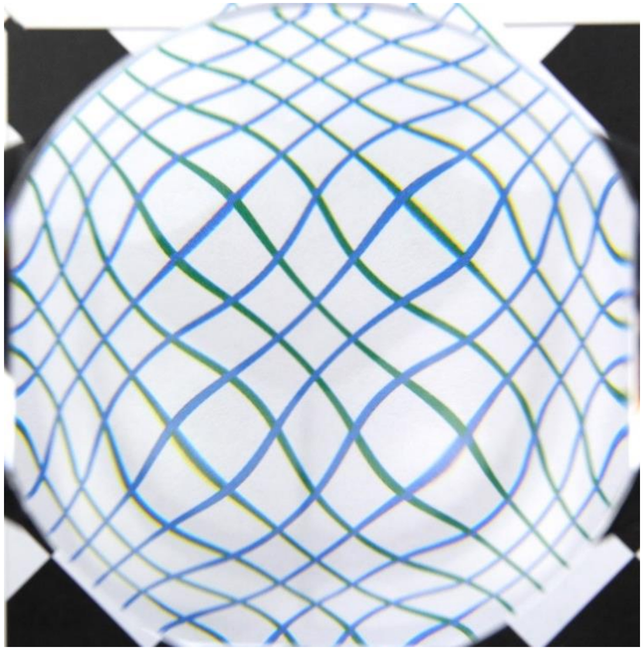


Freeform Advances at Optimax: Manufacturing and Measurement

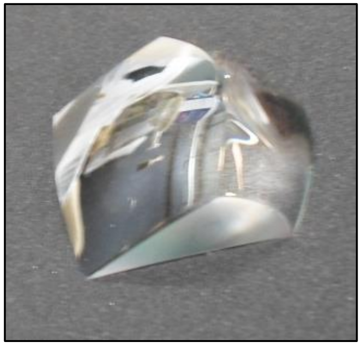
Presented By:
Todd Blalock, Kate Medicus, Brian Myer, Jessica DeGroote Nelson

November 2015 NASA Mirror Tech Days

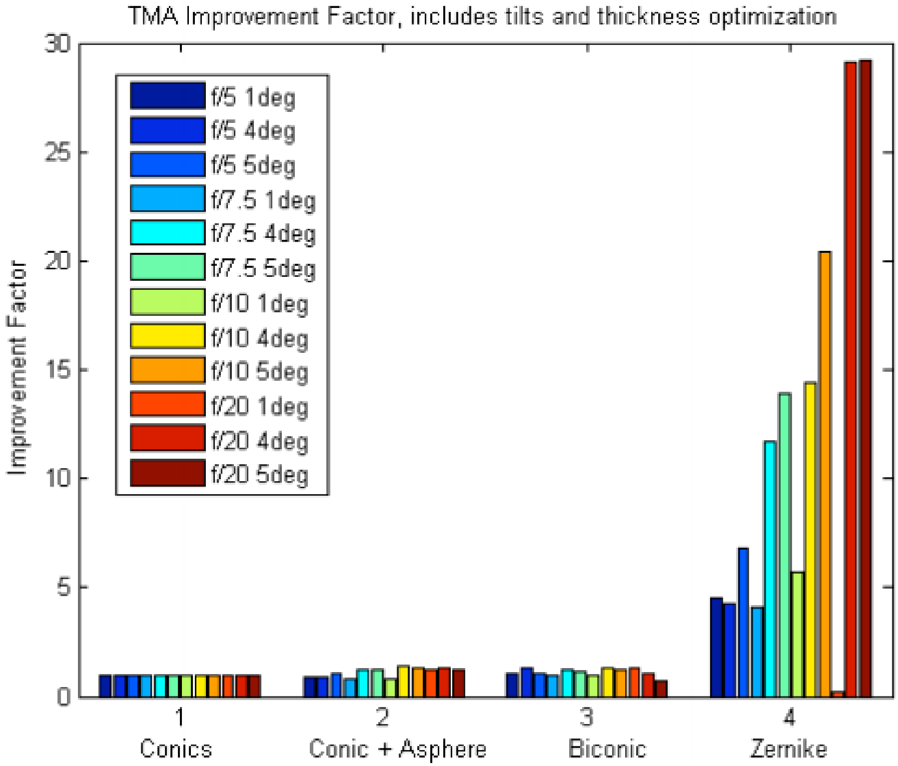
Prototype Optics In One Week

Freeforms are desirable optical components

- Lighter weight
- Reduced number of components
- Reduced aberrations



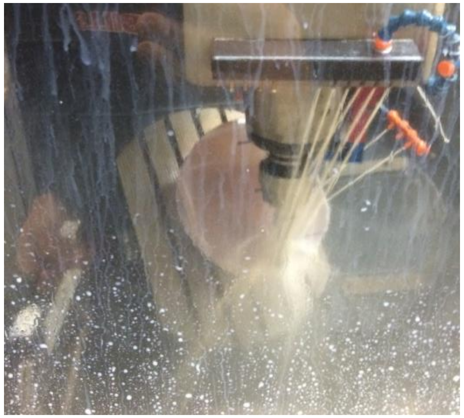
- Off-axis asphere
- Toroids, biconics
- Polynomial functions
- Anamorphic equations
- Zernikes
- Other equation based models
- Solid models

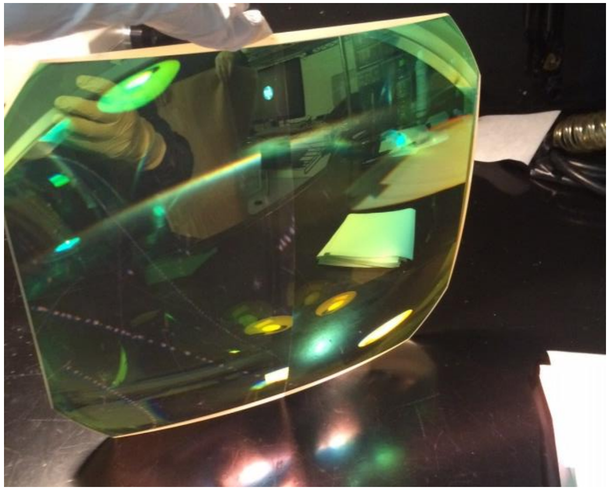


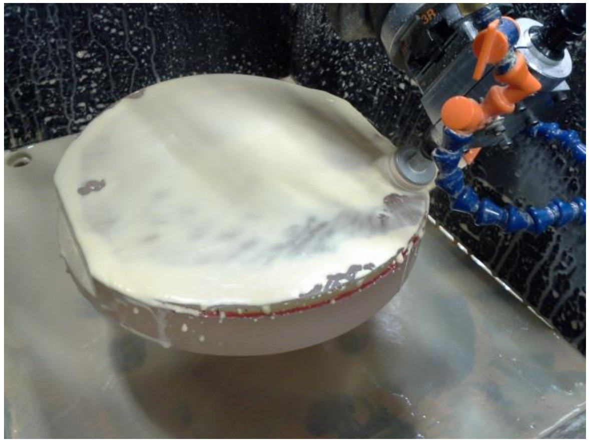
J M Howard and S Wolbach, "Improving the performance of three-mirror imaging systems with Freeform Optics," OSA Freeform Optics Conference, November 2013

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



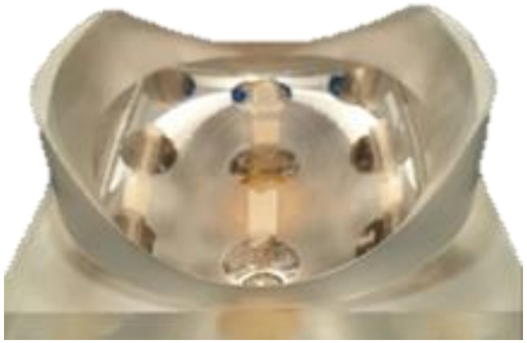


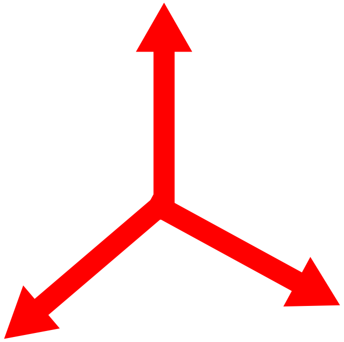


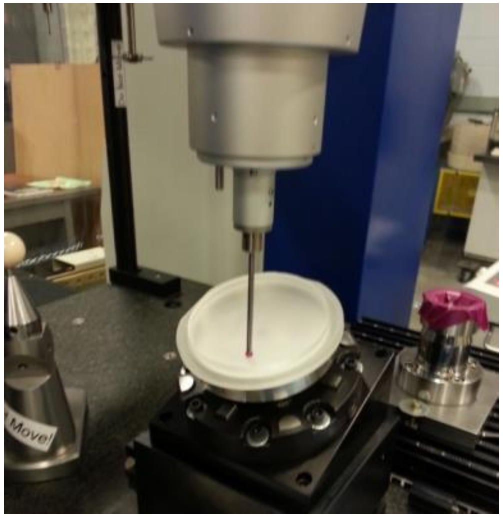
Challenges in Freeform Manufacturing

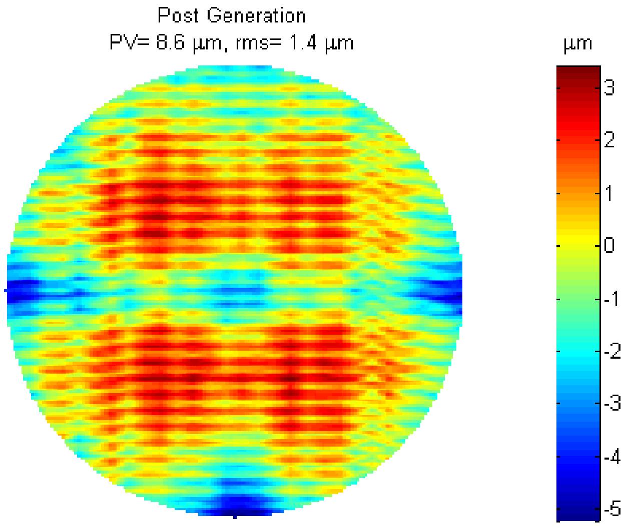
What makes freeform manufacturing hard?

