Freeform Optical Design of Two Mirror Telescopes

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What is a Freeform?

• A freeform optical surface is a non-rotationally symmetric mirror or lens, typically with large departures from a best-fit spherical surface (µm or mm).

Rotationally Symmetric

Plane-symmetric Freeform

• New manufacturing and testing methods have enabled the production of these types of surfaces, but knowledge about the capabilities of freeform optical systems is still limited.
Why Use Freeform?

- **Freeform optics enable**
  - Smaller optical packages
  - Larger fields of view
  - Increased imaging performance

- **Benefits to NASA**
  - Less mass in an instrument
  - Improved science data collection
  - Expertise in an emerging field

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**Optical Surface Lifecycle**

- **Fabrication** example with small tool polishing
- **Metrology** example of a computer generated hologram (CGH)

http://www.osa-opn.org/home/articles/volume_19/issue_4/features/testing_aspheres/#.Vb-aL_IViko
Now that you are convinced that freeform optics are the coolest thing…

- This summer, an optical design study of 2 mirror freeform telescopes was completed
  - Provides optical designers with a benchmark
  - Demonstrates the capabilities of freeform

- Exploration of 2 primary design forms of 2-mirror freeform designs
  - Positive/Positive Mirror Tilts
  - Positive/Negative Mirror Tilts
This summer, an optical design study of 2 mirror freeform telescopes was completed

- Provides optical designers with a benchmark
- Demonstrates the capabilities of freeform

RS: Rotationally Symmetric
FF: Freeform
NT: Non-telecentric
FFOV: Full Field of View
T: Telecentric
PN: Positive/Negative Tilt
PP: Positive/Positive Tilt

2 Mirror Design Space | FOV Aspect Ratio of 4:1

F/\#  
\[0, 1, 2, 3, 4, 5, 6, 7\]

FFOV X (deg)  
\[0, 5, 10, 15, 20, 25, 30, 35, 40, 45\]

RS NT 20 \( \mu \text{m} \) Spot
FF PP T 20 \( \mu \text{m} \) Spot
FF PN T 20 \( \mu \text{m} \) Spot
FF PN NT 20 \( \mu \text{m} \) Spot
FF PP NT 20 \( \mu \text{m} \) Spot
Freeform Optical Design

- Tradeoff between extremely large FOV and volume in the FF PN NT design
- Freeform designs generally have smaller volumes and achieve better performance than their rotationally symmetric counterparts

**Volume vs F/#**

![Graph showing volume vs F/# for different freeform optical designs.](image)

**2 Mirror Design Space | FOV Aspect Ratio of 4:1**

![Graph showing 2 mirror design space with different FOV aspect ratios.](image)
Design Tools

- **OSLO Sliders** used to generate starting points for different design forms
  - Solves imaging equations to 2\textsuperscript{nd} order

- **Code V optimizer** used to optimize specific design forms with given constraints
  - F/number, telecentricity (optional)
  - Ray Clearance
• Two unique design forms in the same geometry
• Mirror Powers in Design A has a positive powered primary, whereas Design B has negative powered primary
  – Design forms discovered in OSLO
  – Code V optimizer was unable to jump between these design forms
• To facilitate the analysis of the freeform telescopes, custom design tool needed to be developed
  – Real ray based F/# calculation
  – Real chief ray telecentricity
  – Rectangular enclosed volume

Design Tools

<table>
<thead>
<tr>
<th>F/#</th>
<th>Telecentricity</th>
<th>Volume</th>
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</thead>
<tbody>
<tr>
<td>Cone Angle</td>
<td>Field 1</td>
<td>Field 2</td>
</tr>
<tr>
<td>Detector</td>
<td>Angular Deviation</td>
<td>Freeform Mirror</td>
</tr>
<tr>
<td>Field 1</td>
<td>Field 2</td>
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</tr>
<tr>
<td>Scale: 0.43</td>
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<td>ILT 30-Jul-15</td>
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<tr>
<td>492.2nm</td>
<td>58.14 MM</td>
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</tbody>
</table>

10:09:25
Additional Analysis Tools

- **Use of Matlab to Code V Toolkit:**
  - Measure ground sample distance per pixel across sensor
  - Number of pixels required for the detector, factoring in distortion
Design Survey Recap

2 Mirror Design Space | FOV Aspect Ratio of 4:1

- RS NT 20 μm Spot
- FF PP T 20 μm Spot
- FF PN T 20 μm Spot
- FF PN NT 20 μm Spot
- FF PP NT 20 μm Spot

Points A and B on the graph represent different configurations within the design space.
Case Study

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

- Package volume is the driving constraint
- Prism spectrometer
- Flying in low Earth orbit (LEO)

Initial Design
- 9 total mirrors (3 TMAs linked)
- Volume \( \approx 0.28 \times 0.85 \times 1.3 \) m
- RMS Spot Diameter < 60 \( \mu \)m

- Does not meet packaging requirements
- Freeform is able to reduce the volume significantly

Volume reduction of 97%

(Designs are on same scale)
Case Study

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

- **Freeform Design**
  - 6 mirrors in total (3 two mirror freeform telescopes linked)
  - “Figure 4” design form
  - Volume ≈ 0.08 x 0.33 x 0.33 m
  - RMS Spot Diameter < 35 µm

Volume reduction of 97% from rotationally symmetric design
Case Study

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

- Departure from a best fit sphere (BFS) describes how “freeform” the mirrors are
  - Also influences manufacturability and metrology of the surfaces
- M6 has the largest departure from a sphere, approximately 1 mm PV

<table>
<thead>
<tr>
<th>Surface Sag (mm)</th>
<th>Surface Departure (mm)</th>
<th>Surface Sag (mm)</th>
<th>Surface Departure (mm)</th>
</tr>
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<tbody>
<tr>
<td>M1</td>
<td></td>
<td></td>
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<tr>
<td>M2</td>
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<tr>
<td>M6</td>
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</tbody>
</table>
Case Study: Alternate Design

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

• Alternate Freeform Design
  – 6 powered mirrors in total (3 two mirror freeform telescopes linked)
  – “Figure Z” design form
  – Volume ≈ 0.16 x 0.69 x 0.64 m
  – RMS Spot Diameter < 33 µm

Volume reduction of 76% from rotationally symmetric design
Case Study: Comparison

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

- **Freeform Design: “Figure 4”**
  - Volume ≈ 0.08 x 0.33 x 0.33 m
  - RMS Spot Diameter < 35 µm
  - 97% Volume Reduction

- **Freeform Design: “Figure Z”**
  - Volume ≈ 0.16 x 0.69 x 0.64 m
  - RMS Spot Diameter < 33 µm
  - 76% Volume Reduction

\[ \text{75 mm} \]
Conclusions and Future Work

- Freeform optics have the capability to improve optical performance while maintaining a compact package size.
- Expanding the design survey to include three mirror freeform telescopes
  - Preliminary designs have been generated

Three mirrors span a larger design space, but also offer greater benefits in performance.