Freeform Optical Design of Two Mirror Telescopes

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What is a Freeform?

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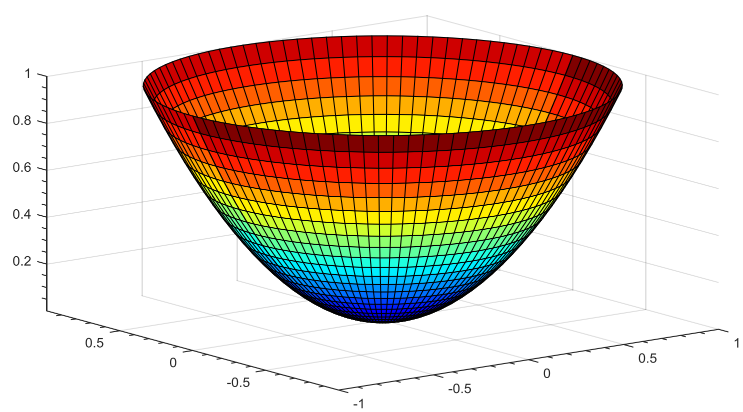
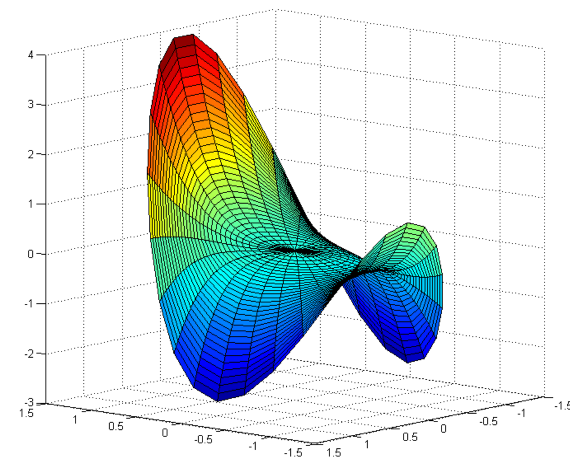
- **A freeform optical surface is a non-rotationally symmetric mirror or lens, typically with large departures from a best-fit spherical surface (µm or mm).**



Rotationally Symmetric



Plane-symmetric Freeform

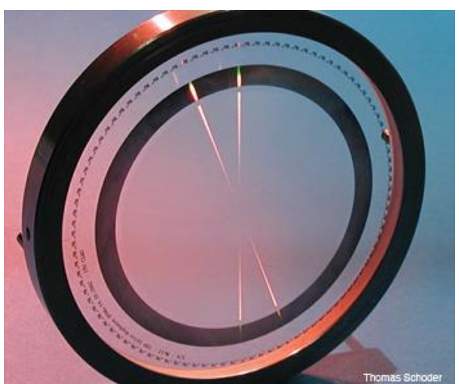
- **New manufacturing and testing methods have enabled the production of these types of surfaces, but knowledge about the capabilities of freeform optical systems is still limited.**

Why Use Freeform?

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

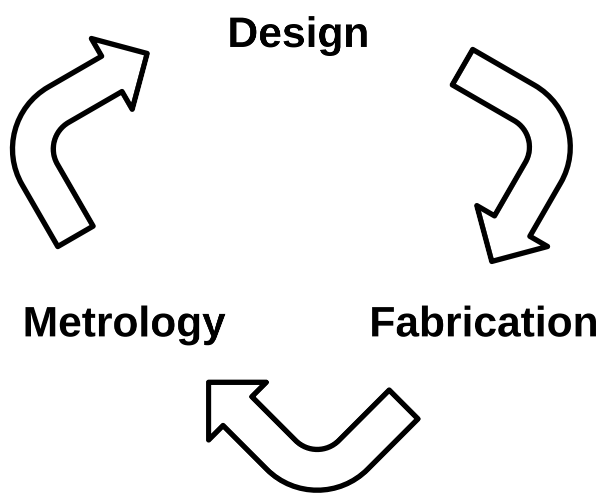
- **Benefits to NASA**
  - Less mass in an instrument
  - Improved science data collection
  - Expertise in an emerging field

Fabrication example with small tool polishing



Metrology example of a computer generated hologram (CGH)

Optical Surface Lifecycle



Freeform Optical Design

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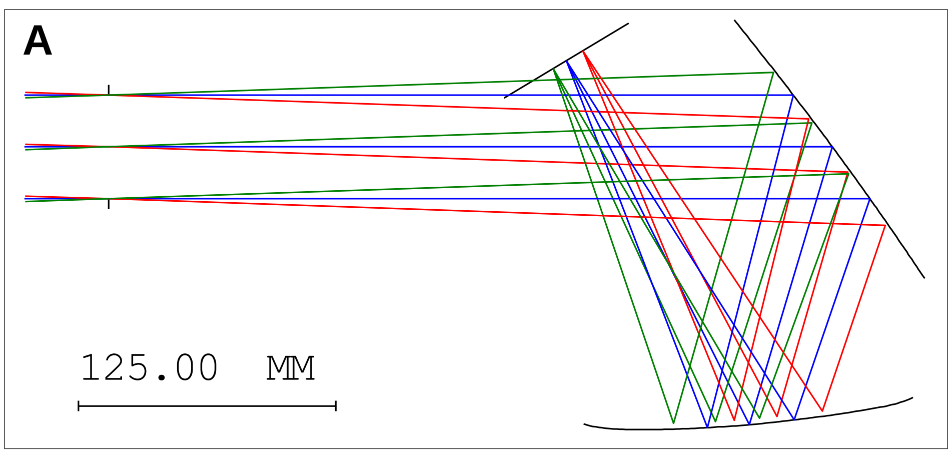
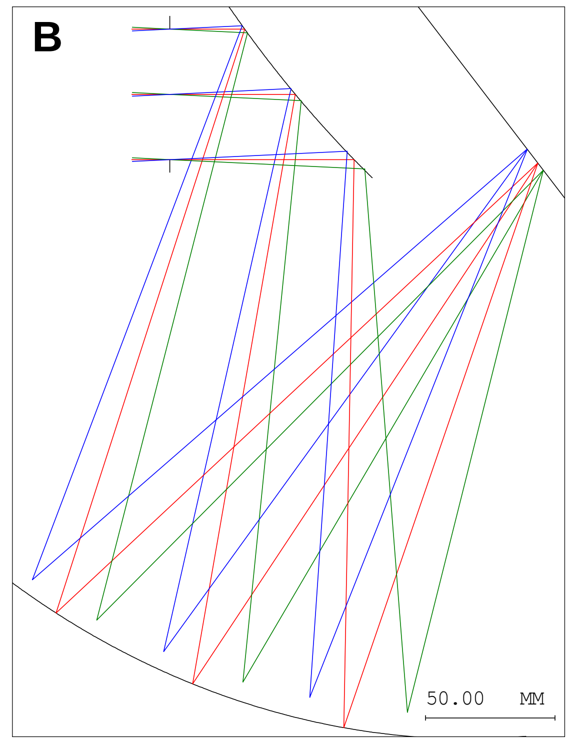
Now that you are convinced that freeform optics are the coolest thing…

