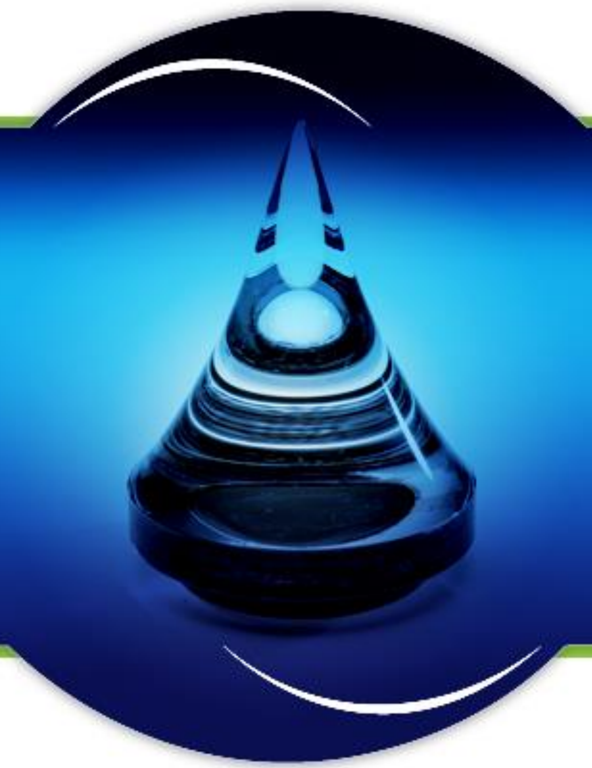


Freeform Monolithic Multi-Surface Telescope Manufacturing

NASA Mirror Tech Days

15 November 2017

Presented By:
Brian Myer, Todd Blalock

Prototype Optics In One Week

Optimax Overview

Inc. 5000

Inc 5000 Top Growing Business

OPTIMAX • 2016 • Aspheres • Cylinders • Prisms • Spheres • 1991

TOP WORK PLACES 2016

D&C Democrat & Chronicle

PART OF THE USA TODAY NETWORK

- Founded 1991
- Ontario NY
- 65,000 ft^2 facility
- 280 employees
- ISO 9001:Certified
- ITAR compliant

OPTIMAX

Optimax Systems, Inc. – Custom Precision Optics
Committed to Small Volume, High Quality, Quick Delivery

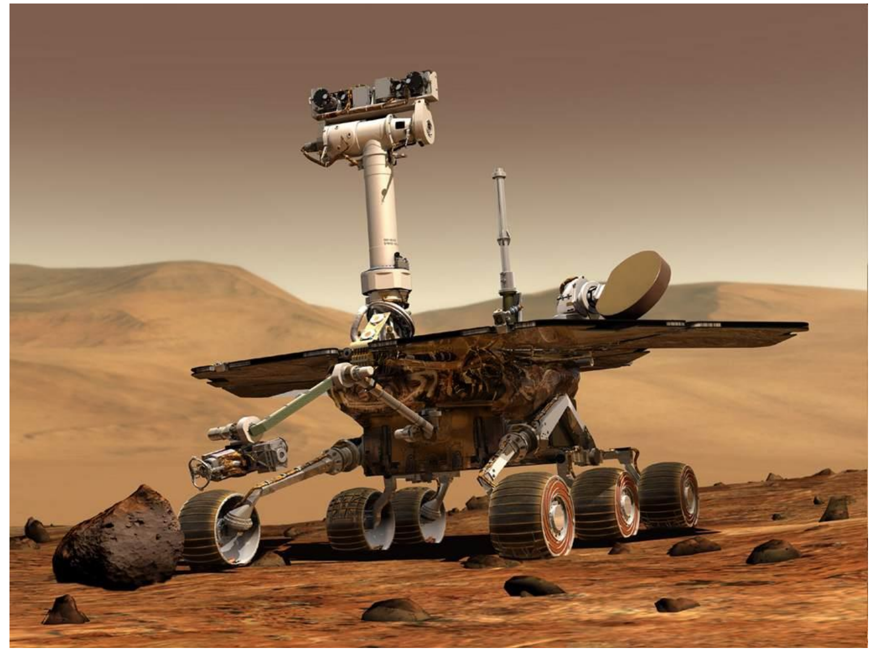




- Materials
  - Glass Materials
  - Ceramics
  - Crystals
  - Fused Silica
  - Low Expansion
- Shapes
  - Aspheres
  - Conformal & Freeform
  - Cylinders
  - Domes
  - Flats
  - Prisms
  - Spheres

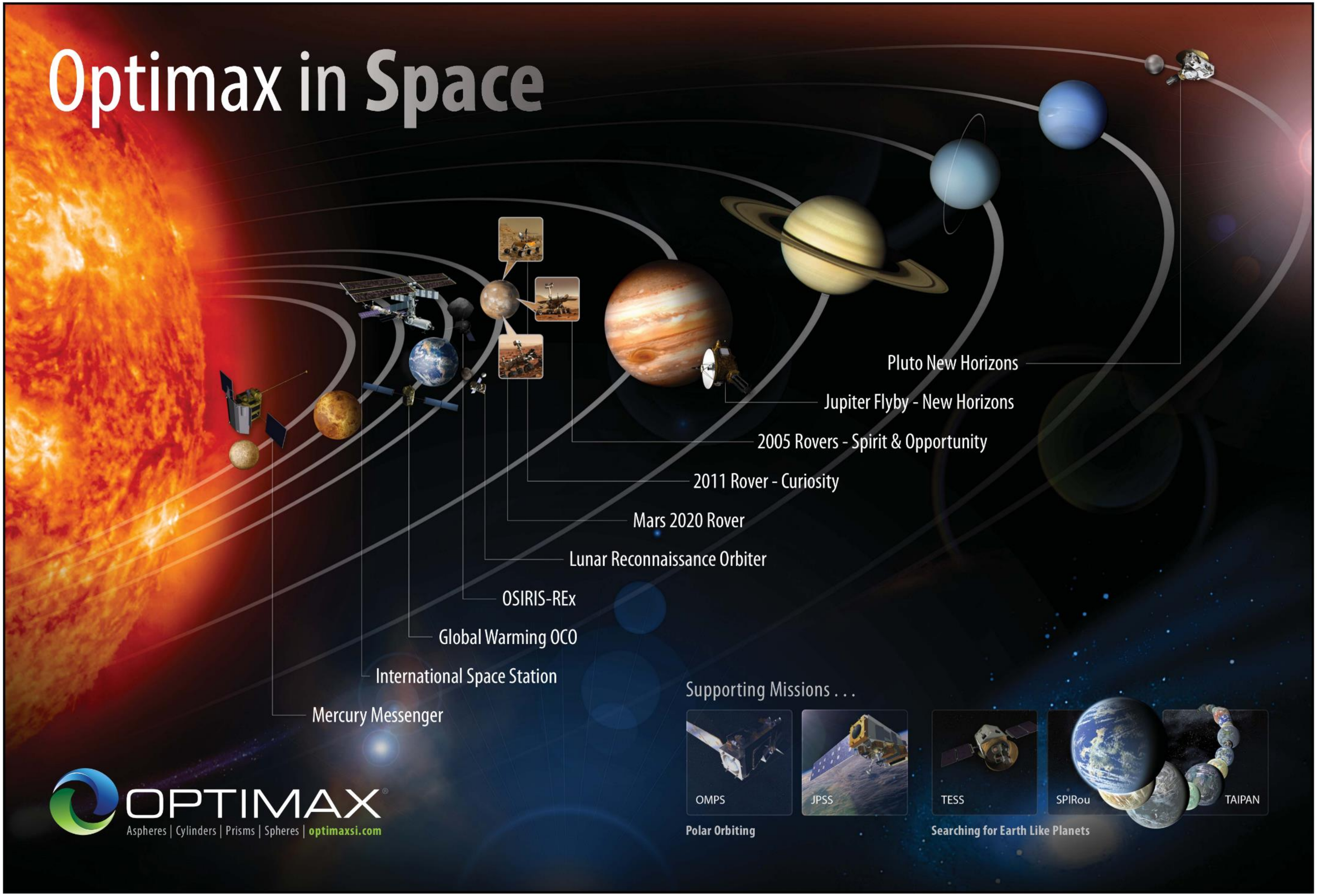
OPTIMAX

Optimax Overview
Markets We Serve



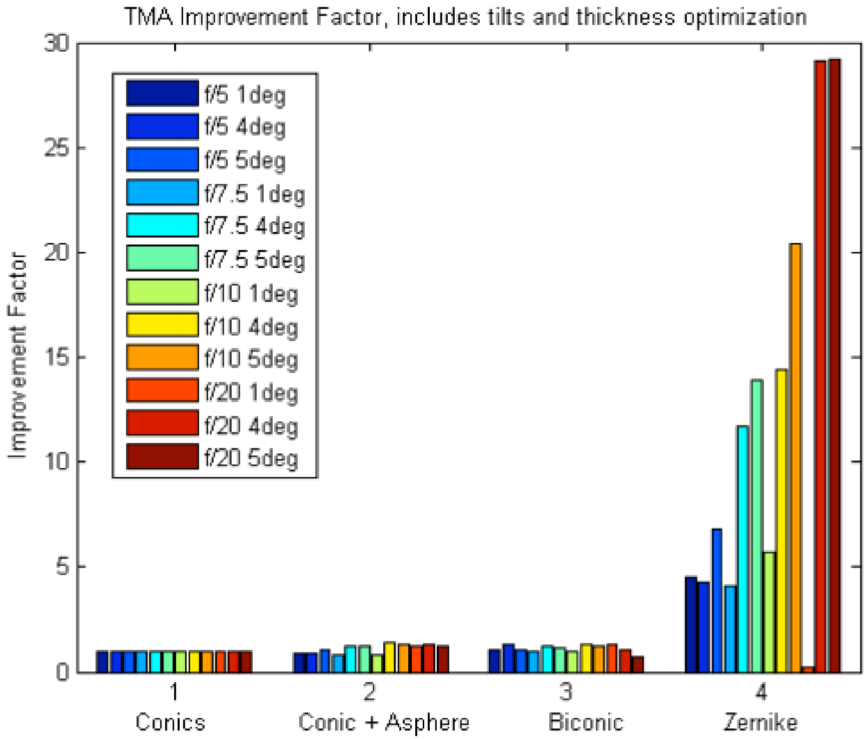
- Semiconductor
- Aerospace & Defense
- Commercial
- Medical

OPTIMAX


Optimax in Space
Pluto New Horizons
Jupiter Flyby - New Horizons
2005 Rovers - Spirit & Opportunity
2011 Rover - Curiosity
Mars 2020 Rover
Lunar Reconnaissance Orbiter
OSIRIS-REx
Global Warming OCO
International Space Station
Mercury Messenger
Supporting Missions . . .
OMPS
JPSS
Polar Orbiting
TESS
SPIRou
TAIPAN
Searching for Earth Like Planets
OPTIMAX
Aspheres | Cylinders | Prisms | Spheres | optimaxsi.com

