3D Printing Overview

- Focus lasers on a substrate
- Build object one layer at a time
- Most use synthetic polymers
- Art project able to build objects with Fresnel Lens and sand
Solar Sintering

- Developed by Takashi Nakamura and tested on Mauna Kea at second PISCES field test
- Able to sinter lunar simulant at 1100 degrees Celsius
- Use fiber optics to guide collected solar energy
- Able to achieve average output of 657 W (32 percent efficient)
- Array weighed 1400 pounds
Solar Sintering
A Solar 3D printer for the Moon

• Important for establishing permanent Lunar settlement
• 3D solar printer can make precision objects without transportation costs
• Uses in-situ resources found on the Lunar surface
Requirements from for PILOT concept

- 2 - 2 meter Primary and 0.5 meter Secondary mirror in Cassegrain configuration
- 169 - 2 mm diameter fused silica cores
- Fiber Acceptance Angle - 14.5 degrees
- Overall Reflectivity - 95 percent
- Total Focused Power - 7.272 kW
- Total System Weight - 34.16 kg
Requirements for Project

- Primary Mirror Diameter - 1 meters
- Telescope f/# - f/2
- Mirror Reflectance - Greater than 95% from 400nm to 1000nm
- Mirror Materials: ULE
- Primary Mirror Mount: Must be able to achieve 100 nm rms from surface irregularities, self-weight deflection and mound induced deflection
- Mirror Mount and fiber support Material: Low CTE Graphite Epoxy
- Operational Position Stability: less than 1 arminute tip/tilt, and 50 µm decenter
- Angle of incidence at Fiber Optic interface: 14.5 degrees
- Beam Width at Fiber Optic interface: less than 350 µm
- Focal plane spot size at printing surface: 50 µm
Project Operational and Survival Requirements

Operational Environment
• Temperature: -100°C to 100°C
• Gravity: 1/6 Earth gravity

Survival:
• Shock: 40G
• Temperature: -100°C to 100°C

Limitations
• Weight limitations: Less than 150 kg
System Design
Total System Mass: 122 kg
System Design

- Use a six point mirror mount to support mirror back
- Use a four point whiffle tree mirror mount to support mirror at horizon
- Mirror design
  - Hyperbolic Primary with conic constant of \(-1.005\)
  - Curved back to reduce weight
  - 1 meter diameter, 25.4 mm thick ULE
  - 4 meter Radius of Curvature
  - Silver Coating
  - Mirror Mass – 45 kg
System Design

- Unidirectional low CTE CFRP (CTE of 0.57 ppm/K) for all parts except swivel leveling mounts
- Zenith Mirror Supports
  - Height - 60 mm
  - Width - 100 mm
  - Length - 631.43 mm
  - Spaced at 120 degrees
- Fiber support rods
  - Height and Width - 50 mm
  - Length - 2144.38 mm
- Horizon Mirror Supports
  - Height - 100 mm
  - Width - 100 mm
  - Length - 721.69 mm
- Mass
  - Mount - 67 kg
  - Back Rocker - 3.87 kg
  - Base Rockers - 4.8 kg
  - Swivel Leveling Mounts - 1.38 kg
System Design

• Titanium swivel leveling mounts
• Fiber material – Fused pure silica with a fluorine doped silica cladding
  – 400 micron diameter fiber with gold coating
• RTV 112 adhesive for bonding swivel leveling mounts to mirror
• Bond diameter of 50 mm and thickness of 0.5 mm
• Fiber interface – 25 mm diameter, through top of supports, made from Beryllium
• Fiber material – Fused pure silica with a fluorine doped silica cladding
## System Design

- **Printing Lens Specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Lens</th>
<th>Material</th>
<th>ROC1</th>
<th>ROC2</th>
<th>CT</th>
<th>Diameter</th>
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<tbody>
<tr>
<td></td>
<td>1A</td>
<td>BK7</td>
<td>25.488</td>
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<td>5.246</td>
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<td>1B</td>
<td>SF5</td>
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<td>-14.009</td>
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<td>BK7</td>
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<tr>
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<td>SF%</td>
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<td>-104.627</td>
<td>2</td>
<td>5.5</td>
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<table>
<thead>
<tr>
<th>Tolerances</th>
<th>Lens</th>
<th>Tip/Til</th>
<th>Decenter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lens 1</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Lens 2</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>
System Design

• Printing Lens Barrel
  – Material Titanium Ti-8Mn annealed
  – Fiber retainer made from Beryllium
  – Vents along the side for heat dissipation
  – Can be produced on a metal lathe
  – Adjustment Ring for focus adjustment
  – Stability rod maintains lens orientation during adjustment
  – Vent holes along the side for temperature stabilization
  – Barrel and Lens Mass - .085 kg
## System Performance - Mirror

<table>
<thead>
<tr>
<th>Contribution</th>
<th>RMS Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Surface Error</td>
<td>20 nm</td>
</tr>
<tr>
<td>Self-weight Deflection at Zenith</td>
<td>37.9 nm</td>
</tr>
<tr>
<td>Self-weight Deflection at Horizon</td>
<td>26.5 nm</td>
</tr>
<tr>
<td>Thermal Deflection</td>
<td>64 nm</td>
</tr>
<tr>
<td>Mount Induced Deflection</td>
<td>57 nm</td>
</tr>
<tr>
<td>RSS</td>
<td>99.42 nm</td>
</tr>
</tbody>
</table>

