# Freeform Monolithic Multi-Surface Telescope Manufacturing

NASA Mirror Tech Days

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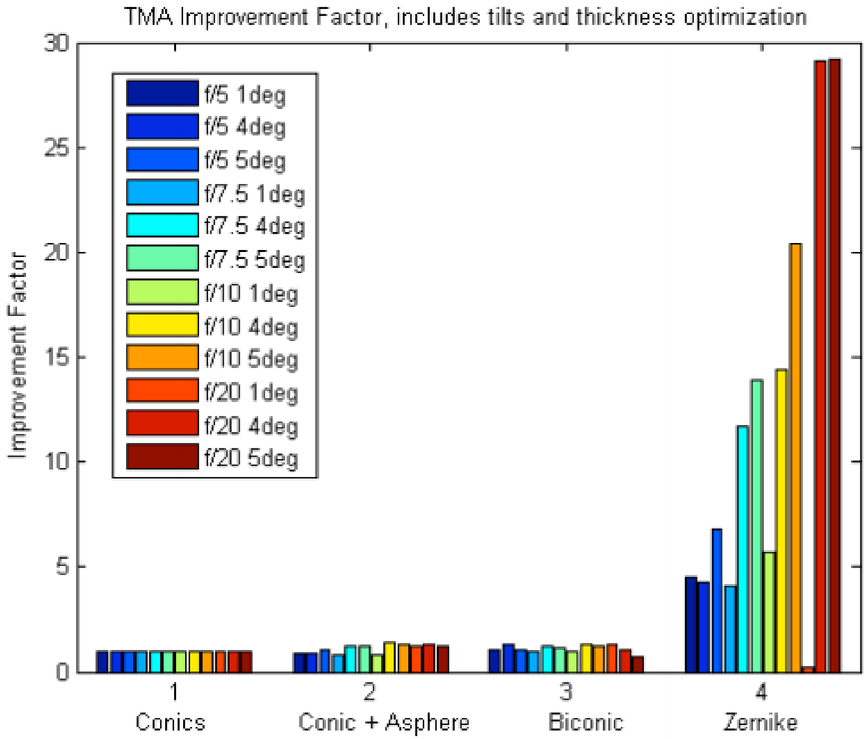
Prototype Optics In One Week

# Freeform Optics Overview

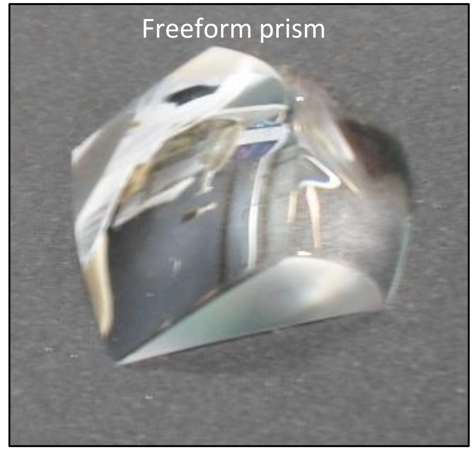
- Freeforms: Optics that do not contain an axis of rotational symmetry.
- Benefits Include:
  - Lighter weight
  - Reduced number of components (less complexity)
  - Reduced aberrations
- Common Freeform Designs
  - Off-axis asphere
  - Toroids, biconics
  - Polynomial functions
  - Anamorphic equations
  - Zernikes
  - Other equation based models
  - Solid models

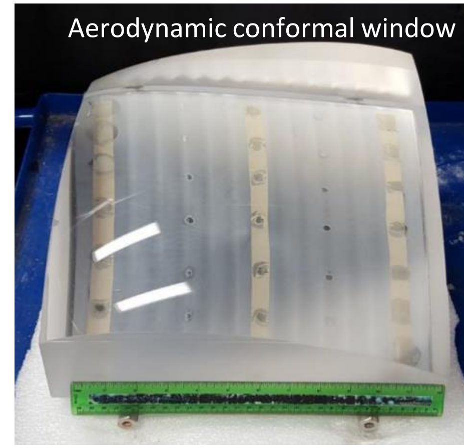



J M Howard and S Wolbach, "Improving the performance of three-mirror imaging systems with Freeform Optics," OSA Freeform Optics Conference, November 2013

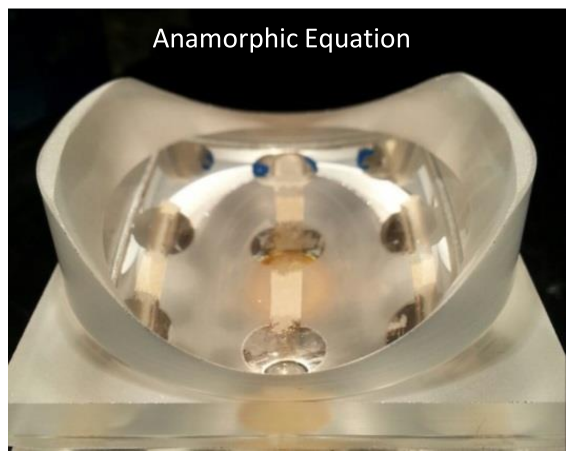
# Freeforms are now a product offering at Optimax

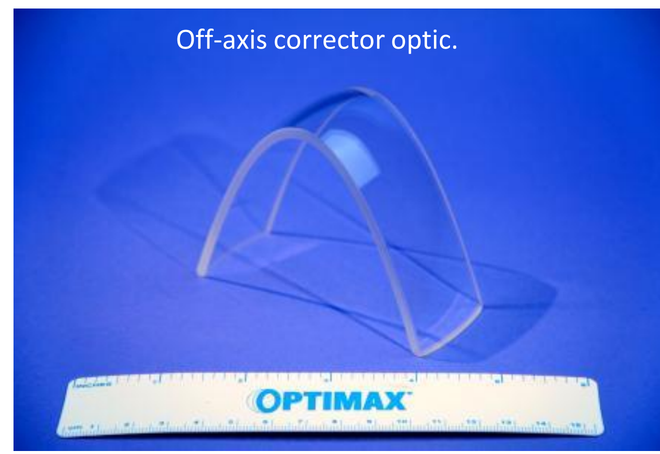
- As of January 2015, freeform optics are a standard product offering for Optimax
- Uses much of the SBIR developed technology
- Many different shapes and sizes
- Optics are current being used by customers in their optical systems


Freeform prism


Aerodynamic conformal window


Toroidal window


Anamorphic Equation



Off-axis corrector optic.

