Overview and Recent Accomplishments of Advanced Mirror Technology Development (AMTD) for Very Large Space Telescopes

H. Philip Stahl, MSFC

AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013
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 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
AMTD Objective

Our 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.

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.
AMTD Team

AMTD uses a science-driven systems engineering approach which depends upon collaboration between a Science Advisory Team and a Systems Engineering Team.

We have assembled an outstanding team from academia, industry, and government with extensive expertise in

- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.
# AMTD Project Technical Team

<table>
<thead>
<tr>
<th><strong>Principle Investigator</strong></th>
<th><strong>Systems Engineering</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. H. Philip Stahl</td>
<td>MSFC</td>
</tr>
<tr>
<td>Dr. W. Scott Smith</td>
<td>MSFC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Science Advisory</strong></th>
<th><strong>Engineering</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Marc Postman</td>
<td>STScI</td>
</tr>
<tr>
<td>Laura Abplanatp</td>
<td>Exelis</td>
</tr>
<tr>
<td>Dr. Remi Soummer</td>
<td>STScI</td>
</tr>
<tr>
<td>Ron Eng</td>
<td>MSFC</td>
</tr>
<tr>
<td>Dr. Arund Sivaramakrishnan</td>
<td>STScI</td>
</tr>
<tr>
<td>William Arnold</td>
<td>MSFC</td>
</tr>
<tr>
<td>Dr. Bruce A. Macintosh</td>
<td>LLNL</td>
</tr>
<tr>
<td>Dr. Olivier Guyon</td>
<td>UoAz</td>
</tr>
<tr>
<td>Dr. John E. Krist</td>
<td>JPL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Integrated Modeling</strong></th>
<th><strong>AMTD-2 Proposal</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gary Mosier</td>
<td>GSFC</td>
</tr>
<tr>
<td>Tony Hull</td>
<td>Schott</td>
</tr>
<tr>
<td>William Arnold</td>
<td>MSFC</td>
</tr>
<tr>
<td>Andrew Clarkson</td>
<td>L3-Brashear</td>
</tr>
<tr>
<td>Anis Husain</td>
<td>Ziva</td>
</tr>
<tr>
<td>Jessica Gersh-Range</td>
<td>Cornel</td>
</tr>
</tbody>
</table>

**Funding**

- NASA ROSES SAT (10-SAT10-0048)
- Space Act Agreement (SAA8-1314052) with Ziva Corp
- NASA Graduate Student Research Program (NNX09AJ18H)
Heritage

AMTD builds on over 30 yrs of US Gov mirror technology development:
AMTD Team

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.
Tasks

Derive engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 6 inter-linked critical technologies.

- **Large-Aperture, Low Areal Density, High Stiffness Mirrors**: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.
- **Support System**: Large-aperture mirrors require large support systems to ensure that 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.
- **Integrated Model Validation**: On-orbit performance is determined by mechanical and thermal stability. Future systems require validated performance models.
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
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 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 & subscale deep core mirror to a < 6 nm rms zero-g 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; and
- validate mechanical models by static load test.
9 Publications from Year 1


Engineering Specifications

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.

Telescope Specifications have been defined for 3 cases:
- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

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

<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>80% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture and slightly bluer wavelength</td>
<td>Vary &lt; 5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF 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>λ/500 at 760 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 (jitter)</td>
<td>~2 mas</td>
<td>Guyon, scaled from HST</td>
<td>~ 0.5 mas floor determined by stellar angular diameter.</td>
</tr>
<tr>
<td>Mid-frequency WFE</td>
<td>&lt; 20 nm</td>
<td>HST</td>
<td></td>
</tr>
</tbody>
</table>
Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

Tues Aug 27, 8:40 am: Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X [8838-23]

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 also requires low areal density.

State of the Art is

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

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 Figure Error

Tues Aug 27, 8:40 am: Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, Optical Manufacturing and Testing X [8838-23]


Tues Aug 27, 11:30 am: Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly* [8837-11]
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 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

Tues Aug 27, 11:30 am: Eng, Ron, et. al., Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model, Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, [8837-11]
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 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 0.05C
12 Thermal Diodes.

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

Mon Aug 2, 5:30 pm Poster: Sivaramakrishnan, Anand, et. al., *Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation [8860-32]
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

A. Sivaramakrishnan, G. L. Carr, R. Smith, X. X. Xi, & N. T. Zimmerman

National Synchrotron Light Source at BNL

STABLE
COLLIMATED
X-RAY – FAR-IR

Apodization mitigates segment gaps
Achromatic apodization in collimated space

Tolerancing can be tight

Gemini Planet Imager (1.1-2.4 um) – 0.5% accuracy req.
UVOIR space coronagraphy - 0.55 – 1.1 um

Metal-on-glass dots look OK

Next

Develop & confirm on reflective surfaces
Reqs. on 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

Wed Aug 28, 5:00 pm: Arnold, William et al, Next generation lightweight mirror modeling software, Optomechanical Engineering 2013 [8836-15]

Wed Aug 28, 5:20 pm: Arnold, William et al, Integration of Mirror design with Suspension System using NASA’s new mirror modeling software, Optomechanical Engineering 2013 [8836-17]
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.