- Machine control and access
- Coordinate system referencing
- Measurements
- Mid-spatial frequency errors



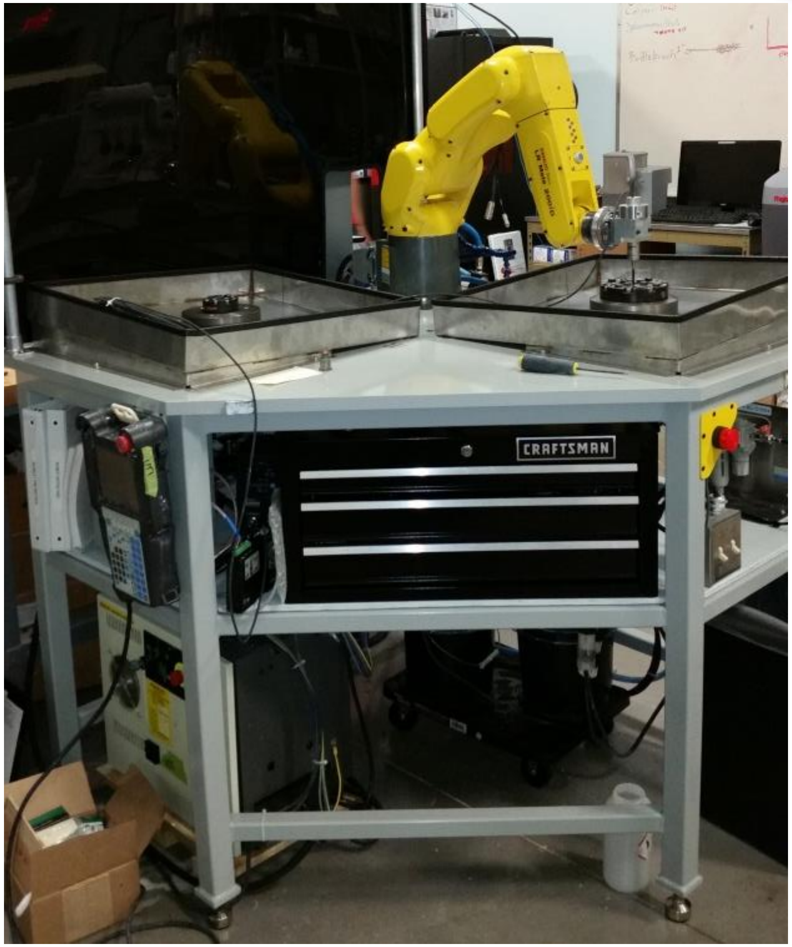






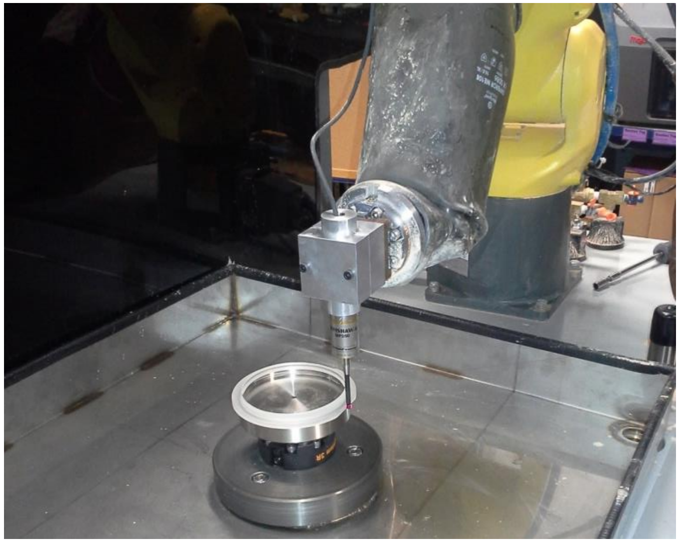
Challenges: The Platform

- Robotic deterministic polishing platform
- Developed specifically to address challenges associated with manufacturing of freeform optics
- Uses a dwell-based correction algorithms
- The flexibility of the platform allows us to lap, polish, and smooth parts all on one machine



Challenges: The Platform

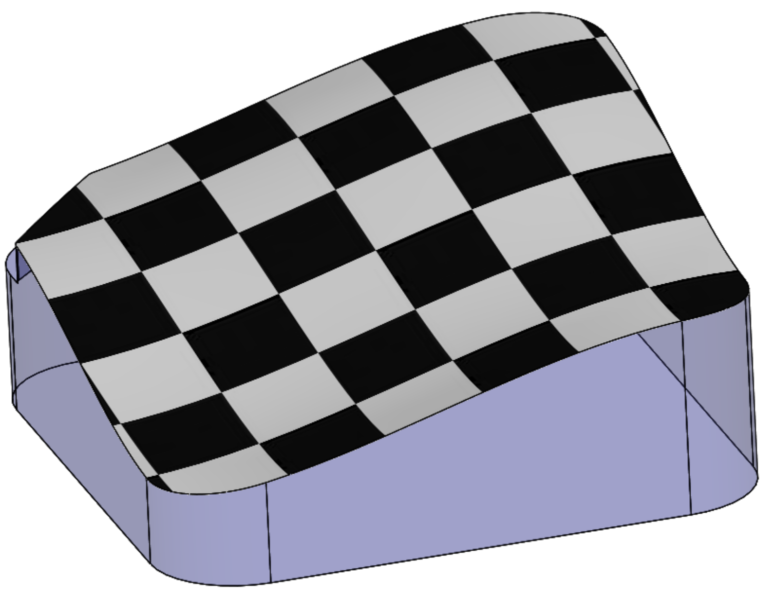
- High torque tooling spindle
- Integrated touch probe capabilities
- Custom machine base with both stationary and precision rotary mounts

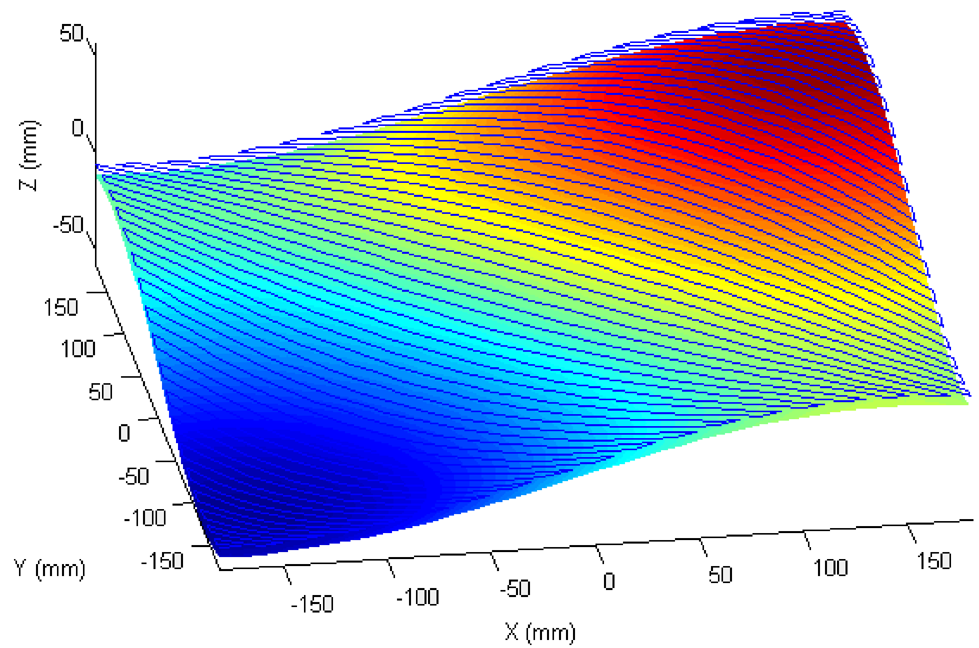


Challenges: The Platform

In-house software development gives us the flexibility to work with unique freeform geometries

All software development is done in-house and can be customized to account for a variety of complex surface definitions