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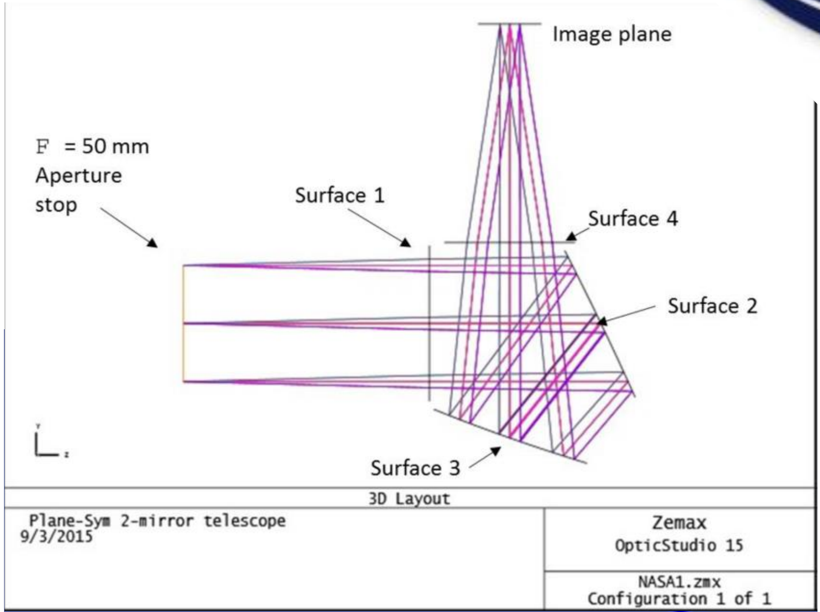
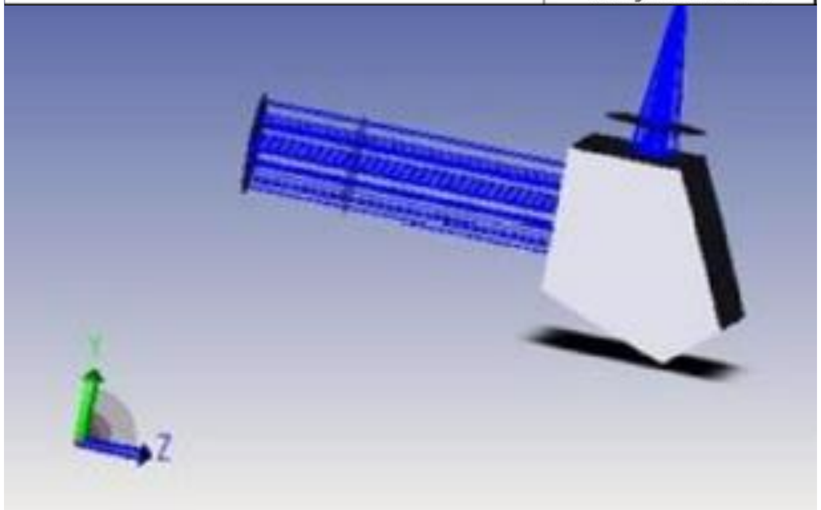
# Freeform Monolithic Telescope Concept.

- Multiple surfaces are polished onto a single block of glass.
- Overall volume is targeted for CubeSat applications.
- Freeforms are used to compensate off axis aberrations.
- Leads to a significant reduction in payload.
- Extremely rugged optomechanical design.
- Assembly tolerances are merged into the manufacturing tolerances

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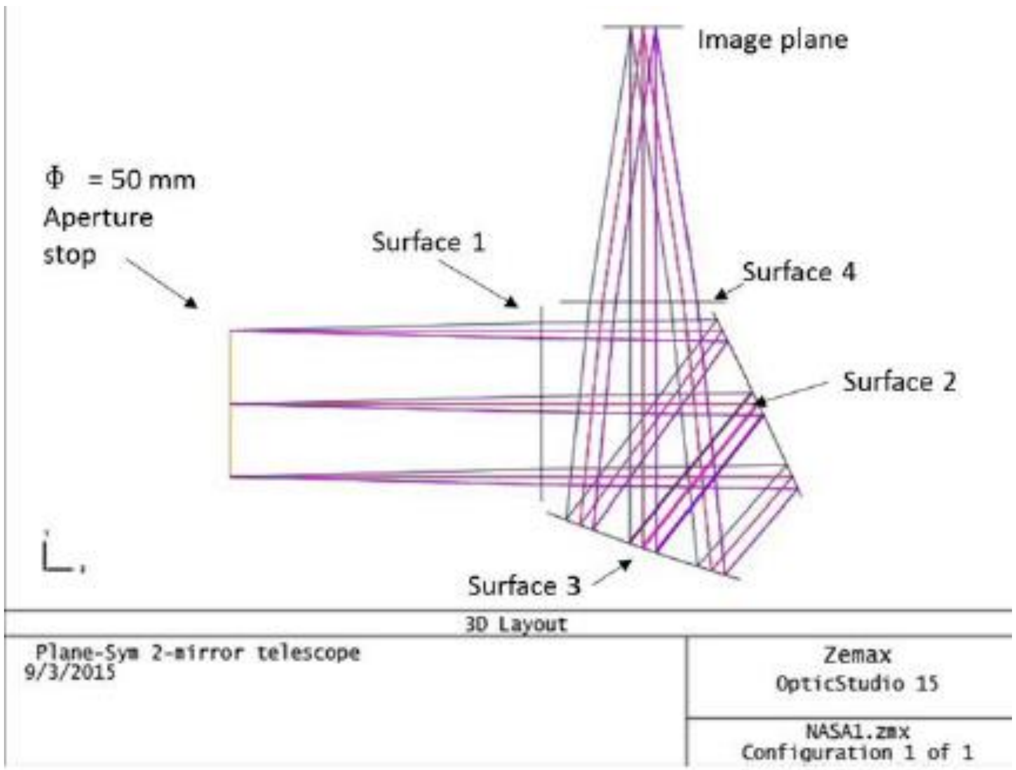
# Phase I Monolith Design