- **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

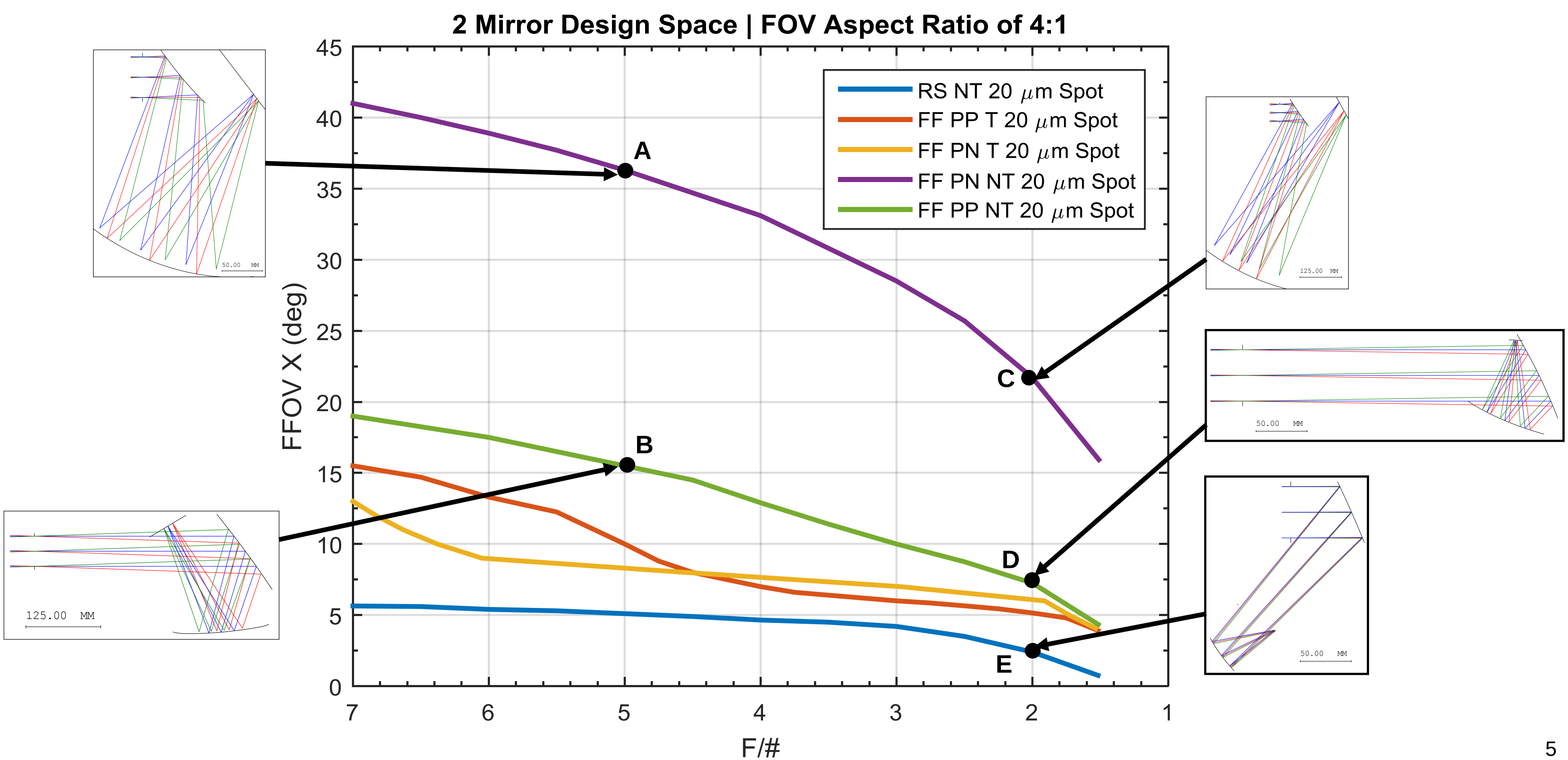




Freeform Optical Design

- **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



Freeform Optical Design

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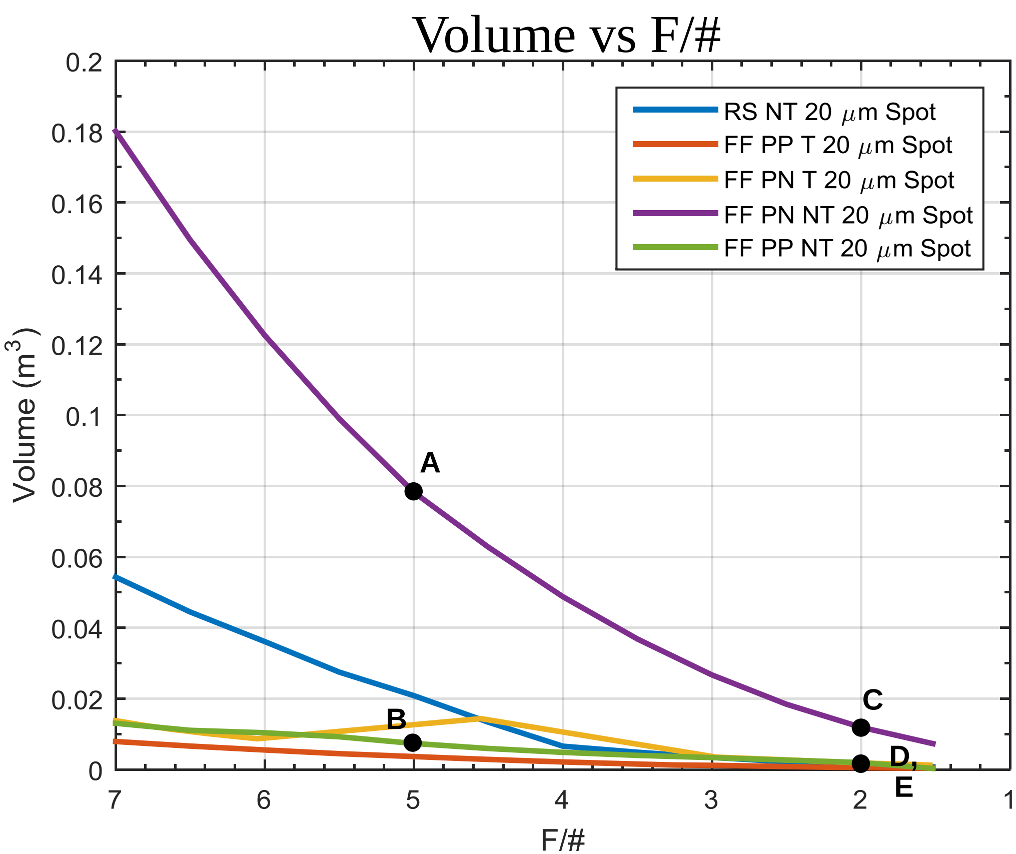
