Advanced mirror technology development (AMTD) project status

Mirror Technology Days in the Government 2014
Albuquerque
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H. Philip Stahl

Programmatic Summary
To date, AMTD Phase 1 has accomplished all of its technical tasks on-schedule and on-budget.

AMTD was awarded a Phase 2 contract.

We are now performing Phase 2 tasks along with those tasks continued from Phase 1.

Technical 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

Objectives and Goals
AMTD’s objective is to 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.

Mature 6 inter-linked critical technologies.
- Large-Aperture, Low Areal Density, High Stiffness Mirrors
- Support System
- Mid/High Spatial Frequency Figure Error
- Segment Edges
- Segment-to-Segment Gap Phasing
- Integrated Model Validation

Technical Approach/Methodology
To accomplish our objective, we:
- Use a science-driven systems engineering approach.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Mature Technology Simultaneous 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.

TRL Assessment

<table>
<thead>
<tr>
<th>Technology</th>
<th>Baseline / TRL</th>
<th>Pre-Phase A / TRL</th>
<th>Post-Phase A / TRL</th>
<th>Pre-Phase B / TRL</th>
<th>Post-Phase B / TRL</th>
<th>Pre-Phase C / TRL</th>
<th>Post-Phase C / TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-Aperture, Low Areal Density, High Stiffness Substrate</td>
<td>TRL6 (AMSD/MMSD note 1)</td>
<td>TRL6 (1.5mDC &amp; 1.2m Zerodur note 2)</td>
<td>TRL6 (1.5m &amp; 1.2m at 250K)</td>
<td>TRL5 (8 m Ground)</td>
<td>TRL3 (43 cm Deep Core)</td>
<td>TRL4 (1.5m Deep Core)</td>
<td>TRL5 (8 m Ground)</td>
</tr>
<tr>
<td>Support System</td>
<td>TRL3 (JWST is not UVOIR)</td>
<td>TRL3 (8-m Point Design)</td>
<td>TRL3.5 (2 stage Actuator)</td>
<td>TRL6 (43 cm Gravity)</td>
<td>TRL4/5 (43 cm Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
</tr>
<tr>
<td>Mid/High Spatial Frequency Error</td>
<td>TRL5 (HST, 8 m Ground)</td>
<td>TRL6 (43 cm @ 250K)</td>
<td>TRL6 (1.5m &amp; 1.2m at 250K)</td>
<td>TRL6 (43 cm Gravity)</td>
<td>TRL4/5 (43 cm Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
</tr>
<tr>
<td>Segment Edges</td>
<td>Polished X X</td>
<td>Polished</td>
<td>Polished</td>
<td>X X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Segment-to-Segment Gap Phasing</td>
<td>Alignment TRL3 (JWST is not UVOIR)</td>
<td>TRL3.5 (2 stage Actuator)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Model Validation</td>
<td>Structural TRL4/5 (JWST &amp; SVMV)</td>
<td>TRL4/5 (43 cm Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
<td>TRL5 (1.5 m Modal &amp; Gravity)</td>
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</tr>
</tbody>
</table>

NOTE 1: AMSD/MMSD Exelis mirror was manufactured from ULE©. Other AMSD mirrors were manufactured from Be & Fused Silica.

NOTE 2: AMTD-2 achieving TRL6 for Segmented requires unfunded Strength, Vibration & Acoustic Test of 1.5 m Deep Core & 1.2 m Zerodur.
Philosophy
Simultaneous technology maturation 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.
We are deliberately pursuing multiple design paths to enable either a future monolithic or segmented space telescope
- Gives science community options
- Future mission architectures depend on future launch vehicles, AND
- We cannot predict future launch vehicle capacities

Phase 1: Goals, Progress & Accomplishments
Systems Engineering:
- derive from science requirements monolithic mirror specifications
- derive from science requirements segmented mirror specifications
Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:
- make a subsection mirror via a process traceable to 500 mm deep mirrors
Support System:
- produce pro-Phase-A point designs for candidate primary mirror architectures;
- demonstrate specific actuation and vibration isolation mechanisms
Mid/High Spatial Frequency Figure Error:
- ‘null’ polish a 1.5-m AMSD mirror & subscale deep core mirror to < 6 nm rms error figure at the 2°C operational temperature.
Segment Edges:
- demonstrate an achromatic edge apodization mask
Segment to Segment Gap Phasing:
- develop models for segmented primary mirror performance; and
- test prototype passive & active mechanisms to control gaps to ~1 nm rms.
Integrated Model Validation:
- validate thermal model by testing the AMSD and deep core mirrors at 2°C
- validate mechanical models by static load test.

