Advanced Mirror Technology Development (AMTD): Year Five Status

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AMTD Status

AMTD-1 completed in 2014.

AMTD-2 will complete in 2017.

- Fabricate $\frac{1}{3}$-scale model of 4-m x 400-mm class ~150 Hz ULE® mirror
  
  Done in 2016 – Harris Mirror Substrate

- Qualify two candidate lightweight primary mirrors by characterizing their optical performance from 250K to ambient

  Done in 2016 – Schott Mirror

  2017 – Harris Mirror

- Integrated Modeling Tools and Point Designs:

  Done in 2016 – Infused into HabEx Study
Space Telescopes require Mirror Technology

Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

- Exoplanet Mission (New-Worlds Explorer)
- UVOIR Space Telescope (4 meter or larger)

2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

- New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …

2014 Enduring Quests Daring Visions recommended:

- LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.
Objective

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.

AMTD’s objective is to mature to towards 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.
Multiple Technology Paths

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 are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

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
‘The’ System Challenge: Dark Hole

- Imaging an exoplanet, requires blocking $10^{10}$ of host star’s light
- An internal coronagraph (with deformable mirrors) can create a ‘dark hole’ with $< 10^{-10}$ contrast.

![Contrast before and after wavefront correction](image)

John Krist, JPL

Inner Working Angle

- Ultra-smooth, Ultra-Stable Mirror Systems are critical to achieving and maintaining the ‘dark hole’

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143
Phase 1 demonstrated stacked core low-temperature fusion process to cost effectively make mirrors thicker than 300 mm by making a 40 cm ‘cut-out’ of a 4-m mirror.
Harris successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m² mirror substrate.

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Mid/High Spatial Frequency Error

- Harris 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).
Large Stable Mirror Substrates

Phase 2 demonstrated lateral scaling of the stacked core process by making a 1.5 m subscale of a 4-m mirror.

Designed 4-m x 500 mm on-axis mirror then scale down to 1.5 m x 185 mm.

- (2) ULE® face plates
- (3) ULE® glass boules

4m PM Conceptual Layout
1.5-m x 185 mm 450 Hz ULE® Mirror

Photo’s courtesy of Harris Corporation
Strength Testing

• AMTD-1: Harris strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.
  • Weibull 99% survival value was 15% above conservative design allowable. Data ranged from 30% to 200% above design allowable.

• AMTD-2: A-Basis test of core rib to core rib LTF bond strength.
  • 60+ MOR Samples: 30+ samples aligned; 30+ core misaligned
  • A-basis Weibull 99% confidence strength allowable for 49 samples is 17.5MPa; ~50% higher than the strength of core-to-plate LTF bonds.
Non-linear visco-elastic modeling predicted Wall Bowing.

Mirror was designed to accommodate predicted bowing.

Unfortunately, while the core walls never touched, they did get within <0.25 mm at four locations.
X-Ray Computed Tomography used to quantify internal mirror structure and correlate with visco-elastic model to create ‘as-built’ STOP model.

Lessons Learn have been documented.
Next is Thermal Performance characterization testing.

Given the importance of mid-spatial frequency errors (both static and dynamic) in producing the ‘dark-hole’, AMTD will quantify:

- Thermal induced quilting.
- CTE variation induced Surface Figure Error
- Surface Thermal Stability

AMTD did this for the Schott 1.2m Extreme-Lightweight Zerodur Mirror (ELZM).

AMTD also predicted and quantified ELZM static and dynamic mechanical performance (gravity sag and first mode frequency).
Schott ELZM Model Correlation Tests

Diameter: 1.2m  ROC: 3.1m  Mass: 45kg; 88% lightweighted
Mechanical Model Validation

Mechanical Model was validated by quantifying:

- Gravity Sag, i.e. mirror’s response to static load
  - Measured: 196.07 Hz

- First Mode Frequency, i.e. mirror’s response to dynamic load
  - Predicted: 125 nm rms
  - Measured: 142 nm rms
  - Difference: 31 nm rms

With foam blocks
F1 = 206.89 Hz

Measured: 196.07 Hz
Thermal Model Validation for 294K to 250K

A Prior Analysis

- Thermal Gradients (1.28 nm RMS)
- Mount Effects (0.81 nm RMS)
- Inhomogeneity* (9.55 nm RMS)

Test Results

- Measured SFE (9.4 nm RMS)

* Random CTE map was generated with Schott specified 5 ppb/K PV homogeneity.

- CTE drives thermal performance.
- Model accuracy depends on CTE knowledge.
MSFC Thermal-Optical Test Capability
Test Measured Data at 250K

ΔT~0.8K

*Likely anomalous measurement ignored
Quilting

While the cryo-deformation phase maps show negligible quilting associated with the mechanical structure of the mirror substrate, there is ‘fringe print through’.

The ‘fringe print-through’ is caused by two factors:

- Mirror surface figure is ~400 nm PV
  - Gravity Sag ~ 300 nm Astigmatism PV
  - Zero-G Figure ~ 115 nm PV
- The PhaseCAM uses a 4-bucket algorithm.

A known feature of the 4-bucket algorithm is that if the phase-shift is not exact, there is a ‘ghost’ pattern in the phase map with spatial frequency 2X that of the fringes.
Arnold Mirror Modeler is designing and analyzing performance of candidate 4-m mirror assemblies for HabEx.

Coronagraph Contrast Leakage Model is informing HabEx Telescope alignment stability tolerances.

<table>
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<th>WFE (pm) for 5x10^{-11} of Systematic Noise</th>
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Conclusions

• AMTD uses science-driven systems engineering to derive performance specifications from science requirements then define & execute a long-term strategy to mature technologies to enable future large aperture space telescopes.

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

• AMTD Phase 2:
  – Fabricate \( \frac{1}{3} \)-scale model of a 4-m x 400-mm class \( \sim \)150 Hz ULE® mirror (1.5-m x 185-mm 450 Hz).
  – Characterize optical performance of two candidate lightweight primary mirrors from 250K to ambient: 1.2-m ELZM and 1.5-m ULE.
  – Correlate Integrated Modeling Tools

• Lessons Learned from the 1.5m ULE mirror have been documented.
AMTD enables & enhances future missions such as **HabEx and LUVOIR**

- Developing process to fabricate 4-m class (& larger) mirrors at lower areal density, lower areal cost & lower risk using stacked core technology.
  - Phase 1: demonstrated ability to make 40-cm thick mirror
  - Phase 2: demonstrating ability to laterally scale to 1.5 meters

- Lessons Learned for future substrate fabrication technology

- Validate Performance Models of Schott Mirror by Test
  - Thermal Characterization (including use of infrared camera)
  - Modal Characterization

- Coronagraph Contrast Leakage vs Telescope Stability Study influencing
  - LUVOIR and HabEx
  - ExEP Coronagraph Performance with Segmented Aperture Study

- Modeling & Analysis Tools are being used on HabEx and PTC
  - Arnold Mirror Modeler enhancement and trade studies transitioned to HabEx
  - Thermal MTF analysis transitioned to Predictive Thermal Control SAT