Freeform Optics Overview

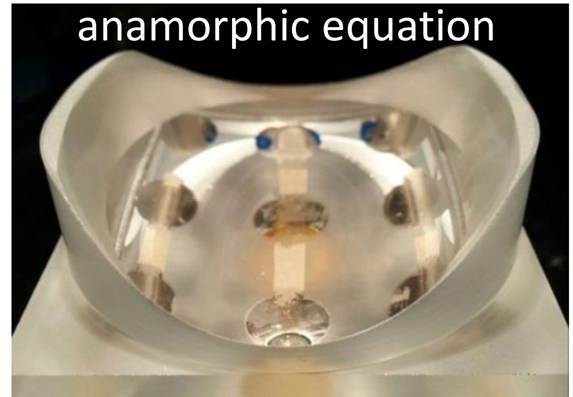
- Freeforms: optics manufactured without using an axis of rotational symmetry.
- Benefits Include:
  - Lighter weight
  - Reduced number of components (less complexity)
  - Reduced aberrations
- Common Freeform Designs
  - Off-axis asphere
  - Toroids, biconics
  - Polynomial functions
  - Anamorphic equations
  - Zernikes
  - Other equation based models
  - Solid models

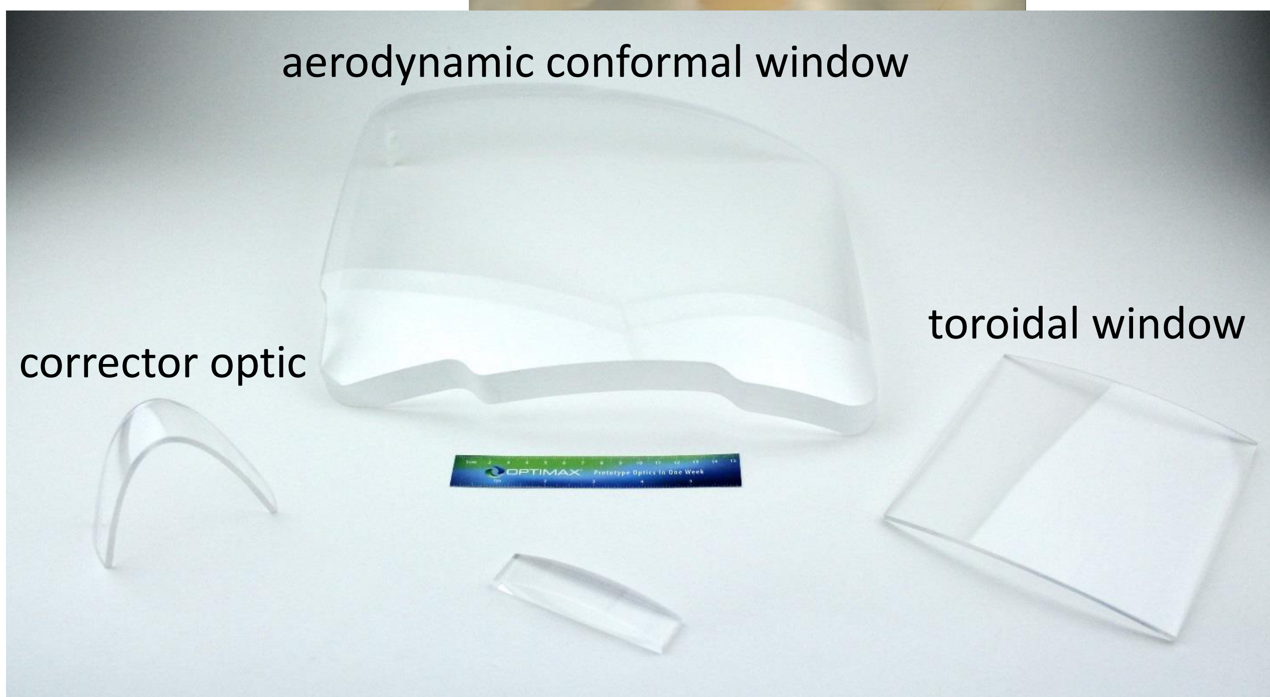


J M Howard and S Wolbach, "Improving the performance of three-mirror imaging systems with Freeform Optics," OSA Freeform Optics Conference, November 2013

Freeforms are now a product offering at Optimax

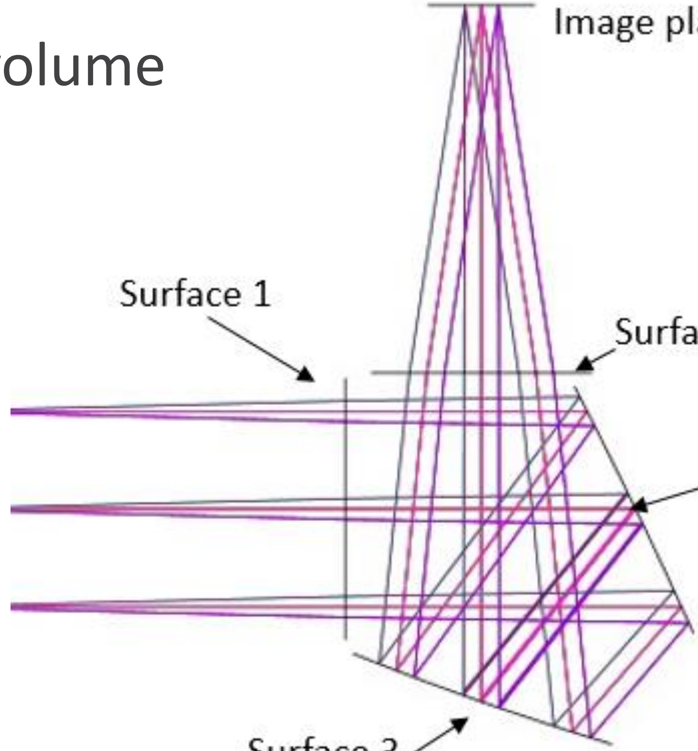
- Since January 2015, freeform optics are a standard product offering for Optimax
- Leverages SBIR-developed technology
- Many different shapes and sizes
- Optics are currently being used by customers in their optical systems





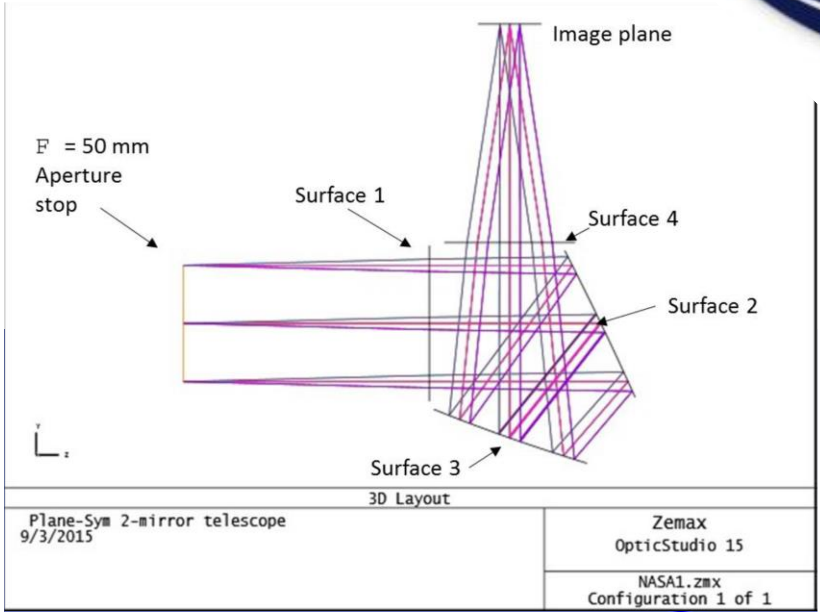
Our first monolith design featured two freeform surfaces

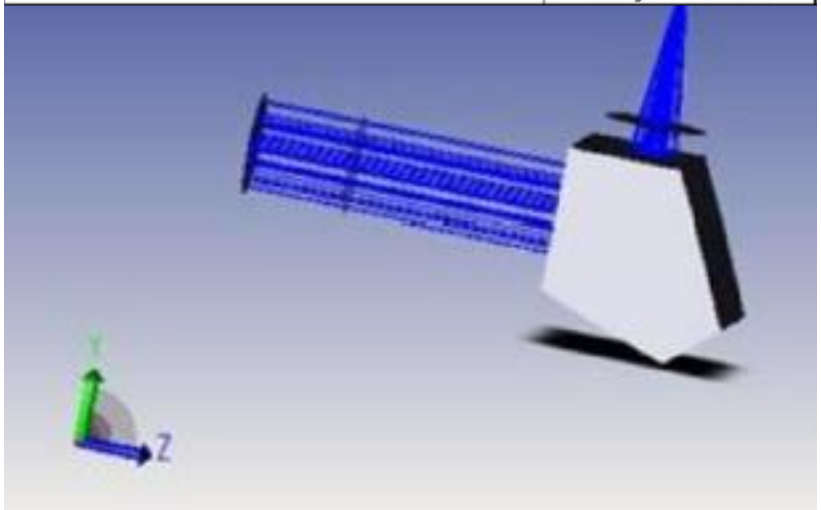
- This provides an extremely rugged optomechanical design
- We incorporated assembly tolerances into the manufacturing tolerances
- Fits in a 1U, 4 inch cubesat volume