AMTD-1 Tasks
Three AMTD-1 technologies are not continued into AMTD-2:
Mid/High Spatial Frequency Figure Error
AMTD-1 demonstrated the ability to achieve a < 6 nm rms surface figure on a facesheet that is representative of and scaleable to a 4 meter or larger primary mirror. The ability to deterministically polish ULE© glass mirrors to < 6 nm rms is at TRL-6.
Segment Edges
AMTD-1 demonstrated a technology to mitigate edge diffraction. Several SBIR contracts have demonstrated ability to polish mirrors to 2 mm of the edge. JWST demonstrated 5-7 mm edges. Thus, until requirement to do better, further development is not warranted.
Segment-to-Segment Gap Phasing
AMTD-1 demonstrated the fine stage of a two-stage actuator for controlling mirror segments. There is no plan to continue this in Phase 2

Phase 2: Tasks
Refine engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 4 inter-linked critical technologies.
Large-Aperture, Low Areal Density, High Stiffness Mirrors
Fabricate a 1/3rd scale model of a 4-m class 400 mm thick deep-core ULE© mirror – to demo lateral scaling.

Support System – continue Phase A design studies
Mid/High Spatial Frequency Figure Error
Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

Integrated Model Validation – continue developing and validating tools

Engineering Specifications

9 Publications from Year 1
Stahl, H. Philip, W. Scott Smith, Marc Postman, Engineering specifications for a 4-meter class UVOIR space telescope derived from science requirements, SPIE Conference on UV-Optical/IR Space Telescopes and Instrumentation, 2013.
Arnold, Williams et al., Integration of Mirror design with Suspension System using NASA’s new mirror modeling software, SPIE Conference on Optomechanical Engineering, 2013.

AMTD-1 Tasks

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Support System – continue Phase A design studies
Mid/High Spatial Frequency Figure Error
Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

Integrated Model Validation – continue developing and validating tools
Engineering Specifications Accomplishment

Derived from Science Requirements, Engineering Specifications for advanced normal-incidence monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast observations of exoplanet missions as a function of potential launch vehicle and its inherent mass and volume constraints.

8m Telescope Requirements for Coronagraph

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Specification</th>
<th>Source</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total system rms WFE</td>
<td>38 nm</td>
<td>Diffraction limit (80% Strehl ratio at 500 nm)</td>
<td></td>
</tr>
<tr>
<td>Encircled Energy Fraction (EEF)</td>
<td>&gt;90% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture and slightly blueer wavelength</td>
<td></td>
</tr>
<tr>
<td>Stability</td>
<td>&lt;2%</td>
<td>JWST</td>
<td></td>
</tr>
<tr>
<td>WFE stability over 20 minutes</td>
<td>~1.5 nm</td>
<td>1/500 at 700 nm</td>
<td></td>
</tr>
<tr>
<td>PM rms surface error</td>
<td>5 - 10 nm</td>
<td>HST / ATLAST studies</td>
<td></td>
</tr>
<tr>
<td>Pointing stability</td>
<td>&lt;2 mas</td>
<td>Guyon, scaled from HST ~0.5 mas floor determined by stellar angular diameter</td>
<td></td>
</tr>
<tr>
<td>Mid-frequency WFE</td>
<td>&lt; 20 nm</td>
<td>HST</td>
<td></td>
</tr>
</tbody>
</table>

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>
</tr>
</thead>
<tbody>
<tr>
<td>ischemia</td>
</tr>
<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>
</tr>
<tr>
<td>Roughness (10 mm to &lt; 0.001 mm)</td>
</tr>
</tbody>
</table>

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.
Phase 2
In AMTD-2 we will continue to refine the Science Derived Engineering Specifications.

