JWST Primary Mirror Technology Development

H. Philip Stahl, Ph.D.
Outline

Introduction

Mirror Technology Development

TRL-6 Certification

Engineering Development Unit

Conclusions
Introduction

JWST was originally called the Next Generation Space Telescope (NGST)


OTA study in summer 1996

Science Drivers
- Near Infrared: 1-5 microns (.6-30 extended)
- Diffraction Limited: 2 microns
- Temperature range: 30-60 Kelvin
- Diameter: At least 4 meters (“HST and Beyond” report)

Programmatic Drivers
- 25% the cost of Hubble: Cost cap - 500 million
- 25% the weight of Hubble: Weight cap ~3,000 kg

Baselines for OTA study
- Atlas IIAS launch vehicle: Low cost launch vehicle
- L2 orbit: Passively cool to 30-60 K
- 1000 kg OTA allocation: Launch vehicle driven

Study Results
- 8 meter segmented telescope, mirror technology at <15 kg/m².
Mirror Technology was identified as a (if not the) critical capability necessary to achieve the Level 1 science goals.

A never before demonstrated space telescope capability was required:
- 6 to 8 meter class primary mirror,
- diffraction limited at 2 micrometers and operates at temperatures below 50K.

Launch vehicle constraints placed significant architectural constraints:
- deployed/segmented primary mirror (4.5 meter fairing diameter)
- 20 kg/m2 areal density (PM 1000 kg mass)

Such mirror technology had never been demonstrated – and did not exist.
Assessment of pre-1996 state of art indicated that necessary mirror technology (as demonstrated by existing space, ground and laboratory test bed telescopes) was at TRL-3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JWST</th>
<th>Hubble</th>
<th>Spitzer</th>
<th>Keck</th>
<th>LAMP</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>8</td>
<td>2.4</td>
<td>0.85</td>
<td>10</td>
<td>4</td>
<td>meters</td>
</tr>
<tr>
<td>Segmented</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>36</td>
<td>7</td>
<td>Segments</td>
</tr>
<tr>
<td>Areal Density</td>
<td>20</td>
<td>180</td>
<td>28</td>
<td>2000</td>
<td>140</td>
<td>kg/m²</td>
</tr>
<tr>
<td>Diffraction Limit</td>
<td>2</td>
<td>0.5</td>
<td>6.5</td>
<td>10</td>
<td>Classified</td>
<td>micrometers</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>&lt;50</td>
<td>300</td>
<td>5</td>
<td>300</td>
<td>300</td>
<td>K</td>
</tr>
<tr>
<td>Environment</td>
<td>L2</td>
<td>LEO</td>
<td>Drift</td>
<td>Ground</td>
<td>Vacuum</td>
<td>Environment</td>
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<tr>
<td>Substrate</td>
<td>TBD</td>
<td>ULE Glass</td>
<td>I-70 Be</td>
<td>Zerodur</td>
<td>Zerodur</td>
<td>Material</td>
</tr>
<tr>
<td>Architecture</td>
<td>TBD</td>
<td>Passive</td>
<td>Passive</td>
<td>Hexapod</td>
<td>Adaptive</td>
<td>Control</td>
</tr>
</tbody>
</table>
Mirror Technology Development Program

JWST initiated a systematic $300M effort

Several key technological and manufacturing advances have been developed

- Cryogenic Materials - CTE uniformity, dynamic dampening, stiffness, etc.
- Fabrication Techniques - ability to make size & areal density to required figure.
- Cryogenic Performance Characterization - optical testing, cryo-behavior.

...to dramatically reduce cost, schedule, weight and risk for large-aperture space optical systems.
Programmatic Challenge of NGST

In 1996, the ability to affordably make NGST did not exist. Substantial reductions in ability to rapidly and cost effectively manufacture low areal density mirrors were required.

<table>
<thead>
<tr>
<th>Mirror Diameter (m)</th>
<th>Cost Per Unit Area ($FY96/M$2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>SBMD</td>
</tr>
<tr>
<td>7.5</td>
<td>AMSD</td>
</tr>
<tr>
<td>8.0</td>
<td>Flight</td>
</tr>
<tr>
<td>8.5</td>
<td>1.2X</td>
</tr>
<tr>
<td>9.0</td>
<td>1.7X</td>
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</tbody>
</table>

Primary Mirror Cost Allocation $40~70M

<table>
<thead>
<tr>
<th>Mirror Diameter (m)</th>
<th>Production Rate for 36 Month Fab</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>SBM</td>
</tr>
<tr>
<td>7.5</td>
<td>AMSD</td>
</tr>
<tr>
<td>8.0</td>
<td>Flight</td>
</tr>
<tr>
<td>8.5</td>
<td>1.8X</td>
</tr>
<tr>
<td>9.0</td>
<td>8X</td>
</tr>
</tbody>
</table>

8 Fab Lines 0.8
Mirror Technical Challenges

Challenges for Space Telescopes:
- Areal Density to enable up-mass for larger telescopes.
- Cost & Schedule Reduction.

Areal Density in FY00 $

<table>
<thead>
<tr>
<th>Mirror Diameter in Meters</th>
<th>PM Areal Density in kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>420 kg/m²</td>
</tr>
<tr>
<td>4</td>
<td>200 kg/m²</td>
</tr>
<tr>
<td>6</td>
<td>150 kg/m²</td>
</tr>
<tr>
<td>8</td>
<td>100 kg/m²</td>
</tr>
<tr>
<td>10</td>
<td>50 kg/m²</td>
</tr>
<tr>
<td>12</td>
<td>0 kg/m²</td>
</tr>
</tbody>
</table>

Primary Mirror Time & Cost

<table>
<thead>
<tr>
<th>Mirror Diameter</th>
<th>Time &amp; Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST (2.4 m)</td>
<td>$10M/m²/yr</td>
</tr>
<tr>
<td>Spitzer (0.9 m)</td>
<td>$10M/m²/yr</td>
</tr>
<tr>
<td>AMSD (1.2 m)</td>
<td>$4M/m²/yr</td>
</tr>
<tr>
<td>JWST (8 m)</td>
<td>&gt; 6 m²/yr</td>
</tr>
</tbody>
</table>

Note: Areal Cost in FY00 $
Mirror Technology Development 2010

Lessons Learned

Mirror Stiffness (mass) is required to survive launch loads.