![Free-Free 1st Mode: 4 m dia 40 cm thick substrate](image1)

![Internal Stress: 4 m dia with 6 support pads](image2)

**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
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

<table>
<thead>
<tr>
<th>SET</th>
<th>TIME/FREQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.026</td>
</tr>
<tr>
<td>2</td>
<td>18.035</td>
</tr>
<tr>
<td>3</td>
<td>42.449</td>
</tr>
<tr>
<td>4</td>
<td>42.452</td>
</tr>
<tr>
<td>5</td>
<td>47.827</td>
</tr>
<tr>
<td>6</td>
<td>74.041</td>
</tr>
<tr>
<td>7</td>
<td>74.045</td>
</tr>
<tr>
<td>8</td>
<td>75.174</td>
</tr>
<tr>
<td>9</td>
<td>75.176</td>
</tr>
<tr>
<td>10</td>
<td>112.96</td>
</tr>
</tbody>
</table>
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
Modeling Tool
**Program Control Window**

![Program Control Window](image-url)

### Arnold Lightweight Mirror Modeler (Ver 2.0)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Dia</td>
<td>2</td>
</tr>
<tr>
<td>Inner Dia</td>
<td>0.25</td>
</tr>
<tr>
<td>Cell Width</td>
<td>0.3</td>
</tr>
<tr>
<td>Lip Inner</td>
<td>0.05</td>
</tr>
<tr>
<td>Segment Lip</td>
<td>0.05</td>
</tr>
<tr>
<td>Mirror Lip</td>
<td>0.1</td>
</tr>
<tr>
<td>Num Rings</td>
<td>0</td>
</tr>
<tr>
<td>Sgmt Span</td>
<td>1</td>
</tr>
<tr>
<td>Sgmt Gap</td>
<td>0.15</td>
</tr>
<tr>
<td>Merge Tol</td>
<td>0.025</td>
</tr>
<tr>
<td>Grid Zoom</td>
<td>1</td>
</tr>
<tr>
<td>Segment Shown</td>
<td>1</td>
</tr>
<tr>
<td>Strink Factor</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Supports**
- [ ] Each Segment
- [x] Whole Mirror

**Show Options**
- [ ] Show Whole Grid
- [ ] Show Supports
- [ ] Show Fillets

**Grid Options**

<table>
<thead>
<tr>
<th>Grid Option</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal (PSD)</td>
<td></td>
</tr>
<tr>
<td>Boule Mapping</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Reals</td>
</tr>
<tr>
<td>Core</td>
<td>Hexapod</td>
</tr>
</tbody>
</table>

**Modal Options**

- [ ] Outer Sgmt Lip
- [ ] Outer Mirror Lip
- [ ] Inner Mirror Lip
- [ ] Circular Segment
- [ ] Circular Mirror
- [ ] Seal Ring Outer
- [ ] Seal Ring Inner
- [ ] Seal Ring Mirror
- [ ] Segment Lip Ribs

**Cell Level Options**

- [ ] Cell Level 0
- [ ] Cell Level 1
- [x] Cell Level 2

**Status**

- [ ] Display Grid
- [ ] Display Model
- [ ] Write Model
- [ ] Save
- [ ] Restore
- [ ] Merge Nodes
Monolithic Mirrors
Segmented Mirrors
Support Systems

Radial

Axial

Hexapod
Segment to Segment Gap Phasing
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:

- Built a Delron plastic pendulum to investigated utility of correlated magnetic interfaces.
- Correlated magnetic interface provided only marginally improved dampening over conventional magnets.
- Given the inability to reduce dynamic below the required level, we plan no further investigation of this approach.

Figure 6: Delron Pendulum Test Setup

Figure 7: Oscillation Amplitude vs. Time for Unconstrained (black), Conventional Magnetic Interface (blue), and Correlated Magnetic Interface (red)
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
BACKUP
Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions

