Mirror Requirements for Far-IR & Sub-MM

W. Scott Smith
H. Philip Stahl
Executive Summary

Large-aperture lightweight low-cost cryogenic mirrors are an enabling technology for planned NASA far-infrared and sub-millimeter missions such as CMB-Pol, SAFIR and SPECS.

Technical Requirements

< 10K Temperature – Active or Passive Cooling
< 10 kg/m2 Areal Density
> 2 meter diameter Segments for Large Apertures
< $500K/m2 Areal Cost

JWST Mirror Technology can meet SAFIR requirements but is expensive.
Far-Infrared and Sub-Millimeter Missions

Planned future NASA infrared, far-infrared and sub-millimeter missions:

- Cosmic Microwave Background Polarization (CMB-Pol),
- Single Aperture Far-IR (SAFIR)
- Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS)
- Terrestrial Planet Finder Interferometer Concept (TPF-I)

need large-aperture lightweight cryogenic optics with similar requirements.
Comparison of Primary Mirror Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JWST</th>
<th>SAFIR</th>
<th>CMB-Pol</th>
<th>SPECS</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Primary Diameter</td>
<td>6.5</td>
<td>8 to 12</td>
<td>&gt; 5</td>
<td>15 to 25</td>
<td>meter</td>
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<tr>
<td>Segment Diameter</td>
<td>1.3</td>
<td>1.6 to 2.4</td>
<td>~ 1</td>
<td>&gt; 2</td>
<td>meter</td>
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<tr>
<td>Area</td>
<td>25</td>
<td>50 to 100</td>
<td>20</td>
<td>175 to 500</td>
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<tr>
<td>Areal Density</td>
<td>25</td>
<td>5 to 10</td>
<td>25</td>
<td>&lt; 5</td>
<td>kg/m²</td>
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<tr>
<td>Diffraction Limit</td>
<td>2</td>
<td>20</td>
<td>250</td>
<td>20</td>
<td>μm</td>
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<tr>
<td>Surface Figure</td>
<td>0.02</td>
<td>~ 1</td>
<td>~ 10</td>
<td>~ 1</td>
<td>μm rms</td>
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<tr>
<td>Wavelength Range</td>
<td>0.6 to 40</td>
<td>20 to 800</td>
<td>250 to 800</td>
<td>20 to 800</td>
<td>μm</td>
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<tr>
<td>Operating Temperature</td>
<td>&lt;50</td>
<td>~ 4</td>
<td>~ 4</td>
<td>~ 4</td>
<td>K</td>
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<tr>
<td>Cost</td>
<td>$3 to $4M</td>
<td>&lt; $500K</td>
<td>&lt; $100K</td>
<td>&lt; $500K</td>
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<tr>
<td>Production Rate</td>
<td>&gt; 0.5</td>
<td>&gt; 2</td>
<td>&gt; 0.5</td>
<td>&gt; 10</td>
<td>m²/mo</td>
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<td>Segment Stiffness</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
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<td>Seg Dynamic Survival</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>G’s</td>
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</table>
Mirror Technology

JWST mirrors could be used for SAFIR.

- Optical Performance is Better Than Required
- Beryllium has proven track record at 4K, i.e. Spitzer

But,

- Segments larger than 1.3 meters requires new facility infrastructure
- Cost and Schedule is Prohibitive give SAFIR has 2X to 4X more Area.
- Areal Density is probably a solvable challenge.

Based on wavelength scaling alone the Areal Cost for:

- SAFIR should be 3X less than JWST
- CMB-POL should be 10X less than JWST

But, Goal should be 10X for SAFIR and 50X for CMB-POL.
Mirror Technology Development

• For more than 10 years, the primary goal has been to reduce Areal Density.
• Cost & Schedule is just as important.
• Stiffness is more important.