Need another 10X Cost & Schedule reduction for larger telescopes

Primary Mirror Time & Cost

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Diameter (m)</th>
<th>Primary Mirror Time</th>
<th>Cost</th>
<th>Primary Mirror Areal Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST (2.4 m)</td>
<td></td>
<td></td>
<td>$12M/m</td>
<td></td>
</tr>
<tr>
<td>Spitzer (0.9 m)</td>
<td></td>
<td></td>
<td>$12M/m</td>
<td></td>
</tr>
<tr>
<td>AMSD (1.2 m)</td>
<td></td>
<td></td>
<td>$5M/m</td>
<td></td>
</tr>
<tr>
<td>JWST (6.5 m)</td>
<td></td>
<td></td>
<td>$6M/m</td>
<td></td>
</tr>
</tbody>
</table>

Note: Areal Cost in FY10 $
Mirror Technology Development Program
Mirror Technology Development

A systematic development program was undertaken to build, test and operate in a relevant environment directly traceable prototypes or flight hardware:

- Sub-scale Beryllium Mirror Demonstrator (SBMD)
- NGST Mirror System Demonstrator (NMSD)
- Advanced Mirror System Demonstrator (AMSD)
- JWST Engineering Test Units (EDU)

Goal was to dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

Requirement was to achieve TRL-6 before Non-Advocate Review (NAR)

A critical element of the program was competition – competition between ideas and vendors resulted in:

- remarkably rapid TRL advance in the state of the art
- significant reductions in the manufacturing cost and schedule

It took 11 years (and ~$40M) to mature mirror technology from TRL 3 to 6.
## Mirror Technology Development

### Systematic Study of Design Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>SBMD</th>
<th>NMSD</th>
<th>AMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>Circle w Flat</td>
<td>Hex</td>
<td>Hex</td>
</tr>
<tr>
<td>Prescription</td>
<td>Sphere</td>
<td>Sphere</td>
<td>OAP</td>
</tr>
<tr>
<td>Diameter</td>
<td>&gt;0.5 m</td>
<td>1.5 - 2 m</td>
<td>1.2 - 1.5 m</td>
</tr>
<tr>
<td>Areal Density</td>
<td>&lt; 12+ kg/m2</td>
<td>&lt;15 kg/m2</td>
<td>&lt;15 kg/m2</td>
</tr>
<tr>
<td>Radius</td>
<td>20 m</td>
<td>15 m</td>
<td>10 m</td>
</tr>
<tr>
<td>PV Figure</td>
<td>160 nm</td>
<td>160/63 nm</td>
<td>250/100 nm</td>
</tr>
<tr>
<td>RMS Figure</td>
<td></td>
<td></td>
<td>50/25 nm</td>
</tr>
<tr>
<td>PV Mid</td>
<td>63 nm</td>
<td>63/32 nm</td>
<td></td>
</tr>
<tr>
<td>(1-10 cm⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS Finish</td>
<td>3/2 nm</td>
<td>2/1 nm</td>
<td>4 /2 nm</td>
</tr>
</tbody>
</table>
## Mirror Technology Development

Wide Variety of Design Solutions were Studied

<table>
<thead>
<tr>
<th>Item</th>
<th>SBMD</th>
<th>NMSD</th>
<th>AMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>Be (Ball)</td>
<td>Glass (UA)</td>
<td>Be (Ball)</td>
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<tr>
<td></td>
<td></td>
<td>Hybrid (COI)</td>
<td>ULE Glass (Kodak)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fused Silica (Goodrich)</td>
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<tr>
<td>Reaction Structure</td>
<td>Be</td>
<td>Composite</td>
<td>Composite (all)</td>
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<tr>
<td>Control Authority</td>
<td>Low</td>
<td>Low (COI)</td>
<td>Low (Ball)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High (UA)</td>
<td>Medium (Kodak)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>High (Goodrich)</td>
</tr>
<tr>
<td>Mounting</td>
<td>Linear Flexure</td>
<td>Bipods (COI)</td>
<td>4 Displacement (Ball)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>166 Hard (UA)</td>
<td>16 Force (Kodak)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37 Bi/Ax-Flex (Goodrich)</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.53 m</td>
<td>2 m (COI)</td>
<td>1.3 m (Goodrich)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6 m (UA)</td>
<td>1.38 m (Ball)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4 m (Kodak)</td>
</tr>
<tr>
<td>Areal Density</td>
<td>9.8+ kg/m2</td>
<td>13 kg/m2</td>
<td>15 kg/m2</td>
</tr>
</tbody>
</table>
Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations.
Ball Subscale Beryllium Mirror Demonstrator (SBMD)

0.5 m diameter, 20 m ROC, 9.8 kg/m² areal density, O-30 Beryllium Mirror

Cryo Tested at MSFC

Cryogenic Surface Error (34K -288K)
- Total (0.571 µm p-v; 0.063 µm rms)
- Low Order (0.542 µm p-v, 0.062 µm rms)