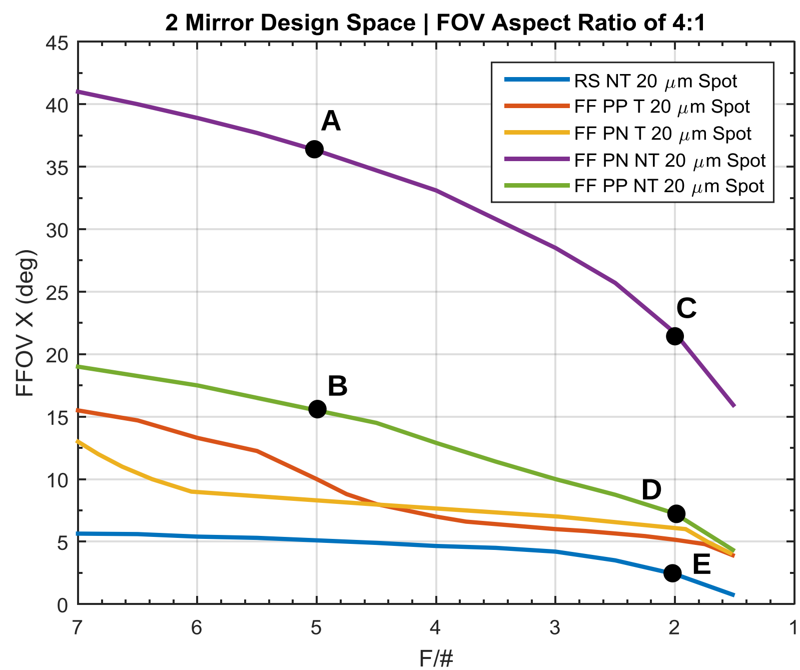
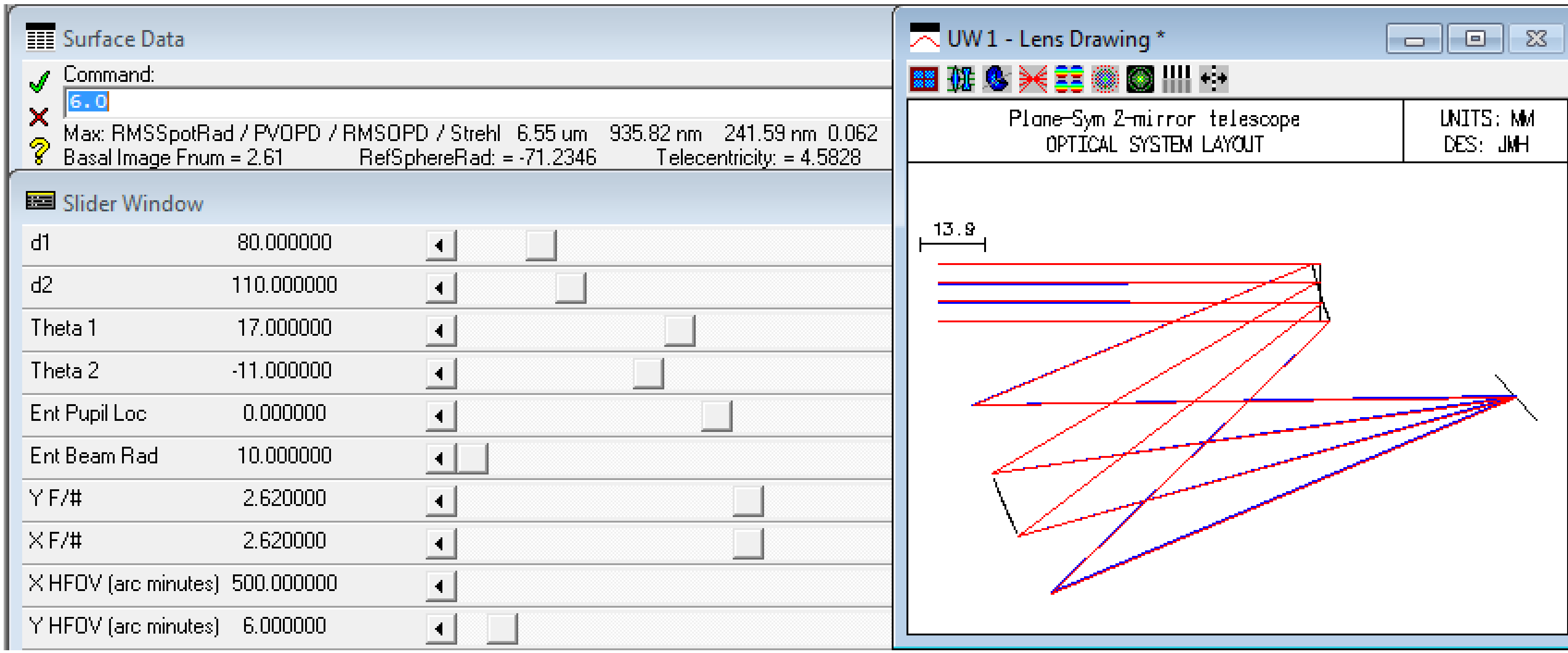
- **Tradeoff between extremely large FOV and volume in the FF PN NT design**
- **Freeform designs generally have smaller volumes and achieve better performance than their rotationally symmetric counterparts**





