Smoothing mid-spatial frequency errors on freeform surfaces

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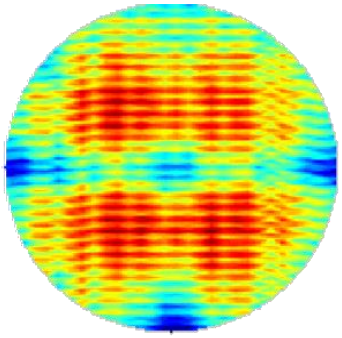
Acknowledgement:
NASA SBIR Phase I Funding

OPTIMAX

Smoothing mid-spatial frequency errors on freeform surfaces

Freeforms



Mid-spatial frequency error

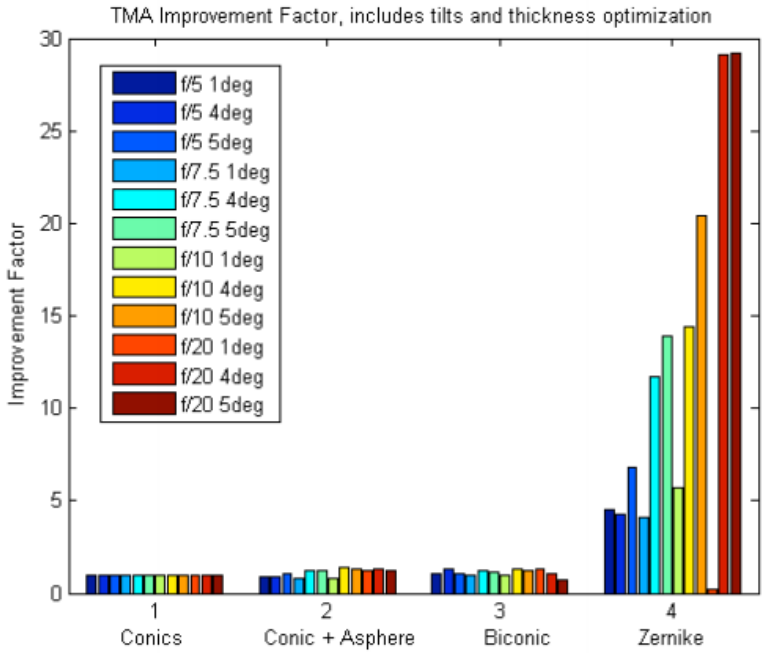
Manufacturing freeforms

Smoothing and results

OPTIMAX

Freeform optical surfaces have:

- Improved optical performance – less aberration
- Lightweight systems – reduced number of optical components
- Increased ability to go off axis – smaller/tighter packing



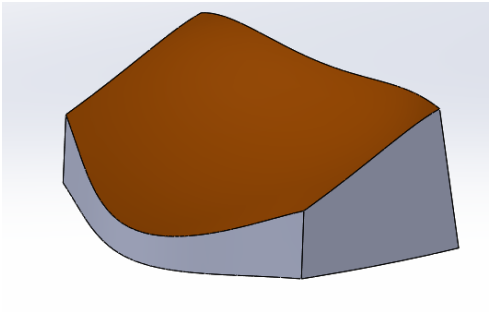
3-Mirror system shows up to 30 times improvement in system performance with freeforms, Partially for larger field of views.

J M Howard and S Wolbach, "Improving the performance of three-mirror imaging systems with Freeform Optics," OSA Freeform Optics Conference, 3-7 November 2013

OPTIMAX

A freeform can be defined in many ways

- Equation
  - asphere equation with X and Y terms
  - toroid
  - Atoriod
  - anamorphic asphere
  - Acylinder
  - Zernikes
- Cloud of points
- Solid model

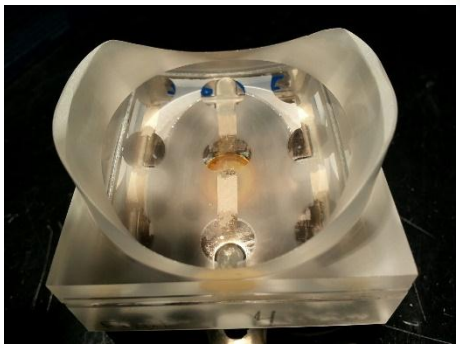


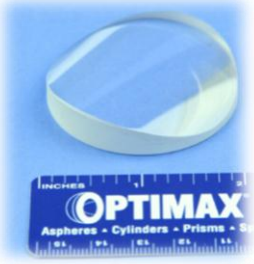
- Little to no symmetry
- Every part is different

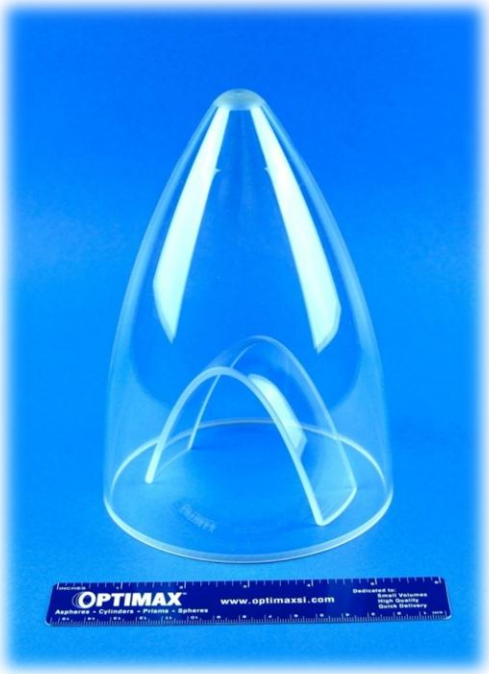
US_ANAMR	Anamorphic asphere. This aspheric surface is defined by the following expression: $Z = \frac{CxX^2 + CyY^2}{1 + \sqrt{1-(1+Kx)(Cx^2X^2)-(1+Ky)(Cy^2Y^2)}} + AR[(1-AP)X^2+(1+AP)Y^2]^2 + BR[(1-BP)X^2+(1+BP)Y^2]^3 + CR[(1-CP)X^2+(1+CP)Y^2]^4 + DR[(1-DP)X^2+(1+DP)Y^2]^5$
Zemax	