Higher Order Residual (0.134 µm p-v; 0.012 µm rms)
SBMD Lessons Learned

SBMD’s cryo-deformation was interesting:

- Initially, we were unable to model the quilting
- Mounting design issues introduced low-order error
- Interface issues resulted in a non-stable deformation

Lessons Learned:

- Learned how to optimize substrate light-weighting to minimize quilting
- Support structure design and interface to substrate is critical
- Very high stiffness of small mirrors means that extrapolating their results to large (low-stiffness) mirrors is unreliable
COI Hybrid NGST Mirror System Demo (NMSD)

Hybrid Concept

**Zerodur Facesheet to Meet Optical Requirements**
Conventional Grind/Polish Fab Methods

**Composite Structural Support for Glass**
Low Mass, High Stiffness
Match Thermal Expansion from Ambient to 35K

Specifications

- Diameter: 1.6 meter
- Radius: 20 meter
- Areal Density: < 15 kg/m²
- Areal Cost: < $2.5M/m²

Delivered Polished with Cryo-Null Figure

- 25K Figure: 800 nm rms

Ambient Surface  Surface at Cryo  25K Figure (Low Order Zernikes Removed)
0.8micron RMS Full Aperture
University of Arizona NGST Mirror System Demonstrator

2m Dia 2 mm Thick Glass with Backplane, 166 Actuators, 9 Point Load Spreader

- Polish convex side.
- Fabricate blocking body. Figure is not critical.
- Attach glass to blocking body.
- Generate glass to thickness. Grind and polish.
- Remove glass from blocking body. (“De-block glass.”)

Hartmann 4 µm rms

10.6 µm 2.5 µm rms
NMSD Lessons Learned

Both NMSD mirrors took significantly longer than expected and
achieved significantly lower performance than expected.

CTE matching is difficult for a Cryo-Mirror.

Stiffness is much more important than Areal Density.

Stiffness is required for multiple reasons:
  Substrate/Facesheet Handling
  Standard Fabrication Processes assume a given Stiffness
  Figure Adjustment and Stability

Expect a high infant mortality rate (~30%) on Actuators

Standard Processes and Intuition no not scale for large aperture
low stiffness mirrors.
  Stiffness decreases with Diameter$^2$
  Stiffness increases with Thickness
Advanced Mirror System Demonstrator

AMSD was a joint NASA, Air Force & NRO program.

AMSD developed two mirror technologies for JWST yielding data on:
- Ambient and Cryogenic Optical Performance
- Manufacturability
- Cost
- Schedule
AMSD was Phased Down Select Program

AMSD PHASE I
MAY-SEPT. 1999

5 Contractors
8 Mirror Designs

Raytheon(3)
Ball
Kodak(2)
COI
UOA

Beryllium
Hybrid
Glass

Glass Meniscus
CSiC
SiC,Be,Glass Meniscus
Ball AMSD Mirror

Ball’s Beryllium Semi-Rigid Design for AMSD

1.39-m point-to-point open back light-weighted O-30 beryllium semi-rigid mirror

< 15 kg/m² areal density for mirror system including mirror, reaction structure, flexures, and actuators

Graphite Epoxy (M55J)
Reaction Structure

4 Ball Actuators (3-rigid body and one for ROC).

Major Subcontractors: SVG Tinsley, AXSYS, Brush-Wellman, COI
Goodrich AMSD Mirror

- Reaction Structure
  - Stiff, passive
  - Graphite composite
  - CTE matched to facesheet

- Facesheet
  - Fused silica
  - Thinned, iso-grid structure
  - 1.3 m corner-to-corner

- Actuators
  - 37 actuators
  - 6 bipod, 31 axial
  - Cryogenic operation

- AMSD Program
  - Proven on HALO
  - Extension to lower area mass density
  - Extension to cryogenic ops

1.3 m SiO2 Iso-Grid Thin Meniscus Mirror
Graphite Composite Reaction Structure from ATK
37 Displacement Actuators from Moog
Kodak AMSD Mirror

1.4 m Diameter Semi-Rigid ULE Closed-Back Sandwich Construction Mirror

- Low Temperature Fusion into a Flat Substrate
- Grind Facesheets to Final Mass
- Low Temperature Slump into Sphere

Graphite Epoxy (M55J) Reaction Structure by COI

16 Force Actuators by Moog

- 7 for wavefront & radius
- 9 for gravity offloading

No Rigid Body Adjustments
Performance Characterization

Ambient and Cryogenic Optical Performance was measured at XRCF.
Each mirror tested multiple times below 30K
## AMSD ± Ball & Kodak

### Specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>1.4 meter point-to-point</td>
</tr>
<tr>
<td>Radius</td>
<td>10 meter</td>
</tr>
<tr>
<td>Areal Density</td>
<td>&lt; 20 kg/m2</td>
</tr>
<tr>
<td>Areal Cost</td>
<td>&lt; $4M/m2</td>
</tr>
</tbody>
</table>

### Beryllium Optical Performance

- Ambient Fig: 47 nm rms (initial)
- Ambient Fig: 20 nm rms (final)
- 290K – 30K: 77 nm rms
- 55K – 30K: 7 nm rms

### ULE Optical Performance

- Ambient Fig: 38 nm rms (initial)
- 290K – 30K: 392 nm rms
- 55K – 30K: 55 nm rms
- 290K – 30K: 188 nm rms (w/ adjust)
- 55K – 30K: 20 nm rms (w/ adjust)
AMSD Figure Change: Ambient-to-Cryo (30 K)

Beryllium

- Surface Figure With Alignment Compensation
- RMS: 0.0770 μm
- PV: 0.6378 μm
- Data Pts: 150971