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

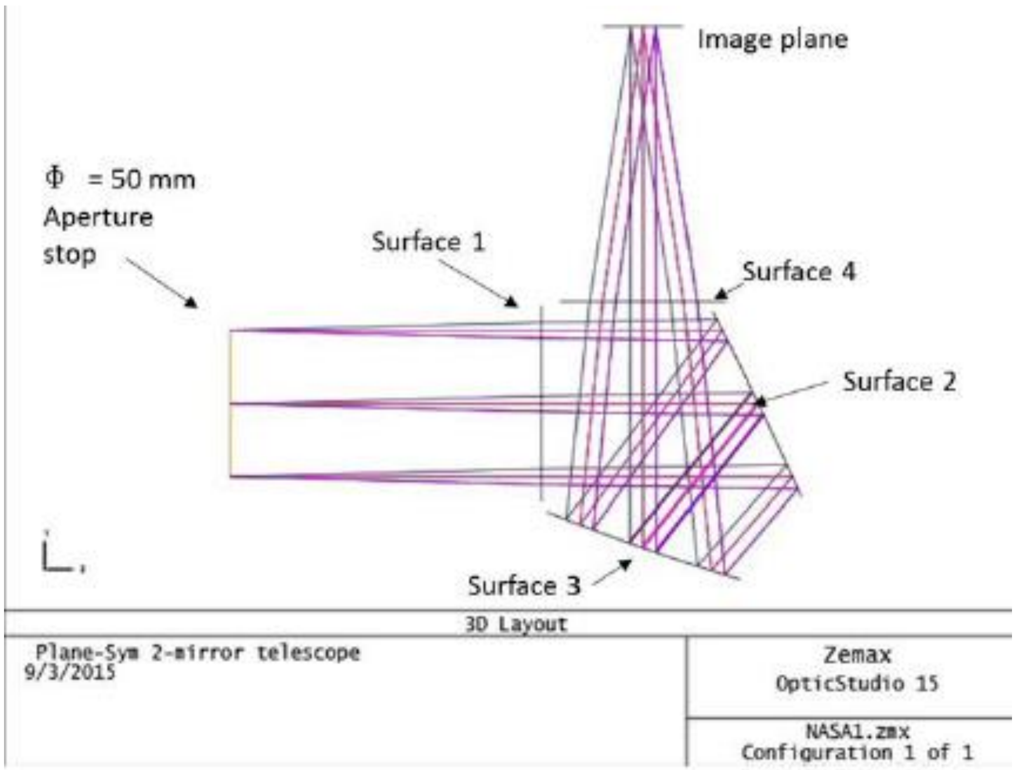




Phase I Monolith Design

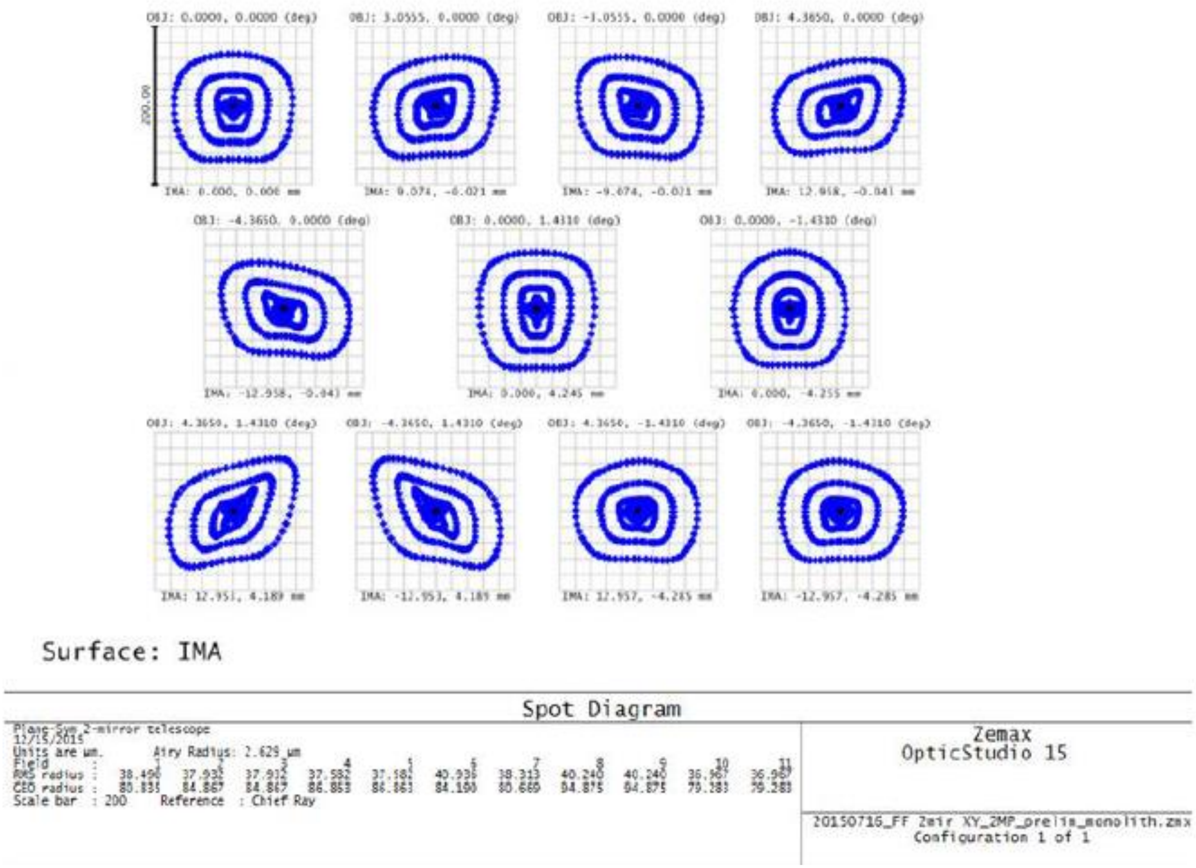
Both freeform surfaces are defined by xy polynomials of the same form:

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



- Effective focal length of 183 mm at f/3.4
- Tolerance level was "best effort"

Phase I Monolith Design

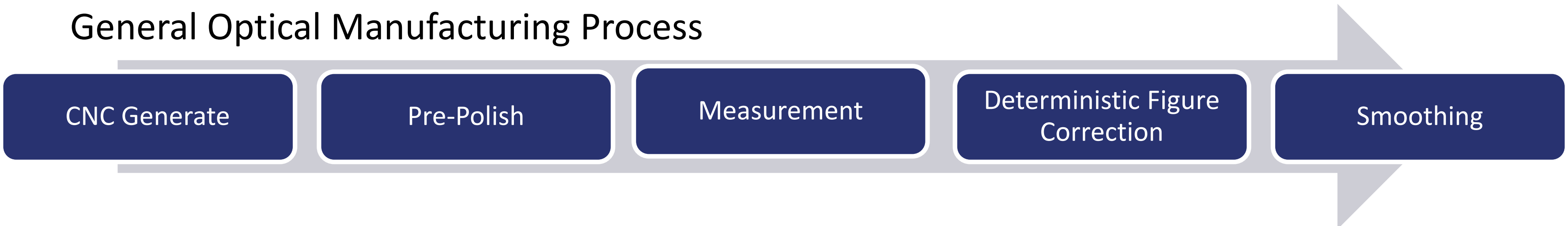


- Diffraction limited spot has a diameter of 2.6 µm.
- rms radius is approximately 35 µm.
- The given design is over an order of magnitude off of diffraction limit.
- Field of view modeled at:
  - ±1.431° along x-direction
  - ±4.365° along y-direction

OPTIMAX

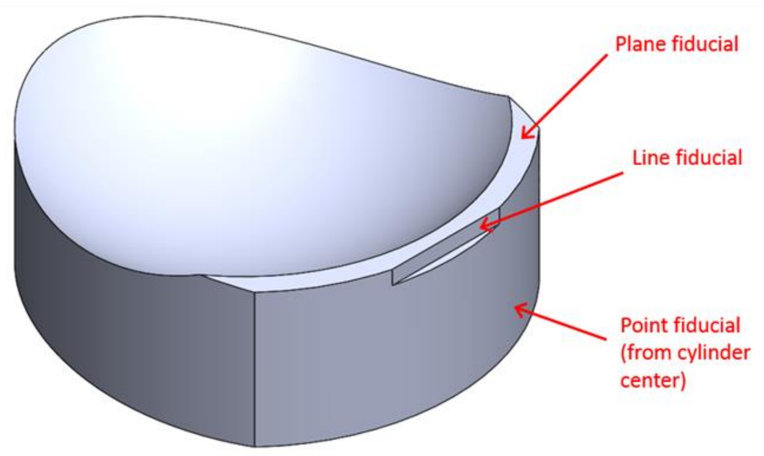
Standard Freeform Optical Manufacturing Process

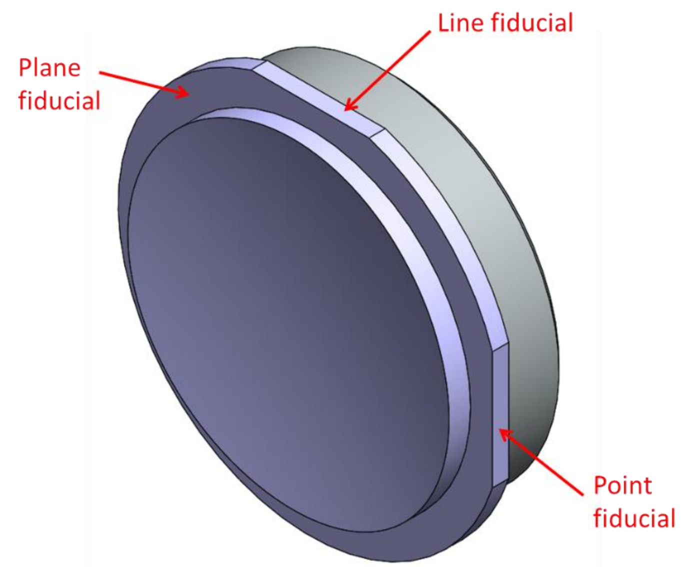
General Optical Manufacturing Process



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

Detour: Optical fiducials

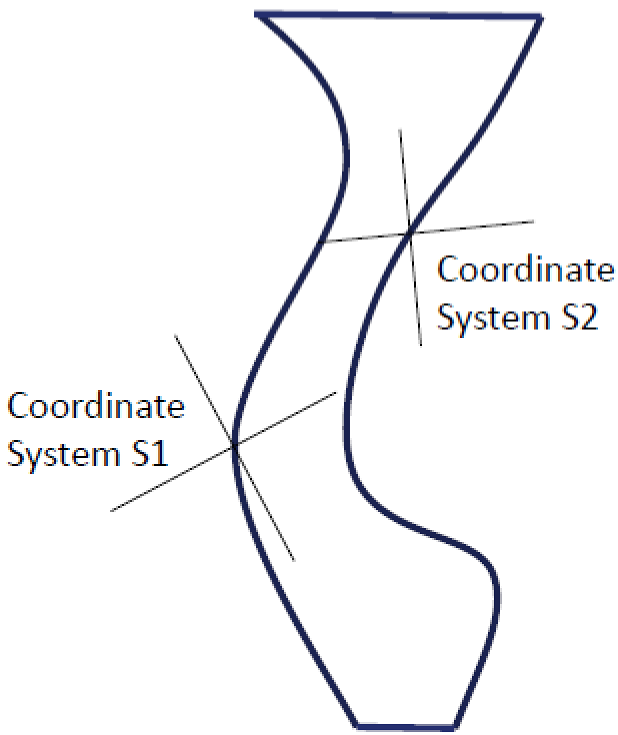




- There must be some reference that defines the location of the freeform surface.
- Three orthogonal planes are common, but must define 6 DOF.
- Fiducial surfaces could act as alignment features.
- Datum features may have an impact on the system volumetric constraints.