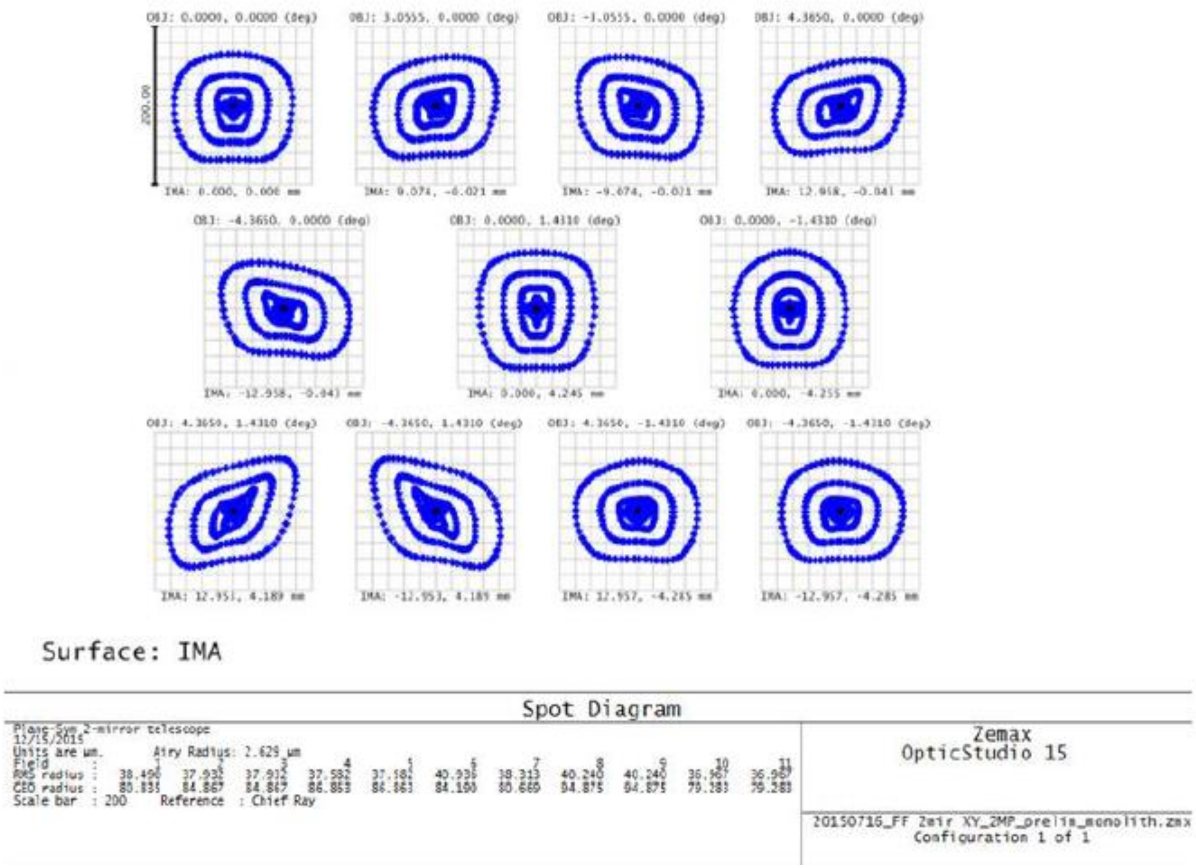
Both freeform surfaces are defined by xy polynomials of the same form:

$$f(x,y) = c_1x^2 + c_2y^2 + c_3x^2y + c_4\,y^3 + c_5\,x^4 + c_6\,x^2y^2 + c_7y^4$$




- Effective focal length of 183 mm
- f/3.4
- Foot print of a 1U CubeSat.

# Phase I Monolith Design




- Diffraction limited spot has a diameter of 2.6 µm.
- rms radius is approximately 35 µm.
- The given design is over an order of magnitude off of diffraction limit.
- Field of view was tested at:
  - ±1.431° along x-direction
  - ±4.365° along y-direction

# Standard Freeform Optical Manufacturing Process

General Optical Manufacturing Process

CNC Generate → Pre-Polish → Measurement → Deterministic Figure Correction → Smoothing

- Deterministic processing : sub-aperture tools
- Iterative Processing : metrology ↔ fine finishing tools
- Fabrication process for Phase I and Phase II monoliths are analogous.

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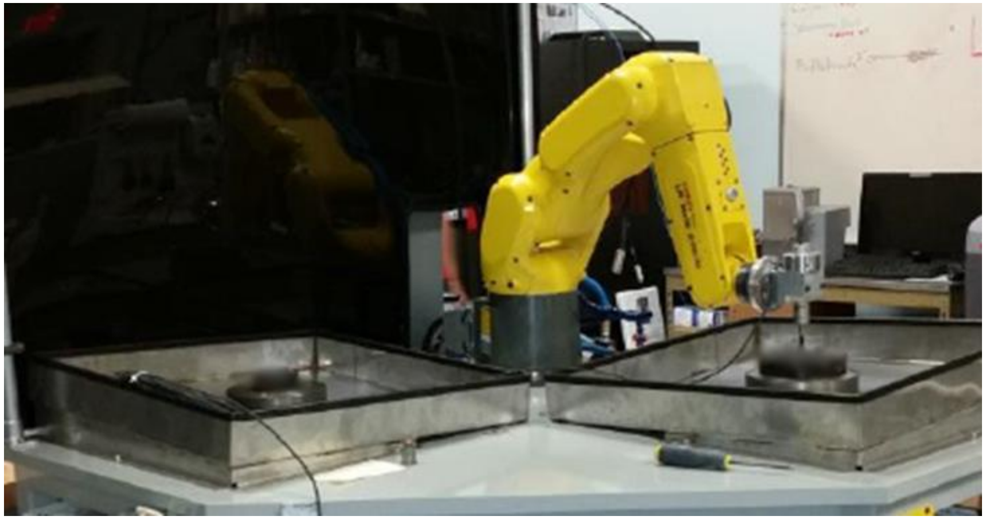
# Manufacturing Process: Monolith Generation

- Ultrasonic grinding with ball diamond tooling.
- Leaves a fine ground surface finish.
- After generation, the monolith had 5 µm of form error and 50 µm or positioning error (tilt)

# Manufacturing Process: Monolith Polishing



- Industrial robot with proprietary software and tooling.
- Robot provides flexibility with size shape and control.
- For Phase I monolith, polishing completed when the surface error was less than 5μm.