### Primary Mirror Time & Cost

<table>
<thead>
<tr>
<th>镜面直径（米）</th>
<th>时间成本（m^2/年）</th>
<th>成本（$/m^2）</th>
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<tbody>
<tr>
<td>HST（2.4米）</td>
<td>≈ 1 m^2/年</td>
<td>≈ $10M/m^2</td>
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<tr>
<td>SIRTF（0.9米）</td>
<td>≈ 0.3 m^2/年</td>
<td>≈ $25M/m^2</td>
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<tr>
<td>AMSD（1.2米）</td>
<td>≈ 0.7 m^2/年</td>
<td>≈ $4M/m^2</td>
</tr>
<tr>
<td>JWST（6米）</td>
<td>&gt; 6 m^2/年</td>
<td>&lt; $3M/m^2</td>
</tr>
<tr>
<td>SAFIR</td>
<td>&gt; 15 m^2/年</td>
<td>&lt; $.5M/m^2</td>
</tr>
</tbody>
</table>

Current Total World Capacity is < 50 m^2/年
Stable Operation is Critical for Space Telescopes

Lessons Learned from AMSD & JWST

Specific Stiffness is very important:
- Drives Ground Testing via Gravity Sag
- On-Orbit G-Release impacts Error Budgets
- Drives Design for Launch Survival
- Long Term Mechanical Stability

Thermal Stability is other most important parameter:
- Thermal Deformation – Ambient to Cryogenic
- Thermal Gradients – On-Orbit Figure Changes
- CTE, Conductivity, Thermal Capacity, Emissivity

Ideal Material has
- High Stiffness and Low Density – High Specific Stiffness
- High Conductivity and Low CTE – High Thermal Stability
Candidate Materials

Beryllium has been selected for JWST.
  High Specific Stiffness – low density.
  Adequate Thermal Stability

On AMSD, Be experienced a 170 nm rms figure change from Ambient to 30K.

This change is smaller than surface figure error requirement for SAFIR.

Be could be used on SAFIR without need for Cryo-Null Figuring.

Any material with better Thermal Stability than Be is acceptable.
  Such Materials include SiC, C-SiC, and MgGr (Magnesium Graphite Composite)

Materials (other than Be) with good Specific Stiffness: SiC, C-SiC, MgGr.
Specific Properties of Candidate Mirror Materials
(from MMCC Tech Days 2003)

![Graph showing specific properties of candidate mirror materials.](image)

Legend:
- Be
- ULE
- Zerodur
- Fused Silica
- Silicon
- Gr/Mg P-I Phase I
- Ceraform SiC
- Poco SiC
- CVD SiC
- SSG HP SiC
- SSG RB SiC
- Mg/Gr Quasi Isotropic
Design for Stiffness

JWST is designing its Be mirrors for > 200 Hz free-free
Complex trade between:
   - Mirror Depth
   - Face Sheet Thickness
   - Rib Thickness
   - Cell Size
   - Etc.

Xinetics reported on a trade study for SiC Mirrors with >200 Hz free-free stiffness and <10 kg/m² areal density at Tech Days 2003

Any material with comparable or higher Specific Stiffness to Xinetics SiC should be able to achieve both requirements.
SiC Stiffness to Weight Trade for 1 meter Hex
(from Xinetics Tech Days 2003)
SAFIR

Leading concepts for SAFIR include deployed segmented architectures similar to JWST and membrane concepts.

JWST class architecture for SAFIR offers:
  Demonstrated flight deployment, phasing & pointing to precision greater than required
  Re-use of support structure design, mechanisms, actuators, spacecraft, etc.

Mirror Challenges are Cost, Schedule, Stiffness, Mass & Thermal Control.
Cryogenic Mirror Technology Development
The Need for Mirror Technology Development

From its start in 1995, JWST took 8 years to advance lightweight optics for a 30K telescope from TRL-2 to TRL-6 (2003).

Leveraging JWST 30K optics technology, it might be possible to mature SAFIR 4K optics technology to TRL-6 in 6 years if we start today.

SAFIR & SPECS mirror requirements are easier than TPF Interferometer

CMB-POL is on the Technology Roadmap for SAFIR and TPF-I.