- Residual with 36 Zernikes Removed
- Gravity

Filename: C:\My Documents\jwst\Be_data\29a-294a_all.dat

ULE Glass

- Surface Figure With Alignment Compensation
- RMS: 0.1884 μm
- PV: 1.5094 μm
- Data Pts: 154476

- Residual with 36 Zernikes Removed
- Gravity

Filename: C:\My Documents\jwst\ULE_data\v30293c4_all.dat

...
AMDS Figure Change: 30-55K Operational Range

**Beryllium**
- RMS: 0.0070 μm
- PV: 0.0622 μm
- Data Pts: 148774

**ULE Glass**
- RMS: 0.0206 μm
- PV: 0.1710 μm
- Data Pts: 151638

Surface Figure With Alignment Compensation

Residual with 36 Zernikes Removed
NASA and DoD Partners invested $40M in mirror technology development:

**AMSD** - Advanced Mirror System Demonstrator
  - Ball Semi-Rigid Low-Authority Be
  - Kodak Semi-Rigid Medium-Authority ULE Glass
  - Goodrich Iso-Grid High-Authority Fused Silica Glass

**NMSD** - NGST Mirror System Demonstrator
  - Arizona Meniscus Very-High-Authority Glass
  - COI Rigid Hybrid-Glass-Composite

**SBMD** - Small Beryllium Mirror Demonstrator
  - SiC & C/SiC
    - IABG (ECM) 0.5 meter 7.8 kg/m2 mirror has been cryo-tested
    - Xinetics 0.5 meter 25 kg/m2 mirror has been cryo-tested

**Foam Mirrors**
  - Schafer Corp Foam Si
  - MER and UltraMet Foam SiC

**JBMD** - Joined Beryllium Mirror Demonstrator
  - MSFC Nickel Replication
Enabling Technology

It is my personal assessment that there were 4 key Technological Breakthroughs which have enabled JWST:

- O-30 Beryllium (funded by AFRL)
- Incremental Improvements in Deterministic Optical Polishing
- Metrology Tools (funded by MSFC)
  - PhaseCAM Interferometer
  - Absolute Distance Meter
- Advanced Mirror System Demonstrator Project (AMSD)
  funded by NASA, Air Force and NRO
AMSD Lessons Learned

Any proposal which seems overly conservative to me is probably just about right. Required cost and schedule reserve is always more than what you think it needs to be.

Standard process tooling and handling procedures are not scaleable to large aperture light-weight mirrors.

It is very hard to polish a mirror all the way to the edge.

Fiducialization is critical for knowing where you are.

Imaging Distortion through a CGH can cause edge miss-hit by as much as 50 mm.

A properly designed support structure interface will not distort a light-weight substrate.

A properly designed substrate does not have cryo-quilting.

Substrate CTE variation drives cryo-deformation.
Mirror Technology TRL-6 Certification
Mirror Technology was required to be assessed at TRL-6 by a Technical Non-Advocate Review (T-NAR) panel before JWST Optical Telescope Assembly (OTA) could undergo its Critical Design Audit (CDA).

On 31 January 2007, the T-NAR declared that all key mirror technology for a JWST Primary Mirror Segment Assembly (PMSA), as defined directly from the JWST Level 1 Science Requirements, have been developed and matured from a Technology Readiness Level (TRL) of 3 to 6.
# PMSA Requirements Traceability

PMSA Requirements are fully traceable from Level 1 Science Requirements to Level 2 Mission Requirements to Level 3 Observatory Requirements.

<table>
<thead>
<tr>
<th>Level 1 Requirements</th>
<th>Level 2 Requirements</th>
<th>PMSA Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1-01: Spectral Range</td>
<td>MR-211: Optical Transmission</td>
<td>PMSA-110: Spectral Reflectance 0.6-28 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PMSA-530: Operational Temp 28-50K</td>
</tr>
<tr>
<td>L1-04: Celestial Coverage</td>
<td>MR-115: EE Stability</td>
<td>PMSA-170: Thermal Change &lt; 0.3 nm rms/K</td>
</tr>
<tr>
<td>L1-12: L2 Orbit</td>
<td>MR-099: Mass</td>
<td>PMSA-410: Mass &lt; 39.17 kg</td>
</tr>
<tr>
<td></td>
<td>MR-283: Launch Loads</td>
<td>PMSA-180: Launch Distortion &lt; 2.9 nm rms</td>
</tr>
<tr>
<td>L1-13: PM Collecting Area</td>
<td>MR-198: PM Collecting Area</td>
<td>PMSA-70: Polished Surface Area &gt; 1.46 m²</td>
</tr>
<tr>
<td>L1-14: Observ Strehl Ratio</td>
<td>MR-228: OTE WFE</td>
<td>PMSA-150: Uncorrectable Fig &lt; 23.7 nm rms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PMSA-195: Creep &lt; 1.8 nm rms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PMSA 1560: ROC Resolution &lt; 10 nm sag</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PMSA 370: 6 DOF (Resolution &lt; 10 nm)</td>
</tr>
</tbody>
</table>
## JWST Requirements vs pre-JWST SOA

