Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

H. Philip Stahl
Objective

Define and initiate a long-term program to mature six inter-linked critical technologies for future UVOIR space telescope mirrors to TRL6 by 2018 so that a viable flight mission can be proposed to the 2020 Decadal Review.

- **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.

We are pursuing multiple design paths give the science community the option to enable either a future monolithic or segmented space telescope.
Approach

Technology must enable mission capable of doing both general astrophysics and ultra-high contrast observations of exoplanets.

Outstanding team of academic, industry & government with expertise:
• UVOIR astrophysics and exoplanet characterization,
• monolithic and segmented space telescopes, and
• optical manufacturing and testing.

Integrate science & systems engineering to:
• derive engineering specifications from science measurement needs and implementation constraints;
• identify technical challenges in meeting these specifications;
• iterate between science and systems engineering to mitigate challenges; and
• prioritize the challenges.

Systematically mature TRL of prioritized challenges using
• design tools to construct analytical models and
• prototypes/test beds to validate models in relevant environments.
Goals

Defined quantifiable goals for each of the six key technologies:

*Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:*
  • make a sub-scale mirror via a process traceable to 500 mm deep mirrors

*Support System:*
  • produce pre-Phase-A point designs for candidate primary mirror architectures; and
  • 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:*
  • derive edge specifications traceable to science requirements; and
  • demonstrate an achromatic edge apodization mask.

*Segment to Segment Gap Phasing:*
  • develop models for segmented primary mirror performance; and
  • test prototype passive and active mechanisms to control unconstrained, damped and constrained 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.
Work Breakdown Structure

Project is managed according to WBS. Each quantitative Milestone is scheduled.

### Advanced Normal Incidence Mirror Technology Development
for Large UVOIR Telescope

<table>
<thead>
<tr>
<th>WBS</th>
<th>Name</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
<td>1 2 3</td>
</tr>
<tr>
<td>1.0</td>
<td>Management</td>
<td>K/O Mtg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>Science Advisory Team</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Systems Engineering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>Technology Development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Monolithic Technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1.1</td>
<td>Deep Core</td>
<td>Design Trades, MOR Tests</td>
<td>Fab of Test Mirrors</td>
<td>8m Monolithic</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Support Structure</td>
<td></td>
<td></td>
<td>4m Monolithic</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Mid/High Spatial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1.3.1</td>
<td>AMSD</td>
<td></td>
<td>Ambient Polishing Charac</td>
<td>Null Polish</td>
</tr>
<tr>
<td>4.1.3.2</td>
<td>Deep Test Mirrors</td>
<td></td>
<td>Null Polish</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Segmented Technologies</td>
<td></td>
<td>Mitigation via Apodization Mask Coating (STScI)</td>
<td>Fabrication Process Improvements (ITT)</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Edges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2.2</td>
<td>Phasing</td>
<td>Mitigation via Apodization Mask Coating (STScI)</td>
<td>Fabrication Process Improvements (ITT)</td>
<td></td>
</tr>
<tr>
<td>4.2.2.1</td>
<td>Design Trades</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2.2.2</td>
<td>Correlated Magnetic</td>
<td>Define &amp; Build Constrained I/F</td>
<td>Define &amp; Build Damped Interface</td>
<td>Define &amp; Build Adjustable Interface</td>
</tr>
<tr>
<td>4.2.2.3</td>
<td>I/F Mechanisms Characterization</td>
<td>Design &amp; Build Test Setup</td>
<td>Unconstrained Perf</td>
<td>Constrained Perf</td>
</tr>
<tr>
<td>4.2.2.4</td>
<td>Design AOSD Interface Devices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Model Verification &amp; Validation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3.1</td>
<td>Thermal</td>
<td>AMSD 2C Test</td>
<td></td>
<td>2C Test</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Mechanical</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Milestone Project

Project was rephased from 2 years to 3 years.

