OPTICAL SURFACE RESULTS UTILIZING THE 5&6-AXIS ULTRAFORM FINISHING PLATFORM

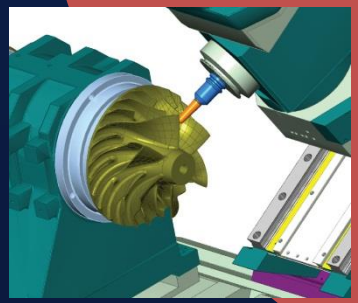
Mirror Technology Days 2015
Annapolis, Maryland

OptiPro Systems, LLC
Ontario, NY 14519

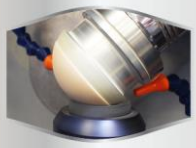
Edward Fess, Jayson Tierson, Frank Wolfs

Presented by: David Mohring

OptiPro Systems



SBIR Partners

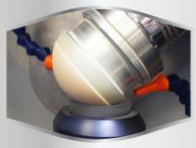





NASA

U.S. ARMY RDECOM

NAVAL AIR SYSTEMS COMMAND



NASA SBIR Contracts

NASA Contract Number: NNX14CM23P – Phase I
Title: Figuring and Polishing Precision Optical Surfaces
COTR: Mikhail Gubarev

NASA Contract Number: NNX13CM02C – Phase II
Title: Optical Fabrication and Metrology of Aspheric and Freeform Mirrors
COTR: W. Scott Smith and Roy Young

Small Business Innovation Research

Fabrication of Freeform Conic Mirrors and Mandrels

OptiPro Systems, LLC
Ontario, NY

INNOVATION

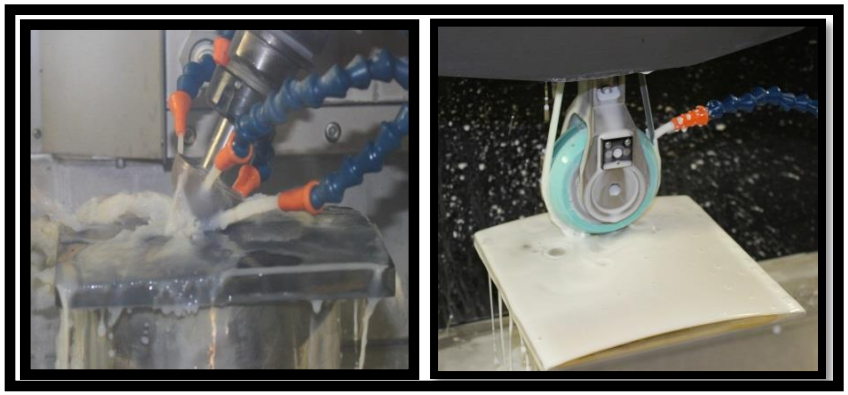
The UltraForm Finishing (6-Axis UFF) and the UltraSurf platforms developed by OptiPro Systems deterministically polish and measure complex aerodynamic and conformal mirror shapes made of difficult to manufacture glass, crystal and ceramic materials.

ACCOMPLISHMENTS

- 2008 OSA – Paul Forman "Excellence in Engineering Award" for first affordable Computer Controlled Optical Machining Center.
- Optical fabrication companies and prime contractor suppliers are embracing the new technology to cost effectively manufacture axisymmetric domes and optics for newly designed defense systems. The technologies developed under the SBIR contracts have provided a cost effective manufacturing solution for DoE, DoD, MDA and NASA components.
- The integration of the UFF (CNC controlled finishing platform) and the UltraSurf (Automated non-contact measurement device) provides a deterministic fabrication solution for a wide range of newly developed windows , domes and mirrors.

COMMERCIALIZATION

- UltraForm Finishing (UFF) : Asphere, Axisymmetric Dome , Freeform Polisher
  - Private Sector installations at Universities, Material manufacturers and Precision optical component manufacturers
  - US Patent No. 7,662,024 B2 : "Method and Apparatus for precision polishing of Optical Components"
- UltraSurf : Non-Contact Asphere, Axisymmetric Dome measurement platform
  - Private Sector Asphere and Dome Measurement System for production
- Primary market focus is on companies engaging in the optical fabrication and measurement of spherical domes, aspheres, parabolic mirrors, torics and conformal/freeform shapes.
- Private sector investment into the UFF and UltraSurf platforms has been through Beta site partners and production level machine purchases.
- OptiPro Systems, LLC has alliances with material manufacturing firms who require new manufacturing techniques to test and enhance their prototype components and determine the pathway to production level quantities