<table>
<thead>
<tr>
<th>Science Question</th>
<th>Science Requirements</th>
<th>Measurements Needed</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is there life elsewhere in Galaxy?</td>
<td>Detect at least 10 Earth-like Planets in HZ with 95% confidence.</td>
<td>High contrast ($\Delta$Mag $&gt; 25$ mag) SNR=10 broadband ($R = 5$) imaging with IWA $\sim 40$ mas for $\sim 100$ stars out to $\sim 20$ parsecs.</td>
<td>$\geq 8$ meter aperture Stable $10^{-10}$ starlight suppression $\sim 0.1$ nm stable WFE per 2 hr $\sim 1.3$ to 1.6 mas pointing stability</td>
</tr>
<tr>
<td>What are star formation histories of galaxies?</td>
<td>Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets</td>
<td>High contrast ($\Delta$Mag $&gt; 25$ mag) SNR=10 low-resolution ($R=70-100$) spectroscopy with an IWA $\sim 40$ mas; spectral range $0.3 - 2.5$ microns; Exposure times $&lt;500$ ksec</td>
<td>$\geq 8$ meter aperture Symmetric PSF 500 nm diffraction limit 1.3 to 1.6 mas pointing stability</td>
</tr>
<tr>
<td>What are kinematic properties of Dark Matter</td>
<td>Determine ages ($\sim 1$ Gyr) and metallicities ($\sim 0.2$ dex) of stellar populations over a broad range of galactic environments.</td>
<td>Color-magnitude diagrams of solar analog stars (Vmag$\sim 35$ at 10 Mpc) in spiral, lenticular &amp; elliptical galaxies using broadband imaging</td>
<td>$\geq 8$ meter aperture</td>
</tr>
<tr>
<td>How do galaxies &amp; IGM interact and affect galaxy evolution?</td>
<td>Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies</td>
<td>0.1 mas resolution for proper motion of $\sim 200$ stars per galaxy accurate to $\sim 20\ \mu$as/yr at 50 kpc</td>
<td>$\geq 4$ meter aperture 500 nm diffraction limit</td>
</tr>
<tr>
<td>How do stars &amp; planets interact with interstellar medium?</td>
<td>Map properties &amp; kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to $\sim 10$ Mpc.</td>
<td>SNR = 20 high resolution UV spectroscopy ($R = 20,000$) of quasars down to FUV mag = 24, survey wide areas in $&lt; 2$ weeks</td>
<td></td>
</tr>
<tr>
<td>How did outer solar system planets form &amp; evolve?</td>
<td>Measure UV Ly-alpha absorption due to Hydrogen “walls” from our heliosphere and atmospheres of nearby stars</td>
<td>High dynamic range, very high spectral resolution ($R = 100,000$) UV spectroscopy with SNR = 100 for V = 14 mag stars</td>
<td>$\geq 8$ meter aperture 500 nm diffraction limit Sensitivity down to 100 nm wavelength.</td>
</tr>
<tr>
<td></td>
<td>UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth</td>
<td>SNR = 20 - 50 at spectral resolution of $R \sim 10,000$ in FUV for 20 AB mag</td>
<td></td>
</tr>
</tbody>
</table>
Technology Challenges are derived directly from Science & Mission Requirements, and Implementation Constraints

<table>
<thead>
<tr>
<th>Science</th>
<th>Mission</th>
<th>Constraint</th>
<th>Capability</th>
<th>Technology Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Aperture</td>
<td>EELV 5 m Fairing, 6.5 mt to SEL2</td>
<td>4 m Monolith</td>
<td>4 m, 200 Hz, 60 kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 m support system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 m, 200 Hz, 15 kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 m deployed support</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLLV-Medium 10 m Fairing, 40 mt to SEL2</td>
<td>8 m Monolith</td>
<td>8 m, &lt;100Hz, 200 kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 m, 10 mt support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2-4m, 200Hz, 50kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16 m deployed support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8m, &lt;100Hz, 480kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 m, 20 mt support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16 m deployed support</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLLV-Heavy 10 m Fairing, 60 mt to SEL2</td>
<td>8 m Monolith</td>
<td>2-4m, 200Hz, 120kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16 m deployed support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 m deployed support</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt; 20 hr thermal time constant</td>
</tr>
<tr>
<td>2 hr Exposure</td>
<td>Thermal 280K ± 0.5K 0.1K per 10min</td>
<td>&lt; 5 nm rms per K</td>
<td>low CTE material</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 20 hr thermal time constant</td>
<td>thermal mass</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamics TBD micro-g</td>
<td>&lt; 5 nm rms figure</td>
<td>passive isolation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>active isolation</td>
<td></td>
</tr>
<tr>
<td>Reflectance</td>
<td>Substrate Size</td>
<td>&gt; 98% 100-2500 nm</td>
<td>Beyond Scope</td>
<td></td>
</tr>
<tr>
<td>High Contrast</td>
<td>Diffraction Limit</td>
<td>Monolithic</td>
<td>&lt; 10 nm rms figure</td>
<td>mid/high spatial error</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>fabrication &amp; test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segmented</td>
<td>&lt; 5 nm rms figure</td>
<td>edge fabrication &amp; test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 2 mm edges</td>
<td>passive edge constraint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 1 nm rms phasing</td>
<td>active align &amp; control</td>
</tr>
</tbody>
</table>