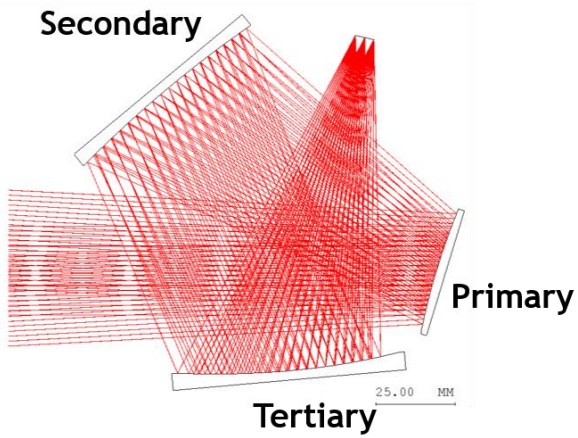
Who/What is using freeforms?

- 3-mirror telescope systems
- Beam shaping
- Corrector plates
- Conformal windows
- Corrector optics for aerodynamic domes
- Heads-up displays







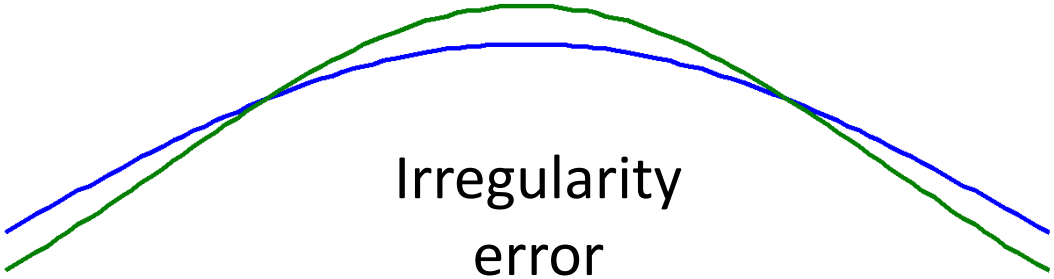


Fuerschbach, et. al., Realizing Freeform, Freeform Optics ISBN: 978-1-55752-986-2, FW1B 2013

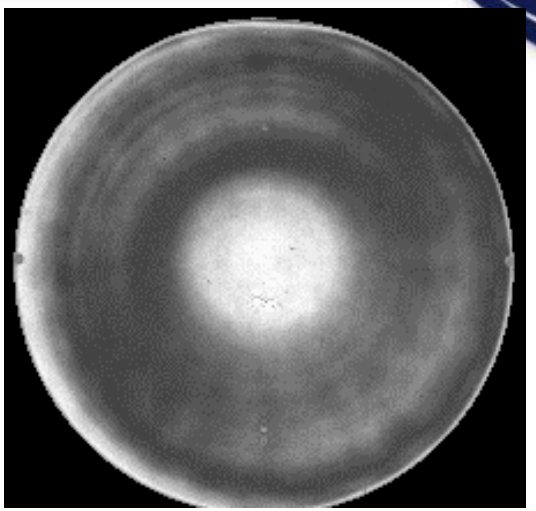
OPTIMAX

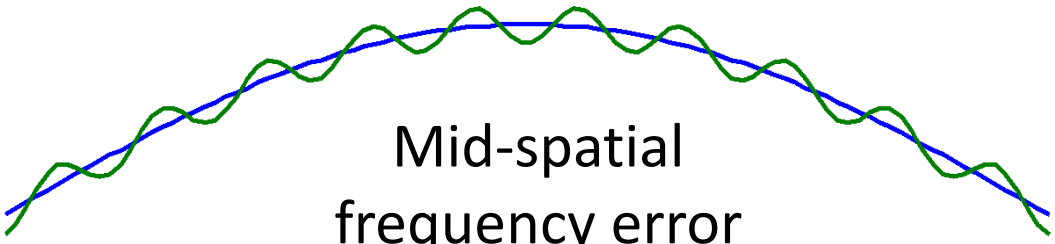
Simple definition of mid-spatial frequency

‘The wiggles’
Spatial periods of ~1 mm - 5 mm
(depends on part size)