OPTIMAX

Locating freeform surface(s) in space

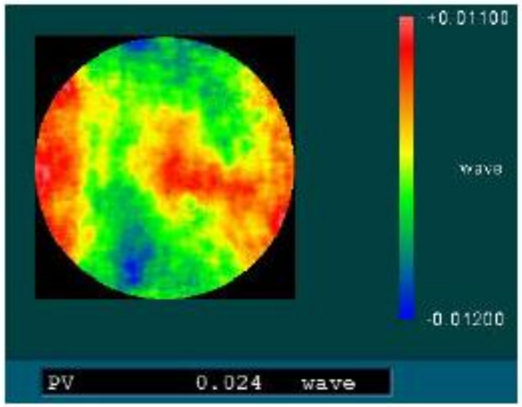


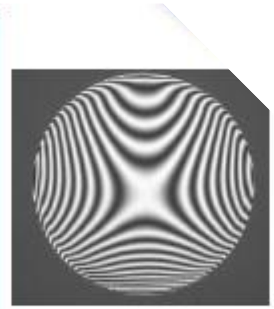
- Optical equations are relative to some coordinate system
- Surfaces on same optic may have different coordinate systems
- Coordinate systems may not be orthogonal to optics' edges

OPTIMAX

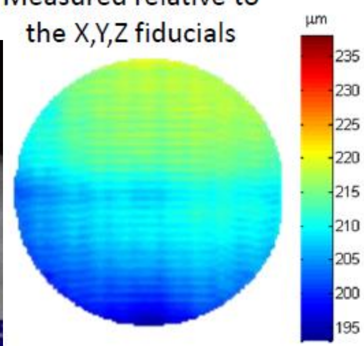
Monolithic Telescopes *Require* Tactile measurements

Interferometer
Off-axis parabola
30 mm CA
λ/40 PV





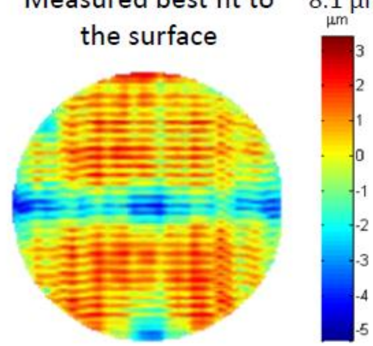
Measured relative to the X,Y,Z fiducials



93 mm Ø

Measured best fit to the surface

8.1 µm PV



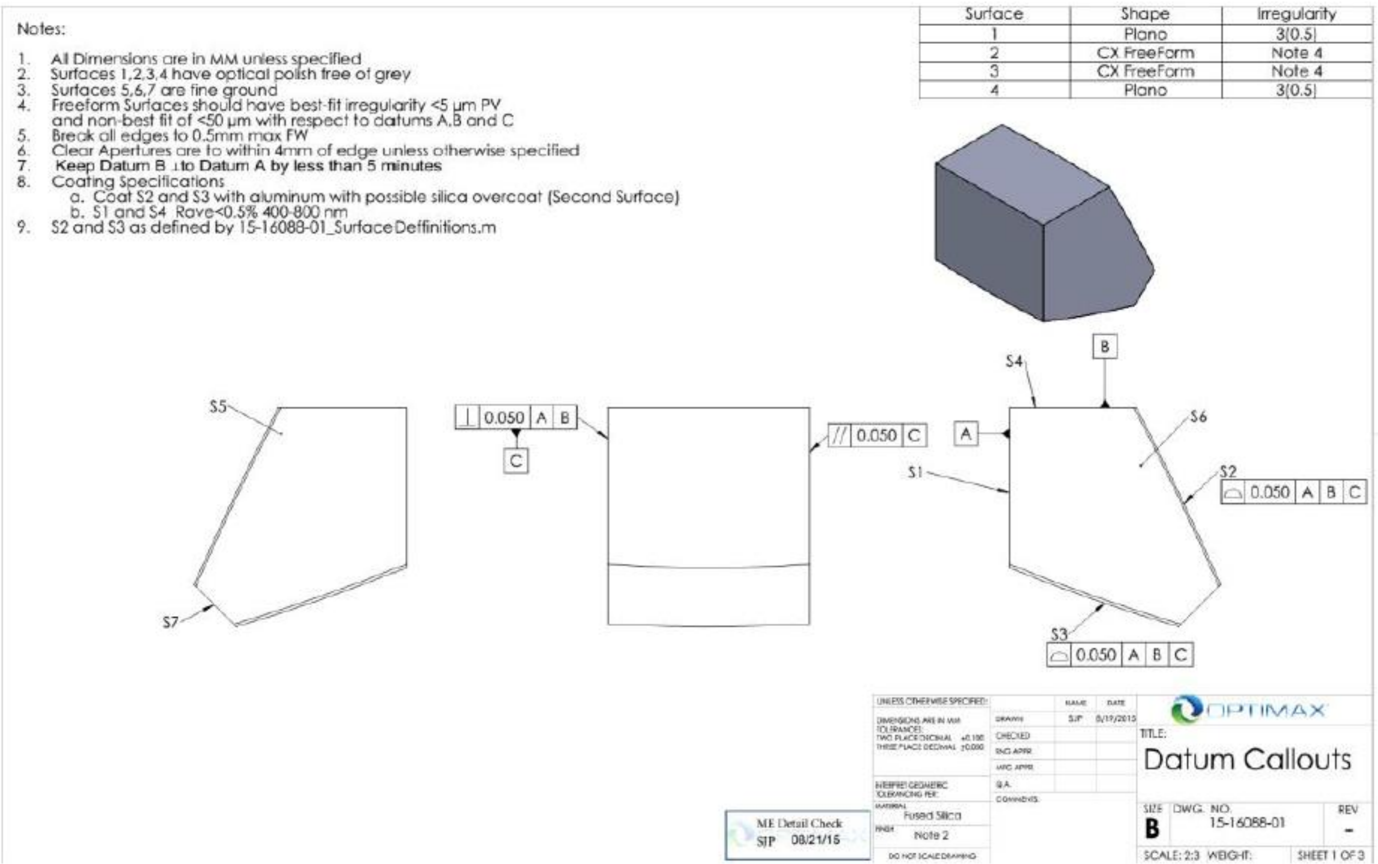
2

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



Surface	Shape	Irregularity
1	Plano	3(0.5)
2	CX FreeForm	Note 4
3	CX FreeForm	Note 4
4	Plano	3(0.5)

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.

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 of positioning error (tilt)

Manufacturing Process: Monolith Polishing

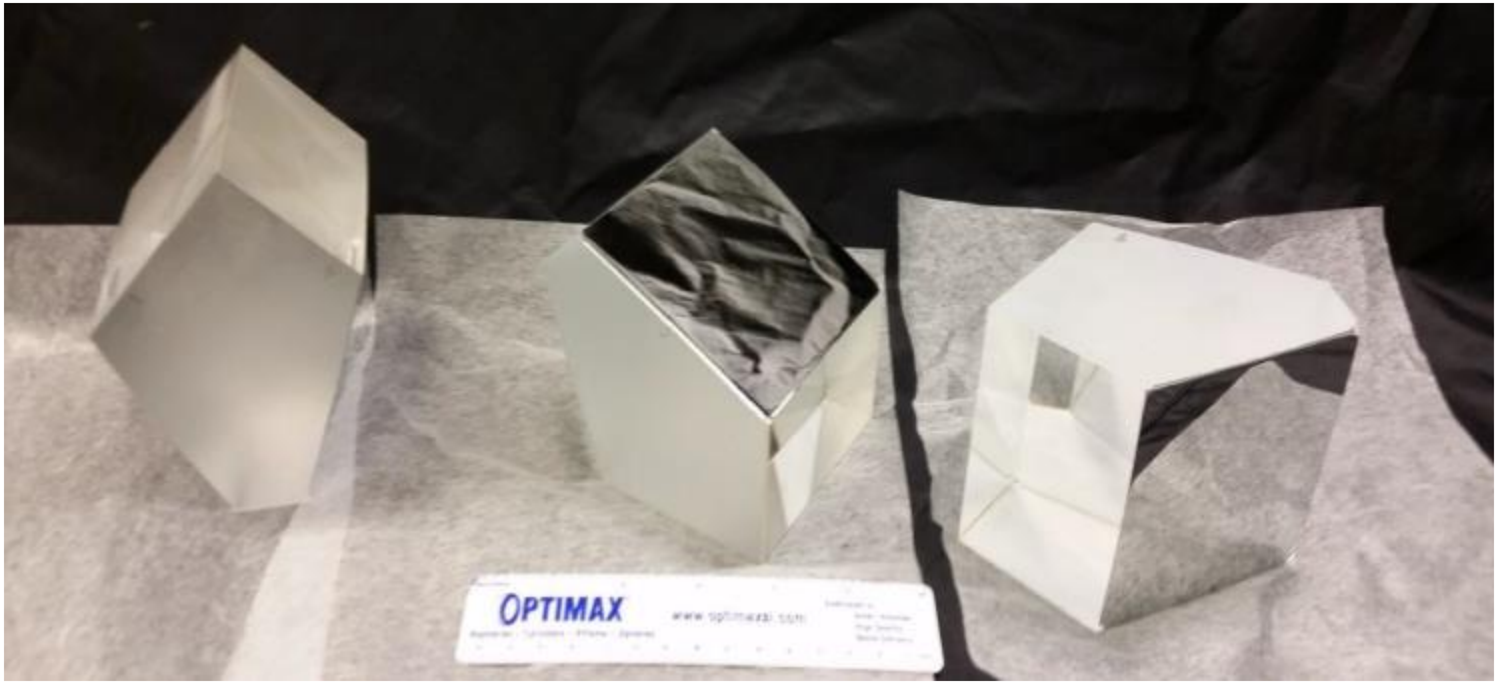
- Industrial robot with proprietary software and tooling.
- Robot provides flexibility with size shape and control.
- For Phase I monolith, polishing completed when the surface error was less than 5 µm.