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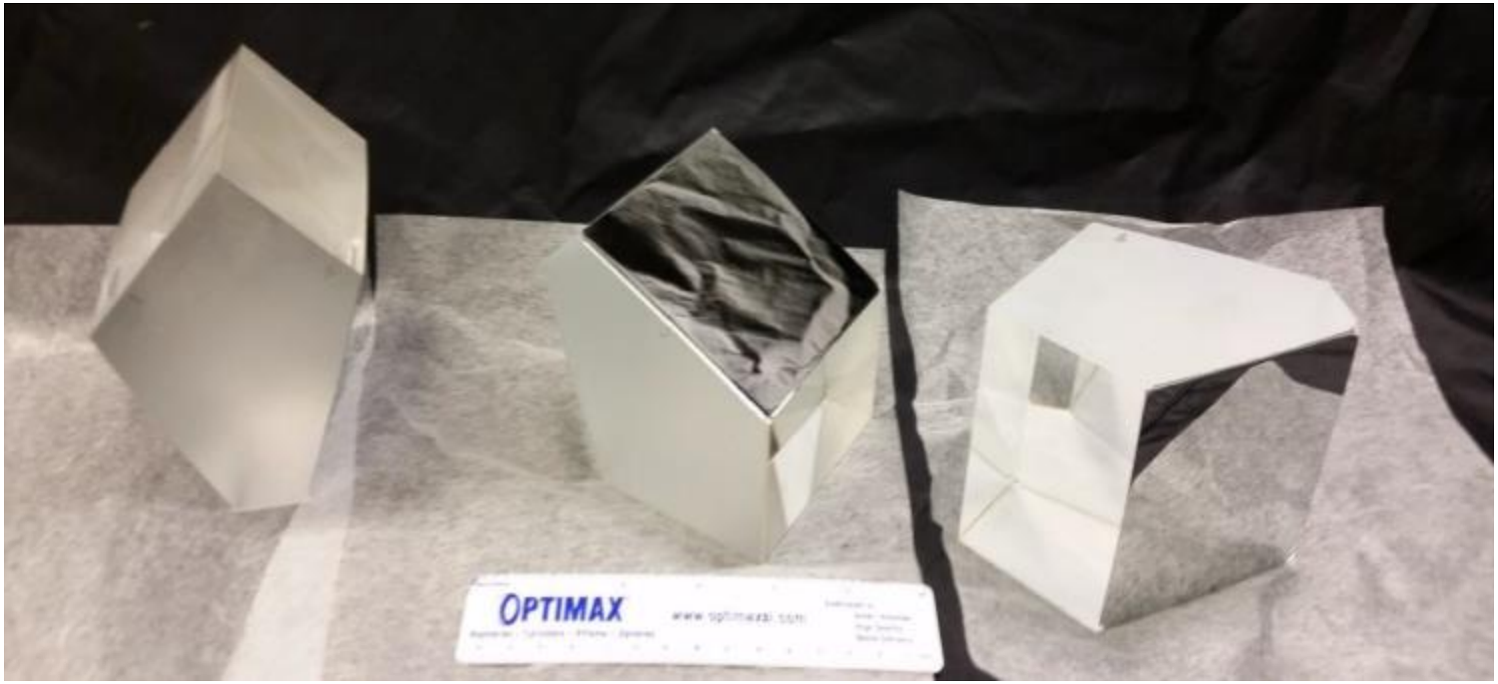
# Manufacturing Process: Metrology

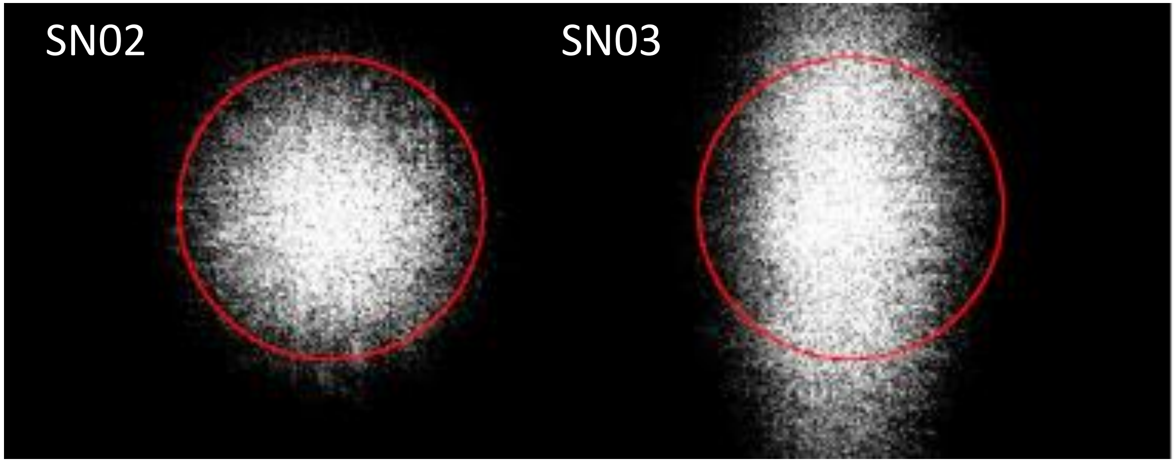
- All surfaces were verified using a Leitz coordinate measuring machine (CMM).
- Micron level positioning accuracy
- Higher accuracy would require CGH investment.
- Optimax is actively working to bridge metrology gap between CMM and CGH

# Manufacturing Process: Surface Coating



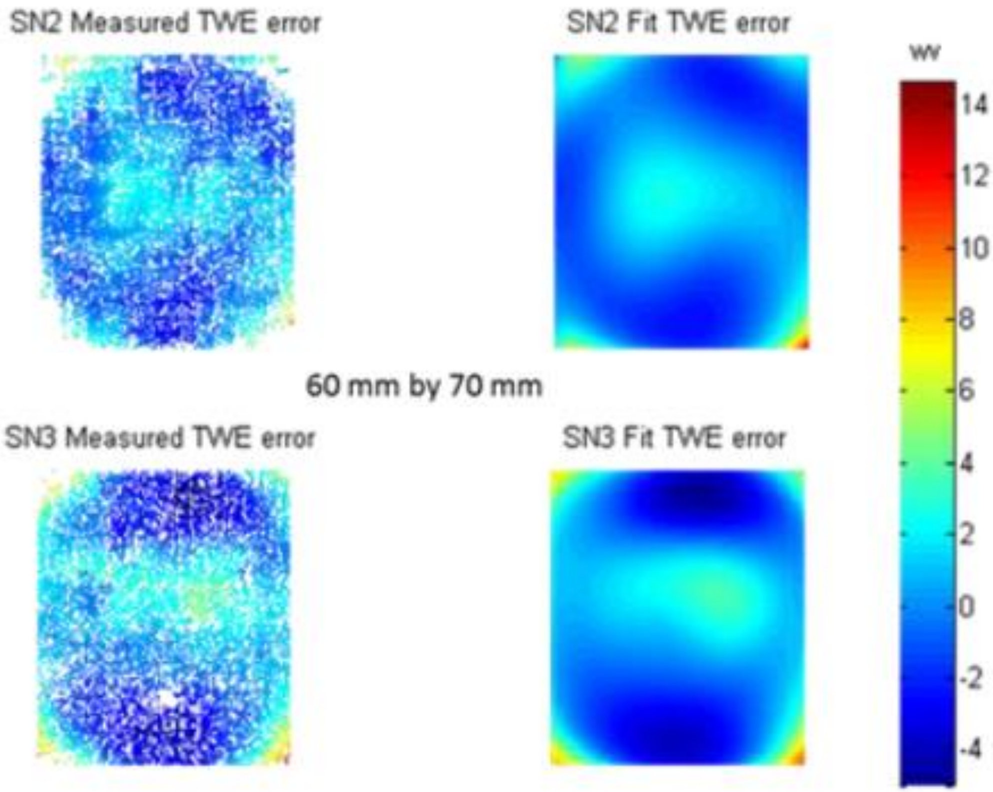

- All freeform surfaces were coated with a layer of Aluminum
- All coating operations were performed in-house at Optimax