Mirror Technology Development requires a Technology Triangle:
  Science Team define science requirements
  Engineering Team matures enabling technology & infrastructure.
  Industry & Universities participate in all phase.
Mirror Technology Development Program

NASA and DoD Partners have invested $40M in mirror technology development projects (via contracts, SBIR’s and NRA’s):

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

NMSD - NGST Mirror System Demonstrator
- Arizona Meniscus Very-High-Authority Glass
- COI Rigid Hybrid-Glass-Composite (cryo tested 3 times)

SBMD - Subscale Beryllium Mirror Demonstrator (cryo tested 7 times)

Glass Mirrors
- Hextek Gas Infusion (cryo tested twice and CNF)
- Kodak SiO2 LTF (cryo tested)
- Schott Zerodur LTB (cryo tested)

SiC & C/SiC
- IABG/ECM 0.5 meter 7.8 kg/m² (cryo tested)
- Xinetics 0.5 meter 25 kg/m² (cryo tested)

Foam Mirrors
- Schafer Foam Si (cryo tested)
- MER and UltraMet Foam SiC

Other Mirrors
- JBMD Joined Beryllium Mirror Demonstrator (cryo tested)
- MSFC Nickel Replication
AMSD – Ball & Kodak

Specifications
- Diameter 1.4 meter point-to-point
- Radius 10 meter
- Areal Density < 20 kg/m²
- Areal Cost < $4M/m²

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)
Static Cryogenic Figure Change

~30 K minus Ambient with Virtual Hexapod Alignment Adjustment

Kodak ULE

Ball Be
Operational Range Thermal Stability

~30 K minus ~55 K with Virtual Hexapod Alignment Adjustment

Kodak ULE

Ball Be
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

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

Total Figure Error

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

- Diameter: 0.125 meter
- Radius: 0.6 meter
- Areal Density: < 10 kg/m2
- Areal Cost: < $2.5M/m2

Delivered Polished

- Ambient Fig: 29 nm rms (free)
- 290K – 30K: 10 nm rms (free)
- 290K – 30K: 46 nm rms (mounted)
- 75K – 30K: < 4 nm rms (free)
Ball Subscale Beryllium Mirror Demonstrator (SBMD)

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

Higher Order Residual: (0.134 µm p-v; 0.012 µm rms)

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

Cryo Tested at MSFC
COI Hybrid Mirror

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

25K Figure (Low Order Zernikes Removed)

Ambient Surface
Surface at Cryo

0.8micron RMS Full Aperture
0.48micron RMS Masking Gravity Offload influences
Ability to Cryo-Test JWST Segments is TRL 6

Cryogenic Testing at MSFC is Routine
   Performed 10+ Tests to 30K, Reduced Test Times from 7 to 5 to 3 weeks

Invested in Special Test Equipment and Procedures
   PhaseCAM Instantaneous Interferometer
   Stroboscopic Modal Test Interferometry
   Leica Absolute Distance Meter (ADM)
   100X Accuracy/Resolution Improvement
   Segment Radius of Curvature Matching
NASA Space Optics Manufacturing Technology Center (SOMTC)
Executive Summary

Space Optics is a core technology at MSFC

MSFC’s world-class optics personnel & facilities enable:
  James Webb Space Telescope (JWST)
  Constellation X (ConX).
  Extreme Universe Space Observatory (EUSO)

MSFC Optics Group is committed to supporting future Code S missions:
  Single Aperture Far Infrared (SAFIR),
  Terrestrial Planet Finder (TPF),
  Modern Universe Space Telescope (MUST).

Cryo Mirror Technology Development:
  AMSD, NMSD & SBMD
  Funded SBIR Contracts
  MSFC IRAD Investments
  Submitted Large Cryo Mirror NRA
Proven Record in Large Optics

Recognized experts in optical fabrication & testing
  Worked on most of world’s largest monolithic & segmented telescopes: SUBARU, KECK, HET, LAMP, AMOS, Starfire, VLT, Gemini, etc.
  Ultra-Precision Metrology – LIGO, Lithography, etc.