OPTIMAX

Manufacturing Process: Metrology

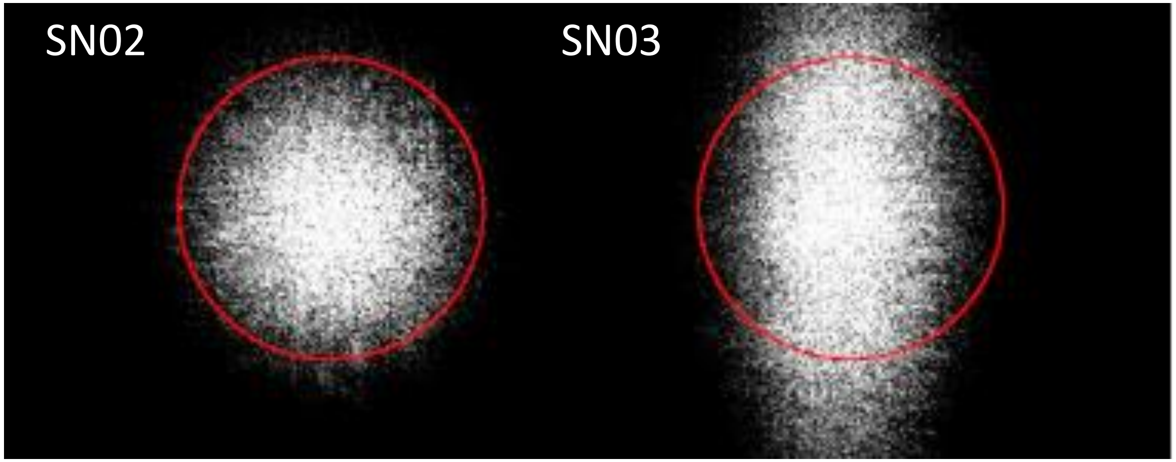
- All surfaces were verified using a Leitz coordinate measuring machine (CMM).
- Micron level positioning accuracy
- Higher accuracy would require CGH investment.
- Optimax is actively working to bridge metrology gap between CMM and CGH

Manufacturing Process: Surface Coating



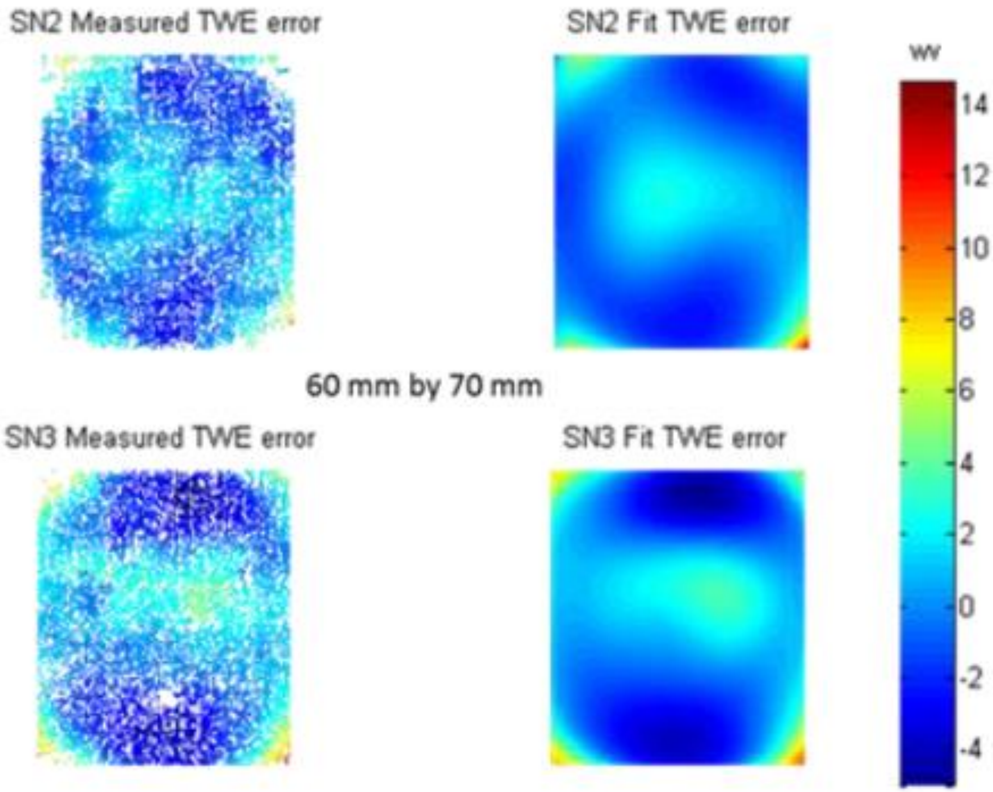
- All freeform surfaces are coated with protected aluminum in-house

System Testing – optical bench

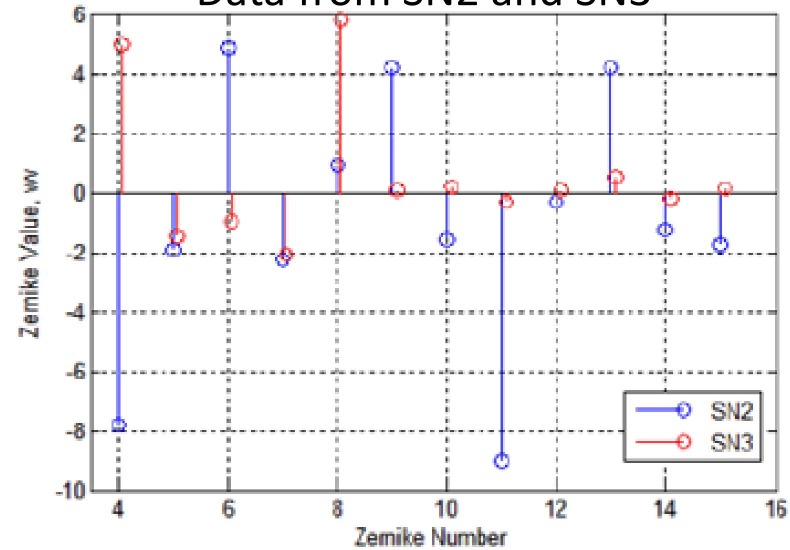


- Spot size measurements were collected on all finished monoliths.
- SN03 had noticeable astigmatism error.
- Performance issues will be resolved by improvements that we have made from this project and will integrate into Phase II

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)

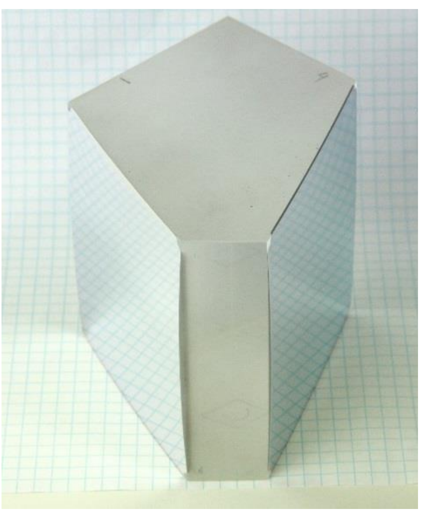
OPTIMAX

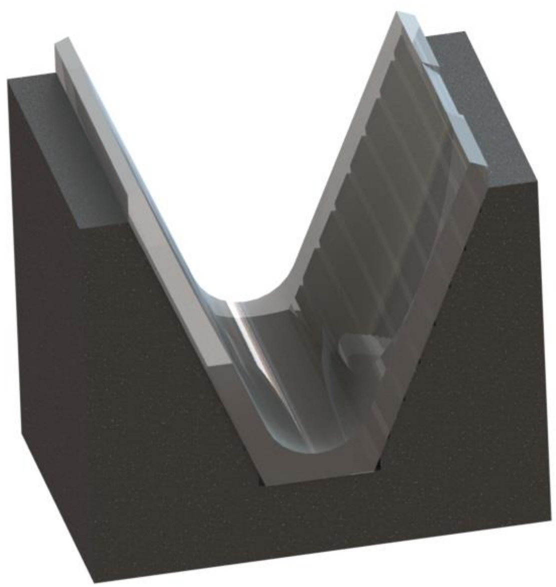
Design evolution of monolithic telescopes

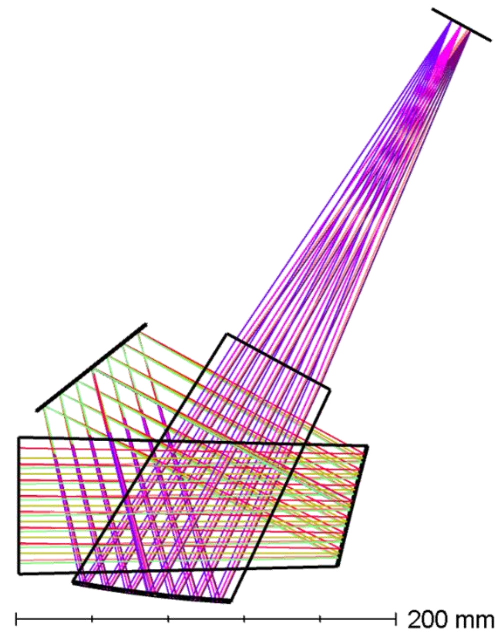
STAGE 1:
Two freeform surface reflective monolith

STAGE 2:
Light-weighted two freeform surface reflective monolith

STAGE 3:
Diffraction-limited 3+ freeform surface monolith with reflective & refractive surfaces

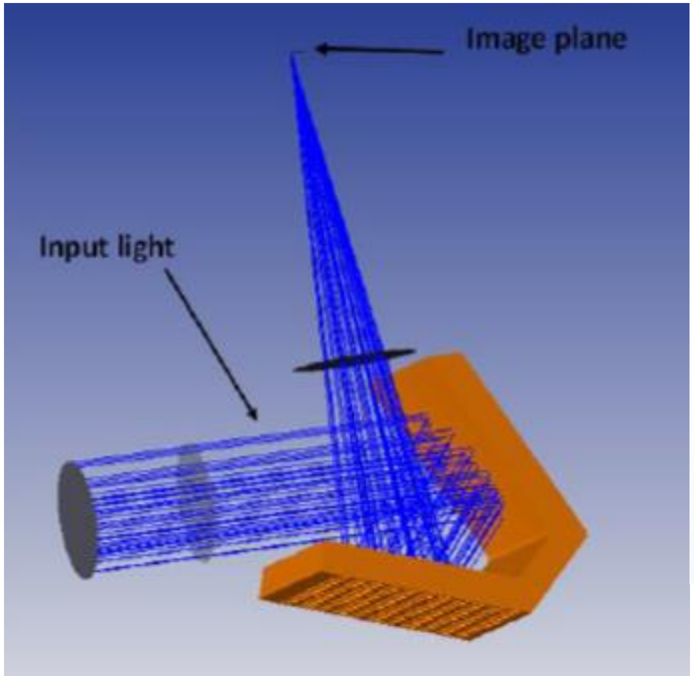






OPTIMAX

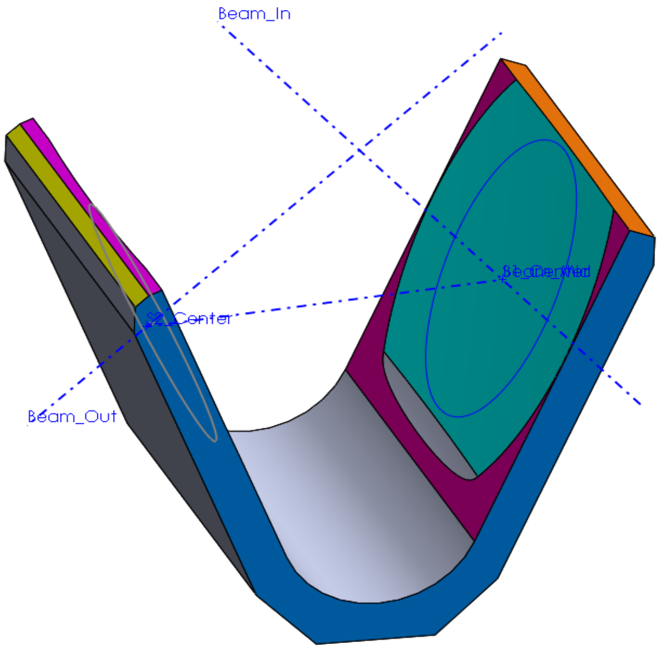
Lightweight, LW, or “open jaw” Monolith

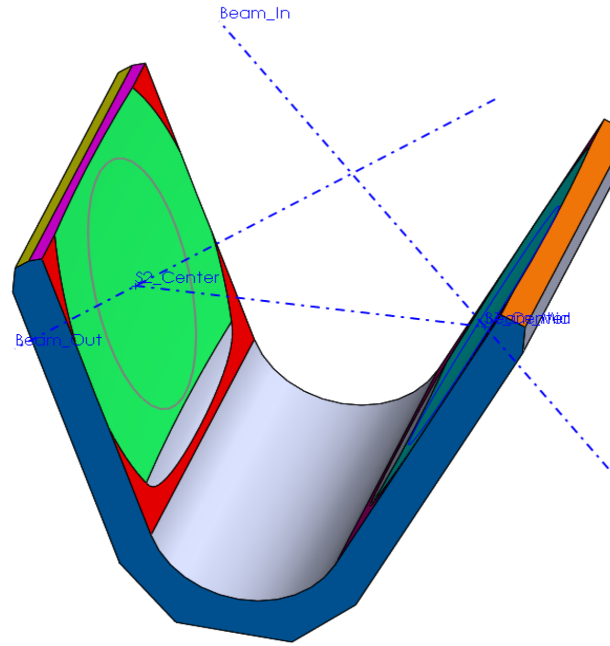


- 183 mm effective focal length at f/3.4
- “Best Effort” surface irregularity.