Specific Analysis includes:
- Monolithic vs Segmented
- Segments Size – many small or few large
- Diffraction Effects on High Contrast Imaging
- Mid-Spatial Frequency Error Effects on High Contrast Imaging

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 launch vehicle capacity limits requires low areal density.
State of the Art is
- ATT Mirror: 2.4 m, 3-layer, 0.3 m deep, 24 kg/m² substrate
- AMSD ULE©: 1.4 m, 3 layer, 0.06m deep, 13 kg/m² substrate
- Kepler: 1 m

Large Substrate: Achievements
Successfully demonstrated a new fabrication process (stacked core low-temperature fusion).
New process offers significant cost and risk reduction over incumbent process. It is difficult (and expensive) to cut a deep-core substrate to exacting rib thickness requirements. Current SOA is ~300 mm on an expensive custom machine. But, < 130 mm deep cores can be done on commercial machines.
Extended state of the art for deep core mirrors from less than 300 mm to greater than 400 mm.
Successfully ‘re-slumped’ a ULE© fused substrate.
This is interesting because it allows generic substrates to be assembled and placed in inventory for re-slumping to a final radius of curvature.

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.

Phase 2
In Phase 2 we will build a 1/3rd scale model of a 4 meter mirror.
Mirror will demonstrate the ability to scale the ‘stacked-core’ construction approach to larger diameter.
The mirror will be 1.5 m diameter and 200 mm thick.

Subject to budget constraints, we plan to thermal test, modal test, and maybe vibe & acoustic test this mirror and a 1.2 meter lightweight Zerodur mirror owned by Schott.
**Strength Testing**

AMTD-1: Exelis strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.

- Resulting Weibull 99% survival value was 15% above the most conservative design allowable. And, the data ranged from 30% to 200% above design allowable.

AMTD-2: Exelis is performing an A-Basis characterization of the core rib to core rib LTF bond strength.

- 60+ Modulus of Rupture Samples: 30+ samples for nominal alignment and 30+ samples for core mis-alignment

**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:**

- AMTD partner Exelis designed facesheet to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress.
- Exelis ion polishing process produced 5.4 nm rms surface
- Thermal test showed no measurable cryo-deformation or quilting

**Phase 2**

In AMTD-2 we will characterize the thermal response of the:

- 1.5 m 1/3rd scale deep-core ULE© mirror, and
- Schott’s 1.2 meter Extreme-Lightweight Zerodur Mirror

This characterization data will be used to predict the need for ‘null’ polishing to correct low and mid-spatial frequency errors

Actual ‘null polish ’ is not recommended because capability is demonstrated

**Integrated Model Validation**
**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 & thermal gradients for the 43 cm mirror & validated them by interferometric and thermal imaging test

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**Deep Core Thermal Model**

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

43 cm deep core mirror tested from 250 to 300K

**Test Instrumentation**
- 40 Instantaneous Interferometers to measure surface Wavefront Error
- InSb Micro-bolometers to measure front surface temperature gradient to 0.05°C
- 12 Thermal Diodes

**Figure 8:** 43-cm mirror test setup. **Figure 9:** Predicted Thermal Model (left) vs. Measure Performance (right)

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

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**Phase 2**

In AMTD-2 we will continue to refine tools to predict on-orbit system level optical performance using validated model inputs.

We will validate models via predicting and characterizing:
- thermal response
- static load deformation
- modal testing of available mirrors

**Within budgetary constraint:**
- willing to add contributed mirrors to characterization testing
- try to perform vibe & acoustic model validate via test

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**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.