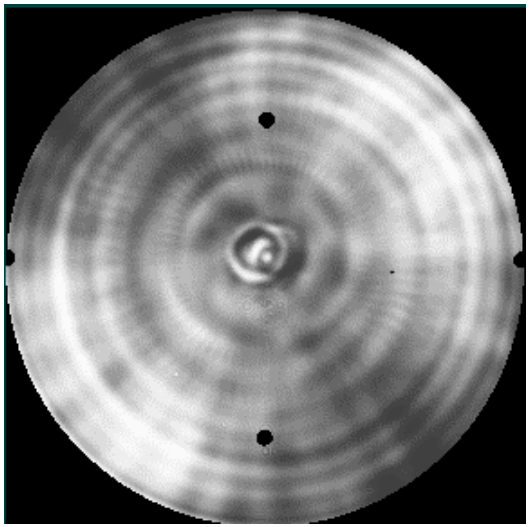


Irregularity
error





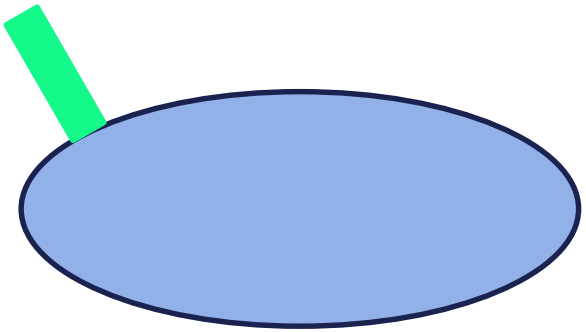
Mid-spatial
frequency error



Why is MSF such a factor for freeforms? (aspheres, too)

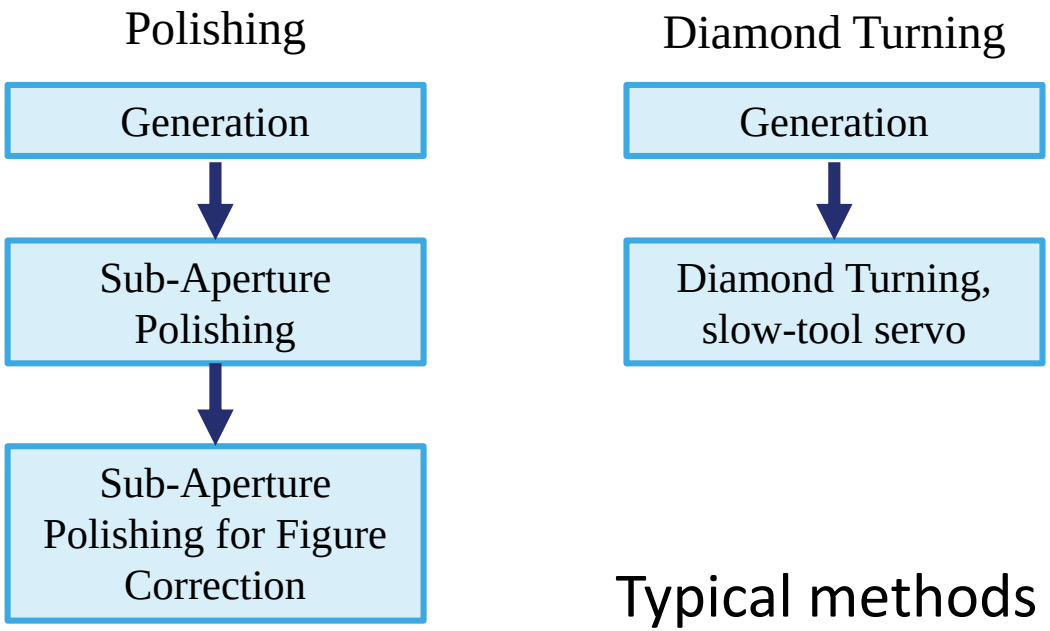
Generating and machining is done on a 5 - (or more) axis with complicated toolpaths and possible error motions (more/higher than for spherical optics)

Polishing is done with small tools – which (depending on the spatial period of interest) can only create MSF, can't remove it.



