(\rho)$$

where:

- $PSF_{TP}$ size $\sim \frac{\lambda}{d_{seg}}$
- Grid space $\sim \frac{\lambda}{d_{seg}}$

and Phased Telescope has:

- $PSF_{seg}$ size $\sim \frac{\lambda}{d_{seg}}$

Tip/Tilt Errors

A segmented aperture with tip/tilt errors is like a blazed grating which removes energy from central core to higher-order peaks.

If the error is ‘static’ then a segmented tip/tilt deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then higher-order peaks will ‘wink’.

Segmented Aperture Point Spread Function (PSF)

For perfectly phased telescope with no gaps & optically perfect segments, zeros of $PSF_{seg}$ coincide with peaks of $Grid$ function resulting in $PSF_{seg}$ with a central peak size $\sim \frac{\lambda}{d_{seg}}$

In a real telescope: gaps, tip/tilt errors, piston errors, rolled edges & figure errors move energy from the central core to higher-order peaks and into the speckle pattern.
Co-Phasing Errors

Co-phasing errors introduce speckles.

If the error is ‘static’ then a segmented piston deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then speckles will move.

Per Guyon:

- Co-phasing required to meet given contrast level depends on number of segments; is independent of telescope diameter.
- Time required to control co-phasing depends on telescope diameter; is independent of number of segments.
- To measure a segment’s co-phase error takes longer if the segment is smaller because there are fewer photons.
- But, allowable co-phase error is larger for more segments.

Table 1: Segment cophasing requirements for space-based telescopes (wavefront sensing done at λ=550nm with an effective spectral bandwidth δλ= 100 nm)

<table>
<thead>
<tr>
<th>Telescope diameter (D) &amp; λ</th>
<th>Number of Segments (N)</th>
<th>Contrast</th>
<th>Target</th>
<th>Cophasing requirement</th>
<th>Stability timescale</th>
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<tbody>
<tr>
<td>4 m, 0.55 μm</td>
<td>10</td>
<td>1e-10</td>
<td>m&gt;8</td>
<td>2.8 pm</td>
<td>22 mn</td>
</tr>
<tr>
<td>8 m, 0.55 μm</td>
<td>10</td>
<td>1e-10</td>
<td>m&gt;8</td>
<td>2.8 pm</td>
<td>5.4 mn</td>
</tr>
<tr>
<td>8 m, 0.35 μm</td>
<td>100</td>
<td>1e-10</td>
<td>m&gt;8</td>
<td>8.7 pm</td>
<td>5.4 mn</td>
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Summary Science Driven Specifications

Science is enabled by the performance of the entire Observatory: Telescope and Science Instruments.

Telescope Specifications depend upon the Science Instrument.

Table 4m Telescope Requirements for use with Coronagraph

- Maximum total system rms WFE: 35 nm
- Encircled Energy Fraction (EEF): 80% within 32 mas at 500 nm
- Telescope WFE stability: < 10 μm per 800 sec
- PM rms surface error: 5 - 10 nm
- Pointing stability (jitter): < 4 mas
- Mid-frequency WFE: < 4 nm
### 8m Telescope Requirements for use with Coronagraph

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Specification</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total system rms WFE</td>
<td>38 nm</td>
<td>Diffraction limit (80% Strehl at 500 nm)</td>
</tr>
<tr>
<td>Encircled Energy Fraction (EEF)</td>
<td>&lt;5% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture &amp; blue wavelength, Vary &lt;5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF stability</td>
<td>&lt;5%</td>
<td>HST</td>
</tr>
<tr>
<td>WFE stability</td>
<td>5-10 nm</td>
<td>Depends on number of segments</td>
</tr>
<tr>
<td>Pointing stability (jitter)</td>
<td>&lt;2 mas</td>
<td>Depends on number of segments, scaled from HST</td>
</tr>
<tr>
<td>Mid-frequency WFE</td>
<td>&lt;4 nm</td>
<td>Depends on number of segments</td>
</tr>
</tbody>
</table>

### 8m Telescope Requirements for use with Occulter

<table>
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<tr>
<td>EEF stability</td>
<td>&lt;5%</td>
<td>HST</td>
</tr>
<tr>
<td>WFE stability</td>
<td>&lt;10 pm per 200 sec</td>
<td>Depends on number of segments</td>
</tr>
<tr>
<td>Number and Size of Segments</td>
<td>TBD</td>
<td>Summer, McIntosh 2013</td>
</tr>
<tr>
<td>Segment co-phasing stability</td>
<td>TBD</td>
<td>Summer, McIntosh 2013</td>
</tr>
<tr>
<td>Pointing stability (jitter)</td>
<td>&lt;2 mas</td>
<td>Depends on number of segments, scaled from HST</td>
</tr>
</tbody>
</table>