Unsurpassed experience in cryogenic & x-ray performance testing
  Over 40 cryogenic tests of large optics, structures and mechanisms since 1999.
  Over 12 X-ray performance tests since 1999 (plus HEAO-B, SXI & Chandra < ‘99)

Unique world class test facilities & instruments
  XRCF, Straylight, Metrology
MSFC Optics Core Capabilities Compliment those of GSFC & JPL

Fabrication and Test of:
  - Large Space Optics
  - Cryogenic Optics
  - Transmissive and Fresnel Optics
  - X-Ray Optics
  - Replicated and Gossamer Optics.

Laser Technology Development
- Diffractive Optics and Photonic Sensors
- Coating Technology Development
- Material Research
- Segmented Telescope Alignment
- Space Power
- Optical Propulsion and Solar Sails
- Optical Diagnostics for Microgravity Research
- Optical Diagnostics for Propulsion Research
- Optical Education and Public Outreach
MSFC Optics Support Code S Missions

Current Programs:
- James Webb Space Telescope (JWST) – GSFC
  - Optical Components Lead – Insight/Oversight
  - Cryogenic Testing of Flight Mirror Segments
- Constellation X (ConX) – GSFC
  - Support Optics Fab & Metrology, X-Ray Testing
- Solar X-Ray Imager (SXI) – GSFC
- Solar B - MSFC
- Gravity Probe B - MSFC
- SUMI - MSFC
- Extreme Universe Space Observatory (EUSO) - MSFC
- Terrestrial Planet Finder (TPF) – JPL/GSFC
- Space Interferometer Mission (SIM) – JPL

MSFC has significant Flight Heritage

Skylab Telescope
1973

HEAO -1978

Hubble - 1992

Chandra - 1999
MSFC’s Record on JWST

Pre-Phase A Activities
Significant contributions to NGST Strawman Concept
Performed L2 Environment study for JWST.

Mirror Technology Development Lead
Managed SBMD, NMSD & AMSD Programs
Cryogenic Performance Testing of SBMD, NMSD, AMSD, etc.
Created new commercial tools – 4D PhaseCAM, Leica ADM, SRS IODA
Material Property Testing
Integrated Modeling
Risk Planning

Procurement Support
Voting Member on Source Evaluation Board
Voting Member on Primary Mirror Material Selection Board
Lead OTE Cost Modeling

Flight Program
Key members of the OTE Management Team
Optical Components: primary, secondary & tertiary mirrors
Primary Mirror Segment Testing at MSFC - FY05 to FY07/08
Ambient Verification – prevents prescription error.
Cryogenic Characterization – enables on-orbit performance.
X-Ray and Cryogenic Test Facility

Facility
- 7 x 23 m Stainless 10-8 Torr Chamber
- Vibration Isolated (LOS Jitter 5 - 10 urad)
- 5DOF Remote Controlled Test Stand

Personnel
- Experience Team provides 24/7 support
- 35+ Cryogenic Mirror & Structure Tests
- 12+ X-Ray tests

Cryogenic Testing
- 6 x 18 m LN2 Shroud with Heaters for 166K to 344K Thermal Range
- 2.7 x 3.3 x 10 m 20K Closed Loop He Shroud (design for 4.4 x 3.9 x 18 m)

X-Ray Testing
- Full aperture testing up to 1.46 m
- Collimation via 0.518 km evacuated tube.
- Instrumentation (0.1 to 10.0 KEV).

Telescopes/Components Tested
- Einstein, Chandra, SXI, HEAO, CXM
- SBMD, NMSD, AMSD, JWST
- Continuous Usage since 1999; 47% Vacuum
- Projected Usage for JWST and ConX
XRCF is a Unique World Class Facility

No other facility has the XRCF’s combination of size, stability, cleanliness, cryogenic optical test and x-ray test capabilities.

<table>
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<tr>
<th>Large Thermal Vacuum Chambers</th>
</tr>
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<tbody>
<tr>
<td>Chamber</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>MSFC XRCF</td>
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<td>GSFC SES</td>
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<td>Glenn SPF</td>
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<td>AEDC Mark 1</td>
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<tr>
<th>X-Ray Test Facilities</th>
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<tbody>
<tr>
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<tr>
<td>MSFC XRCF</td>
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<tr>
<td>MSFC Straylight</td>
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<tr>
<td>German Panther</td>
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