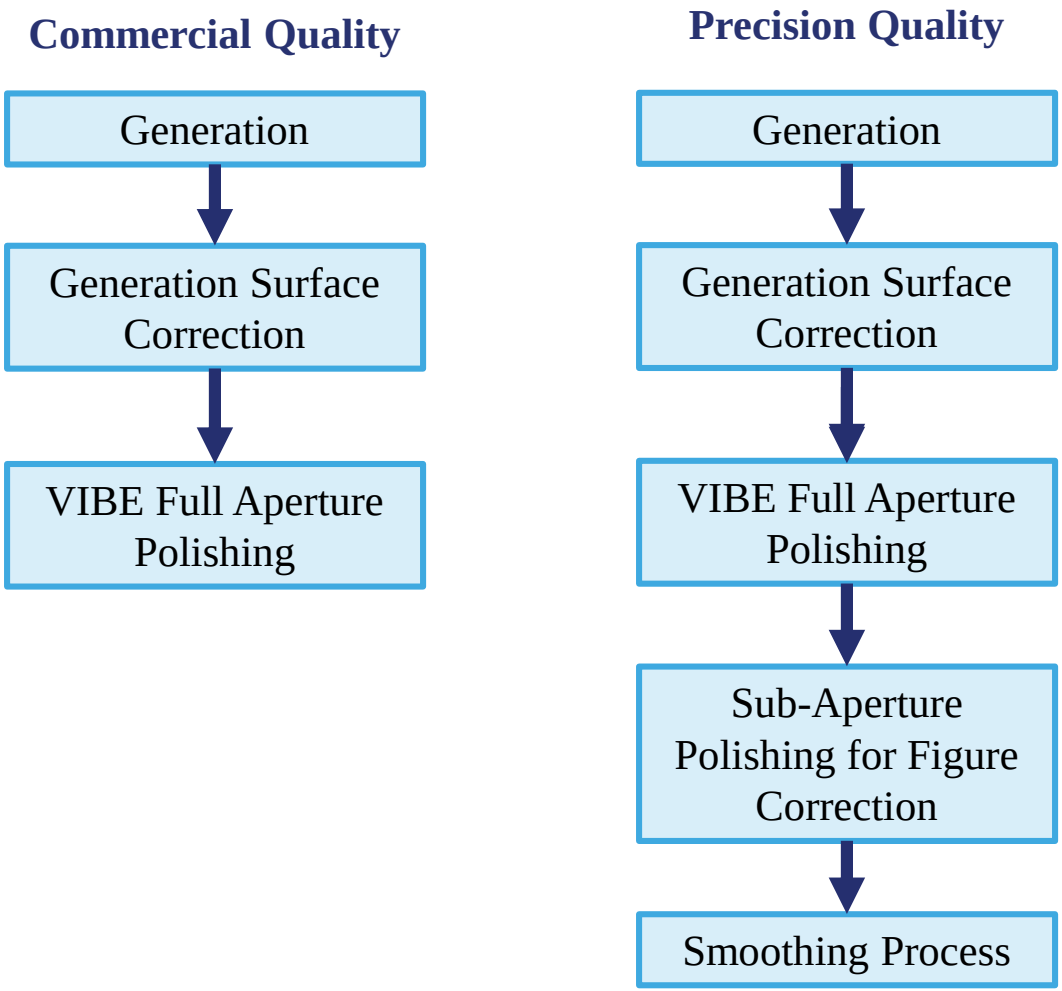
OPTIMAX

Typical freeform manufacturing steps

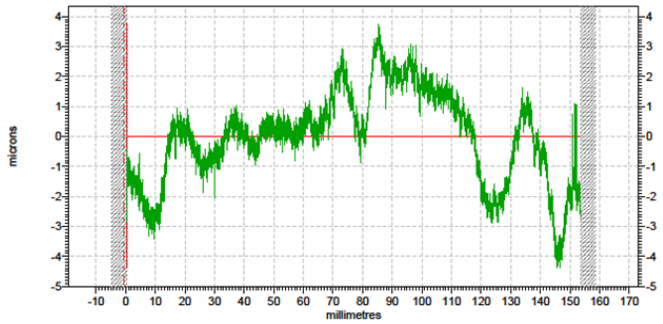


Typical methods induce MSF inherently and can't fix it.

Optimax's freeform manufacturing steps



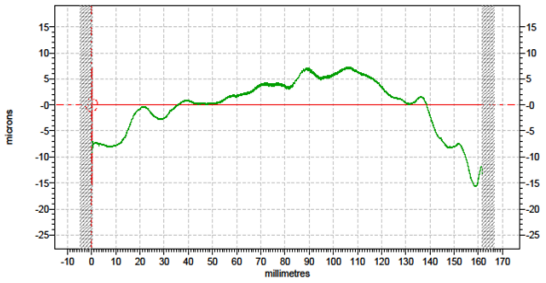
CNC generation process produces freeform shape with minimal surface form error



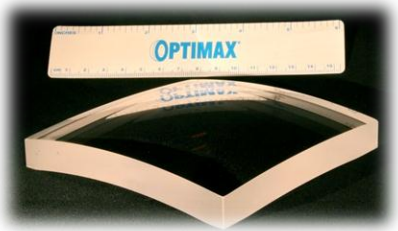
CNC Generate → Pre-Polish → Measurement → Deterministic Figure Correction → Smoothing

OPTIMAX

Pre-polishing required to remove damage while maintaining freeform shape



VIBE process removes material using proprietary conformal pad technology



CNC Generate | **Pre-Polish** | Measurement | Deterministic Figure Correction | Smoothing

OPTIMAX

Measurement of freeforms is still a gating item

Coordinate Measuring Machine

- Touch-trigger scanning probe
- Measures the deviation between the nominal shape and actual shape
- Good to ~ 1 µm

CNC Generate | Pre-Polish | **Measurement** | Deterministic Figure Correction | Smoothing

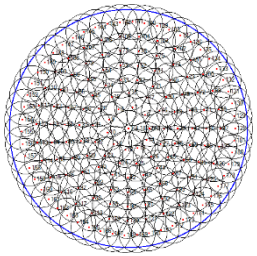
OPTIMAX

Measurement of freeforms is still a gating item

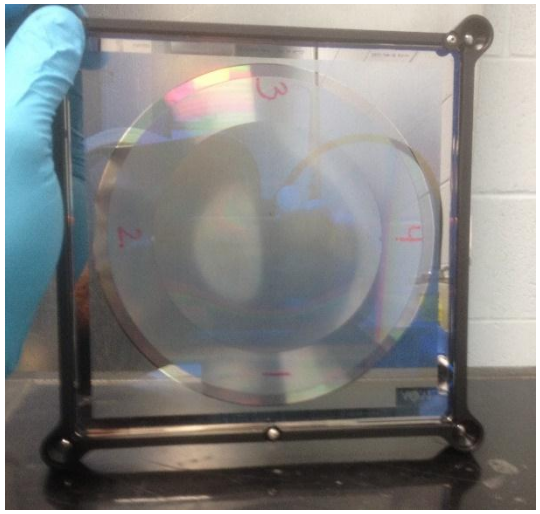
QED Technologies

Stitching Interferometer

Projects are ongoing with QED to adapt aspheric stitching interferometer to measure ‘mild’ freeforms



CGHs –Computer Generated Hologram

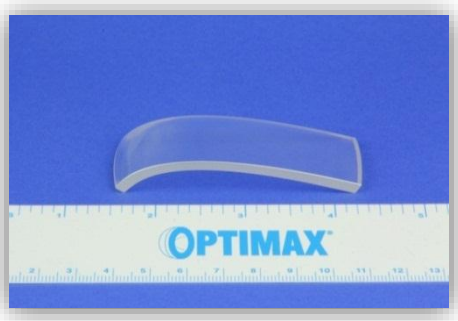


Difficult to separate alignment and surface errors. We have ongoing projects to design CGHs which measure the part fiducials to eliminate alignment problems.