Challenges: The Platform

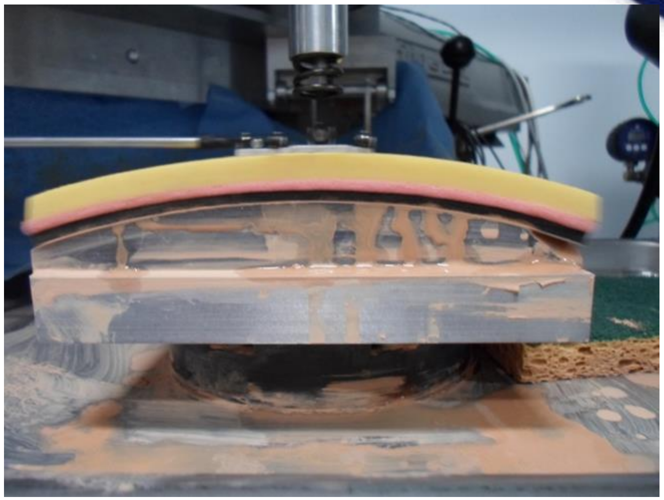
The robotic platform gives us the flexibility to accurately track along unique freeform geometries

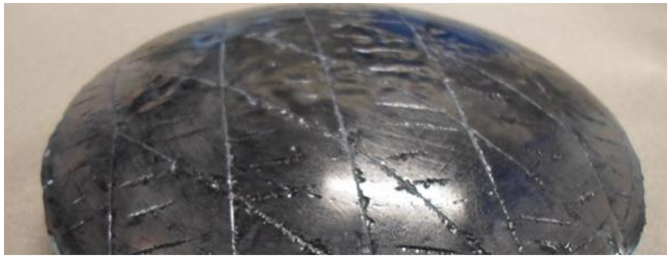
Challenges: Mid-spatial Frequency Error

- Because freeforms are made using sub-aperture polishing, mid-spatial frequency error is likely
- Compliant full aperture polishing can be used to smooth the MSF errors

SN1: Not smoothed

SN2: Smoothed

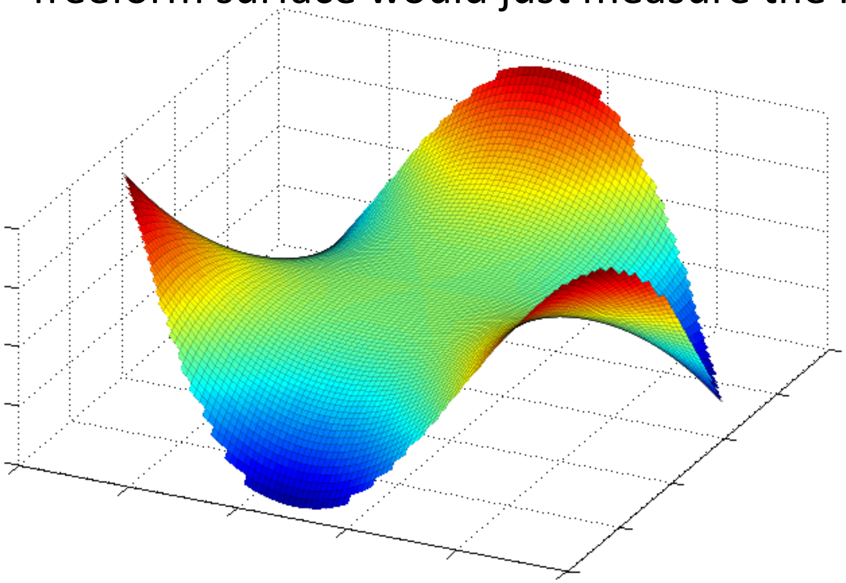


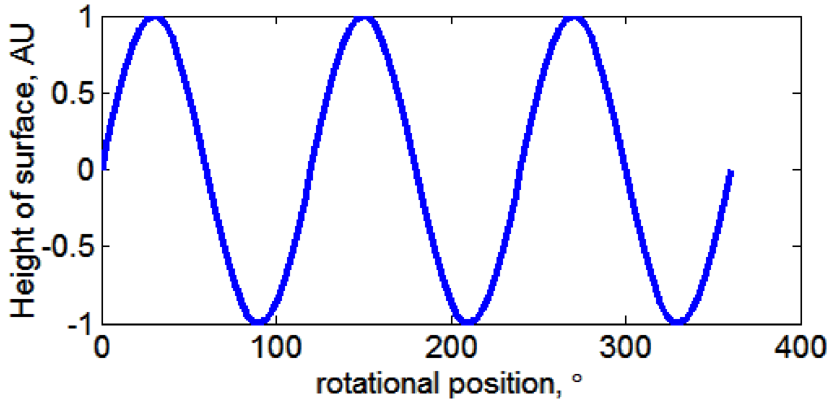


Challenges: Coordinate System Referencing

With freeform surfaces, there is no clear method to reference the location of the freeform surface relative to the other surfaces on the optic.

Wedge Example: Placing an indicator on the edge of a freeform surface would just measure the nominal shape

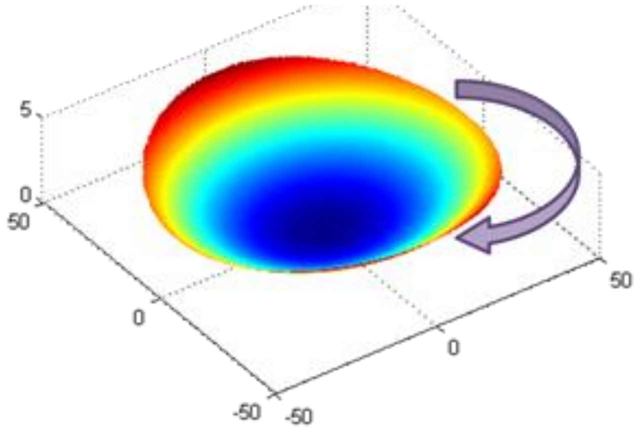


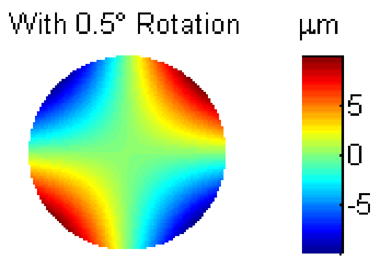


Challenges: Coordinate System Referencing

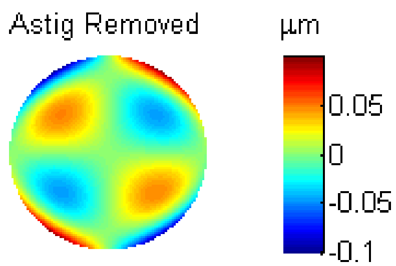
Also, it is difficult to separate out form error from misalignment in measurement due to incorrect coordinate system referencing

- A 0.5° rotational error in measurements
- 100 mm diameter biconic
- Error is 19 µm PV astigmatism and 0.2 µm higher order error





19 µm PV, 3.9 µm rms

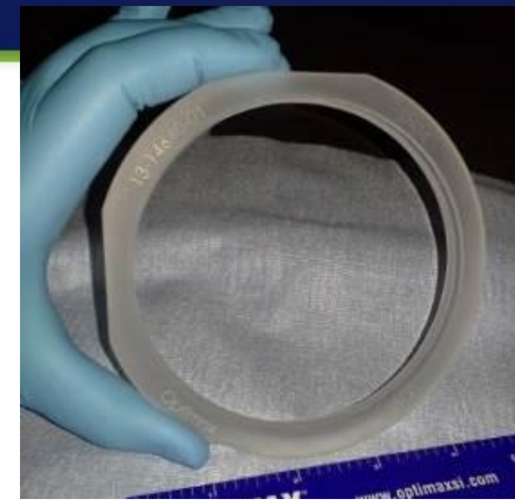


0.2 µm PV, 0.03 µm rms

Rx = 333.5 mm, kx = 1.1, Ry= 243.50 mm, ky = 1.3

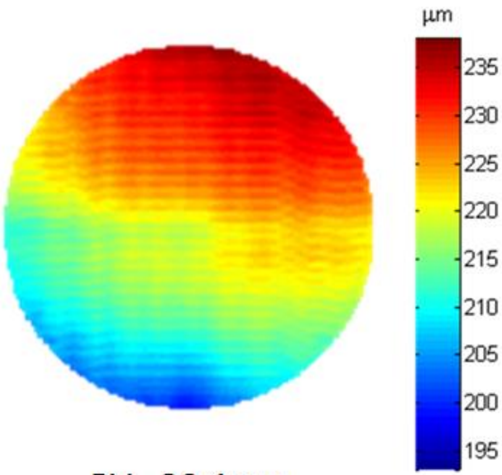
Challenges: Coordinate System Referencing

Freeforms should be manufactured with fiducials to clearly define the part coordinate system for manufacturing and measurement



Concave biconic

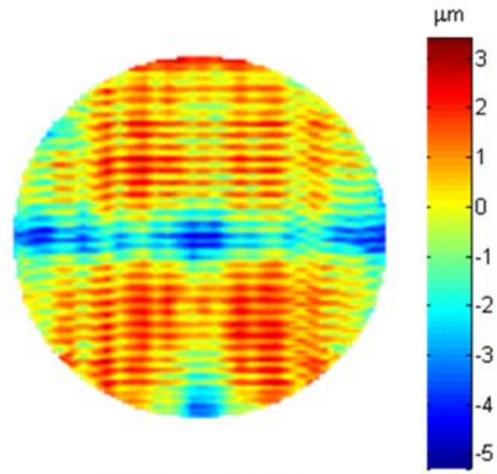
Measured Relative to the X,Y,Z Fiducials



