Advanced mirror technology development (AMTD) project status

Mirror Technology Days in the Government 2014
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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

TRL Assessment

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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.

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.
Philosophy

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- 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 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 nm 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**

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 facetsheet 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

9 Publications from Year 1


Engineering Specifications

- **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 subsecon mirror via a process traceable to 500 nm deep mirrors
  - **Support System**
    - produce pre-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 & sub-scale 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;
    - 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.
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 exoplanets missions as a function of potential launch vehicle and its inherent mass and volume constraints.

Telescope Performance Requirements
Telescope Specifications depend upon the Science Instrument.

WFE Specification is before correction by a Deformable Mirror
WFE/EE Stability and MSF WFE are the stressing specifications
Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.

8m Telescope Requirements for Coronagraph

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:

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.

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-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

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, 0.06 m 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.

Exelis: 2.4 m ATT Mirror

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

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

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

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

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:
- 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

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

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.

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 is achieved in space
Tolerancing can be tight
- Optical: Plane figure (1.5 um avg. - 0.5%) accuracy avg
- UVIR space consistency - 0.00 - 0.15 um
- Multi-layer dielectric film OK

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

40 test transmissions written with 5 um Al on Cr microdots on Infrasil glass
- Measured vs Design up to ± 5%
- Errors <1% at high transmissions
- 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.

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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

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
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

Carl Blaurock, Nightsky Systems, Inc. at GSFC

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 are 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 are 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

RW Crossing Jitter Critical Mode

* 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>
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<tr>
<th>Property</th>
<th>Performance</th>
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<tbody>
<tr>
<td>Mass</td>
<td>0.313 kg</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>40.9 N/μm</td>
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<tr>
<td>Test Range</td>
<td>14.1 μm</td>
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<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>
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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