Freeform Monolithic Multi-Surface Telescope Manufacturing
NASA Mirror Tech Days
15 November 2017

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Optimax Overview

- Founded 1991
- Ontario NY
- 65,000 ft² facility
- 280 employees
- ISO 9001:Certified
- ITAR compliant
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 Overview
Markets We Serve

- Semiconductor
- Aerospace & Defense
- Commercial
- Medical
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.
Both freeform surfaces are defined by \( xy \) polynomials of the same form:

\[
f(x, y) = c_1 x^2 + c_2 y^2 + c_3 x^2 y + c_4 y^3 + c_5 x^4 + c_6 x^2 y^2 + c_7 y^4
\]

- 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
Standard Freeform 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.
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
Monolithic Telescopes *Require* Tactile measurements

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 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.
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
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 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)
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
Lightweight, LW, or “open jaw” Monolith

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

Difficulty modeling imaging performance with as-built errors. Optical bench test monitors spot size and provides validation to predictive models.
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!
Future outlook: High Resolution Freeform Monolith

- 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

- $\text{efl} = 223\ \text{mm}$
- $f/4$
Future outlook: High Resolution Freeform Monolith

Field of view modeled at:
• $\pm 1.4^\circ$ in x-direction
• $\pm 4.3^\circ$ in y-direction

Surface: IMA

Spot Diagram

Zemax
OpticStudio 15

SBIR_HR_monolith_v2.zmx
Configuration 1 of 1
“High-resolution” monolith predicted performance – optical models

- Wide field of view:
  - $\pm 4.3^\circ$ in Y
  - $\pm 1.4^\circ$ in X

- Simulations show diffraction-limited nominal performance

- Analysis shows high sensitivity to mid-spatial frequency errors (MSF)
Surface Identification

Surf 1: Plano Entrance Face

Surf 2: CC Freeform

Surf 3: CX Freeform

Surf 4: CX Freeform

Surf 5: Plano Exit Face

Optical Path (In Blue)
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
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
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