PV= 39.1 µm

93 mm Ø

Measured Best Fit to the Surface



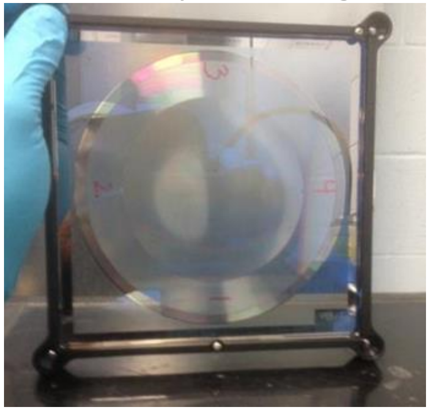
PV= 8.1 µm

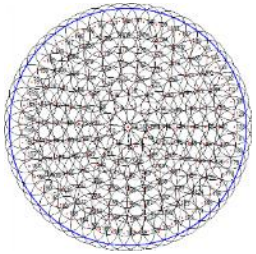
Z-offset shows the part is thick

Challenges: Measurement of freeform surfaces

Point/Trace Methods
- Traditional tactile probe scanning coordinate measuring machines: CMMs
- Non-traditional CMMs with rotation axes and optical non-contact probes
- Profile measurements

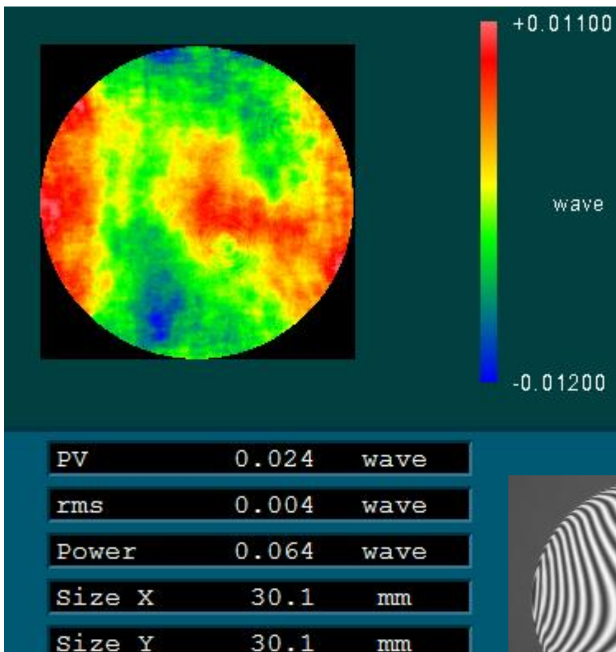
Interferometric Methods
- Computer generated holograms, CGHs
- Straight shot interferometer is possible when slope of freeform departure from a best fit sphere is small (<~30 µm)
- Sub-aperture stitching interferometry is being developed for freeforms

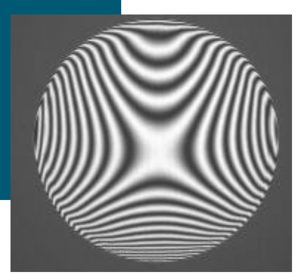




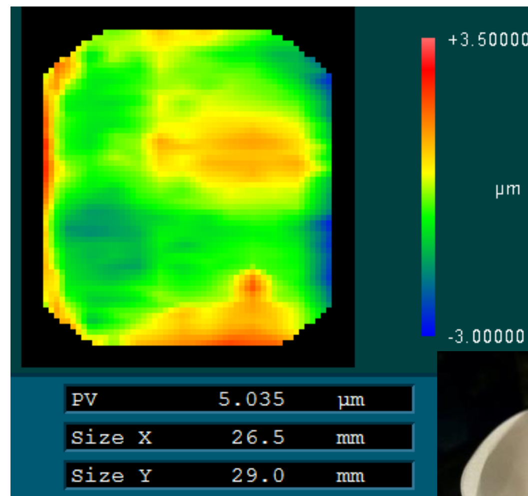
Measurement method dictates achievable form error (irregularity)

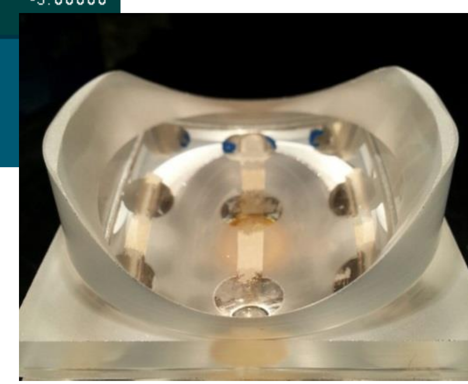
- Interferometric Example
  - Off-axis parabola (OAP)
    - 30 mm CA
    - $\lambda/40$ PV irregularity





- CMM Example
  - Anamorph
    - 26 x 29 mm CA
    - 5 µm PV irregularity



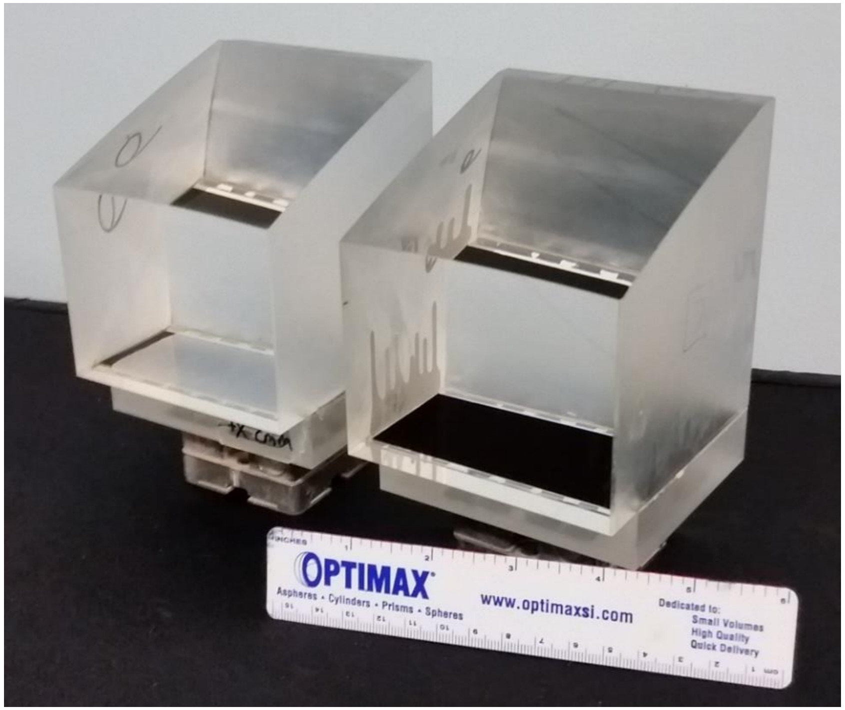


Development Projects

Manufacturing Monolithic Freeform Optics

Freeform Measurements:

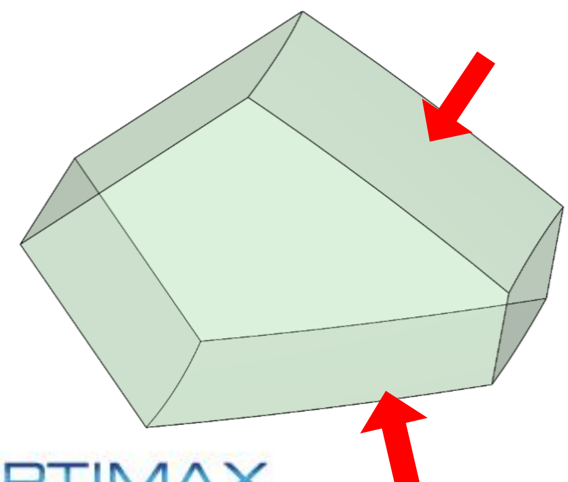
- Self Referencing Referenced Single Point Probing
- Fringe Reflection Deflectometry

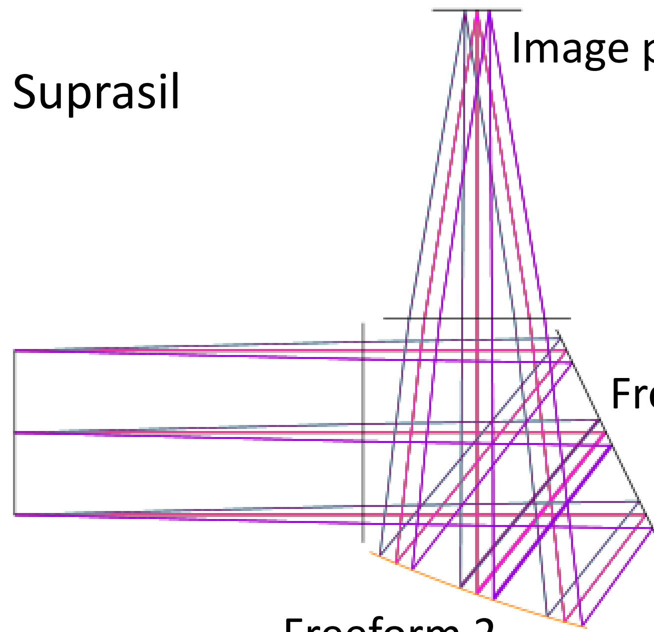


Development Project: Multi Surface Freeform Monolithic Optic

Monolithic optics have promise to reduce assembly need and improve stability

- Four surface: two plano, two freeform
- Plano surfaces are used to create a fixed coordinate system
- About 100 mm cubed
- Fused Silica
    - One of standard quality
    - One of extremely high quality Heraeus Suprasil