![Image of slope X, slope Y, slope magnitude, and surface maps for Mirror System Performance](image-url)
System Performance - Mirror

- Nominal spot size at focal point – 10 microns
- Encircled Energy > 90 % at 6 micron radius
- Beam Angle – 14 degrees
## System Performance – Mount Induced Deflection at Fiber interface

<table>
<thead>
<tr>
<th>Type of Deflection</th>
<th>Deflection RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount at Zenith</td>
<td>9.63E-06 mm</td>
</tr>
<tr>
<td>Mount at Horizon</td>
<td>0.0149 mm</td>
</tr>
<tr>
<td>Telescope weight at Horizon</td>
<td>0.00149 mm</td>
</tr>
<tr>
<td>Telescope weight at Zenith</td>
<td>0.000746 mm</td>
</tr>
<tr>
<td>Rocker Deflection</td>
<td>0.00135 mm</td>
</tr>
<tr>
<td>Horizontal Rocker</td>
<td>0.00169 mm</td>
</tr>
<tr>
<td>Thermal Deflection (Along Optical Axis)</td>
<td>0.111 mm</td>
</tr>
<tr>
<td>RSS - Decenter Deflection</td>
<td>0.0151 mm</td>
</tr>
<tr>
<td>RSS - Total Deflection of focal point</td>
<td>0.112 mm</td>
</tr>
</tbody>
</table>

Deflection along the focal plane is 111 microns, well within tolerances for the beam acceptance.

Able to maintain 1 arcminute tip/tilt and 50micron decenter.
System Performance - Transmission

- Using a silver coating performance between 400-1000 nm is optimal

Percent Reflectance

![Graph showing reflectance percentage over wavelengths from 250 to 2250 nm]
System Performance – Fiber Transmission

• Using a pure fused silica core/fluorine doped silica cladding will provide good performance
System Performance - Lenses

- Achromatic doublet lenses able to maintain spot size below 50 microns
- Broad Band AR coating provides average transmission > 99.5% from 400-1000 nm per surface
- Nominal Spot Size < 15 microns
- Encircled energy > 95% within 10 micron radius
- Lens tolerances are not too strict
  - Precision manufacturing tolerances
  - Element decenter and tilt tolerances greater than 0.05mm
System Performance – Focal Plane

![Diagram showing system performance metrics.](image-url)

- **Fraction of Enclosed Energy**
- **Radius From Centroid in μm**

**Geometric Encircled Energy**

- **5/2/2013**
- **Wavelength**: Polychromatic
- **Data has been scaled by diffraction limit.**
- **Surface**: Image

**IP3 Lenses.ZMX**

Configuration 1 of 1
# System Performance – Total transmission

<table>
<thead>
<tr>
<th>Surface</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>After Mirror</td>
<td>612.60 W</td>
</tr>
<tr>
<td>Entering Fiber</td>
<td>609.54 W</td>
</tr>
<tr>
<td>Exiting Fiber</td>
<td>597.35 W</td>
</tr>
<tr>
<td>Lens 1 Surface 1</td>
<td>594.36 W</td>
</tr>
<tr>
<td>Lens 1 Surface 2</td>
<td>591.39 W</td>
</tr>
<tr>
<td>Lens 2 Surface 1</td>
<td>588.43 W</td>
</tr>
<tr>
<td>Lens 2 Surface 2</td>
<td>585.49 W</td>
</tr>
<tr>
<td>Image Plane</td>
<td>585.49 W</td>
</tr>
</tbody>
</table>
System Performance - Survivability

- Stress of 250 kpa per bond under 40G shock is within the bond strength of 2.24 Mpa
- Applying preload force of 1.27 N on lens 1 and 1 N on lens 2 ensures survival from 40 G shock
- Temperature requirements are met for Mirror and mount through materials
- Lenses and lens barrel will be located inside an enclosure, so temperatures will not fluctuate
- Gold coated fiber optic able survive temperatures from -269 to 700 degrees Celsius
- Fiber interfaces made from Beryllium, for low CTE and high thermal conductivity
Materials and Cost

• Carbon Fiber – up to 250 $ per pound
  – Mount Weight 75 kg
  – Cost of material 41250 dollars plus cost of manufacture
• Swivel Leveling Mounts
  – Custom made from titanium
  – Cost of material ~100 dollars plus manufacture cost
• Corning ULE
  – No price disclosed
  – Mirror will probably be the most costly aspect
• Achromatic Lenses
  – Price quote would be needed from optical design companies
• Fiber
  – Price quote needed for 500m of Gold coated fiber
• Manufacturing will be the most costly aspect (except maybe transport)
References

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  • http://www.corning.com/docs/specialtymaterials/pisheets/ulebro91106.pdf
  • http://www.fiberguide.com/wp-content/uploads/2013/03/All_Silica_Fiber_0301131.pdf
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  • http://www.mcmaster.com/#swivel-leveling-mounts/=md6yhs
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• Introduction to Optical Engineering Notes (OPTI 521)
• Schott Optical Glass Data Sheet
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Thanks for Attending the Presentation

Any Questions?