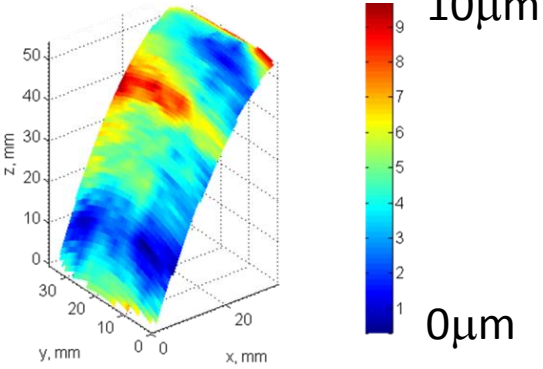
CNC Generate | Pre-Polish | **Measurement** | Deterministic Figure Correction | Smoothing

OPTIMAX

Deterministic figure correction process selection depends on material and part geometry



Deviation from Nominal

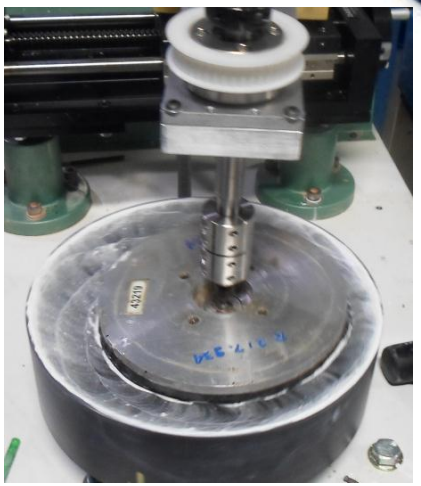


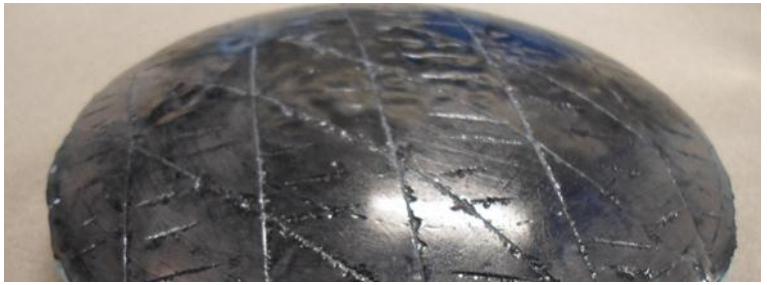
CNC Generate | Pre-Polish | Measurement | **Deterministic Figure Correction** | Smoothing

OPTIMAX

Smoothing reduces the mid-spatial frequency errors in the part

Smoothing reduces the MSF without greatly affecting the figure error with proprietary conformal tooling and active layers





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

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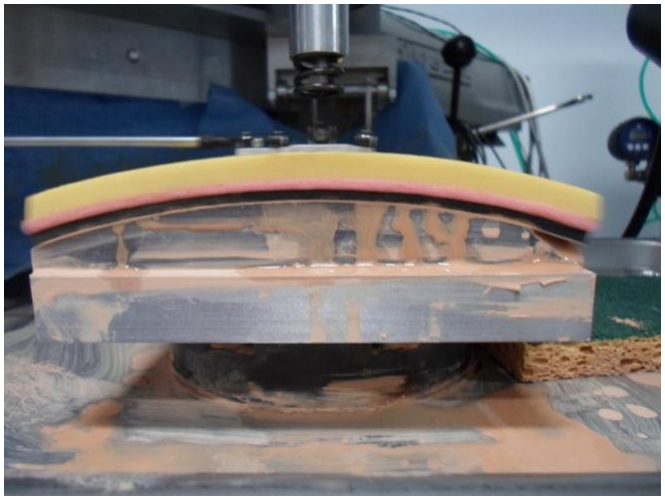
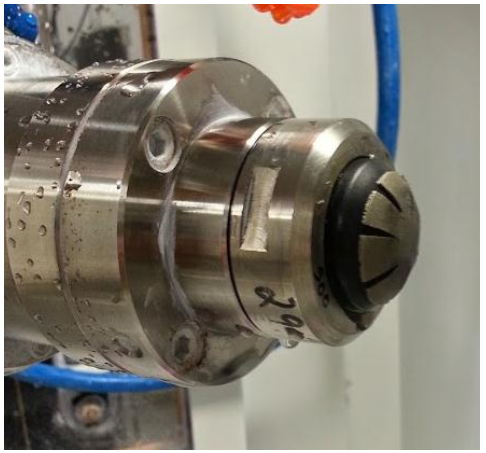