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**Primary mirror segment gap apodization in the optical**

Apodization mitigates segment gaps
- Achromatic apodization in collimated space
- Tolerancing can be tight
- Gemini Planet Imager (1.1 -2.4 um) – 0.5% accuracy exig
- UVOIR space coronagraphy - 0.55 – 1.1 um

Metal-on-glass dots look OK
Use larger dots to reduce non-linearity

Develop & confirm on reflective surfaces
Use large dots to reduce non-linearity

Next:
- Develop & confirm on reflective surfaces
- Requirements on accuracy, reflectivity, absorption, polarization?
- Use larger dots to reduce non-linearity

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**Figure 10:** 43 cm mirror test setup. **Figure 11:** Predicted Thermal Model (left) vs. Measure Performance (right)

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

Design:
- Diameter: 4 meters
- Thickness: 26.5 mm
- Mass: 716 kg
- First Mode: 9.8 Hz

Trade Study Concept #2: 4 meter Lightweight

Design:
- Diameter: 4 meters
- Thickness: 410 mm
- Facesheet: 3 mm
- Mass: 621 kg
- First Mode: 124.5 Hz

THEIA PM design: 4m, 381mm thick, ~6mm pocktmilled faceplates, 600kg, first mode 140-160 Hz
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

Exelix AMTD-I: 8m, 420mm thick, 2.5/2.0mm faceplates (front/back), 3,042 kg, first mode 33 Hz

Phase 2
AMTD-2 will continue to use all our tools to generate and refine Pre-Phase A point designs for 4 meter mirrors on various potential launch vehicles.

Modeling Tool

Program Control Window

Monolithic Mirrors
**Segmented Mirrors**

**Support Systems**

**Fast Response Simulator for Telescopes (FaRSiTe)**
- Suite of tools to compute optical response metrics from Integrated Modeling analysis results for spacecraft modeling
- Incorporated direct integration to transform optical path difference to Point Spread Function (PSF) and between PSF to modulation transfer function.

**FaRSiTe: STOP**
Structural-Thermal-Optical Performance (STOP)
Degradation in optical response due to changes in thermal environment

**Discipline models**
- Thermal: thermal loads, heat transfer paths
- Structural: thermally induced strain
- Optical: change in line-of-sight (LOS) and wavefront error (WFE) as a function of mechanical strain
- Rigid body motion of the optics (alignment error)
- Bending of individual mirrors (figure error)

**Outputs**
- OPD maps and LOS versus time

**FaRSiTe: Jitter**
Jitter Degradation in optical response due to excitation of flexible modes

**Discipline models**
- Disturbances: Reaction Wheel Actuators, High Gain Antennae, Solar Arrays, cryocoolers
- Structural: Normal Modes responses
- Optical: change in LOS and WFE as a function of motions of optics
- Optionally: jitter mitigation technologies
  - Isolators (e.g. reaction wheel or payload isolators)
  - Fast Steering Mirrors
  - Tuned Mass Dampers

**Outputs**
- LOS and spatial RMS WFE as a function of disturbance operating frequency
- Can be added to alignment/figure errors from STOP analysis for telescope performance modeling

**WFIRST-AFTA Jitter**

*Courtesy GSFC/WFIRST-AFTA*
Phase 2
AMTD-2 will continue to add capabilities to modeling tools:

We will investigate parametric optimization to find the best opto-mechanical design solution.

Segment to Segment Gap Phasing

Technical Challenge:
• Diffraction limited performance requires co-phased segments.

Achievements:
• Demonstrated the ‘fine’ stage of a low mass two stage actuator which could be used co-phase segments.

<table>
<thead>
<tr>
<th>Property</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>0.313 kg</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>40.9 N/μm</td>
</tr>
<tr>
<td>Test Range</td>
<td>14.1 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>6.6 nm (noise limited result) [expected is 0.8 nm]</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1.1 μm</td>
</tr>
</tbody>
</table>

Segment to Segment Gap Phasing

Technical Challenge:
• To avoid speckle noise which can interfere with exo-planet observation, Internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Achievements:
• Investigated utility of Correlated magnetic interface to reduce vibration amplitude, but it provided only marginally improved dampening over conventional magnets.
• Given the inability to reduce dynamic vibration below the required level, we plan no further investigation of this approach.

Conclusions
AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones.