Section 6

ALI Silicon Carbide (SiC) Technology
Introduction

(SSG Precision Optronics Background

- 20+ year old small business
- Specializes in the design, fabrication, and test of all-reflective telescope systems for space applications
- 30+ space systems developed and delivered
- 10+ years of experience with SiC materials and SiC instruments

SSG NMP EO-1 Mission Contributions

- Partner in NMP IPDT
- ALI optical design, fabrication and test support to MIT/LL
- Incorporate SiC technology into ALI instrument
- SSG also responsible for design, fabrication and test of Hyperion optical system in support to TRW
**Primary Telescope Specifications**
- Aperture: 12.5 cm
- Focal Length: 94 cm
- Field of View: 1.0 x 15 degrees
- Wavelength: 0.4 - 2.5 μm
- MTF @ 0.6 μm (37.5 lp/mm): > 0.5
- Distortion: < 275 μm; < 250 μm

**Primary Design Elements**
- 4 mirror, all reflective, unobscured optical design
- Flat focal surface
- Hot Pressed SiC optics
- Invar 36 metering structure
**ALI Optical Design**

- **Optical Design**
  - Reflective version of Cooke Triplet
  - Aperture stop on secondary mirror
  - Off-axis, wide field of view
  - Flat image plane

- **ALI Mirrors**

<table>
<thead>
<tr>
<th></th>
<th>Primary</th>
<th>Secondary</th>
<th>Tertiary</th>
<th>Fold Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical Shape</strong></td>
<td>General Asphere</td>
<td>Ellipsoid</td>
<td>Sphere</td>
<td>Flat</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>13.1” x 6.6”</td>
<td>3” diameter</td>
<td>11.7” x 5.3”</td>
<td>10.8” x 3.4”</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>Si on SiC</td>
<td>Si on SiC</td>
<td>SiC</td>
<td>SiC</td>
</tr>
<tr>
<td><strong>Base Radius</strong></td>
<td>-65.5”</td>
<td>23.7”</td>
<td>-36.6”</td>
<td>NA</td>
</tr>
</tbody>
</table>
ALI Optical Performance (Image Quality)

On Axis, system level Wavefront Error (WFE)

- **System Level Wavefront Error**
  - WFE derived from MTF specification using Code V
  - Required system WFE (@ temp) < 0.15 \( \lambda \) RMS (@ 0.63 \( \mu \)m)
  - 12 Field points tested, System WFE (@ temp) 0.089 - 0.148 \( \lambda \) RMS (@ 0.63 \( \mu \)m)

- **System Level MTF**
  - MTF performance projected from wavefront maps input specification using Code V
  - System meets or exceeds spec at 18.75 and 37.5 lp/mm
**Optical Distortion**

- Distortion measured by mapping the angular locations of 40 points on a scribed target through the ALI optical system.
- Uncorrected data shows maximum distortion vector length of 928 µm.
- Cubic polynomial data correction (Dr. David Hearn, MIT/LL) brings residual distortion values down below 9 µm.
Stray Light

- ALI Flight optics do not meet ALI stray light requirements for 5 of the 8 spectral wavebands (Lambda Research)
  - Bands out of spec by 2x - 10x
- System level stray light requirement has been converted to component level BRDF requirements (Lambda Research)
- BRDF needs 20x improvement (ALI M1) to meet stray light requirements

Component BRDF Comparison

Individual Mirror Goal
ALI Performance Summary

- **ALI SiC optical system meets or exceeds most of the telescope requirements**
  - Component level surface figure
  - Reflectivity
  - Field of view
  - Angular resolution
  - Point spread function
  - System throughput
  - Image quality over FOV
  - Distortion map over FOV
  - Focal length
  - Aperture uniformity
  - Mechanical stability
  - Thermal stability
  - Size
  - Weight

- **The one exception noted is the system stray light performance of the system, component level BRDF of SiC optics**
  - NASA funded technology program has been completed at SSG in order to demonstrate that this limitation, associated with these specific flight optics, is not a fundamental limitation associated with SiC optics technology
Technology Description

- **Optical Design**
  - Wide field of view
  - Flat image plane
  - Low distortion
  - Excellent image quality

- **SiC Materials Technology**
  - Hot Pressed SiC Optics
  - Polished SiC flat and spherical surfaces
  - Polished, Silicon coated SiC aspheric surfaces
  - Protected silver coatings
SiC Materials Advantages

- **Different forms of SiC suitable for different applications**
  - **Specific Stiffness of SiC (HP, RB, CVD)** 70% - 90% of Beryllium
  - **Thermal Stability of SiC** 3x - 1.5x better than ULE glass
  - **Hot Pressed SiC** suitable for simple “slab”-type geometries
  - **Reaction Bonded SiC** produces rib-supported, lightweighted mirrors without any costly ceramic machining steps
ALI SiC Description

- **Hot Pressed SiC Optics**
  - *HP SiC has flight heritage through NMP DS-1 MICAS payload*
  - *Spherical and flat surfaces polished directly in SiC material*
  - *Aspheric surfaces produced in a silicon cladding over SiC mirror substrate*
  - *Moderate mirror lightweighting*
  - *Denton protected silver on all optics*

- **Invar 36 Metering Structure - Optical Bench**
  - *Invar selected to avoid brittle damage risks associated with conventional SiC materials*
  - *Composite SiC technology not deemed sufficiently mature*
  - *Aggressively lightweighted Invar structure provides structural stability and good CTE match to SiC optics*
    - *MIT/LL machine shop responsible for bench fabrication*
EO-1 Technology Program

- Technology program funded by NASA, augmented with SSG internal R&D efforts

- Three main objectives
  - Demonstrate bare SiC (flat), and silicon coated SiC (aspheric) optics with finish/scatter suitable for future ALI-like missions
  - Better quantify the effects of Denton silver coating on SiC optics scatter performance
  - Incorporate current state-of-the-technology SiC materials into the technology program (RB SiC mirror substrates)

- A number of witness samples and small aspheric optics produced in order to facilitate coating and polishing process optimization
  - Results of these process optimizations applied to the spare ALI primary mirror in order to demonstrate this improved result on a representative, flight-like mirror
Process Optimization Samples

- Numerous process optimization samples produced
  - RB SiC flats
    - 2” diameter
  - Silicon coated RB SiC Aspheres
    - Convex hyperboloid (3” diameter)
    - Concave ellipsoid (4” diameter), rib supported
  - Spare ALI Primary Mirror

- Data collected
  - Surface figure
  - Surface roughness (before and after Denton Silver)
  - BRDF (before and after Denton Silver)
**RB SiC Flat Sample Results**

**Surface Figure - Finish**

<table>
<thead>
<tr>
<th>Surface Roughness (prior to Denton coating)</th>
<th>Sample #1</th>
<th>Sample #2</th>
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<tbody>
<tr>
<td>Surface Figure</td>
<td>0.016 λ RMS (@ 0.6 µm)</td>
<td>0.016 λ RMS (@ 0.6 µm)</td>
</tr>
<tr>
<td>Surface Roughness (after Denton coating)</td>
<td>7.18 Angstroms RMS</td>
<td>8.14 Angstroms RMS</td>
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**Surface Scatter - BRDF**

- **RB SiC samples shows dramatic improvement in scatter compared to ALI flight optics meeting EO-1 ALI specifications**
Silicon Coated SiC Asphere Sample Results

- **Surface Figure - Finish**

  - **Si coated SiC Asphere BRDF Data**
    - **Surface Scatter - BRDF**
      - **Spare ALI Primary Mirror surface figure**
      - 0.035 λ RMS
      - 0.294 λ Pk-valley
      - **Surface Figure - Finish**
        - **Cv x Hyper**
          - 0.035 λ RMS
          - 0.035 λ RMS
          - 0.035 λ RMS
          - 0.035 λ RMS
        - **Cv x Ellips**
          - 0.035 λ RMS
          - 0.035 λ RMS
          - 0.035 λ RMS
          - 0.035 λ RMS
        - **Surface Roughness (prior to Denton coating)**
          - 27.0 Angstroms RMS
          - 10 Angstroms RMS
          - 27.0 Angstroms RMS
          - 10 Angstroms RMS
        - **Surface Roughness (after Denton coating)**
          - 28.6 Angstroms RMS
          - TBD
          - TBD
          - TBD
      - **EO -1 Tech Program Asphere**
      - **EO -1 Mirror Goal**
      - **ALIM1**
      - **ALIM2**
      - **SO -1 Mirror Goal**
      - **0.633 µm BRDF**
      - **Angle from specular (deg)**

- **Si coated SiC samples show improved scatter, all BRDF measurements (with the exception of one close angle data set from one test point) meet ALI specs**
Summary

- **ALI SiC flight instrument demonstrates excellent image quality, MTF, and distortion performance over a wide field of view**

- **SSG’s continuing SiC materials development allows new SiC materials to be applied to similar missions**
  - Significant cost savings
  - Significant weight savings
  - Improved material properties

- **EO-1 Technology Program has demonstrated RB SiC flats and silicon coated RB SiC aspheres which meet or exceed BRDF-stray light requirements associated with next generation ALI-like missions**
  - Stray light - scatter performance demonstrated on spare ALI primary mirror with excellent results