### JWST Mirror Technology vs State of Art

<table>
<thead>
<tr>
<th>PMSA Technology</th>
<th>JWST Requirement</th>
<th>Hubble</th>
<th>Spitzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSA-110: Spectral Reflectance 0.6-28 µm</td>
<td>Gold Coating on O-30 Be with 28K Survival</td>
<td>UV/Visible</td>
<td>Uncoated</td>
</tr>
<tr>
<td>PMSA-530: Operational Temperature 28-50K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMSA-170: Surface Figure Thermal Change</td>
<td>&lt; 7.5 nm rms for 30 to 55K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMSA-410: Mass &lt; 39.17 kg</td>
<td>Areal Density &lt; 26.5 kg/m²</td>
<td>180 kg/m²</td>
<td>28 kg/m²</td>
</tr>
<tr>
<td>PMSA-180: Surface Distortion from Launch</td>
<td>&lt; 2.9 nm rms</td>
<td></td>
<td>&lt; ~ 20 nm rms</td>
</tr>
<tr>
<td>PMSA-70: Polished Surface Area</td>
<td>1.3 meter diameter Segment</td>
<td>2.4 meter</td>
<td>0.85 meter</td>
</tr>
<tr>
<td>PMSA-150: Uncorrectable Surface Error</td>
<td>&lt; 23.7 nm rms Surface Error</td>
<td>6.4 nm rms</td>
<td>75 nm rms</td>
</tr>
<tr>
<td>PMSA-195: Surface Change from Creep</td>
<td>Design to O-30 Be PEL</td>
<td>ULE PEL</td>
<td>I-70 Be PEL</td>
</tr>
<tr>
<td>PMSA 1560: ROC Adjustment Resolution</td>
<td>&lt; 10 nm pv sag</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>PMSA 370: Hexapod 6 DOF</td>
<td>&lt; 10 nm step Actuators at 30K</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>PMSA-530: Operational Temperature 28-50K</td>
<td>Operates 28-50K</td>
<td>300K</td>
<td>4.5K</td>
</tr>
</tbody>
</table>
## Success Criteria & Results Summary

### Mirror Technology Success Criteria

<table>
<thead>
<tr>
<th>PMSA Technology</th>
<th>Success Criteria</th>
<th>Achieved</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSA-110: Spectral Reflectance 0.6-28 µm</td>
<td>Gold Coating on O-30 Be with 28K Survival</td>
<td>Gold Coating on O-30 Be with 28K Survival</td>
<td>SBMD</td>
</tr>
<tr>
<td>PMSA-530: Operational Temperature 28-50K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMSA-170: Surface Figure Thermal Change</td>
<td>&lt; 7.5 nm rms for 30 to 55K</td>
<td>7 nm rms from 30 to 55K</td>
<td>AMSD</td>
</tr>
<tr>
<td>PMSA-410: Mass &lt; 39.17 kg</td>
<td>Areal Density &lt; 26.5 kg/m²</td>
<td>Areal Density = 15.6 kg/m²</td>
<td>AMSD</td>
</tr>
<tr>
<td>PMSA-180: Surface Distortion from Launch &lt; 2.9 nm rms</td>
<td>Less than metrology error budget of 14 nm rms</td>
<td>10.6 nm rms Surface Change from Vib &amp; Acoustic Test</td>
<td>JWST B1</td>
</tr>
<tr>
<td>PMSA-70: Polished Surface Area &gt; 1.46 m2</td>
<td>1.3 meter diameter Segment delivered from AXSYS</td>
<td>1.3 meter diameter</td>
<td>AMSD</td>
</tr>
<tr>
<td>PMSA-150: Uncorrectable Surface Error</td>
<td>&lt; 23.7 nm rms Surface Error</td>
<td>18.8 nm rms 30K Figure</td>
<td>SBMD</td>
</tr>
<tr>
<td>PMSA-195: Surface Change from Creep &lt; 1.8 nm rms</td>
<td>Design to O-30 Be PEL</td>
<td>Designed to ensure &lt; 1500 psi residual stress</td>
<td>SBMD</td>
</tr>
<tr>
<td>PMSA 1560: ROC Adjustment Resolution</td>
<td>&lt; 10 nm pv sag</td>
<td>0.8 nm pv sag</td>
<td>AMSD</td>
</tr>
<tr>
<td>PMSA 370: Hexapod 6 DOF</td>
<td>&lt; 10 nm step Actuators at 30K</td>
<td>7.5 nm step Actuators at 30K</td>
<td>AMSD</td>
</tr>
<tr>
<td>PMSA-530: Operational Temperature 28-50K</td>
<td>Operates 28-50K</td>
<td>Operated at 28-50K</td>
<td>AMSD</td>
</tr>
</tbody>
</table>
## Four PMSA Technology Demonstrators for TRL-6

<table>
<thead>
<tr>
<th>Demonstrator</th>
<th>Technology</th>
<th>Validity to JWST</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBMD</td>
<td>Cryogenic Coating</td>
<td>SBMD developed a low stress gold coating application that can be applied to any beryllium mirror. Coating of large mirrors (like JWST) is not material specific and has been developed on other flight programs.</td>
</tr>
<tr>
<td>AMSD Mirror</td>
<td>Figuring</td>
<td>All differences between the JWST PMSA and the AMSD mirror improves manufacturability, cryogenic performance, and provides more actuation degrees of freedom.</td>
</tr>
<tr>
<td>AMSD Stress Coupons</td>
<td>Long term material stability</td>
<td>-67(\times)306$\text{V} - \text{DUH} - \text{PDQXIDFWXUHG} - \text{VXLQJ} - \text{WKH}$ processing developed on AMSD III to assure low residual surface stresses and low material creep.</td>
</tr>
<tr>
<td>JWST EDU &amp; Flight Segment</td>
<td>Launch distortion</td>
<td>JWST flight segment used to show technology readiness.</td>
</tr>
</tbody>
</table>
Gold Coating on O-30 Be with 28K Survival

SBMD survival tested to 28K
Gold Coating provides Spectral Range
Adhesion demonstrates Operational Temperature

Adhesion of Gold on O-30 Be at 28K was technology needing to be demonstrated for TRL-6. Not ability to coat.