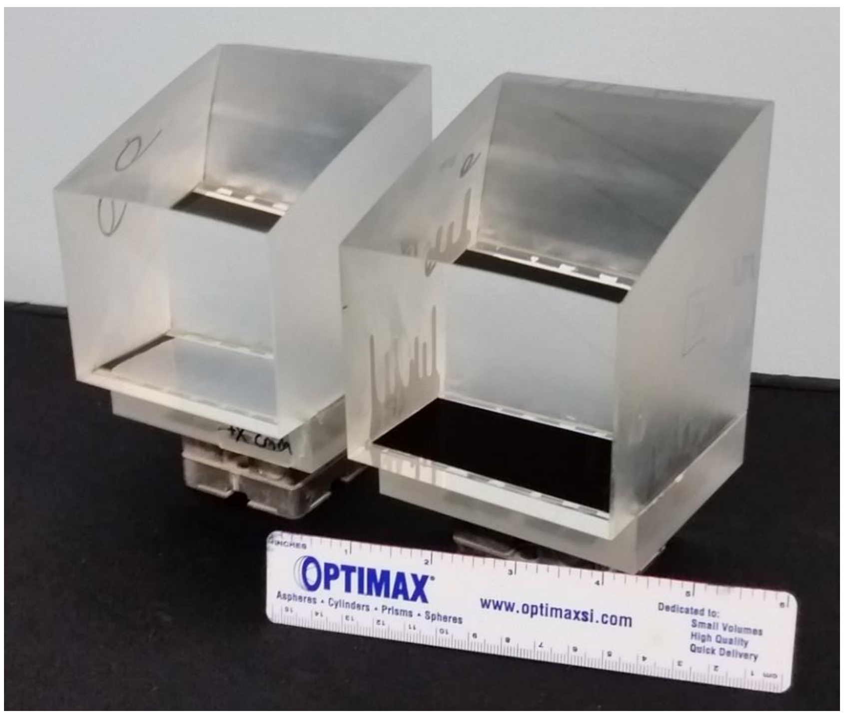


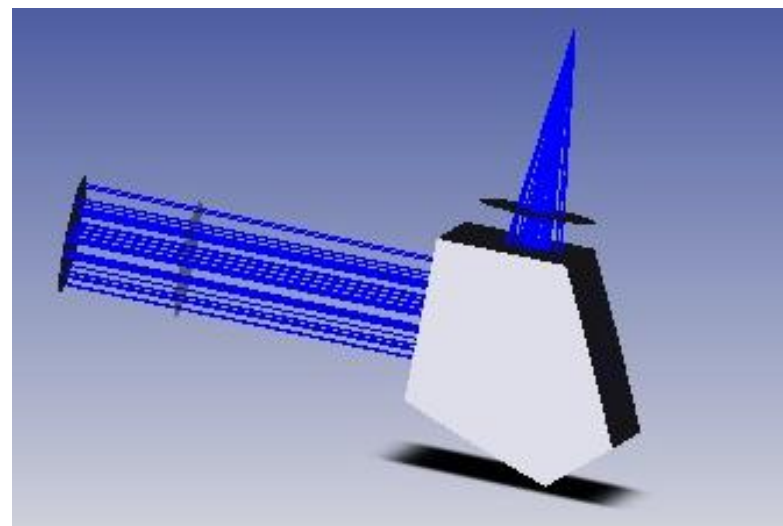


Multi Surface Freeform Monolithic Optic

- Freeform surfaces defined with polynomial X,Y function up to 4th order
- Surface deviations from a best fit sphere is 120 µm and 130 µm

$$Z = AX + BY + CX^2 + DXY + EY^2 + FX^3 + GX^2Y + HXY^2 + IY^3 + JX^4 + KX^3Y + LX^2Y^2 + MXY^3 + NY^4$$

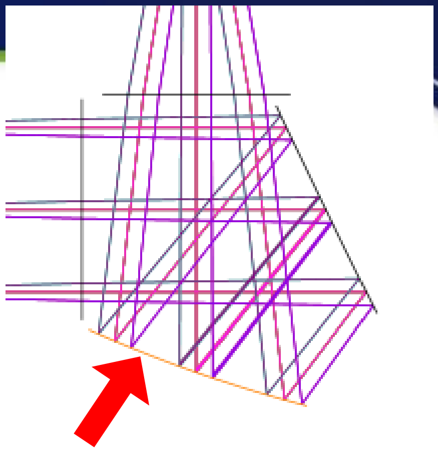




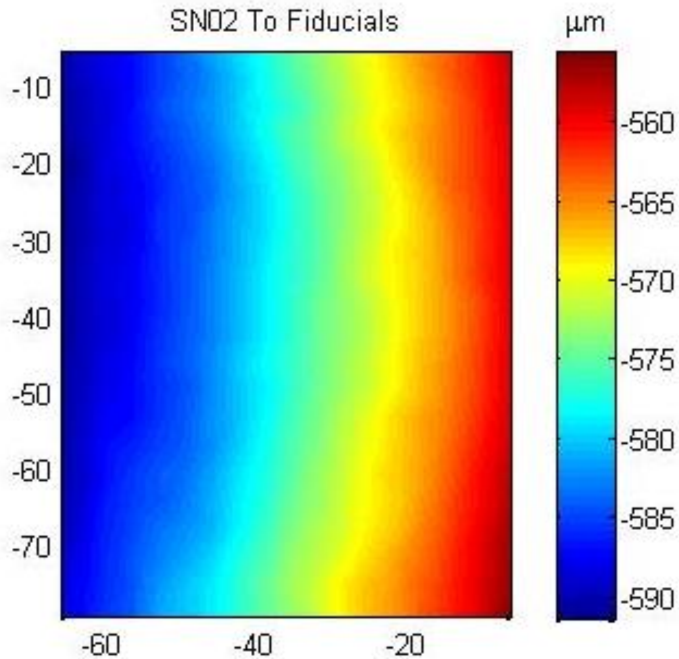
Multi Surface Freeform Monolithic Optic

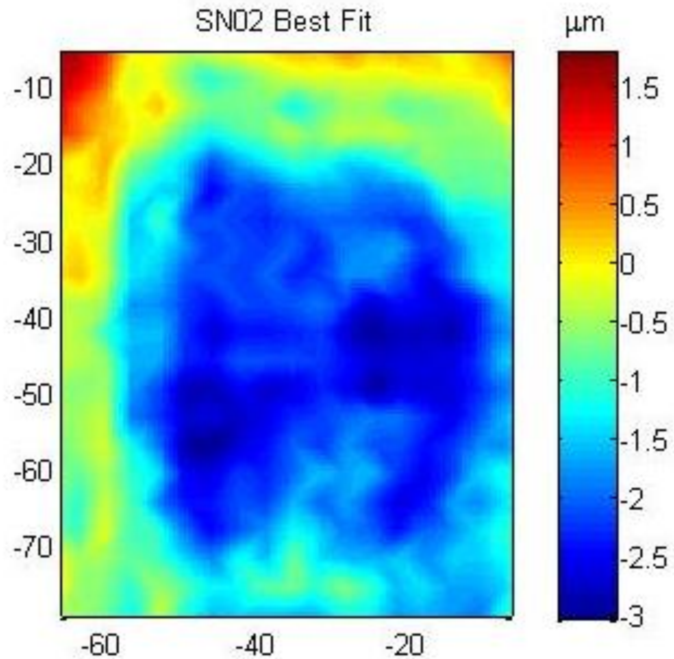


SN02: Freeform Surface 3 is finished



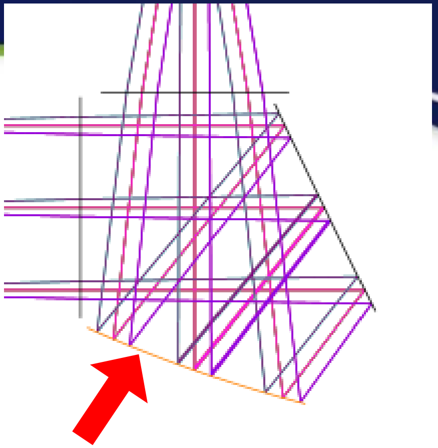
- Standard Quality
- Plano surfaces are complete and polished
- Freeform surface 3 is complete
- Best-Fit PV is 4.8 µm
- Overall surface is thin, 0.57 mm
- About 35 µm tilt