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

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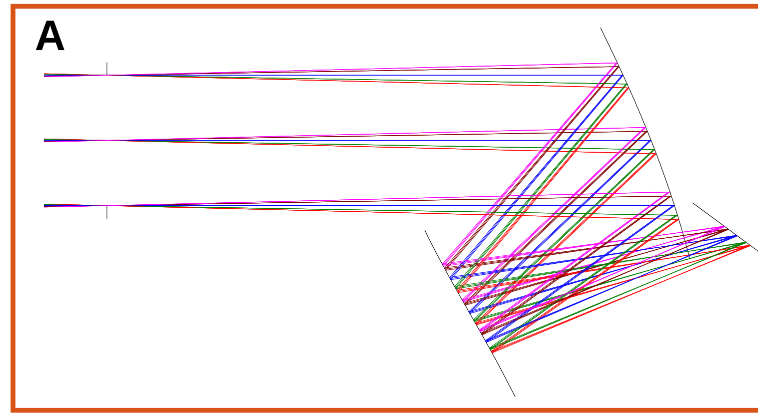
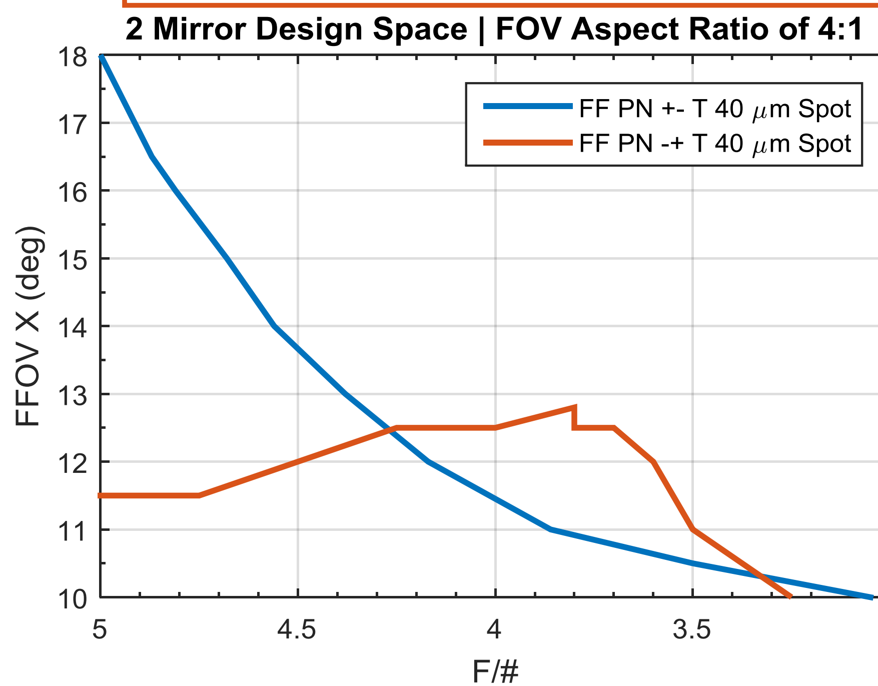
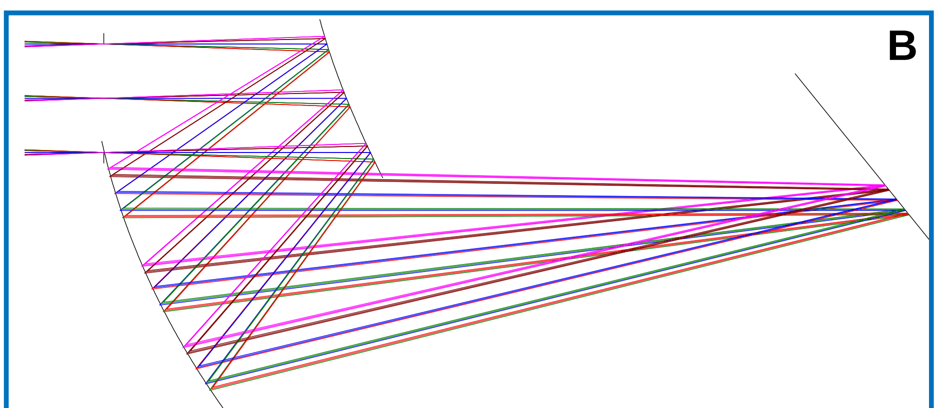
- **Two unique design forms in the same geometry**
- **Mirror Powers in Design A has a positive powered primary, whereas Design B has negative powered primary**
  - Design forms discovered in OSLO
  - Code V optimizer was unable to jump between these design forms



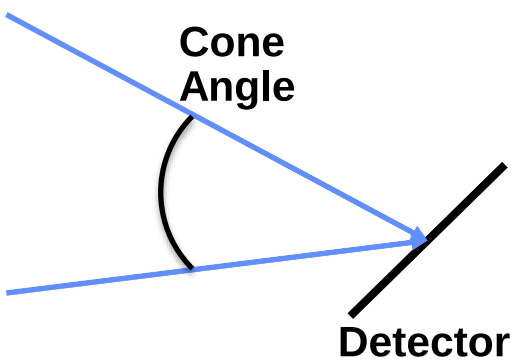




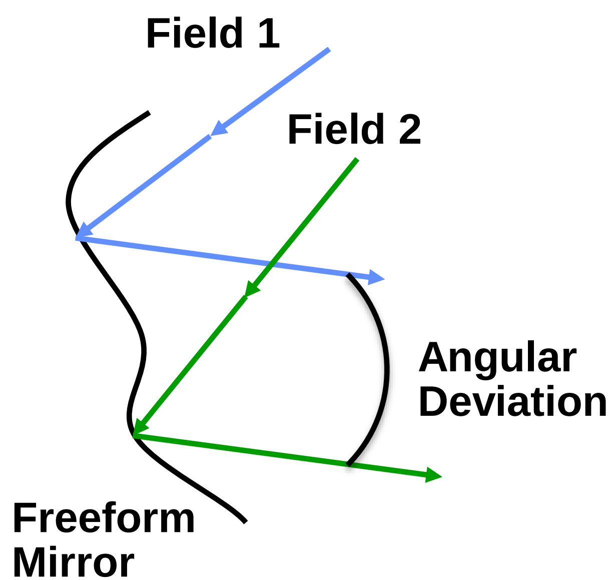
Design Tools

- **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

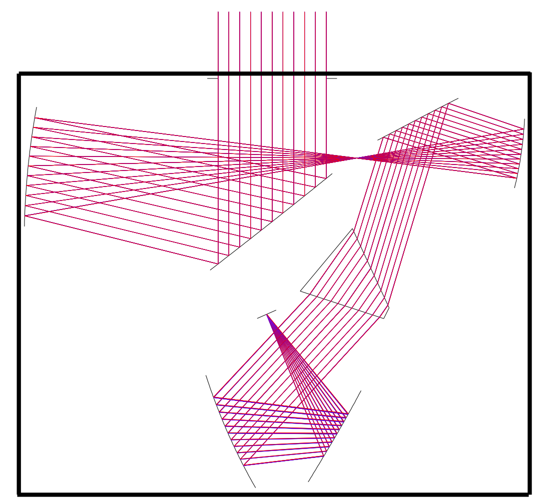
F/#



Telecentricity

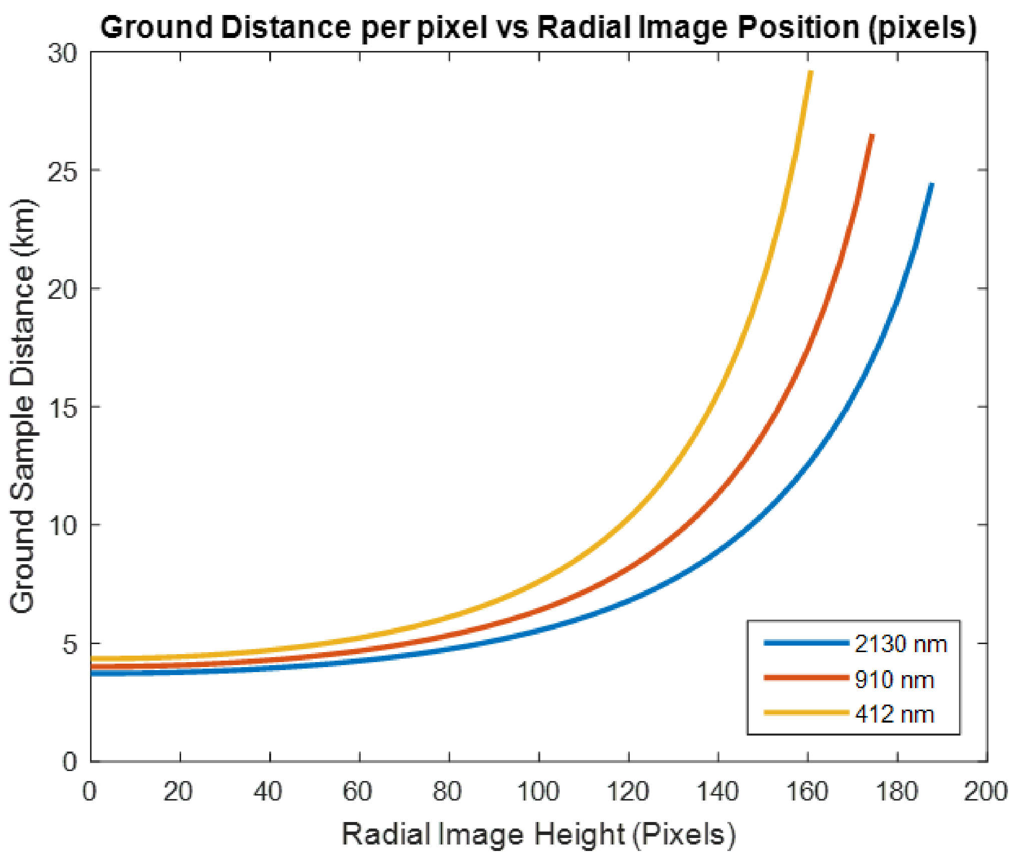


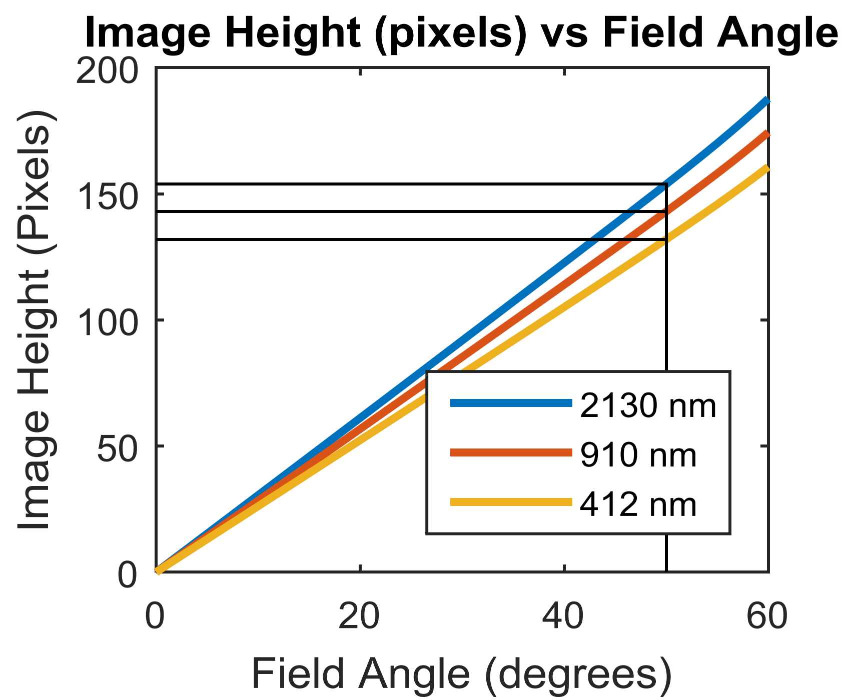
Volume



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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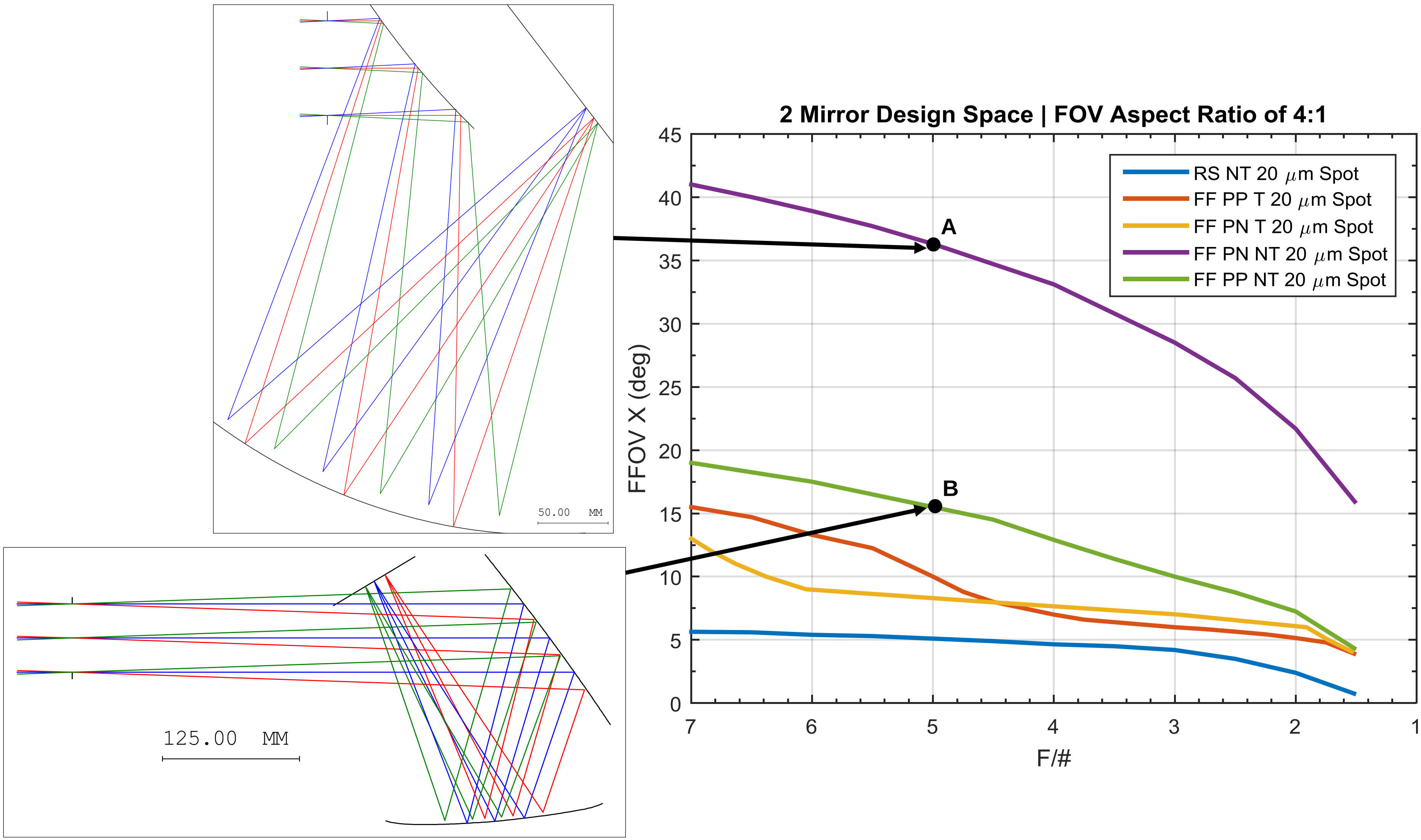
Design Survey Recap

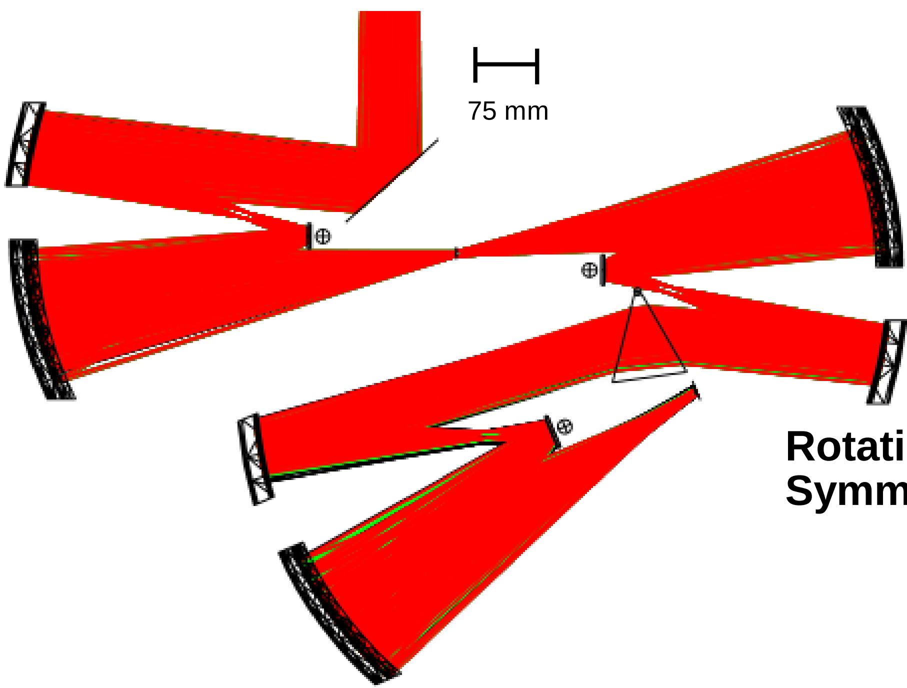


Case Study

Coastal Ocean Ecosystem Dynamics Imager (COEDI)

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

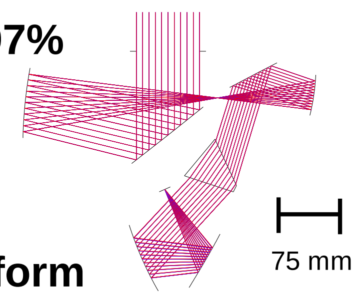
- **Initial Design**
  - 9 total mirrors (3 TMAs linked)
  - Volume ≈ 0.28 x 0.85 x 1.3 m
  - RMS Spot Diameter < 60 µm
- **Does not meet packaging requirements**
- **Freeform is able to reduce the volume significantly**



Rotationally Symmetric

Volume reduction of 97%

Freeform

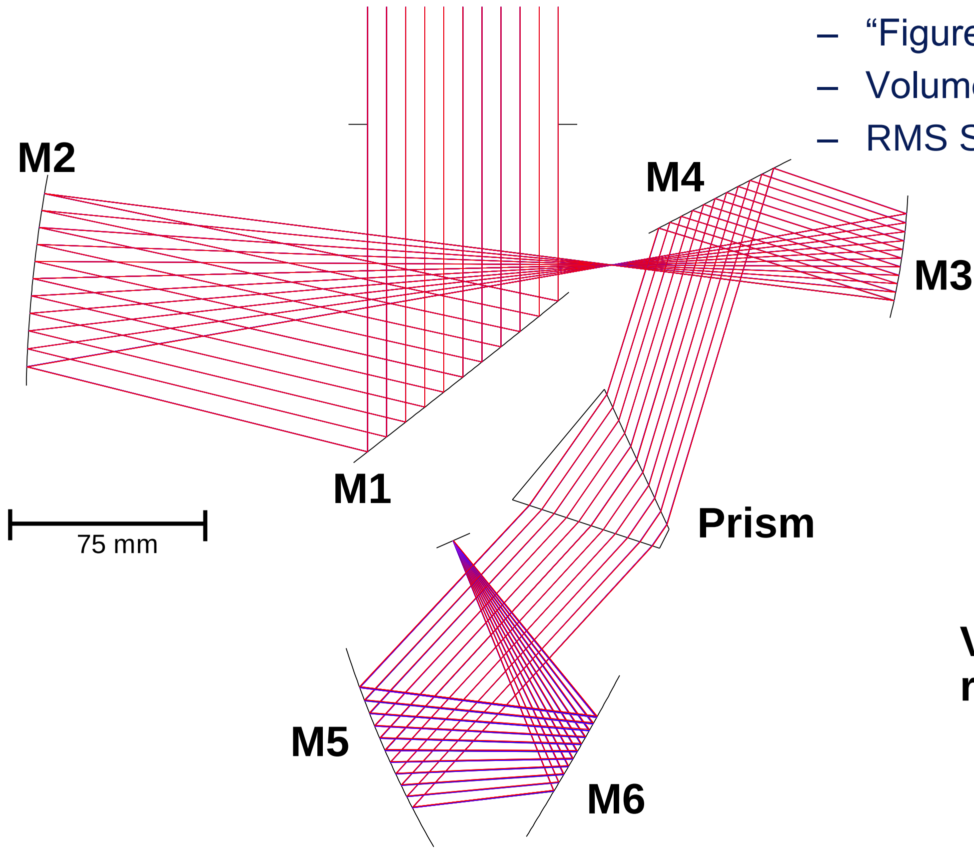


(Designs are on same scale)

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

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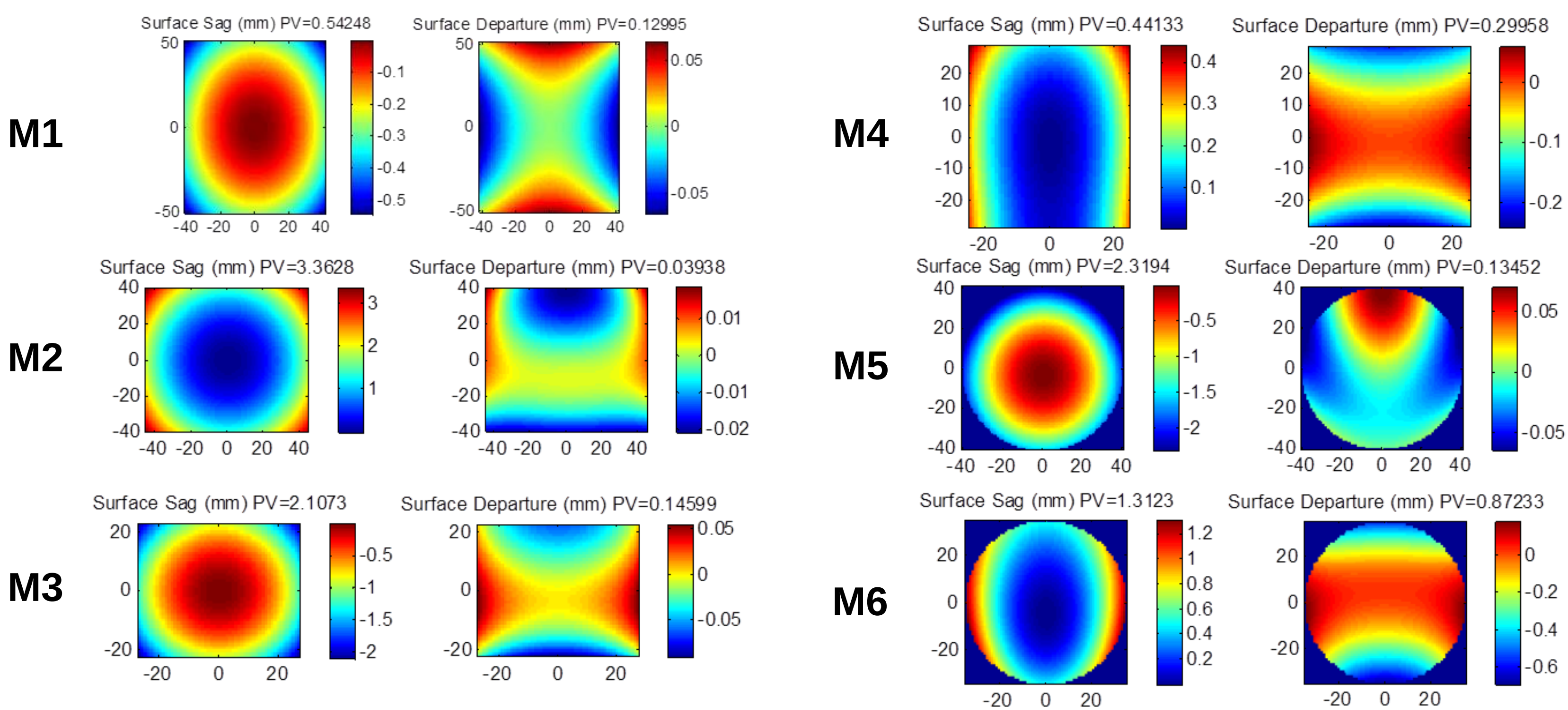
Coastal Ocean Ecosystem Dynamics Imager (COEDI)

- **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**

Surface Sag (mm) Surface Departure (mm) Surface Sag (mm) Surface Departure (mm)



Case Study: Alternate Design

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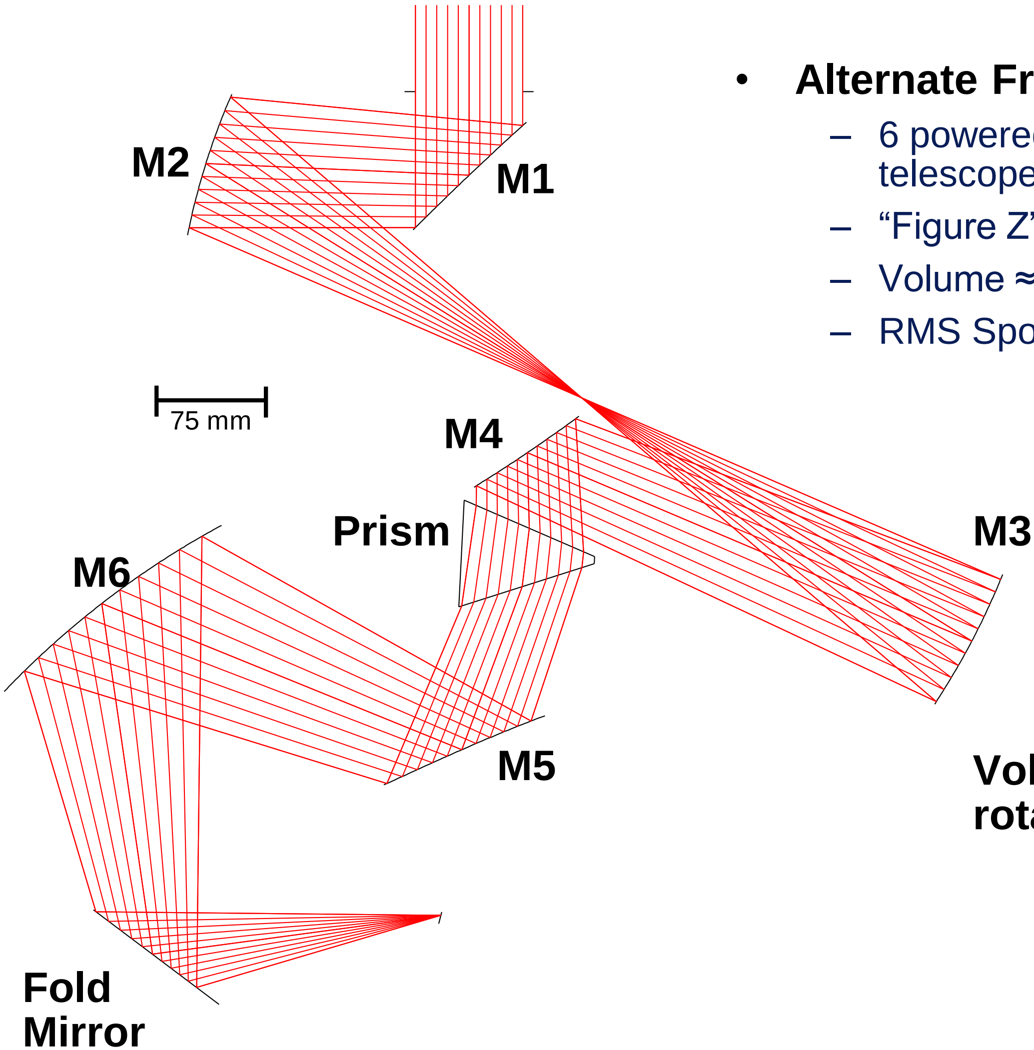
Coastal Ocean Ecosystem Dynamics Imager (COEDI)