<table>
<thead>
<tr>
<th>TASK</th>
<th>FY 2012</th>
<th>FY 2013</th>
<th>FY 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JUL Y</td>
<td>AUG</td>
<td>SEP</td>
</tr>
<tr>
<td>Major Milestones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates</td>
<td>Mirror Fabrication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support System</td>
<td></td>
<td>4m Point Design</td>
<td></td>
</tr>
<tr>
<td>Mid/High Spatial Frequency Figure Error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Segment Edges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Model Validation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Project Organization**

### Principle Investigator
- Dr. H. Philip Stahl | MSFC

### Systems Engineering
- SE Lead | Dr. W. Scott Smith | MSFC
- Integrated Modeling | Gary Mosier | GSFC

### Science Advisory

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Marc Postman</td>
<td>STScI</td>
<td>ITT Project Manager</td>
</tr>
<tr>
<td>Dr. Remi Soummer</td>
<td>STScI</td>
<td>Systems Engineer/Sys. Lead</td>
</tr>
<tr>
<td>Dr. Anand Sivaramakrishnan</td>
<td>STScI</td>
<td>Process Development Lead</td>
</tr>
<tr>
<td>Dr. Bruce A. Macintosh</td>
<td>LLNL</td>
<td>Thermal Analyst</td>
</tr>
<tr>
<td>Dr. Olivier Guyon</td>
<td>UoA</td>
<td>Mechanical Analyst</td>
</tr>
<tr>
<td>Dr. John E. Krist</td>
<td>JPL</td>
<td>Mirror System Design Lead</td>
</tr>
</tbody>
</table>

### Engineering

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Testing</td>
<td>Ron Eng</td>
<td>MSFC</td>
</tr>
<tr>
<td>Structure Mechanical</td>
<td>William Arnold</td>
<td>Jacobs</td>
</tr>
<tr>
<td>Institutional Co-I</td>
<td>Larry Fullerton</td>
<td>CMR</td>
</tr>
</tbody>
</table>

**Chart Key**
- NASA MSFC Lead
- STScI Lead
- ITT Lead
- GSFC Lead
WBS Task Discussion
Science team works with Engineering to:

- derive (and/or confirm) engineering specifications for advanced normal incidence mirrors which flow down from the astrophysical measurement needs and flow up from implementation constraints;
- collaborate with systems engineering to mitigate these challenges via architectural implementation trades; and
- prioritize which challenges should be solved first.

The Science Team has meet 4X by telecon and once face-to-face in FY12.
WBS 3.0 Systems Engineering

Systems Engineering working with Science:

• derives engineering mirror specifications to achieve on-orbit performance requirements;

• identifies technical challenges in meeting these specifications;

• prioritize technology development using a systems perspective to determine which technologies will yield the greatest on-orbit performance improvement; and

• define metrics, evaluate their TRL, and assess their advance.
Systems Engineering will

• develop thermal & mechanical models of candidate mirror systems including substrates, structures, and mechanisms;
• validate models by test of full- and subscale components in relevant thermo-vacuum environments.

Specific analyses include:

• maximum mirror substrate size, first fundamental mode frequency (i.e., stiffness) and mass required to fabricate without quilting, survive launch, achieve stable pointing and maximum thermal time constant;
• segment edge dimensions and roll; and
• segment-to-segment gap dimensions, phasing and stability.
WBS 4.0 Technology Development

WBS 4.0 develops technology

4.1 Monolithic Mirror Technology
4.2 Segmented Mirror Technology
4.3 Model Verification and Validation

Enables our 4 baseline options:

- 4-m monolithic mirror launched by an EELV;
- 8-m monolithic mirror launched by a HLLV;
- 8-m segmented mirror launched by an EELV; and
- 16-m segmented mirror launched by a HLLV.

Same technology can also enable 8-m on HLLV.
WBS 4.1 Monolithic Technologies

Monolithic mirror technology is required to manufacture, test, launch, and operate a 4 or 8-m monolithic mirror also 2-m class mirror segments.

WBS 4.1 matures the 3 key monolithic mirror challenges:

4.1.1 Deep Core Mirror Substrate
4.1.2 Mirror Support Structure
4.1.3 Mid/High Spatial Frequency Surface Errors
WBS 4.2 Segmented Technologies

Segmented mirror technology is required to assemble, align, phase, and operate a segmented mirror as an integrated unit to UVOIR tolerances.

WBS 4.2 matures the 2 key segmented mirror challenges:

4.2.1  Edge Control
4.2.2  Gap Phasing Control
WBS 4.3 Model Verification & Validation

Models are required to predict on-orbit performance for pointing stability, jitter, and thermal-elastic stability, as well as vibro-acoustics and launch loads. Performance data is required to verify and validate models.

WBS 4.3 matures the 2 key modeling challenges:

- 4.3.1 Thermal Model Verification
- 4.3.2 Mechanical Model Verification
WBS 4.1.1 Deep Core Substrate

Need: 500 mm thick mirror substrate.