- 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” or “open jaw” design.

Light Weight Monolith Fiducials



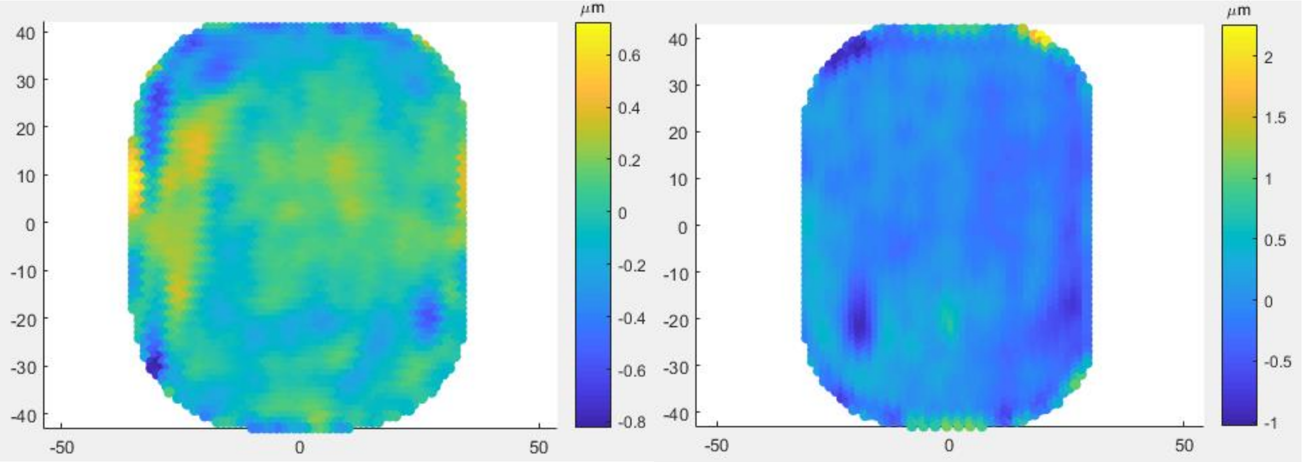


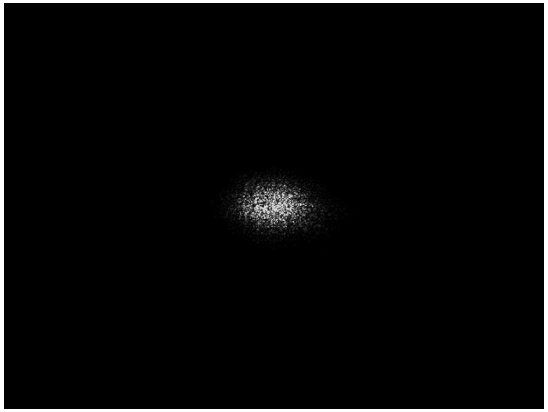
Side 1: (Right Side)
Teal is optical face
Magenta is Z-Alignment face
Blue is Y-Alignment face
Orange is X-Alignment face

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

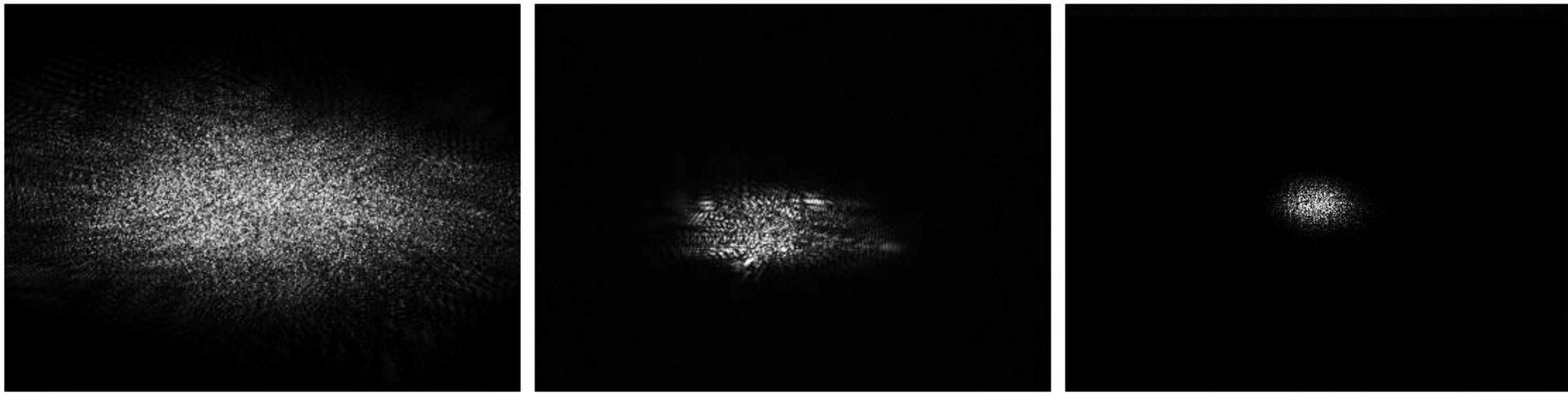
Surface quality requirement





Current state of the open-jaw monolith SN02. Each surface has a P-V error of 1.5 to 2.5 µm with RMS of 0.2 µm. Zemax model using measured surface data used as comparison with spot measurement.

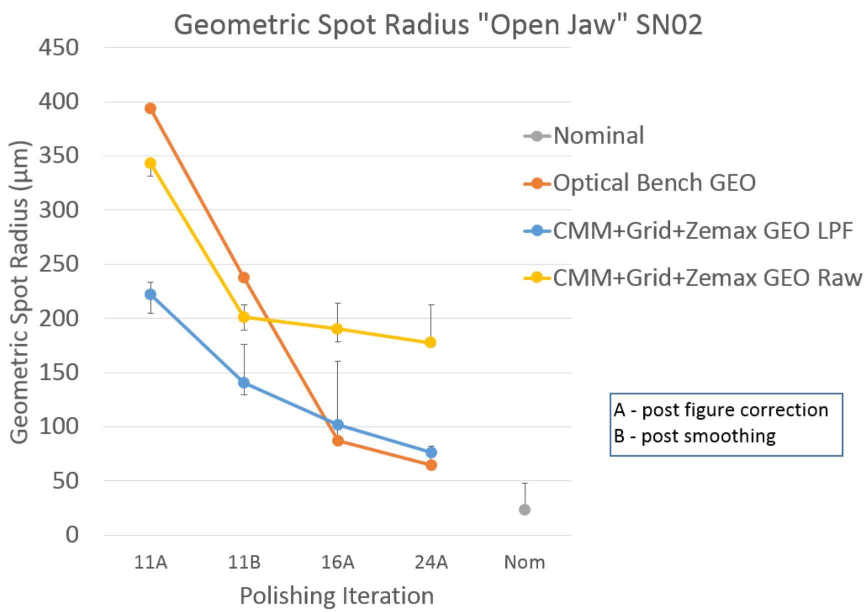
LW Monolith – spot size measurements

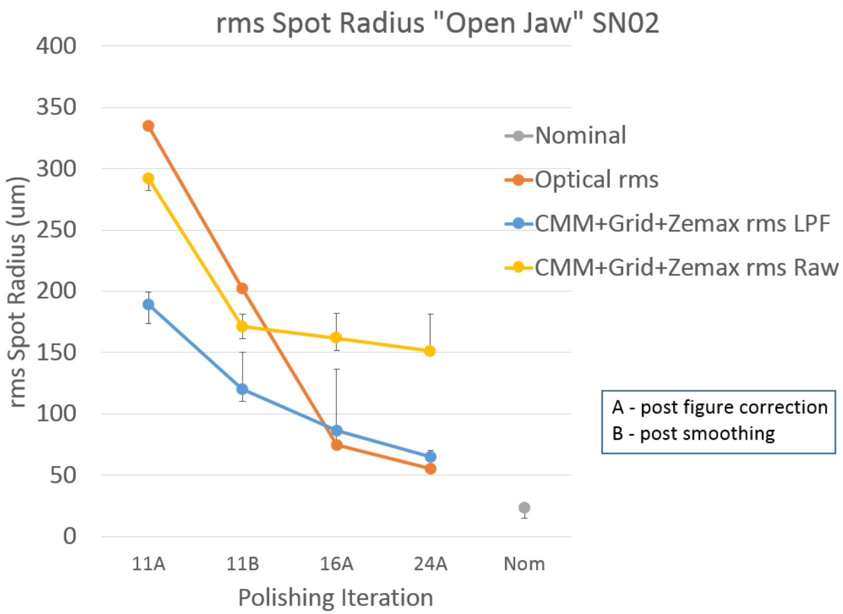


Robot: Grayed-out → Initial Smoothing → Robot: Fine Polish

Difficulty modeling imaging performance with as-built errors. Optical bench test monitors spot size and provides validation to predictive models.