### Implementation Constraints


<table>
<thead>
<tr>
<th>Science</th>
<th>Mission</th>
<th>Capability</th>
<th>Technology Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spartan</td>
<td>Medium</td>
<td>6.5 m Monolith</td>
<td>200 Hz, 60 kg/m², up to 100 Hz, 5000 kg/m³, up to 1000 Hz, 50000 kg/m⁵, up to 10000 Hz, 500000 kg/m⁷, up to 100000 Hz, 5000000 kg/m⁹, up to 1000000 Hz</td>
</tr>
<tr>
<td>HLLV Medium</td>
<td>6.5 m Monolith</td>
<td>200 Hz, 60 kg/m², up to 100 Hz, 5000 kg/m³, up to 1000 Hz, 50000 kg/m⁵, up to 10000 Hz, 500000 kg/m⁷, up to 100000 Hz, 5000000 kg/m⁹, up to 1000000 Hz</td>
<td></td>
</tr>
<tr>
<td>HLLV Large</td>
<td>8.5 m Monolith</td>
<td>200 Hz, 60 kg/m², up to 100 Hz, 5000 kg/m³, up to 1000 Hz, 50000 kg/m⁵, up to 10000 Hz, 500000 kg/m⁷, up to 100000 Hz, 5000000 kg/m⁹, up to 1000000 Hz</td>
<td></td>
</tr>
<tr>
<td>2nd Exposure</td>
<td>6.5 m, 8.5 m Monolith</td>
<td>&lt;20 for spatial mode, &lt;10 for temporal mode</td>
<td>Spatial resolution, Temporal resolution</td>
</tr>
<tr>
<td>3rd Exposure</td>
<td>6.5 m, 8.5 m Monolith</td>
<td>&lt;5 arcmin figure, &lt;1 arcmin figure</td>
<td>Spatial resolution, Temporal resolution</td>
</tr>
<tr>
<td>Refractive</td>
<td>6.5 m, 8.5 m Monolith</td>
<td>&lt;5 arcmin figure, &lt;1 arcmin figure</td>
<td>Spatial resolution, Temporal resolution</td>
</tr>
<tr>
<td>High-Contrast</td>
<td>Diffraction Limit</td>
<td>0.1%</td>
<td>Spatial resolution</td>
</tr>
</tbody>
</table>

### Representative Missions

Four 'representative' mission architectures achieve Science:
- 4-m monolith launched on an EELV.
- 8-m monolith on a HLLV.
- 8-m segmented on an EELV.
- 16-m segmented on a HLLV.

The key difference between launch vehicles is up-mass: EELV can place 6.5 mt to Sun-Earth L2
HLLV is projected to place 40 to 60 mt to Sun-Earth L2

The other difference is launch fairing diameter: EELV has 5 meter fairing
HLLV is projected to have a 8 to 10 meter fairing
Space Launch System (SLS)

Space Launch System (SLS) Cargo Launch Vehicle specifications

Preliminary Design Concept
8.3 m dia x 18 m tall fairing
70 to 100 mt to LEO consistent with HLLV Medium

Enhanced Design Concept
10.0 m dia x 30 m tall fairing
130 mt to LEO consistent with HLLV Heavy

HLLV Medium could launch an 8-m segmented telescope whose mirror segments have an areal density of 60 kg/m².


Mass

Mass is the most important factor in the ability of a mirror to survive launch and meet its required on-orbit performance.

More massive mirrors are stiffer and thus easier and less expensive to fabricate; more mechanically and thermally stable.

Primary Mirror Mass Allocation

Given that JWST is being designed to a 6500 kg mass budget, we are using JWST to define the EELV telescope mass budget:

- Optical Telescope Assembly < 2500 kg
- Primary Mirror Assembly < 1750 kg
- Primary Mirror Substrate < 750 kg

This places areal density constraints of:

- Aperture PMA PM
  - 4 meter 145 kg 62.5 kg
  - 8 meter 35 kg 15 kg

An HLLV would allow a much larger mass budget

- Optical Telescope Assembly < 20,000 to 30,000 kg
- Primary Mirror Assembly < 15,000 to 25,000 kg
- Primary Mirror Substrate < 10,000 to 20,000 kg

Large Substrate: Technical Challenge

Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

Current methods limited in how thick of a core can be fabricated. Current launch vehicle capacity also requires low areal density.