Tappered Cylinder Grind and Polish Fabrication

GOVERNMENT/SCIENCE APPLICATIONS

- NASA Contract Numbers NNX12CF49P, NNX14CM21P
- NASA NNX13CM02C (SBIR 2011-II) (MSFC)
- DOD Contract Numbers W31P4Q-05-C-R048 and W31P4Q-04-C-R101 awarded by the Defense Advanced Research Projects Agency (DARPA); and Contract Numbers N41756-05-M-1390, N68936-06-C-0010 and N68936-09-C-0079awarded by the Navy Engineering Logistics Office and NAVAIR.
- Toric , Acylinder and other freeform geometric shapes made from Si and SiC.
- Freeform reflective mirror applications for the Department of Energy
- Materials Include : Spinel, ALON™, CeraLumina™ , Si, SiC, ceramics, Fused Quartz & standard optical glasses

OptiPro Systems, LLC
6368 Dean Parkway
Ontario, NY 14519
David Mohring (585) 265-0160

Date : November 9, 2015

Outline

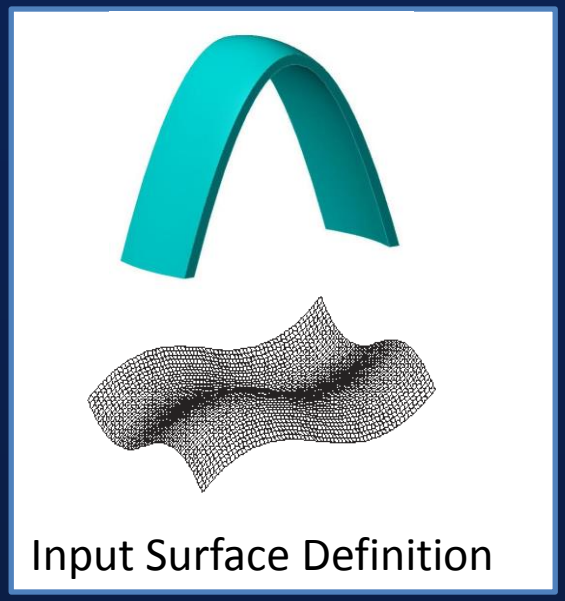
- Surface Definition
- Fabrication Equipment
- Software Tools
- Grinding Process
- Polishing Process
- Surface Metrology
- Fabrication Examples

Complex Optical Surfaces

- Off-Axis Aspheres
- Torics
- Aspheric Cylinders
- Parabolics
- Freeforms and Conformal Optics

Surface Definition

- Mathematical Equation
  - Basis functions
  - Zernike polynomial
  - Q Polynomial
- Wireframe model
- Solid model
- Cloud of points
- Mandrel definition …