4 m PM requires substrate with areal density of <60 kg/m² & ~200 Hz first mode. Analysis indicates this can be achieved with a 500 mm thick mirror. For 8-m, this is an upper thickness limit.

SOA: 300 mm deep substrates

Starting: TRL3/4

2.4 m is TRL9 (HST), Kepler is 1.4m – both are sub-scale.
WBS 4.1.1 Deep Core Substrate

Milestone: demonstrate innovative process to make glass cores with required areal density that can be scaled to 500 mm deep.

Approach: manufacture 40 cm dia x 400 deep subscale (‘cut-out’ of a 4 m dia x 400 mm deep mirror) using 3 ‘stacked’ cores with full size cells and ribs and pocket milled face and back sheets with full sized pockets, ribs and thickness.
WBS 4.1.2 Support Structure

Need: System to support mirror during launch and deploy it into an on-orbit strain free state; maintain operational wavefront and pointing stability.

SOA: Kepler 1.4 m support system

Starting: TRL3/4

    Kepler support system is TRL9, but it is sub-scale.

Milestone: Pre-Phase-A point designs for potential 4-m and 8-m monolithic primary mirrors and an 8-m segmented mirror.

Approach:
    Design structure based on substrate designs, launch vehicle constraints and performance requirements.
    Design, build & demonstrate a two-stage active strut/actuator.
WBS 4.1.3 Mid/High Spatial Frequency

Need: < 10 nm rms surface mirror at 2C

SOA:
- AMSD at <10 nm rms and ATT at <20 nm rms at 20C
- Hubble, 7.8 nm rms at 20C
- 4m & 8m ground telescope mirrors at ~ 10 nm rms at 20C

Starting: TRL4 for 1.5 m; TRL 3 for 4 m or larger.

  AMSD, ATT & HST are sub-scale & not at operational temperature.
  Ground 4m & 8m mirrors are full size, but not flight areal density.

Milestone: polish traceable substrates to UVOIR tolerances at their anticipated operating temperature of 2 C.

Approach:
- Create mechanical and thermal models
- Test AMSD mirror at 2C and cryo-null polish via traceable process
- Demonstrate on 4.1.1 sub-scale mirrors process (traceable to 2m, 4m or 8m mirrors) to polish without introducing quilting
WBS 4.2.1 Edge Control

Need: TBD by Science and Systems Engineering

SOA: Keck is 2 mm (but substrates are 400 Hz); JWST is close to 5 mm; AMSD was 10 mm; QED & Zeeko SBIRs did 2 mm

Starting: TRL3 to 6 depending on Requirement

Milestone:
   Define Requirement
   Demonstrate apodization concept via a test article.

Approach:
   Write an amplitude apodization mask on the edge of a mirror and test its impact on edge diffraction.
WBS 4.2.2 Gap Phase Control

Need: < 5 nm rms segment to segment stability

SOA: JWST, passive, 20 nm 50 Hz rocking mode; Keck, active, < 20 nm rms 50 Hz; ITT AOSD, active, < 10 nm rms 30 Hz; LAMP, active, classified in Vacuum.

Starting: TRL3/4

UVOIR Requirement not achieved.

Milestone:

Demonstrate Active Strut (WBS 4.1.2)

Quantify utility of Correlated Magnetic Interfaces

Approach: design, build and test dynamic dampening devices on sub-scale test-bed and on ITT AOSD test-bed.
Correlated Magnetic (CM) Interface

CMs are useful for vibration isolation & motion constraint. CM can be designed to constrain interface to a single symmetry point; rotate about a symmetry point; or move linearly in one direction but not the orthogonal direction – similar to a mechanical flexure.
WBS 4.3 Integrated Modeling

Need: Predict on-orbit performance

SOA:
   JWST (AMSD, Flight PMSAs, BSTA 4% match);
   Air Force Structural Vibration Modeling and Verification (SVMV)

Starting: TRL4/5

   UVOIR Requirement not achieved.

Milestone:
   Validate Thermal Model
   Validate Mechanical Model

Approach:
   Thermal model predicts AMSD figure sensitivity of 5 nm rms/K.
   Prediction will be validated at the MSFC XRCF. Additionally, thermal figure stability will be quantified.
   Mechanical model will be validated via static load test.