No significant Figure Change

<table>
<thead>
<tr>
<th>SBMD Uncoated</th>
<th>SBMD Coated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure @ 30K</td>
<td>Figure @ 30K</td>
</tr>
<tr>
<td>52.8 nm-rms</td>
<td>53.9 nm-rms</td>
</tr>
</tbody>
</table>
SBMD exhibited a cryo-deformation of approximately 90 nm rms. Shape changed consisted of low-order mount induced error & high-order quilting error (rib structure).

SBMD was cryo-null figured using Tinsley small tool CCOS technology. Predicted final cryogenic surface figure was 14.4 nm rms. Actual final cryogenic surface error was 18.8 nm rms.
AMSD Key Technology Results

Since SBMD demonstrated the ability to cryo-null polish to 20 nm rms. For cost and schedule reasons, AMSD demonstrated 20 nm rms at ambient. AMSD did certify Cryo-Figure Stability over the operating range.

Results of AMSD 20 nm-rms convergence
RMS = 19.2 nm
Area of Mirror = 97.1%

Results of AMSD-II 30 to 55 Kelvin
Operational range
Delta = 7 nm-rms (0.28 nm-rms/K)
Specific modifications were made to the JWST flight PMSA design based on AMSD Lessons Learned to improve producibility, performance, launch survival & reduce risk.

<table>
<thead>
<tr>
<th>Key Design Parameter</th>
<th>AMSD</th>
<th>JWST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Be O-30</td>
<td>Be O-30</td>
</tr>
<tr>
<td>Point to point dimension</td>
<td>1.4 m</td>
<td>1.52 m</td>
</tr>
<tr>
<td>Number of pockets</td>
<td>864</td>
<td>600</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>60 mm</td>
<td>59 mm</td>
</tr>
<tr>
<td>Stiffness (f-f first mode)</td>
<td>180 Hz</td>
<td>260 Hz</td>
</tr>
<tr>
<td>Substrate areal density</td>
<td>10.4 kg/m$^2$</td>
<td>13.8 kg/m$^2$</td>
</tr>
<tr>
<td>Assembly areal density</td>
<td>19.1 kg/m$^2$</td>
<td>26.2 kg/m$^2$</td>
</tr>
<tr>
<td>Surface figure (assy level)</td>
<td>22 nm-rms</td>
<td>24 nm-rms</td>
</tr>
</tbody>
</table>
Mirror Technology has been demonstrated

Flight mirror demonstration
- Launch Load survival
- Acoustic tests

Advanced Mirror System Demonstrator
- Areal density, full scale asphere
- Surface figure requirements
- Radius of curvature control
- Cryo-repeatability

Subscale Beryllium Mirror Demonstrator
- Areal density
- Cryo-figuring
- Radius of curvature control
- Cryo-testing of protected gold coating
Flight PMSA Fabrication

Engineering Development Unit
an EDU is Essential

AMSD ran out of time and money.

Therefore, as discussed, TRL-6 was established via a combination of multiple mirrors: AMSD, SBMD and Flight.

TRL-6 was never established with a single mirror.

Furthermore, the flight mirror design was significantly modified as a result of AMSD lessons learned.

Thus, the EDU was necessary to verify how the new design interacted with the fabrication process.

While the JWST PMSAs have been successful, they could have been even more successful if, as suggested by the recent National Academy Report, more time had been spent during Phase A to fully demonstrate the technology.
Leaning vs Forgetting Curve

Just as there is a ‘learning’ curve, there is also a ‘forgetting’ curve.

Too much time elapsed between end of AMSD and start of flight.

Thus, the process had to be re-established on the EDU.

The process was not stable until the 3rd or 4th PM SA.

To use EDU learning, must keep a gap between EDU and Flight.

No Process should ever be performed to a flight mirror until first performed on a full scale EDU.
Schedule Lessons Learned

Plan for unplanned Activities

Because of unplanned activities, AMSD’s actual schedule was 60% longer than its initial prediction.

At the start of JWST,

Vendor Team estimated an EDU production schedule similar to the AMSD schedule based on the assumption that lessons learned.

Review Team estimated an DEU production schedule 75% longer.

The EDU production schedule was actually 150% longer.

Delay to the EDU schedule impact every flight mirror.
Lessons Learned and Conclusions
Lessons Learned ± in no particular order

Large Mirrors are harder to make than Small Mirrors
Technology must be ‘scaled-up’ by validating increasing larger Mirrors
Technology demo-ed on Sub-Scale Mirrors does not necessarily ‘Scale-Up’
Full Scale Pathfinders are extremely valuable
Low areal density mirrors are harder to make than high areal density mirrors
Processes for high areal density do not necessary work for low areal density
Process Characterization and Control is Critical
Standard tooling and handling procedures are not scaleable to large aperture light-weight mirrors
Mirror Stiffness is at least as important as Areal Density
It is hard to polish a mirror all the way to the edge
Fiducialization is critical for knowing where you are
CGH imaging distortion can cause miss-registration of as much as 50 mm
CGH imaging distortion and depth of focus can introduce Fresnel diffraction effects which blur edges resulting in ‘rolled’ edges
Lessons Learned ± continued

Nothing behaves the same at 300K and 30K
Designing Mechanisms to operate at 30K is difficult
Validate all Components under Operational Conditions before Assembly
Your intuition about how things behave at 30K is probably wrong
Nothing works the way it is initially designed or modeled
Uniform CTE properties are essential for predictable cryo-performance
Manufacturing Production Quantities is harder than a Demo Unit
Things break and mechanisms can have infant mortality as high as 30%
Glass Mirrors will Fracture and Metal Mirrors will be Stressed

Just as there is a learning curve, there is also a forgetting curve. Don’t allow too much time between the end of technology development and the start of flight fabrication.