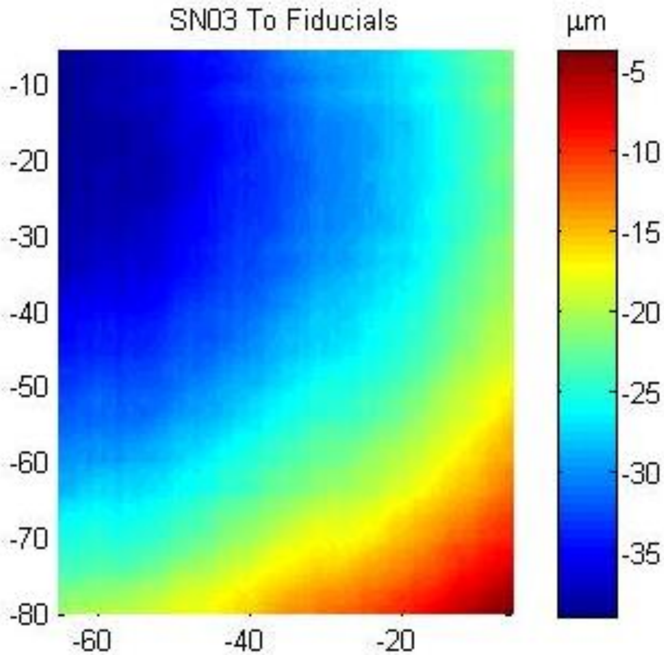


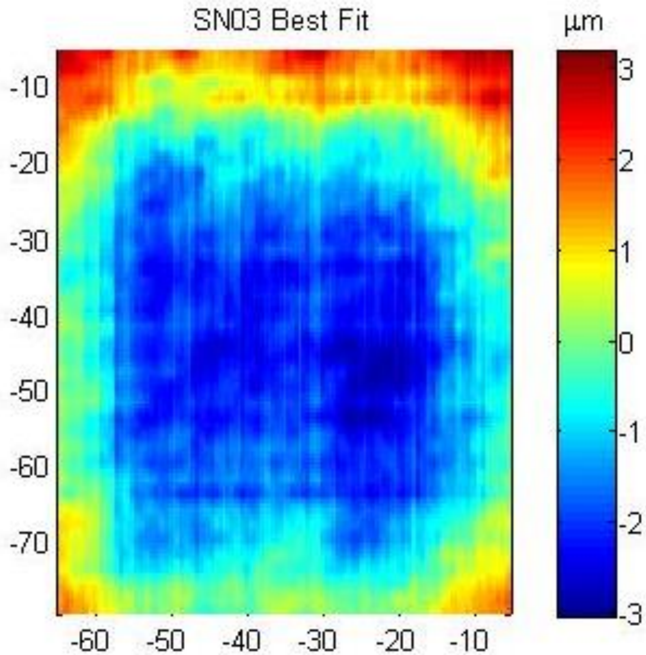


SN03: Freeform Surface 3 is almost finished

- High quality fused silica
- Plano surfaces are complete and polished
- Freeform surface 3 is probably now complete
- Best-Fit PV is 6.2 µm
- Within thickness tolerance
- About 35 µm tilt







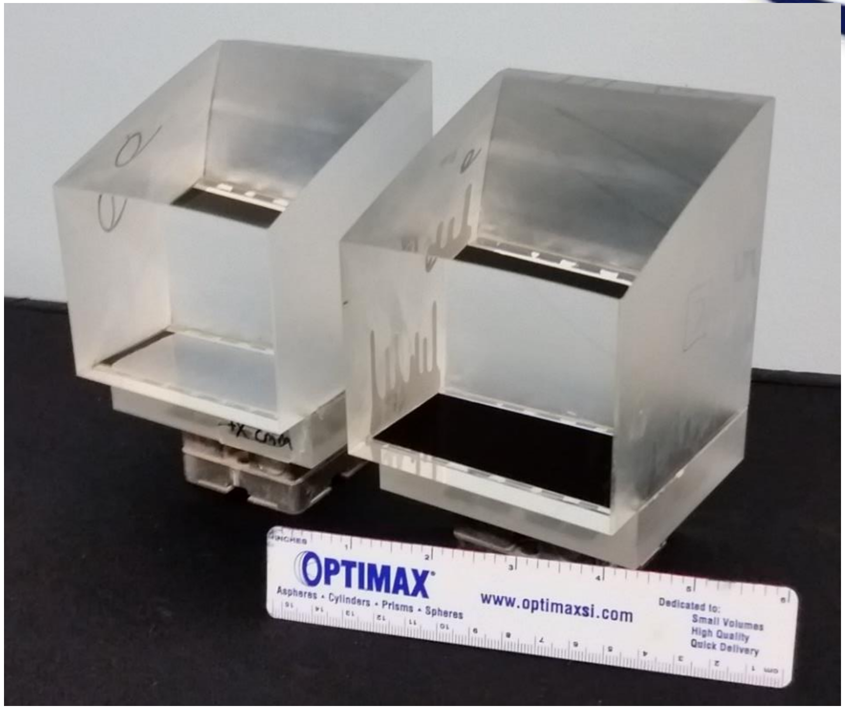
OPTIMAX

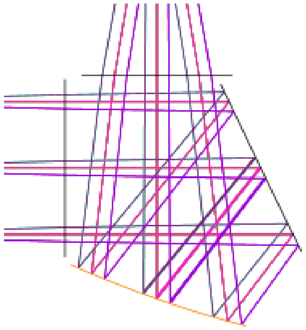
Multi Surface Freeform Monolithic Optic

Next steps

- Polish freeform surface 2
- Mirror coat freeforms
- Test wavefront error and PSF
- Figure correct plano surface(s) to improve wavefront error

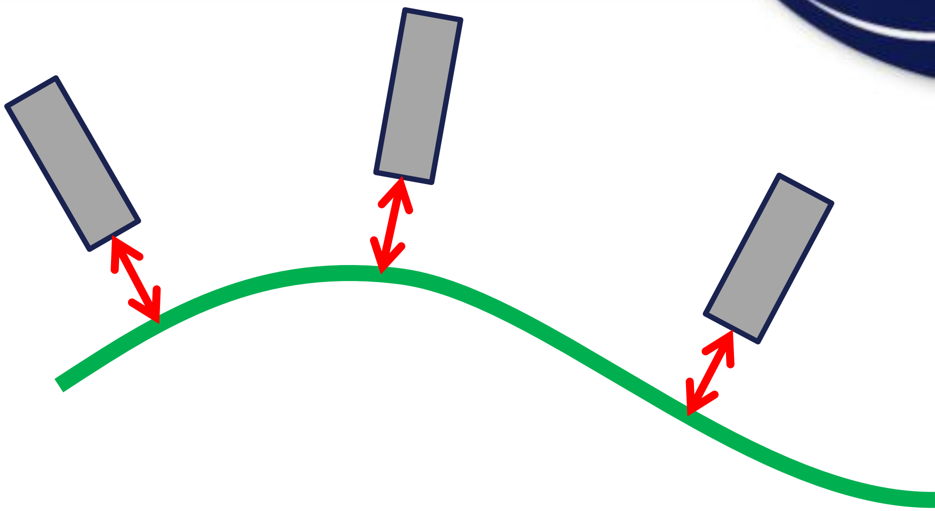
- Coordinate system referencing is critical
- Next versions will have tighter tolerances on the surface to surface error



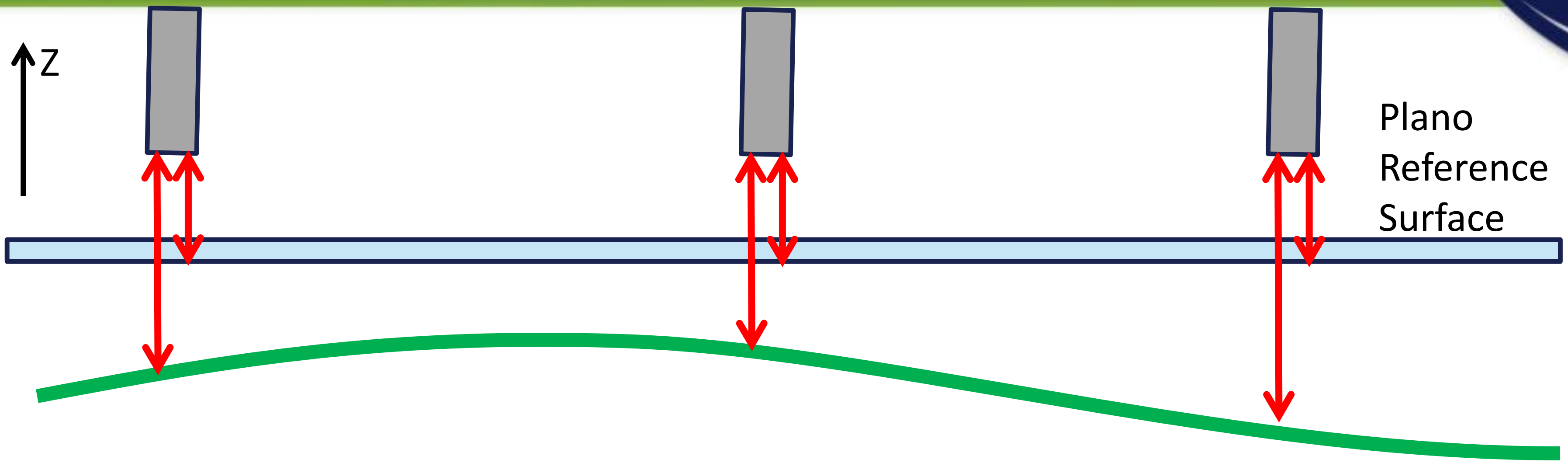


Development Project: Self Referencing Single Point Probing Surface Measurements

- Measurements of surfaces using single point polishing typically require movement in 5 degrees of freedom
- Leads to difficulties in separating error motions and surface figure error
- Using a reference surface can reduce this error