The smoothing method and tooling varies dependent on part geometry and material



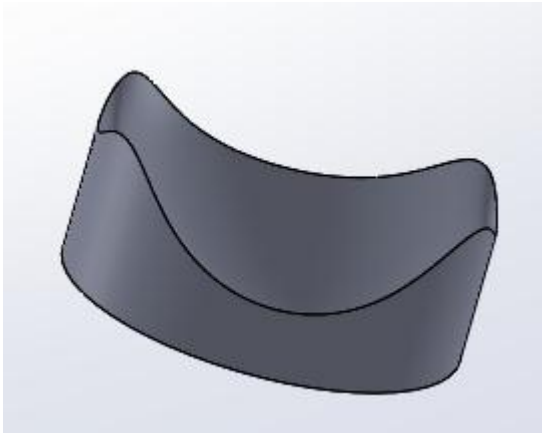
CNC Generate | Pre-Polish | Measurement | Deterministic Figure Correction | Smoothing

OPTIMAX

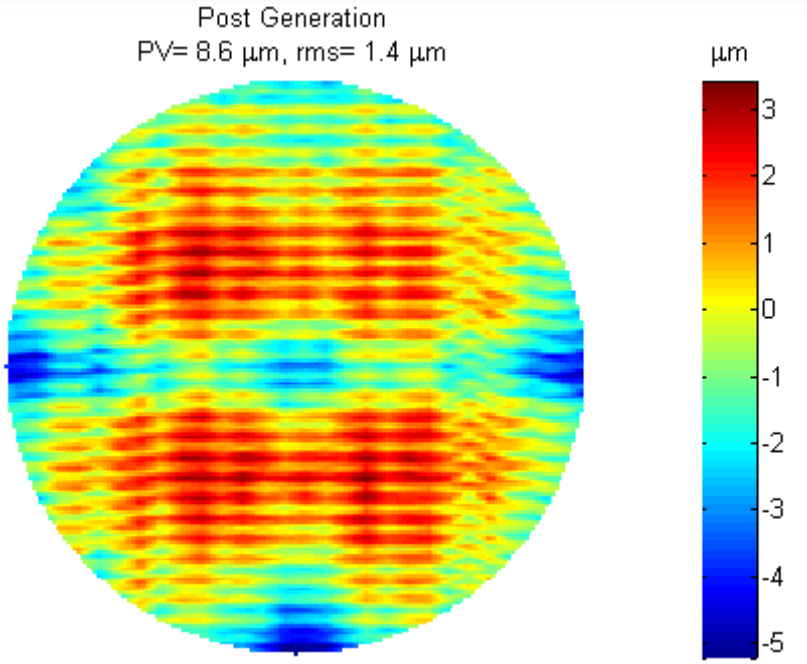
Importance of smoothing, 1/3

~35 mm diameter

Fine lines caused by step-over in the generation process must be smoothed, fixing this ~1-2 mm sized features is not possible with sub-aperture polishing

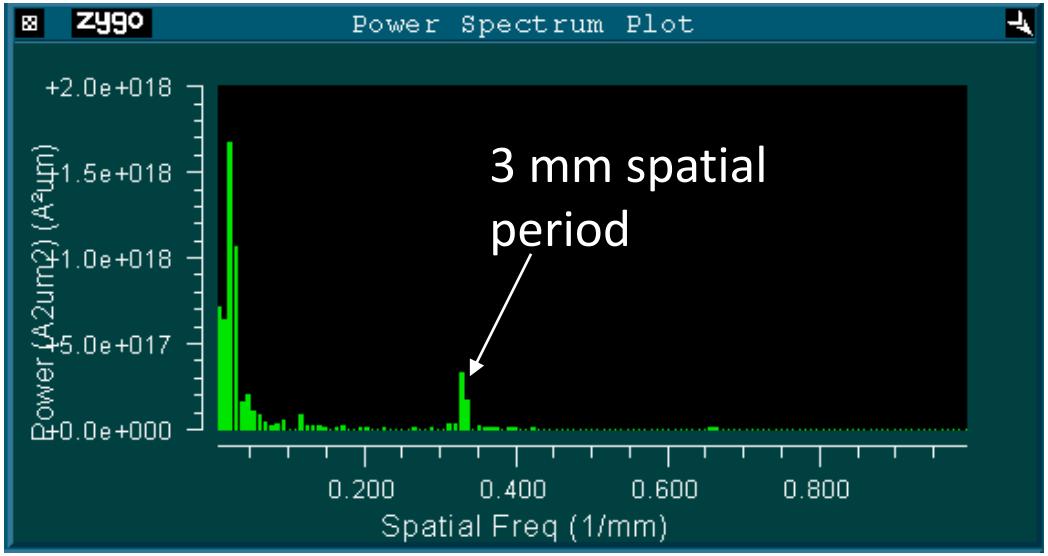


Importance of smoothing, 2/3



90 mm diameter

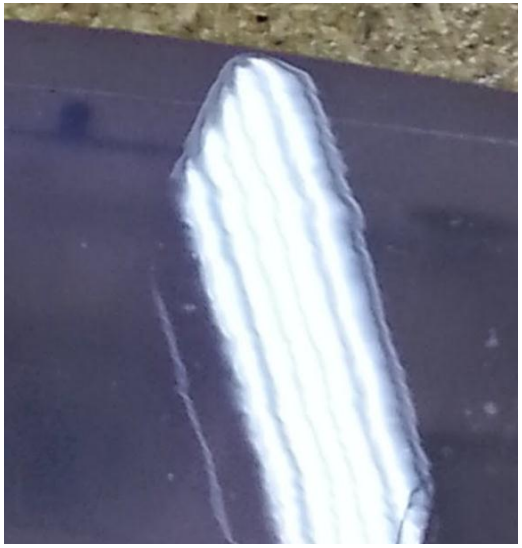
CMM measurement of atoriod after generation showing low form error, but unacceptable MSF