EDUs are critical, but the schedule gap between the EDU and flight mirrors must be maintained – not too large otherwise forgetting occurs, not too short otherwise lessons learned cannot be applied.

There is no substitute for Experience.
Starting in 1996, a systematic development program was undertaken to build, test and operate in a relevant environment directly traceable prototypes or flight hardware:

- Sub-scale Beryllium Mirror Demonstrator (SBMD)
- NGST Mirror System Demonstrator (NMSD)
- Advanced Mirror System Demonstrator (AMSD)
- JWST Engineering Test Units (EDU)

The effort dramatically reduce cost, schedule, mass and risk for large-aperture space optical systems.

TRL-6 was achieved before the Technical Non-Advocate Review (T-NAR)

A critical element of the program was competition – competition between ideas and vendors resulted in:

- remarkably rapid TRL advance in the state of the art
- significant reductions in the manufacturing cost and schedule

It took 11 years (and ~$40M) to mature mirror technology from TRL 3 to 6.
BACK-UP
Mirror Technology Development Program
Other Mirrors Tested at MSFC

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Material</th>
<th>Diameter</th>
<th>Areal Density</th>
<th>Cryo-Distortion [290K to 30K]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beryllium Mirrors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ball SBMD</td>
<td>O-30 Be</td>
<td>0.5 m</td>
<td>10 kg/m²</td>
<td>17 nm rms</td>
</tr>
<tr>
<td>Ball AMSD</td>
<td>O-30 Be</td>
<td>1.4 m</td>
<td>16 kg/m²</td>
<td>77 nm rms</td>
</tr>
<tr>
<td><strong>Glass Mirrors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kodak</td>
<td>Fused Silica</td>
<td>0.23 m</td>
<td>10 kg/m²</td>
<td>17 nm rms</td>
</tr>
<tr>
<td>Hextek</td>
<td>Borosilicate</td>
<td>0.25 m</td>
<td>14 kg/m²</td>
<td>25 nm rms</td>
</tr>
<tr>
<td>Kodak</td>
<td>ULE</td>
<td>0.35 m</td>
<td>10 kg/m²</td>
<td>8 nm rms</td>
</tr>
<tr>
<td>Kodak AMSD</td>
<td>ULE</td>
<td>1.4 m</td>
<td>18 kg/m²</td>
<td>188 nm rms</td>
</tr>
<tr>
<td><strong>SiC Mirrors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schafer</td>
<td>Foam SiC</td>
<td>0.125 m</td>
<td>10 kg/m²</td>
<td>4 nm rms</td>
</tr>
<tr>
<td>POCO</td>
<td>Foam SiC</td>
<td>0.25 m</td>
<td>16 kg/m²</td>
<td>16 nm rms</td>
</tr>
<tr>
<td>TREX</td>
<td>CVD SiC</td>
<td>0.25 m</td>
<td>9 kg/m²</td>
<td>38 nm rms</td>
</tr>
<tr>
<td>Xinetics</td>
<td>RB SiC</td>
<td>0.5 m</td>
<td>22 kg/m²</td>
<td>25 nm rms</td>
</tr>
<tr>
<td>IABG (Note 1)</td>
<td>C/SiC Felt</td>
<td>0.5 m</td>
<td>8 kg/m²</td>
<td>443 nm rms</td>
</tr>
</tbody>
</table>

Note 1: IABG cryo deformation aligned with the felt bias direction, it is anticipated that a mirror facesheet with more felt layers (and more mass) would have had a substantially smaller cryo-deformation.
Hextek Gas Infusion Mirror

Specifications

- Diameter: 0.25 meter
- Radius: 2.5 meter
- Areal Density: < 10 kg/m²
- Areal Cost: < $300K/m²

Polished by MSFC

- Ambient Fig: 23 nm rms
- 30K Figure: 40 nm rms
- 30K – 290K: 27 nm rms
- 30K – 60K: < 5 nm rms

Total Figure Error

- 30K – 290K: RMS = 27.0 nm
- 30K – 60K: RMS = 5.0 nm

Cryo Null Figured by QED with Residual Error of 13 nm rms
POCO SiC Mirror

Specifications

- Diameter: 0.25 meter
- Radius: 2.5 meter
- Areal Density: < 10 kg/m2
- Areal Cost: < $1M/m2

Delivered Polished

- Ambient Fig: 89 nm rms
- 30K Figure: 96 nm rms
- 290K – 30K: 16 nm rms
Xinetics SiC Mirror

Specifications

- Diameter: 0.5 meter
- Radius: 20 meter
- Areal Density: < 20 kg/m²
- Areal Cost: < $1.5M/m²

Delivered Polished

- Ambient Fig: 300 nm rms
- 290K – 30K: 27 nm rms
IABG 0.5 m 20 m Rcv Carbon Silicon Carbide

IABG Carbon Silicon Carbide Mirror  C/SiC
0.5 m Diameter
20 m Rcv
7.8 kg/m² Areal density

Blank polished at General Optics
Figure of ½ wave PV
Finish of 100 Angstroms RMS

Mirror tested to 120K at Kodak (Sept 99)
280 nm RMS, 2.53 µm PV Cryo-Figure Change

Mirror tested to 30K at MSFC (Apr 01).
350 nm RMS, 2.32 µm PV Cryo-Figure Change
Schafer SLIM (Si Foam) Mirror

Specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.125 meter</td>
</tr>
<tr>
<td>Radius</td>
<td>0.6 meter</td>
</tr>
<tr>
<td>Areal Density</td>
<td>&lt; 10 kg/m2</td>
</tr>
<tr>
<td>Areal Cost</td>
<td>&lt; $2.5M/m2</td>
</tr>
</tbody>
</table>

Delivered Polished

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Fig</td>
<td>29 nm rms (free)</td>
</tr>
<tr>
<td>290K – 30K</td>
<td>10 nm rms (free)</td>
</tr>
<tr>
<td>290K – 30K</td>
<td>46 nm rms (mounted)</td>
</tr>
<tr>
<td>75K – 30K</td>
<td>&lt; 4 nm rms (free)</td>
</tr>
</tbody>
</table>
Kodak Actuator V&V at MSFC

Characterize Kodak/Moog Force Actuators at 30K in MSFC 1m Chamber.