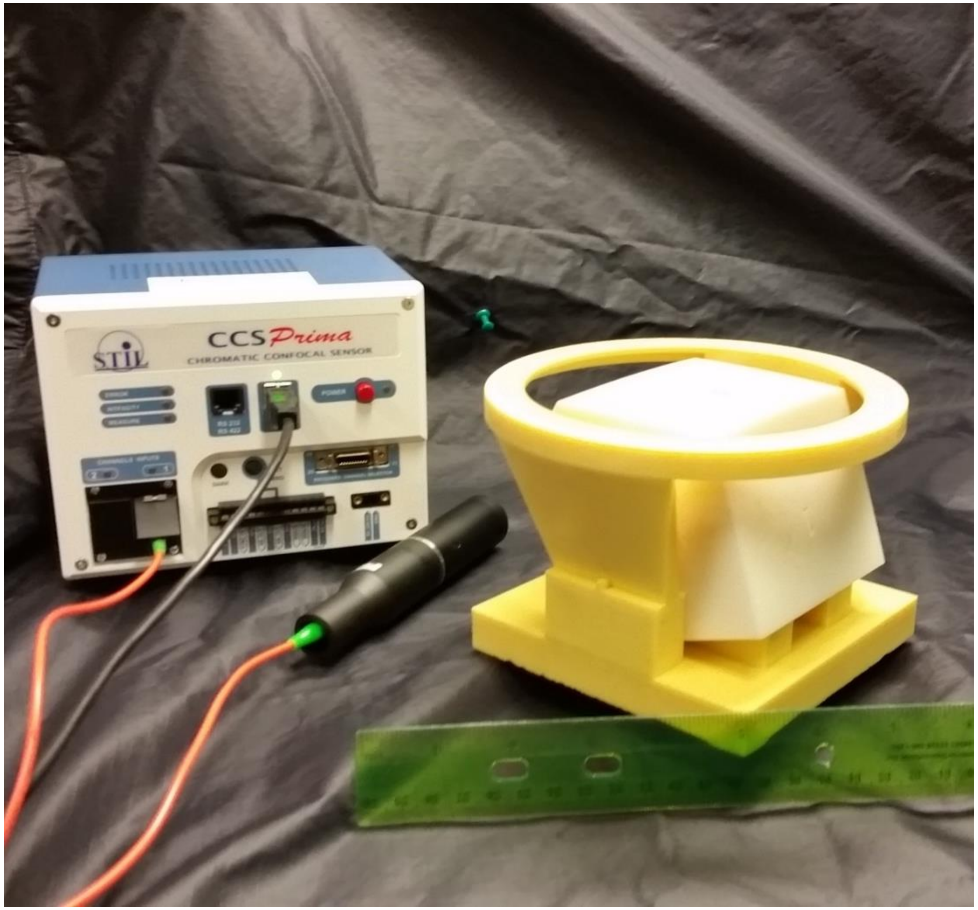
Development Project: Single Point Probing Surface Measurements



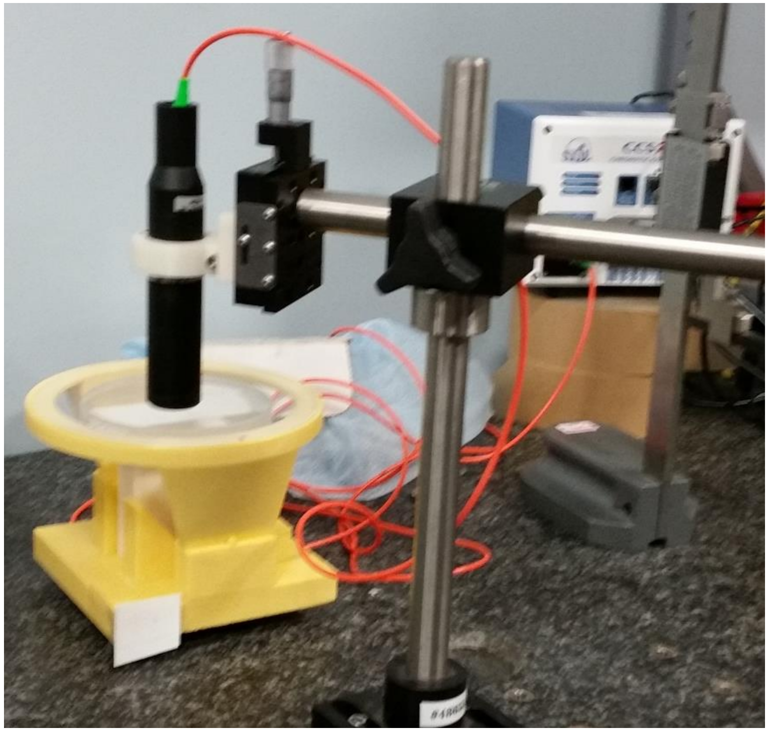
- Chromatic confocal probe can detect multiple surfaces
- Measures distance between reference surface and test optic
- Eliminates errors due to error motions in the Z direction
- Errors in x,y are still a factor, but this is much less critical
- Significant limitations for part's sag and slope
- Both monolithic freeform surfaces will be measurable with our setup

OPTIMAX

Initial Measurements are just being started

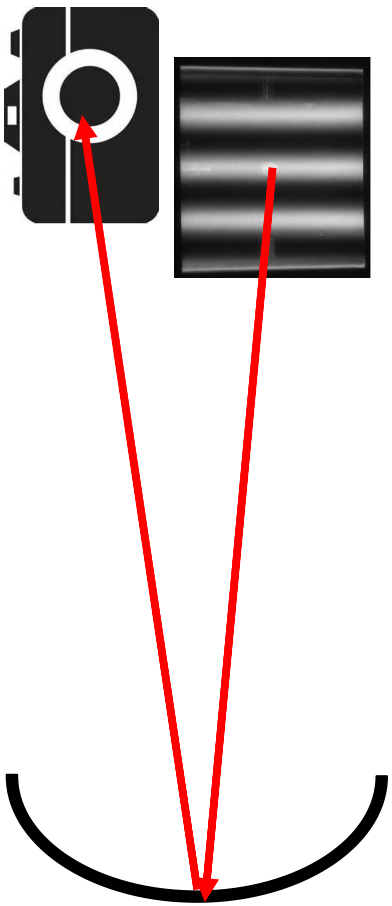


Wafer calibration with an optical flat



Development Project: Fringe Reflection Deflectrometry Measurement

We set out to answer the applicability of this technology to in-process inspection of freeform optics.



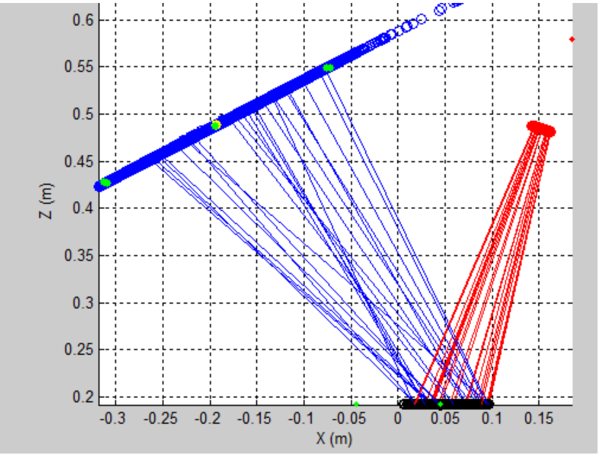
- Used in automotive glass and body parts
- More limited basis for telescope mirrors, solar concentrators
- Imaging system views pattern reflected from or projected on the test surface
- Distortion or "deflection" of the pattern is used to derive surface slopes.
- To test:
  - Materials
  - Ground/Polished
  - Mirror Coated/Uncoated
  - Max slope
  - Part Fixturing
  - Apertures

OPTIMAX

Measured position of components to build geometric model

The geometry of the camera, part and target must be calibrated in 6 DOF.

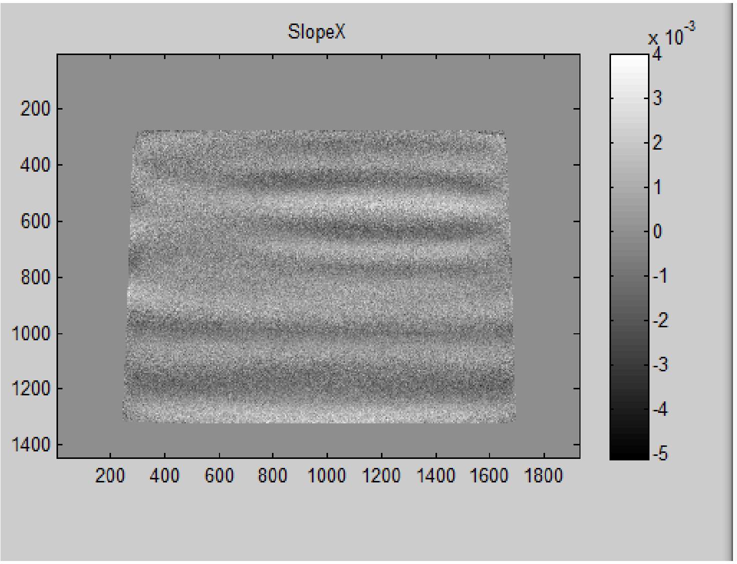
Deflectometry can either give relative slope or absolute shape, depending on how well the geometry is calibrated. To determine absolute surface shape a world coordinate origin, or a measurement between target and part is needed.