# System Testing

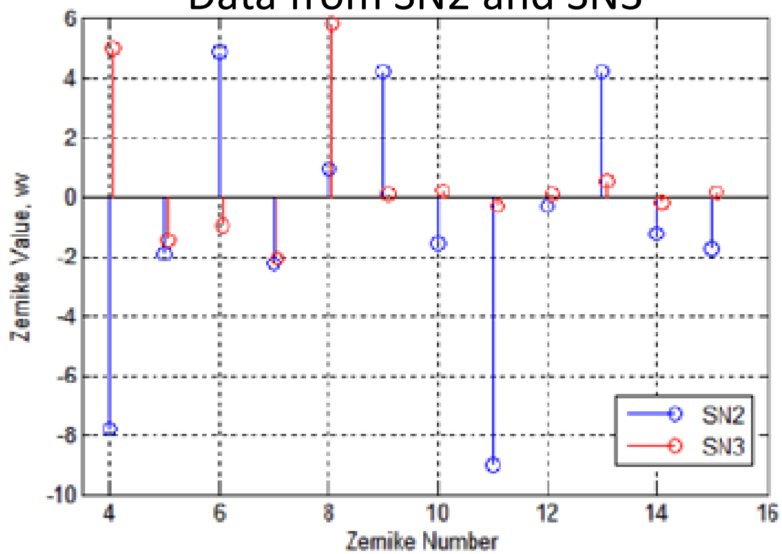



- Spot size measurements were collected on all finished monoliths.
- SN03 had noticeable astigmatism error.
- Performance issues will be resolved by improvements that we have made from this project and will integrate into Phase II

# System Testing




System Test Zernike Fit Data from SN2 and SN3




- System measurements collected with a standard Fizeau Interferometer.
- Additional work would be needed to separate systemic and manufacturing errors (The nominal design is not diffraction limited)

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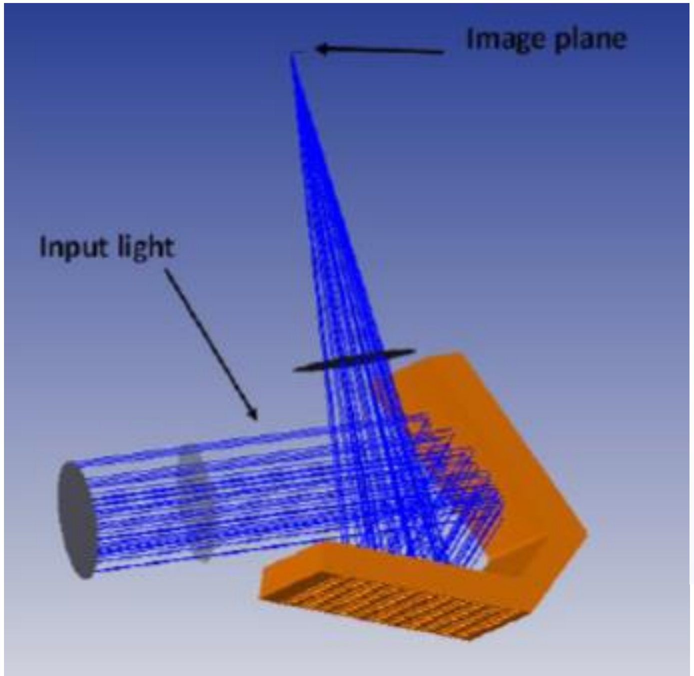
# Future outlook: Lightweight Monolith




- 183 mm effective focal length
- f/3.4
- Designed for CubeSat footprint.

- Lightweight design is based on the same freeform surface prescription as the previous monoliths.
- Instead of polishing the exterior of the monolithic block, the telescope is given a “clam-shell” design.

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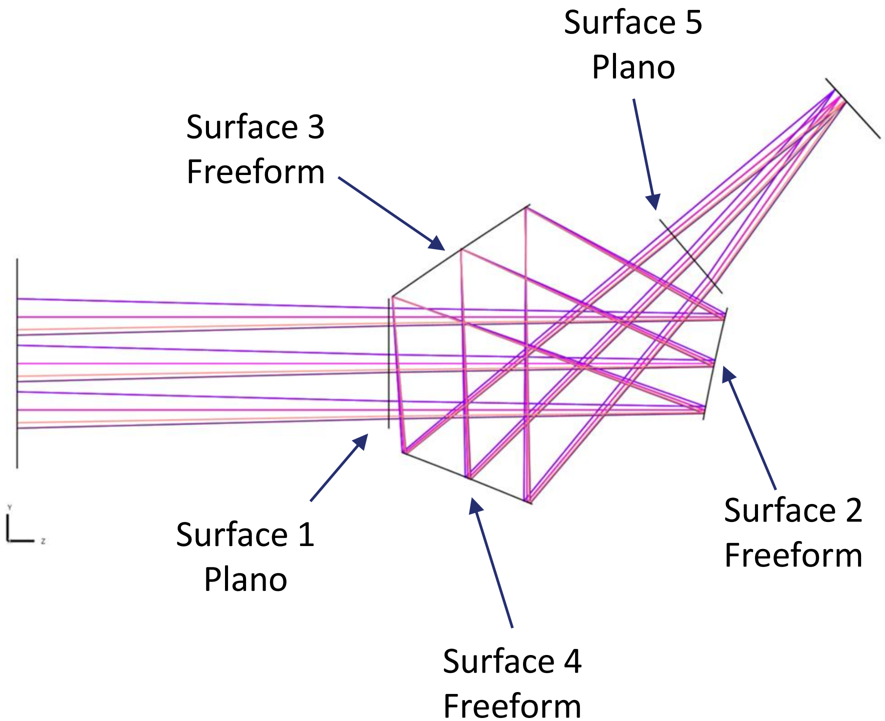
# Future outlook: High Resolution Freeform Monolith




- efl = 223 mm
- F# = 4

- Telescope contains 3+ freeform surfaces. Telescope contains 3+ freeform surfaces.
- Reflector design; similar to initial monolith
- Objective is to achieve diffraction limited performance.
- Requires many additional manufacturing improvements which are rolled in from Phase I
- Optical design and requirements have not been finalized

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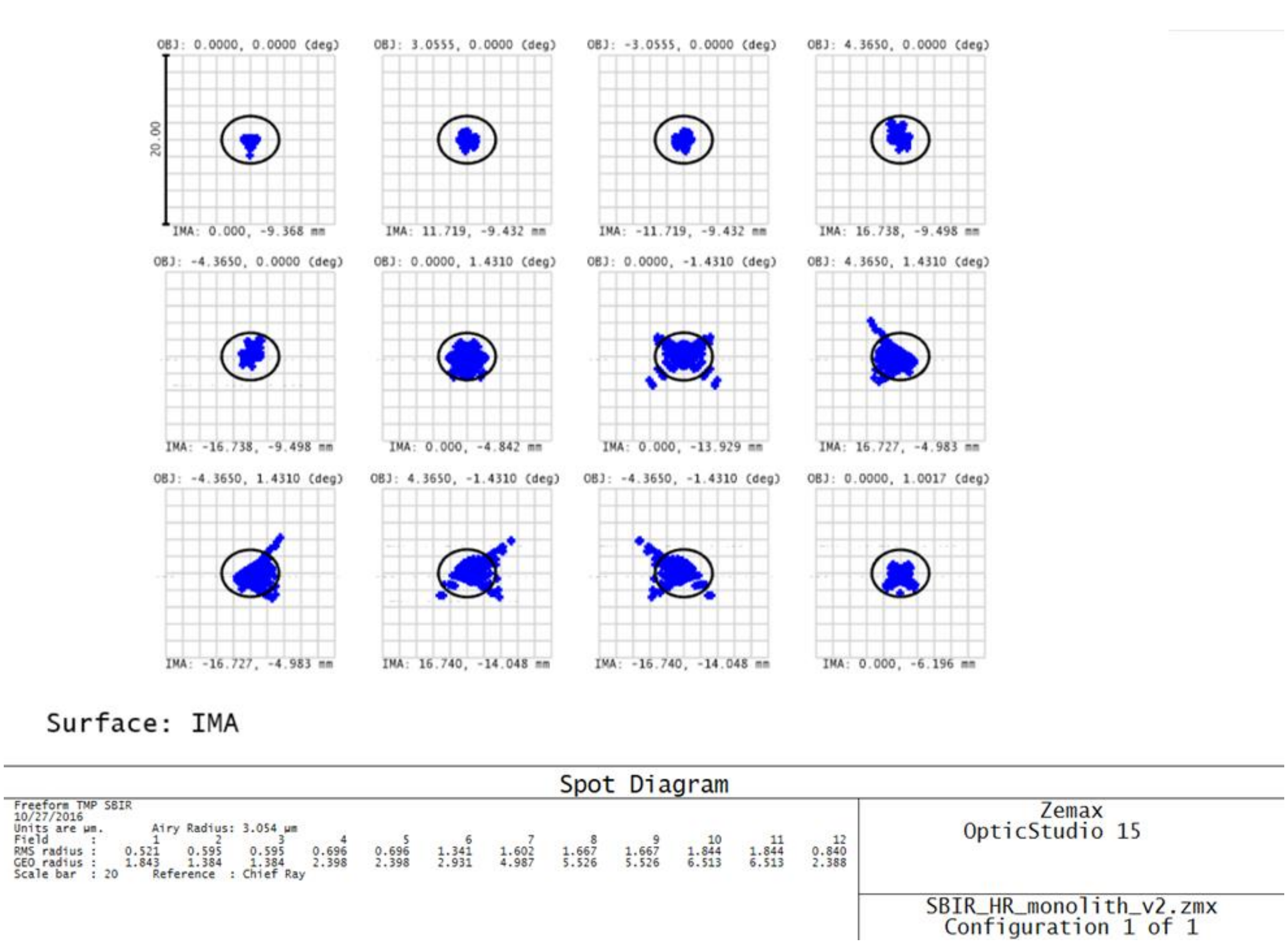
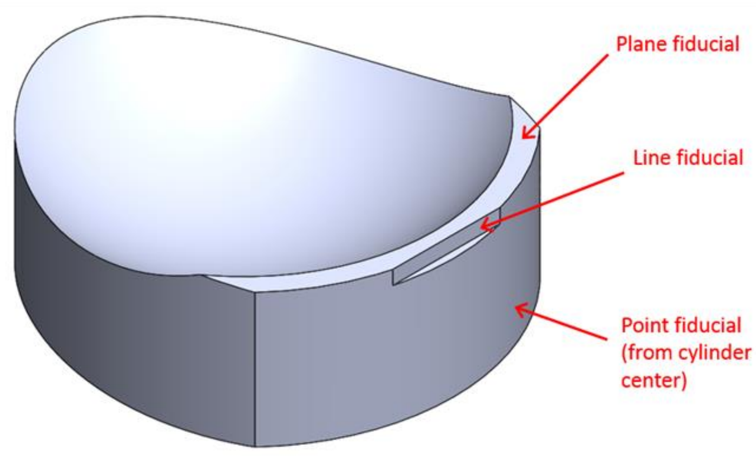
# Future outlook: High Resolution Freeform Monolith

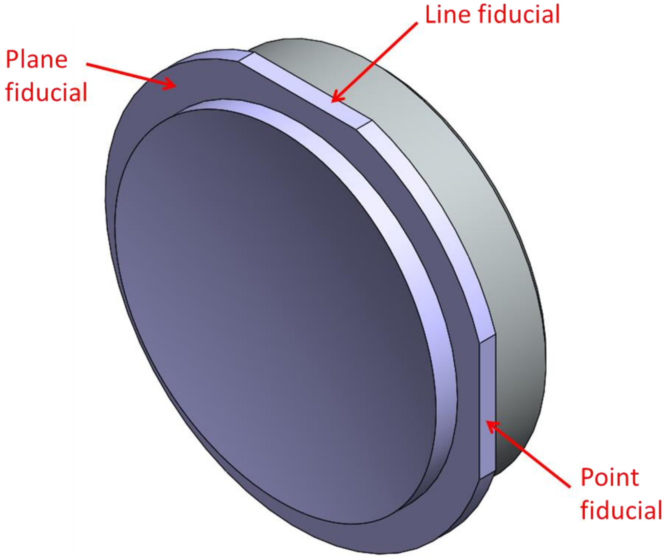



**Field of view was tested at:**

- ±1.431° along x-direction
- ±4.365° along y-direction

# Optical fiducials




- There must be some reference that defines the location of the freeform surface.
- Three orthogonal planes are common, but must define 6 DOF.
- Fiducial surfaces could act as alignment features.
- Datum features may have an impact on the system volumetric constraints.

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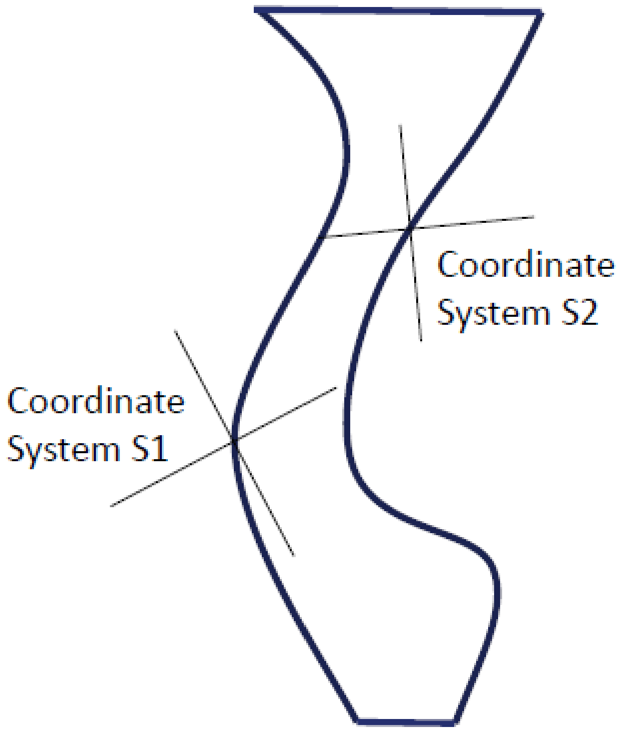
# Locating freeform surface(s) in space




- Optical equations are relative to some coordinate system
- Surfaces on same optic may have different coordinate systems
- Coordinate systems may not be orthogonal to optics' edges

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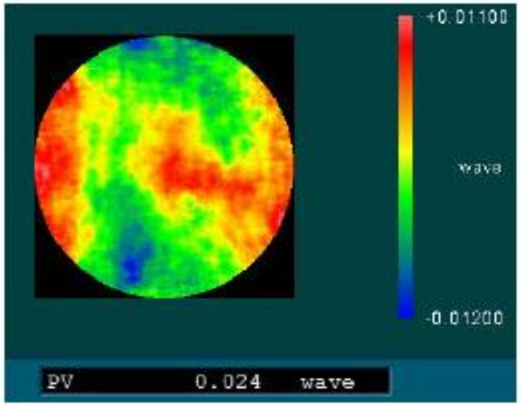
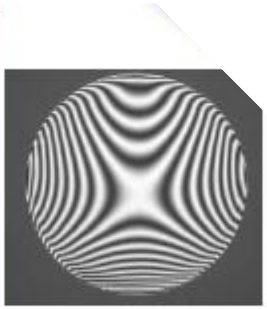
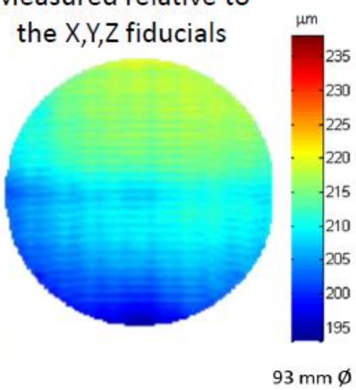
# Monolithic Telescopes *Require* Tactile measurements

Interferometer
Off-axis parabola
30 mm CA
$\lambda/40$ PV



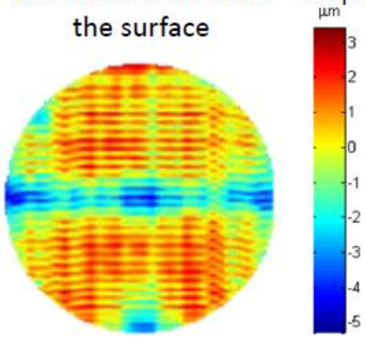




Measured relative to the X,Y,Z fiducials




Measured best fit to the surface

8.1 µm PV

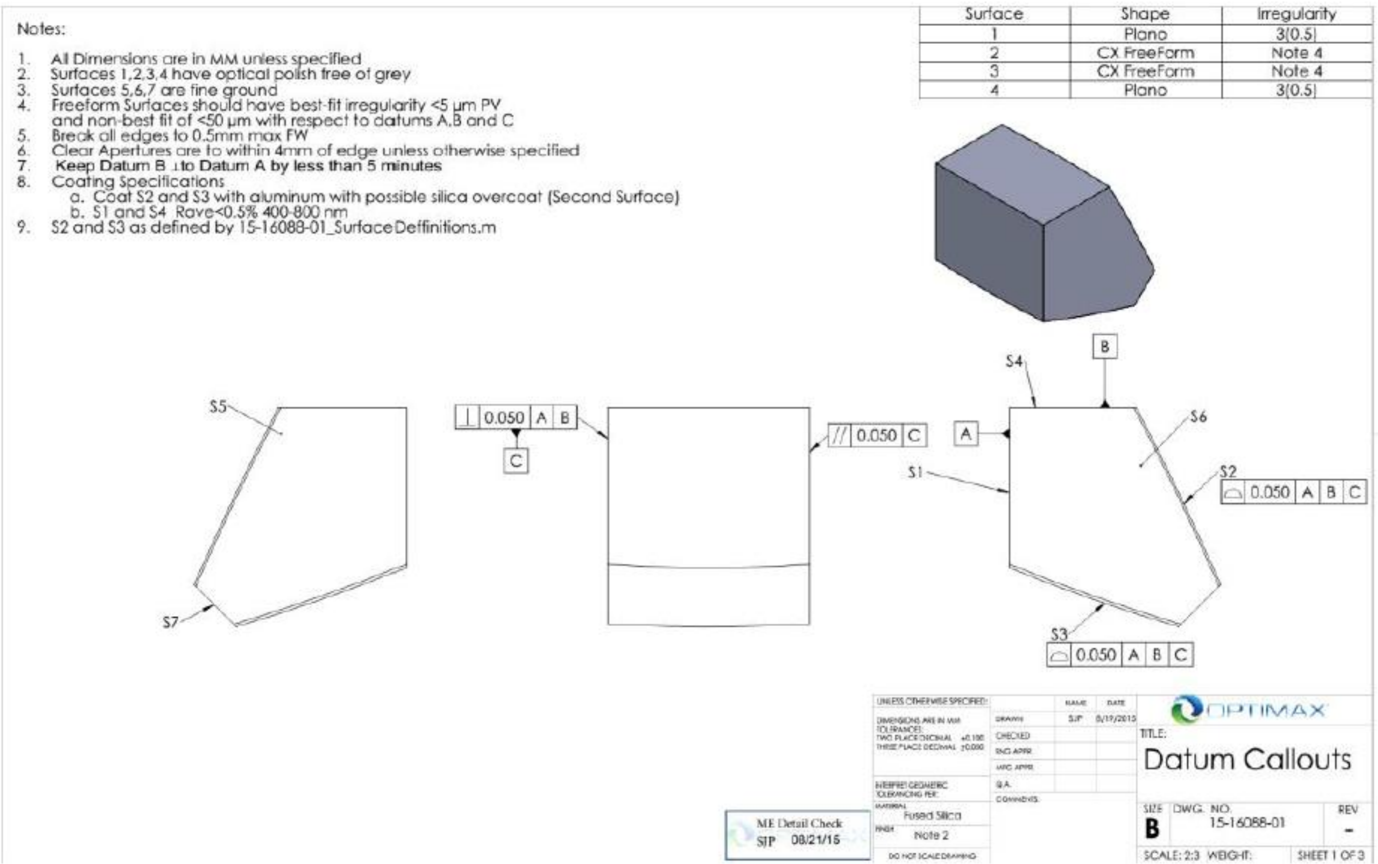



**Interferometer measurements using CGHs only measure the surface under test.**

**Optical system errors – tip, tilt, decentering – are not identified.**

**In order to locate each surface with respect to a global coordinate system, each surface must be referenced to the global fiducials.**

# Phase I Monolith Fiducials




**Phase I monolith used three orthogonal plane fiducials.**

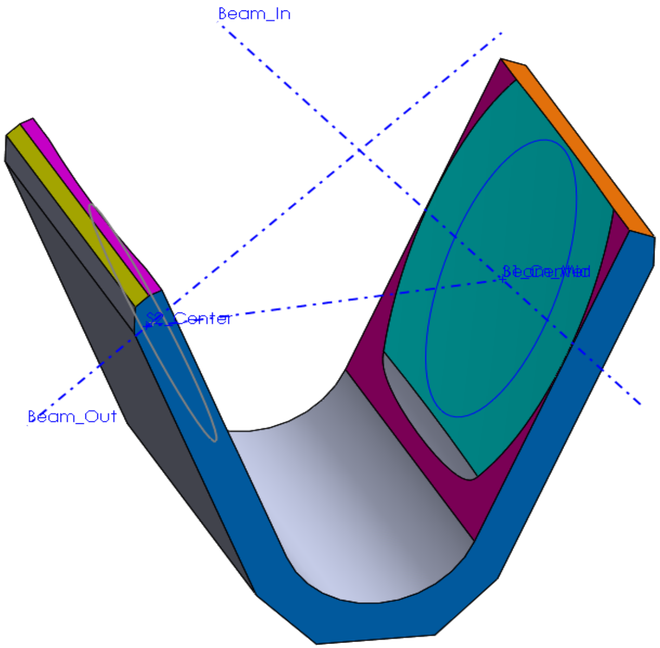
**Datums A and B are polished entrance and exit surfaces.**

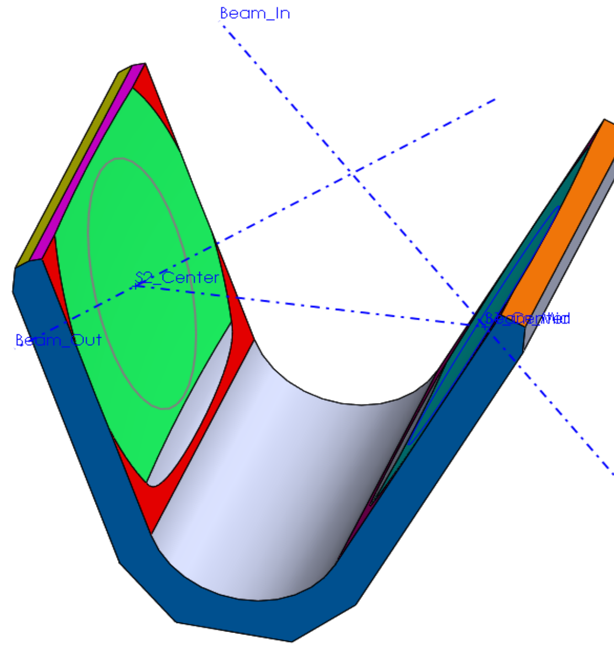
**Datum C is find ground.**

**Both freeform surfaces reference the same datum features.**

**Entrance face is a polished plano enabling easy alignment for system level testing.**

# Light Weight Monolith Fiducials




Side 1: (Right Side)
Teal is optical face
Magenta is Z-Alignment face
Blue is Y-Alignment face
Orange is X-Alignment face

Both:
Yellow is Optical Alignment face

Side 2: (Left Side)
Green is optical face
Red is Z-Alignment face
Blue is Y-Alignment face
Purple is X-Alignment face

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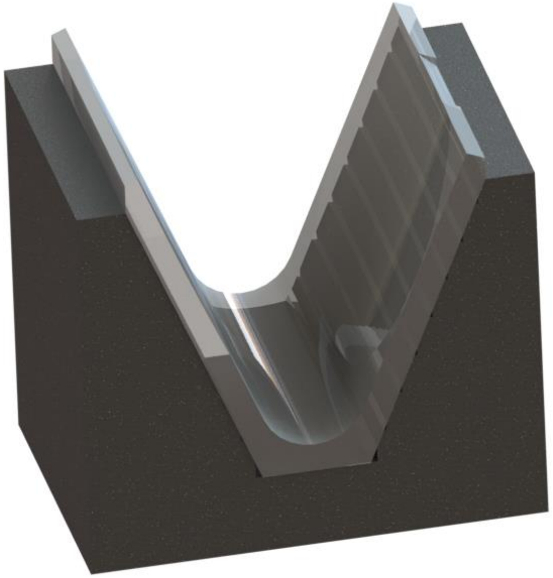
# Optical Blocking

- Multi surface optics may require additional process steps.
- Optical fiducials must be accessible.
- Avoid precarious fixturing requirements.

Initial blocking for surface 2

New blocking for surface 3



Light weight design allows access to all polished surfaces

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