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).

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
Freeform Optical Design

- 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
• 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
Design Tools

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

- **Code V optimizer** used to optimize specific design forms with given constraints
  - F/number, telecentricity (optional)
  - Ray Clearance
Design Tools

- 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
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

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**Graph 1:**
- **Title:** Ground Distance per pixel vs Radial Image Position (pixels)
- **X-axis:** Radial Image Height (Pixels)
- **Y-axis:** Ground Sample Distance (km)

**Graph 2:**
- **Title:** Image Height (pixels) vs Field Angle
- **X-axis:** Field Angle (degrees)
- **Y-axis:** Image Height (Pixels)
- **Legend:**
  - 2130 nm
  - 910 nm
  - 412 nm
Design Survey Recap

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

- 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

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 ≈ 0.28 x 0.85 x 1.3 m
- RMS Spot Diameter < 60 µm

- 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 $\approx 0.08 \times 0.33 \times 0.33$ m
  - RMS Spot Diameter $< 35 \, \mu$m

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>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Surface Sag (mm) PV=0.54248</td>
</tr>
<tr>
<td>M2</td>
<td>Surface Sag (mm) PV=3.3628</td>
</tr>
<tr>
<td>M3</td>
<td>Surface Sag (mm) PV=2.1073</td>
</tr>
<tr>
<td>M4</td>
<td>Surface Sag (mm) PV=2.3194</td>
</tr>
<tr>
<td>M5</td>
<td>Surface Sag (mm) PV=1.3123</td>
</tr>
<tr>
<td>M6</td>
<td>Surface Sag (mm) PV=1.3123</td>
</tr>
</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
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.