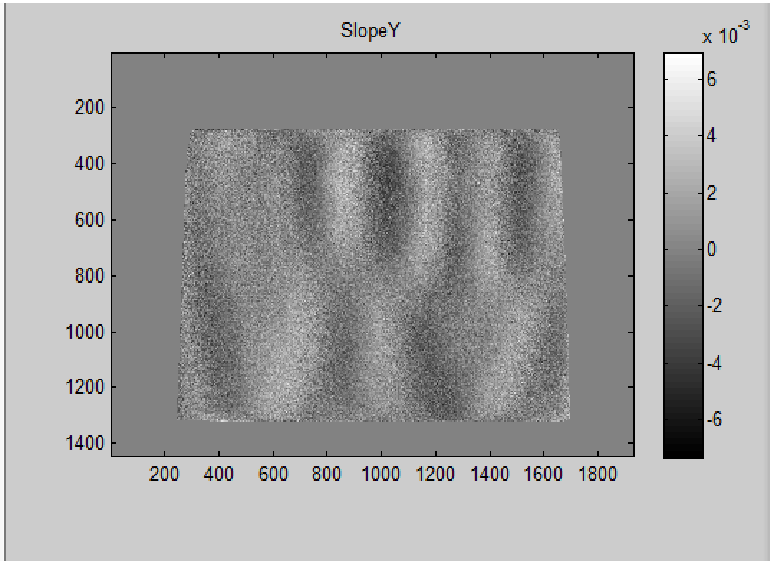


OPTIMAX

Currently limited to milliradians, desired is microradians

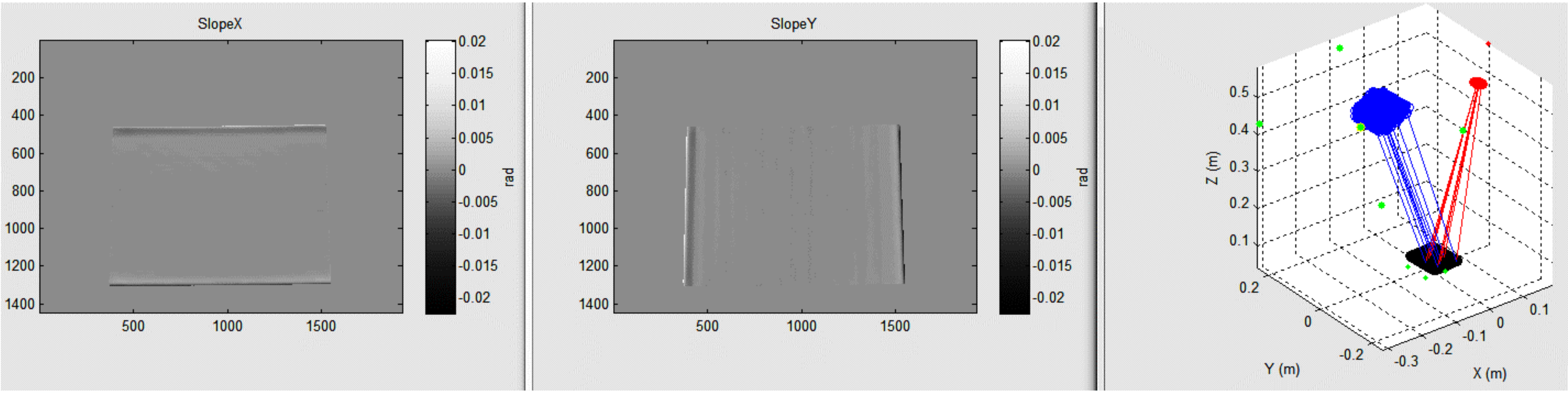
- Systematic noise in the milliradian range
- Source of waviness is probably Moire patterns between the LCD screen and the camera pixels
- Hardware improvement is upcoming in the near future
- Still possibilities for system subtraction





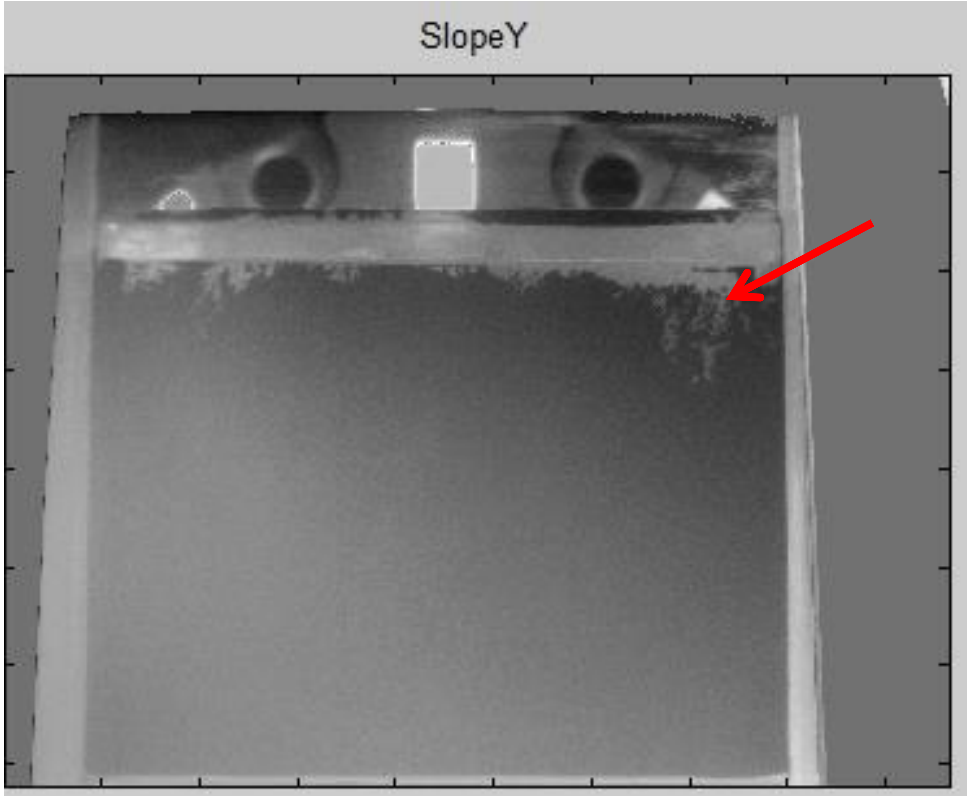
Measurement of Freeform Surface shows rolled edges

- Even with the waviness noise, the rolled edges were seen
- Internal mounting features caused some errors



OPTIMAX

Very Sensitive to Part Condition



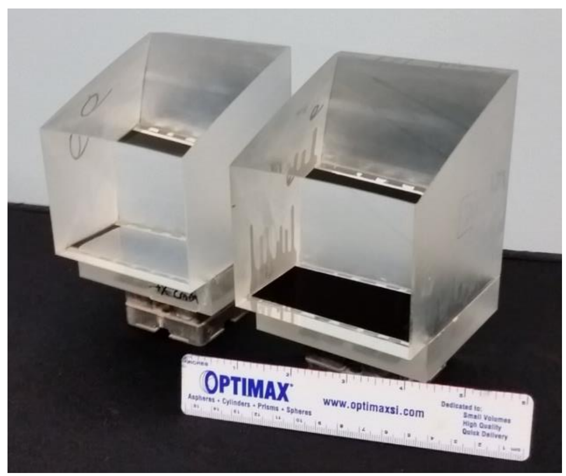
For a glass substrate, all non-measured surfaces must be painted black

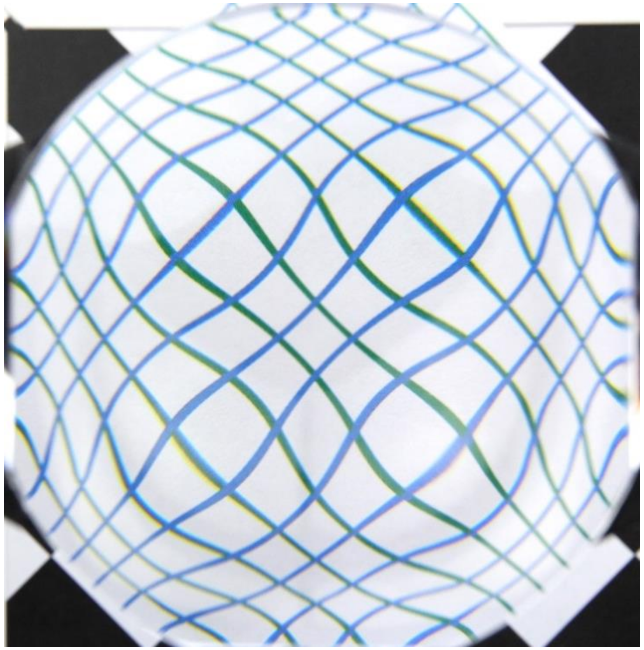
Mounting components can cause errors

We are also looking at commercial systems to see if they are truly applicable in a optical manufacturing shop

Summary

- Freeform optics are a commercial product offering at Optimax
- Development projects:
    - Manufacturing Monolithic Freeform Optics
    - Freeform Measurements:
        - Self Referencing Referenced Single Point Probing
        - Fringe Reflection Deflectometry





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