Modeling as-built performance

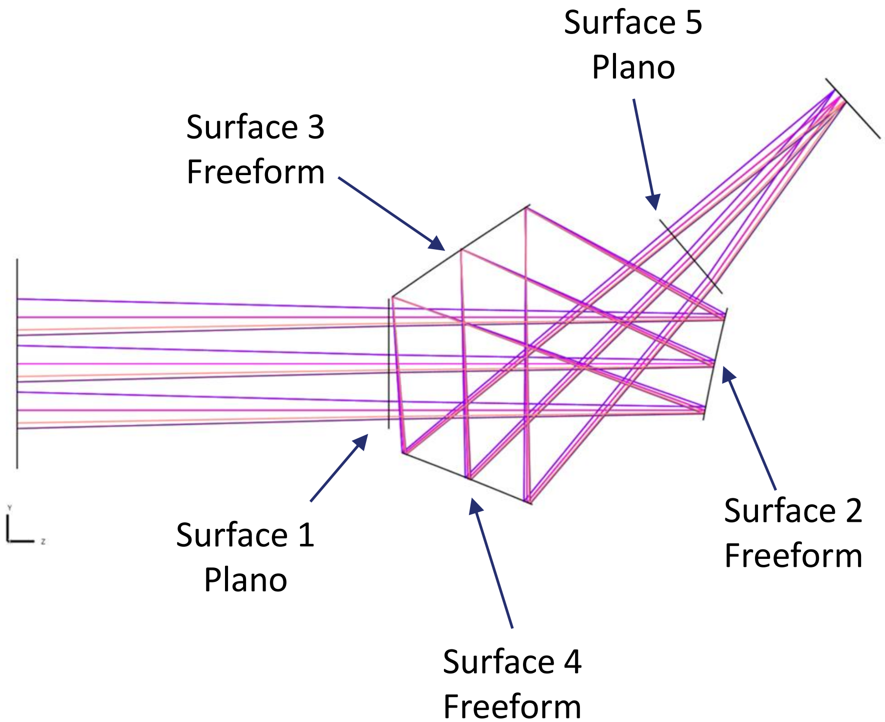




Once scattering due to MSF was reduced, we noticed periodic signature in measurement was due to CMM limitations.
Good news: the surfaces are as good as possible with CMM.
Bad news: we need a better metrology tool for this design!

OPTIMAX

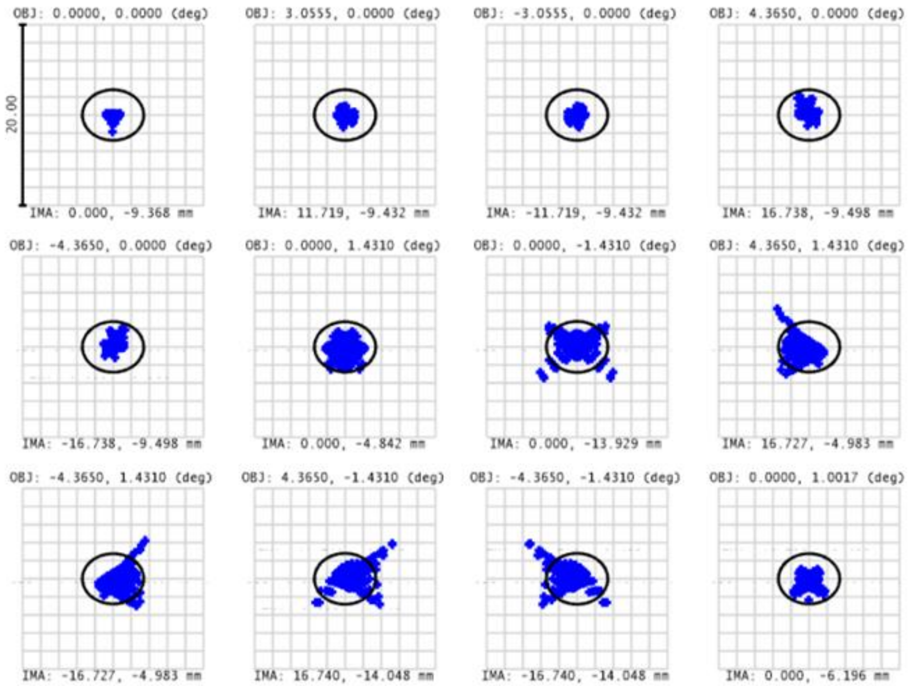
Future outlook: High Resolution Freeform Monolith



- 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

Future outlook: High Resolution Freeform Monolith



Surface: IMA

Spot Diagram

Freeform TMP SBIR
10/27/2016
Units are µm. Airy Radius: 3.054 µm

Field :	1	2	3	4	5	6	7	8	9	10	11	12
RMS radius :	0.521	0.595	0.595	0.696	0.696	1.341	1.602	1.667	1.667	1.844	1.844	0.840
GEO radius :	1.843	1.384	1.384	2.398	2.398	2.931	4.987	5.526	5.526	6.513	6.513	2.388

Scale bar : 20 Reference : Chief Ray

Zemax
OpticStudio 15

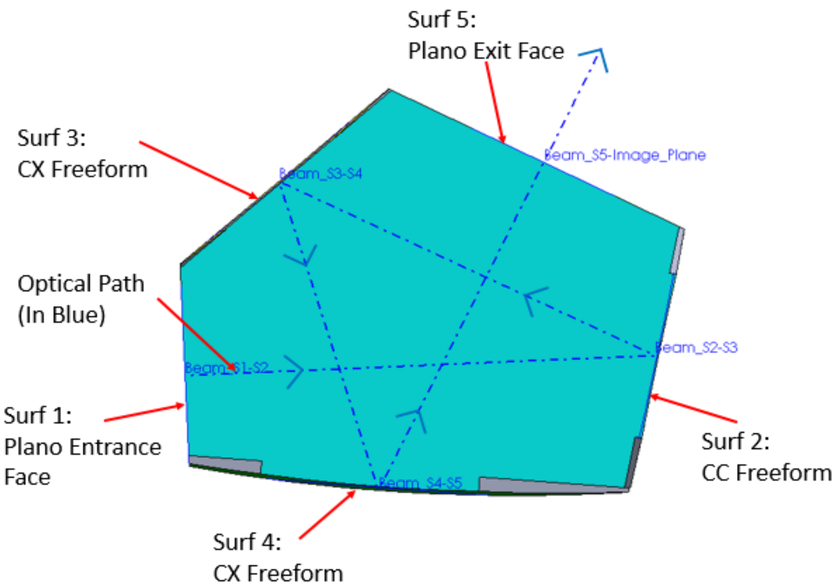
SBIR_HR_monolith_v2.zmx
Configuration 1 of 1

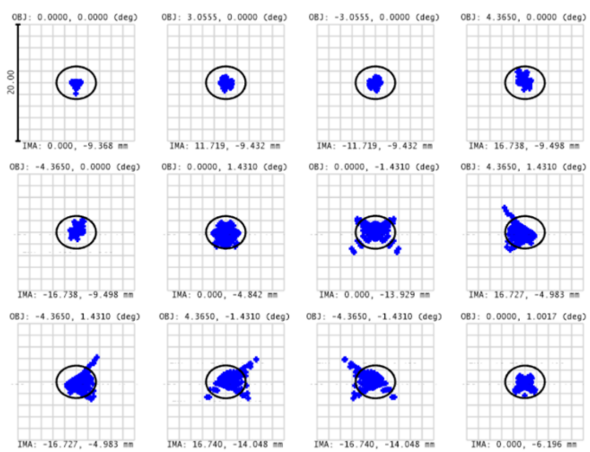
Field of view modeled at:

- ±1.4° in x-direction
- ±4.3° in y-direction

OPTIMAX

"High-resolution" monolith predicted performance – optical models

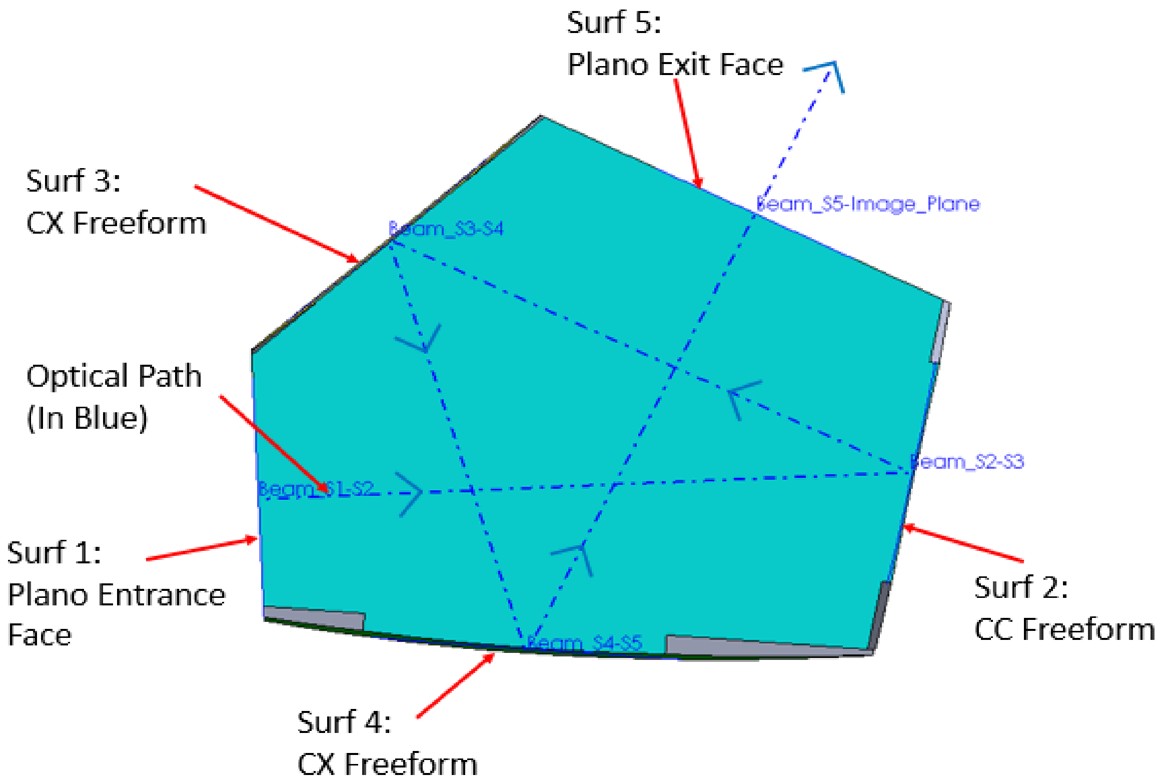


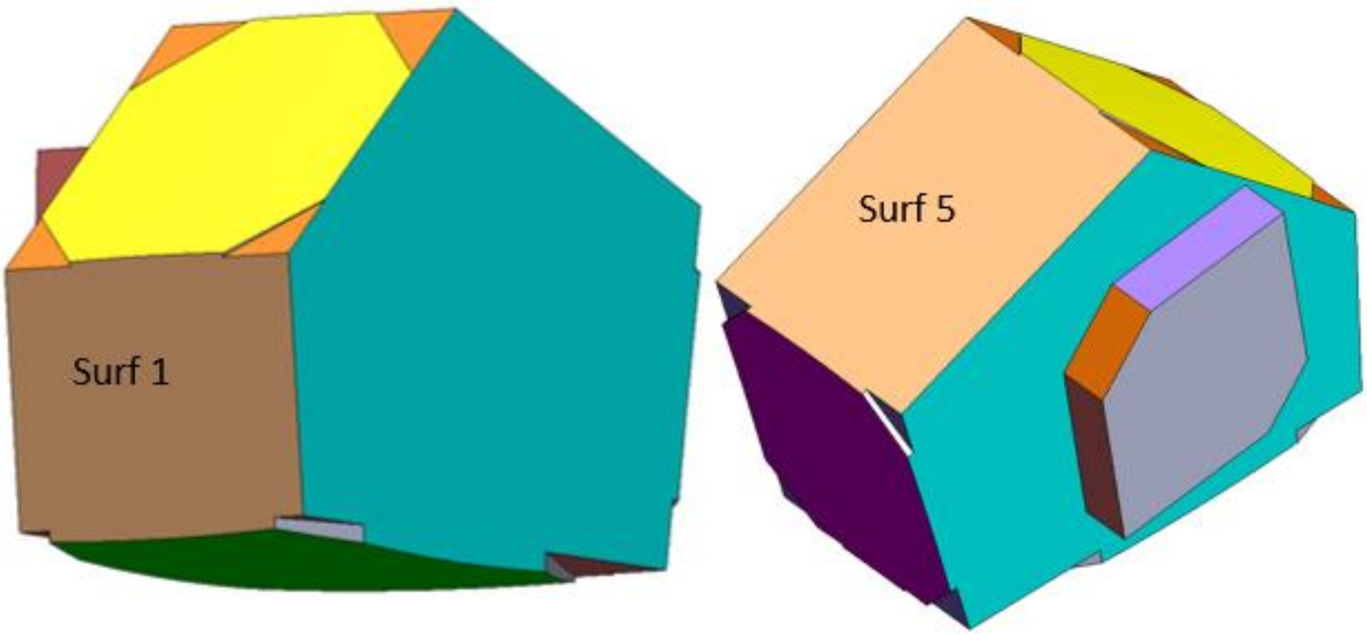


- Wide field of view:
  - ±4.3° in Y
  - ±1.4° in X
- Simulations show diffraction-limited nominal performance
- Analysis shows high sensitivity to mid-spatial frequency errors (MSF)

OPTIMAX

Surface Identification

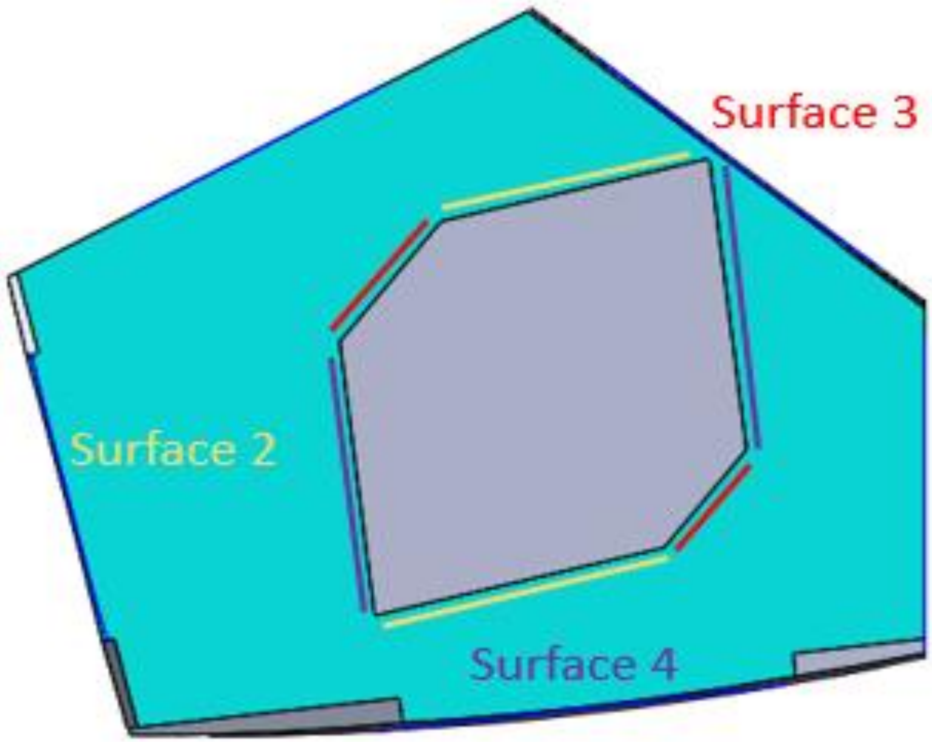




Surfaces 1 and 5 will be fully polished before generating any freeform surfaces.

All surfaces will use the side faces (shown in teal) as the y-fiducial features.

All freeform surfaces have a z-fiducial recess located in the corner region of the face.



An alignment block will be glued to the monolith and plano features will be generated at the same time as the faces.

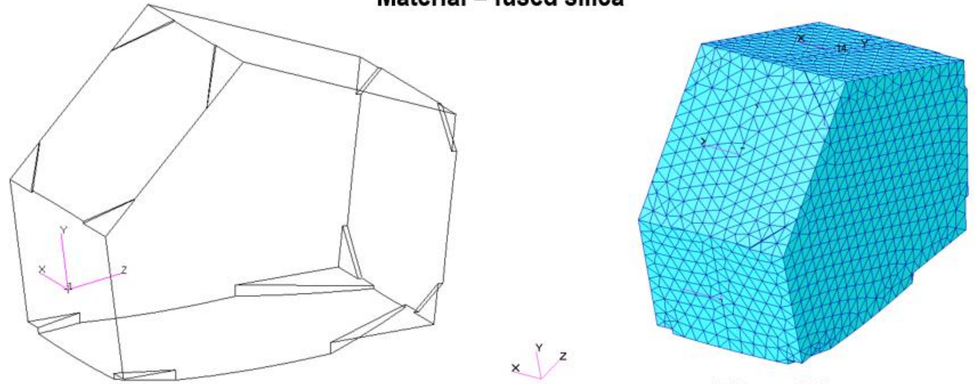
One pair of surfaces will act as the x-fiducials for each freeform surface.

A glass has been ordered and generation will begin once it arrives.

Manufacture of the "high-resolution" monoliths has just begun

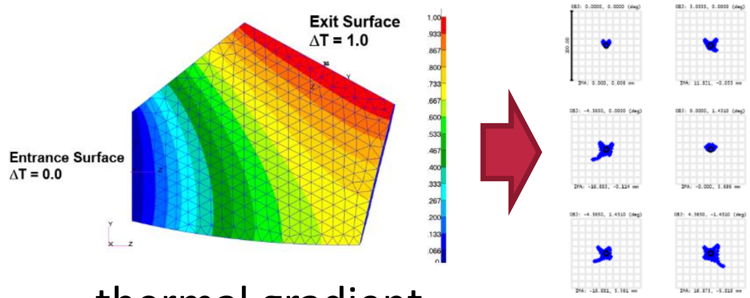
- We collaborated with Vic Genberg at Sigmadyne to model thermal and optical loading cases of interest to our NASA TPOCs

Material = fused silica

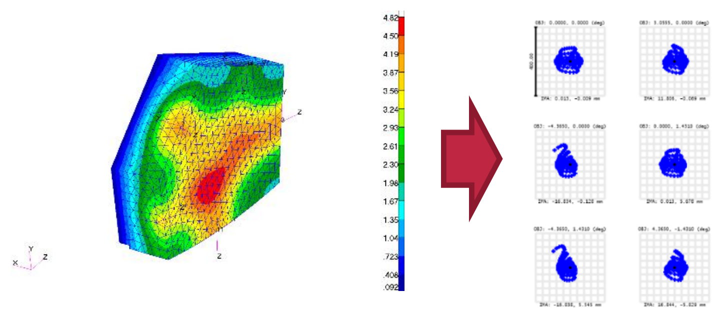


CAD

FE model
Tet10 automesh



thermal gradient



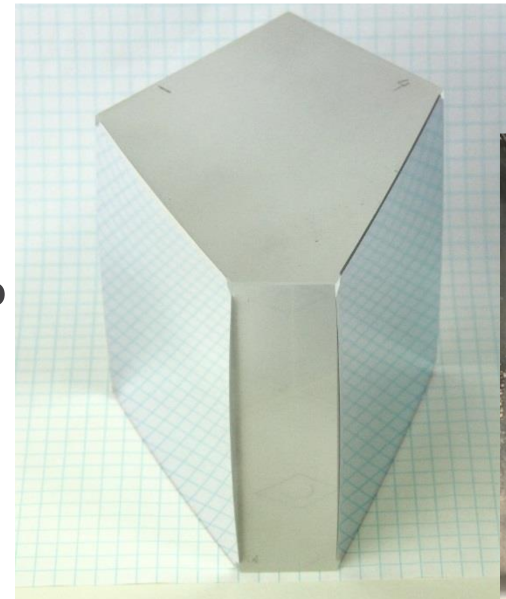
extreme laser absorption

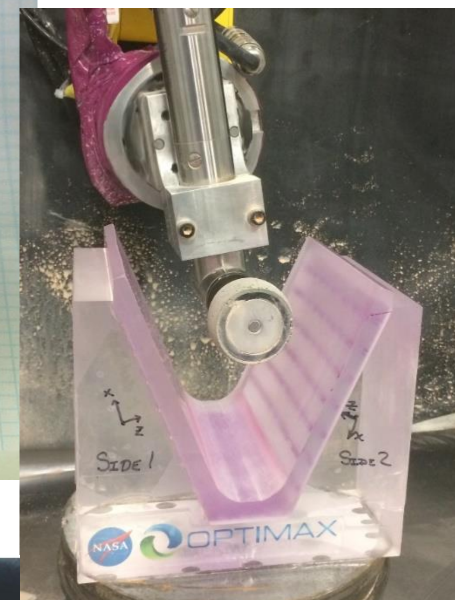
SBIR Data Rights Apply

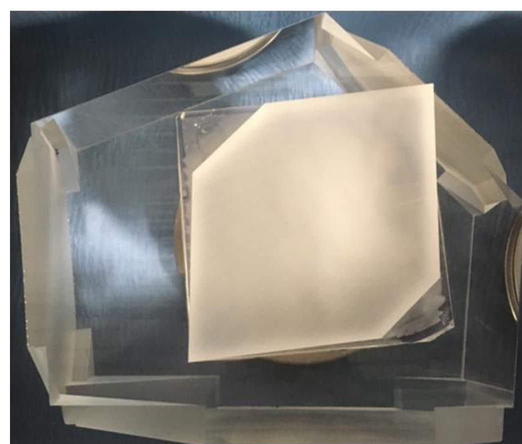
HR Monolith – surface shape generation

Monoliths open up new possibilities

- Monoliths have the ability to reduce assembly needs
- What advantages can be gained by breaking into the third plane?
- Combining with diffractives for spectral sensing
- Color correction may need to be studied in designs with refraction







OPTIMAX

Contact information:
Brian Myer
email: bmyer@optimaxsi.com
phone: (585) 265-1020
www.optimaxsi.com