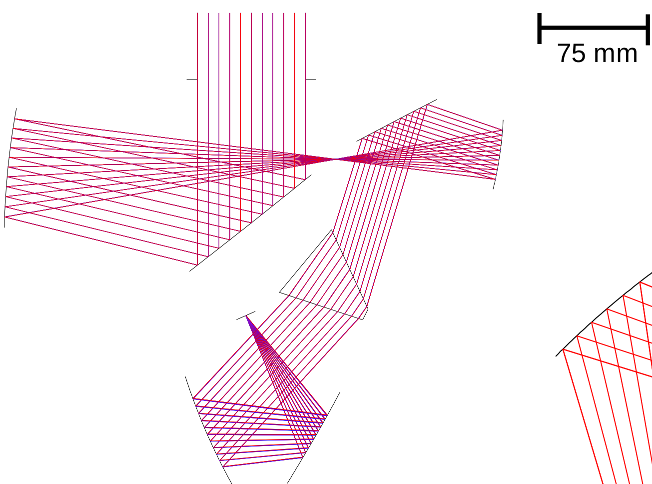
- **Alternate Freeform Design**
  - 6 powered mirrors in total (3 two mirror freeform telescopes linked)
  - "Figure Z" design form
  - Volume ≈ 0.16 x 0.69 x 0.64 m
  - RMS Spot Diameter < 33 µm

Volume reduction of 76% from rotationally symmetric design

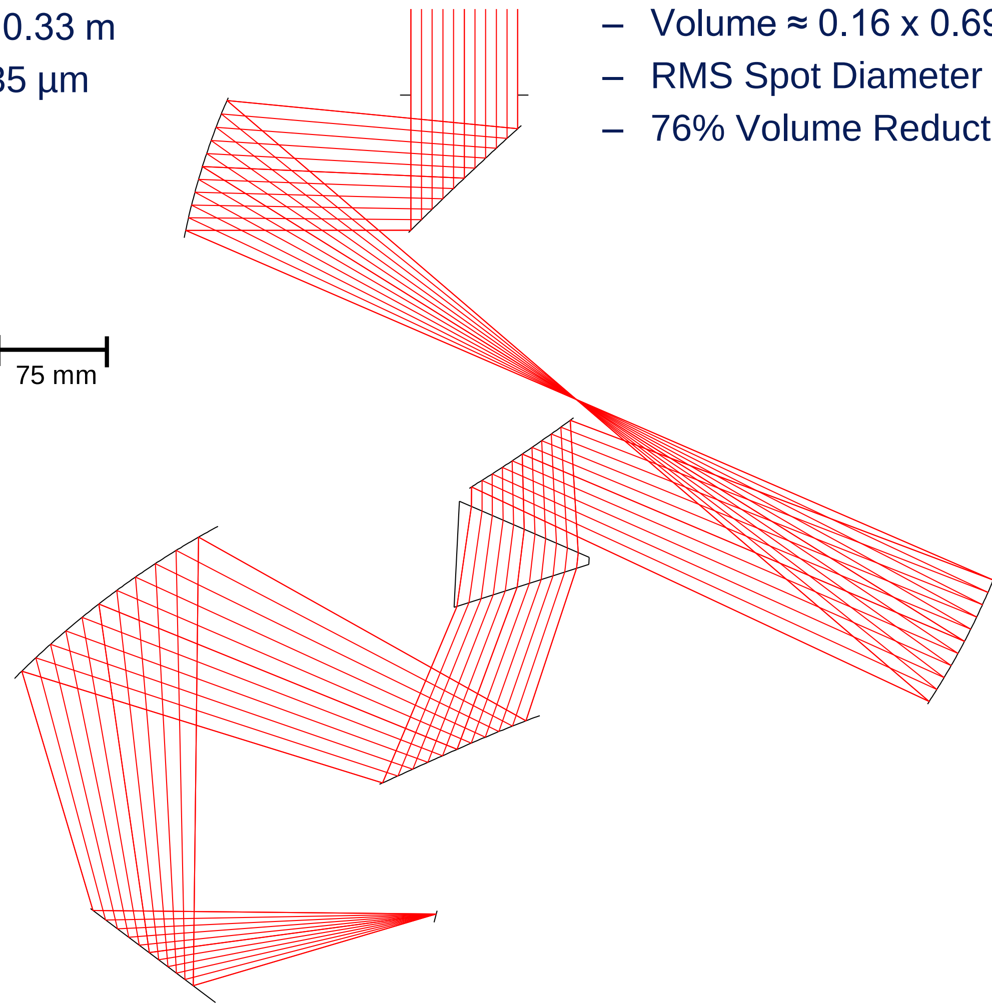
Case Study: Comparison

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

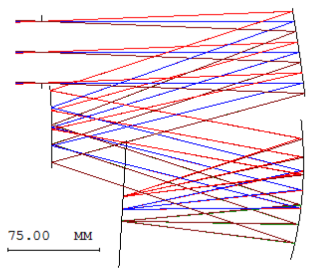


- **Freeform Design: "Figure Z"**
  - Volume ≈ 0.16 x 0.69 x 0.64 m
  - RMS Spot Diameter < 33 µm
  - 76% Volume Reduction

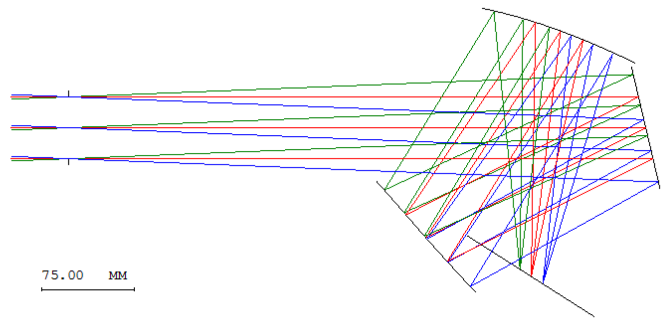


Conclusions and Future Work

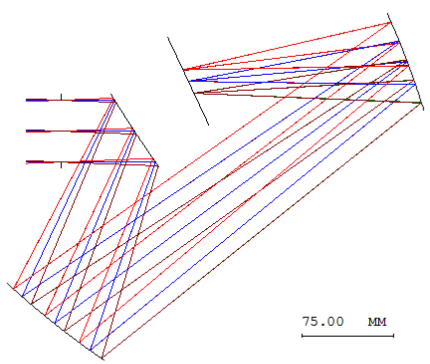
- **Freeform optics have the capability to improve optical performance while maintaining a compact package size.**
- **Expanding the design survey to include three mirror freeform telescopes**
  - Preliminary designs have been generated



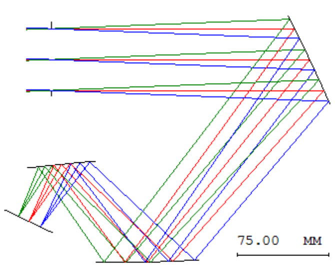
PNP



PPP



PNN



PPN

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