Importance of smoothing, 3/3

Freeform optical surface 75 mm by 25 mm
Both SN1 and SN2 meet the PV specifications

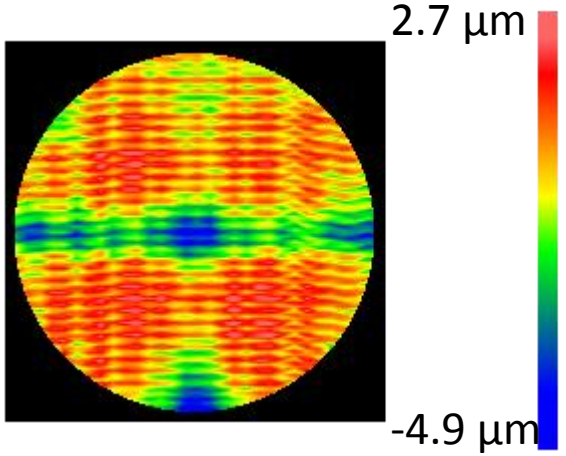
SN1: Not smoothed

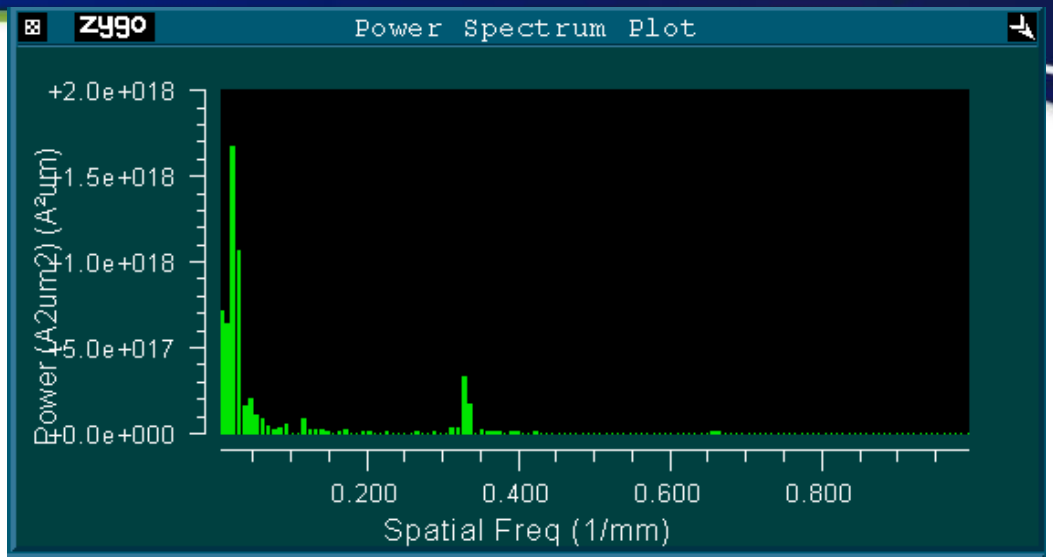


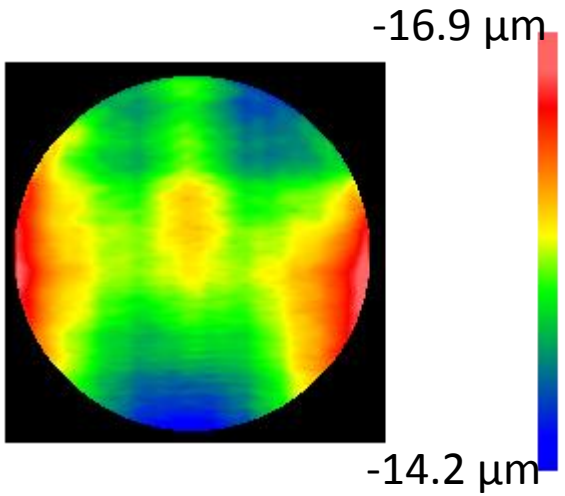
SN2: Smoothed

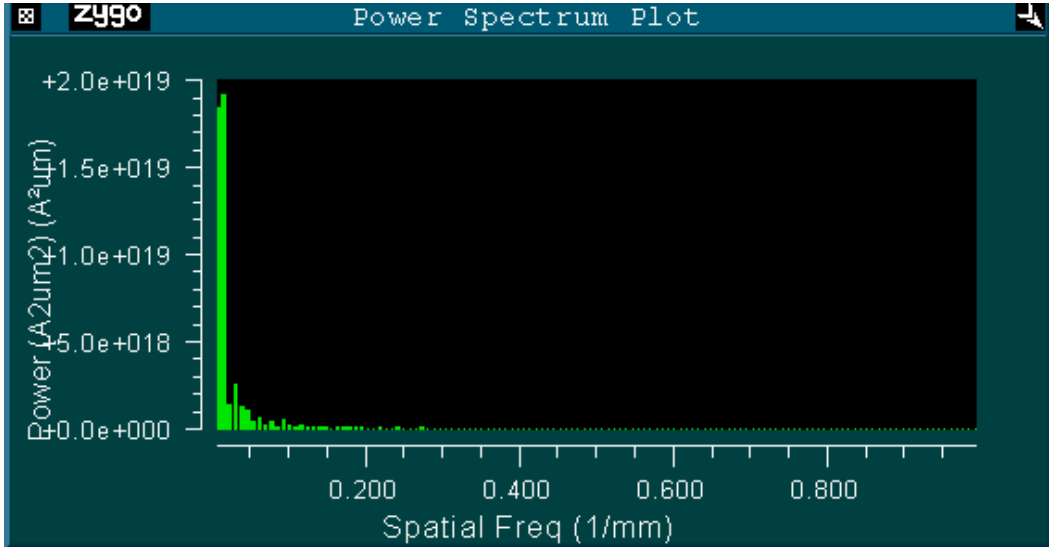
OPTIMAX

Smoothing results show dramatic decrease in MSF





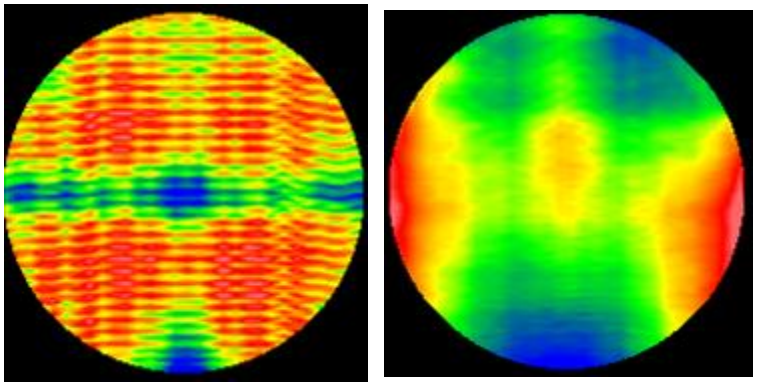


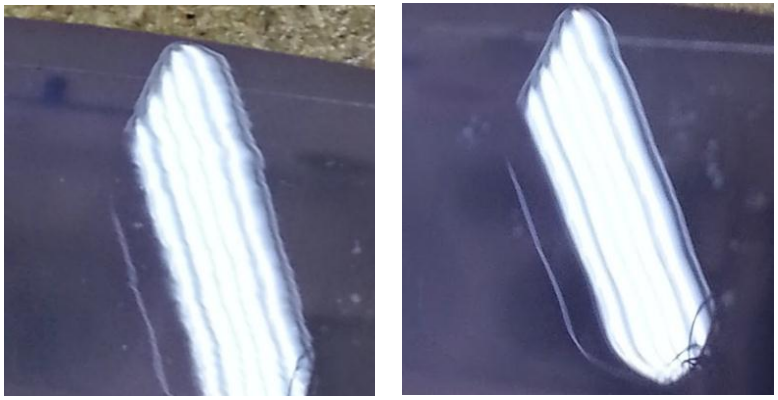


OPTIMAX

Conclusions

- MSF is typically a natural consequence of manufacturing freeforms