Large Substrate: State of the Art

State of the Art is

- 2.4 meter ATT Mirror:
  - 3-layer, 0.3 m deep, 60 kg/m² substrate
  - Also 1.4 m AMSD and 1 m Kepler

Large Lightweight ULE® Primary Mirrors at Exelis

- 1970’s High Temperature Fusion (Hubble Primary Mirror)
- 1980’s Frit Technology with Flame Welded Core
- 1990’s Waterjet Cut Core
- 2000’s Low Temp Fusion Development
- 2005’s Low Temp Fusion
How to make a 4-meter Substrate

Stacked Core Design

12 Core Segments are fabricated from standard thickness boules, then stacked & fused during blank assembly to achieve a deep core
Eliminates need for stack sealing of boules and deep AWJ cutting of cores
Enables lighter weight cores
Reduces cost & schedule

43 cm Deep Core Mirror

Exelis successfully demonstrated 5-layer 'stack & fuse' technique which fuses 3 core structural element layers to front & back faceplates.
Made 43 cm 'cut-out' of a 4 m dia, > 0.4 m deep, 60 kg/m² mirror substrate.

Mid/High Spatial Frequency Figure Error

Technical Challenge:

• High-contrast imaging requires a very smooth mirror (< 10 nm rms)
• Mid/High spatial errors (zonal & quilting) can introduce artifacts
• DMs correct low-spatial errors, not mid/high spatial errors
• On-orbit thermal environment can stress mirror introducing error

Achievements:

• Facesheet designed to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress.
• Ion polishing produced 5.4 nm rms surface
• No measurable cryo-deformation quilting

Pocket Milled Facesheet

AMTD PSD Assessment (Final Ion Iteration)

Before Ion Figuring

After Ion Figuring

Δ Bands were analyzed at >5X above Nyquist limit with ~5 cycles per test aperture
Δ Hanning window used for PSD analysis with magnitude re-scale
Δ Spatial periods smaller than 20mm were negligibly affected by ion figuring as evident in the PSD plot

Mid/High Spatial Frequency Figure Error

Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.

MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)
Integrated Model Validation

Technical Challenge:
• On-orbit performance is determined by mechanical & thermal stability
• As future systems become larger, compliance cannot be 100% tested
• Verification will rely on sub-scale tests & validated high fidelity models

Achievement:
• Developed new opto-mechanical tool to create high-fidelity models
• Created models to predict gravity sag & 2C thermal gradients
• Validated models by interferometric and thermal imaging test

Deep Core Thermal Model

Thermal Model of 43 cm deep core mirror generated and validated by test.

43 cm deep core mirror tested from 250 to 300K

Test Instrumentation
• 4D Instantaneous Interferometer to measure surface Wavefront Error
• InSb Micro-bolometer to measure front surface temperature gradient to 0.05°C
• 12 Thermal Diodes.

NOTE: This was first ever XRCF test using thermal imaging to monitor temperature

Segment Edges

Technical Challenge:
• Segmented primary mirror edge quality impacts PSF for high-contrast imaging applications and contributes to stray light noise.
• Diffraction from secondary mirror obscuration and support structure also impacts performance.

Achievement
• AMTD partner STScI successfully demonstrated an achromatic edge apodization process to minimize segment edge diffraction and straylight on high-contrast imaging PSF

Primary mirror segment gap apodization in the optical

Apodization mitigates segment gaps
Achromatic: apodization in collimated space
Tolerancing can be tight
Gemini Planet (1.1-2.4 μm) - 0.5% accuracy req
UVOIR space coronagraphy - 0.55 - 1.1 μm
Metal-on-glass dots look OK
Shape
• Develop & confirm on reflective surfaces
• High accuracy, reflectivity, absorption, polarization?
• Use larger dots to reduce non-linearity
• Use larger dots to reduce non-linearity
• Next
• Develop & confirm on reflective surfaces
• High accuracy, reflectivity, absorption, polarization?
• Use larger dots to reduce non-linearity

Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.
Support System

Technical Challenge:
• Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

Accomplishments:
• Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
• Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
• Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.

Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

**Point Designs:** AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.

Monolithic Substrate Point Designs

4-m designs are mass constrained to 720 kg for launch on EELV

8-m designs are mass constrained to 22 mt for launch on SLS

Trade Study Concept #1: 4 m Solid

<table>
<thead>
<tr>
<th>Design:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>First Mode</td>
</tr>
</tbody>
</table>

Trade Study Concept #2: 4 meter Lightweight

<table>
<thead>
<tr>
<th>Design:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Facesheet</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>First Mode</td>
</tr>
</tbody>
</table>
Trade Study Concept #3: 8 meter Solid 22 MT

Design:
- Diameter: 8 meter
- Thickness: 200 mm
- Mass: 21,800 kg
- First Mode: 18 Hz

Same as ATLAST Study

Trade Study Concept #4: 8 meter Lightweight

Design:
- Diameter: 8 meter
- Thickness: 510 mm
- Facesheet: 7 mm
- Mass: 3,640 kg
- First Mode: 48.4 Hz

Program Control Window

Modeling Tool

Monolithic Mirrors

Segmented Mirrors
We are using a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture UVOIR space telescopes for both general astrophysics & ultra-high contrast exoplanet imaging.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors. Successfully demonstrated capability to make 0.5 m deep mirror substrate and polish it to UVOIR traceable figure specification.

Questions?