Step Size and Linearity

Operation under Load
Cryo-Deformation of Goodrich reaction structure

MSFC measured reaction structure cryo-change

Instrument with corner cubes

Characterize with Leica ADM

30 micrometer change from Ambient to 25K
Composite cones attach BSF to Center Section (6X)

Fitting for Spacecraft and ground handling interface

Backplane Support Frame (BSF)

Backplane

Center Section (CS)

Wing

AOS Mount

PMSA Mounts

Colors indicate different laminate designs
Cryo-Tested EDU Structures

When cryo-tested to 30K, the Backplane Support Test Assembly (BSTA) demonstrated remarkable agreement with model prediction.
Mirror Technology TRL-6 Certification
PMSA Component Definition

- 3X Strongback Hub Flexure
- ROC Actuator
- 6X Strongback Struts
- 6X Actuators
- Delta Frame
- 3X Whiffles
- Mirror Substrate
- 16X Mirror Flexures

Mirror Substrate focus of technological development
Mirror required Technological Development
Cryogenic Actuators

24 JWST actuators have been tested from 25 to 35K

JWST engineering unit actuators have resolution of 7 nm

Actuator performs single step moves, without backlash, to accuracy of 0.6 nm rms.
ROC Actuation Demonstrated at Cryo on AMSD

ROC actuation demonstrated on AMSD mirror at ambient & 30K
35 course Steps = 38 nm PV
(smallest measurable change)
1 Fine Step = 0.24 nm PV sag
(by calculation)

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Requirement (nm PV)</th>
<th>Cryo Demonstration (nm PV)</th>
<th>Capability (nm PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSD</td>
<td>50</td>
<td>38</td>
<td>0.24</td>
</tr>
<tr>
<td>JWST</td>
<td>10</td>
<td>-</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* Limited by Metrology

JWST RoC actuation design has been optimized to reduce residual figure error by 2X

JWST RoC actuation showed measurement within 1% of model prediction

ROC Actuation Residual Figure Error (JWST Mirror)

Average Measurement

Model Prediction
Hexapod testing in support of TRL-6 demonstrated rigid body control, including mirror deployment and stowage

TRL-6 PMSA hexapod fully integrated & tested prior to and after environmental testing

Demonstrated capabilities

- Fine range of motion (9.5 ± 10.5 microns)
  - Verified throughout TRL-6 testing via global clocking move of hexapod

Deployment

- Several stow / deploy cycles throughout test

Controllability demonstrated in actuator test
(ambient and cryogenic temperatures)

- Actuator testing <8 nm resolution,
  - Requirement < 10 nm
- Actuator single step performance meets accuracy requirements at ambient and cryogenic temperatures of < 2.15 nm error standard deviation

PMSA level hexapod testing

- Surface figure change during rigid body motion shown to be below EPSI noise level
Launch limit loads (maximum expected flight load) for Mirror Substrate

Sine burst testing applied loads higher than limit loads in all axes

Success Criteria:

Measure figure change below the 14 nm-rms figure measurement uncertainty of the Electronic Speckle Pattern Interferometer

Show by analysis that flight units meet 2.9 nm-rms figure change
TRL-6 vibro-acoustics testing completed in August
Pre to post ESPI measurement indicated changes were below measurement error
Mirror saw loads (17.6 G’s in X, 16.3 G’s in Y, 8.5 G’s in Z – Sine Burst) that enveloped worst case flight loads in all three axes.
**Pre to Post change after TRL-6 vibe**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measurement Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure</td>
<td>9.8</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>4.2</td>
</tr>
<tr>
<td>Power</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Mirror Loads:
17.6 G’s in X, 16.3 G’s in Y, 8.5 G’s in Z

- Measured Figure Error is Below Metrology Uncertainty
- Measured Astigmatism is Below Metrology Uncertainty
- Measured Power is Below Metrology Uncertainty

Total change measured is 10.6 nm rms

“All Measurements are within the Test Uncertainty of the State-of-the-Art ESPI metrology device”

Minus piston, tilt, power
Analysis predicts mirror surface launch deformation

<table>
<thead>
<tr>
<th>Load</th>
<th>Piston/Tip/Tilt/Astigmatism Removed, Power Actuated Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>X = 18.75 g</td>
<td>1.0</td>
</tr>
<tr>
<td>Y = 18.75 g</td>
<td>1.1</td>
</tr>
<tr>
<td>Z = 5670 N</td>
<td>0.5</td>
</tr>
<tr>
<td>RSS</td>
<td>1.6</td>
</tr>
</tbody>
</table>

PMSA-180 requirement is < 2.9 nm rms surface figure error for launch loads

Terms Removed: Piston, Tip/Tilt, Astigmatism

X = 18.75 g

Terms Removed: Piston, Tip/Tilt, Astigmatism

Y = 18.75 g

Terms Removed: Piston, Tip/Tilt, Astigmatism

Z=5670 N

Terms Removed: Piston, Tip/Tilt, Astigmatism

Power Actuated Out

RMS: 0.00095 microns
PV: 0.00628 microns

RMS: 0.00112 microns
PV: 0.00671 microns

RMS: 0.00047 microns
PV: 0.00304 microns