- MSF can’t be fixed the sub-aperture polishing
- VIBE polishing minimizes the creation of MSF
- Smoothing removes existing MSF

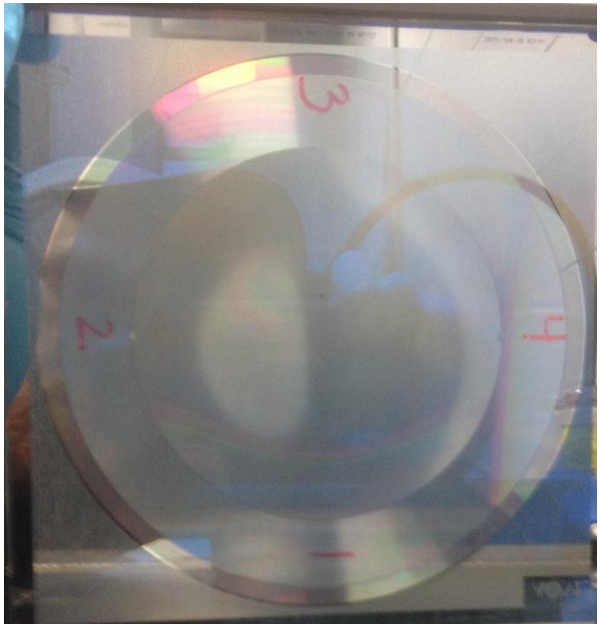


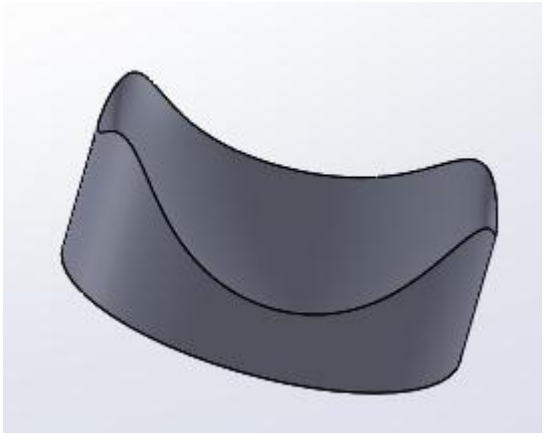


OPTIMAX

Next Steps

- Steeper, more complicated surfaces
- Work toward the <5 nm rms levels of MSF
- Better measurement of the MSF on freeforms using CGHs





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Questions?

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