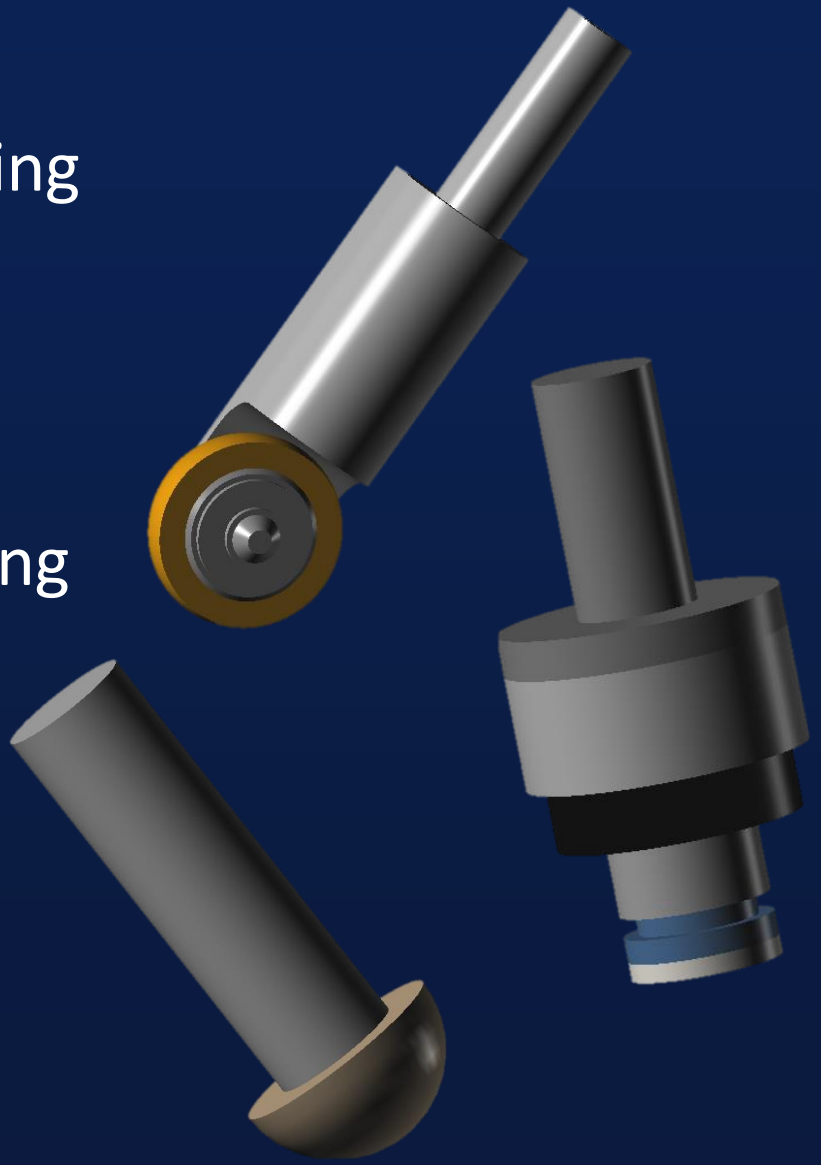
Input Surface Definition

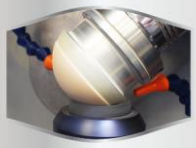
$$r = \sqrt{h_0^2 + 2ky - py^2} \qquad z = \sqrt{r^2 - x^2}$$

r is the radius of the surface at any given *y* coordinate, h_0 is a constant equal to 425 mm, *k* is a constant equal to -3.844346977 mm, *p* is a constant equal to $-3.0810743 \times 10^{-04}$

Manufacturing Tools

- Deterministic Grinding (DMG)
- UltraForm Finishing (UFF)
- UltraSmooth Finishing (USF)



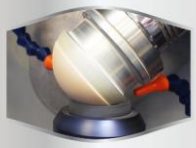





Ultrasonic Machining Centers

- OptiSonic 3X: 3-axis ultrasonic machining
- OptiSonic 5X: 5-axis ultrasonic machining

Optisonic Asphere



Aspheric design

↓

Tool selection (ring, ball, and edge)

↓

Blank set-up (geometry, initial sag and central thickness (CT))

↓

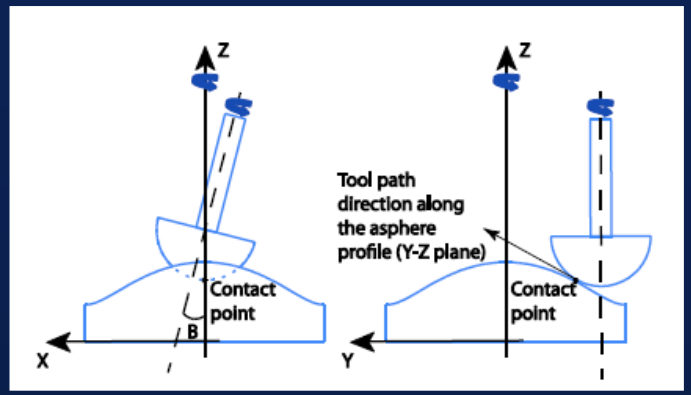
Transferring the aspheric lens equation to CNC machine language (radius of curvature, conic constant k, and a_1 to a_{20} aspheric coefficient)

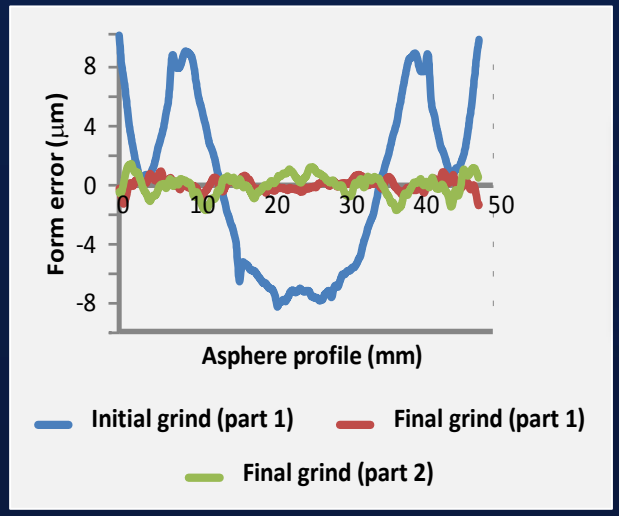
↓

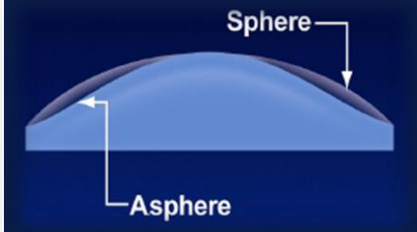
Tool parameters (cut direction, head angle, lens rpm, tool rpm, feed rate)

↓

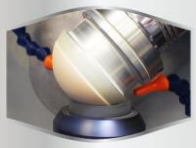
Aspheric grinding (best fit sphere BFS, asphere cut, metrology, final correction cut, and center thickness CT). Edge (optional)







OPTIPRO



Optical Polishing/Finishing Machines

PRO 80P ePX 200

PRO 80 UFF UFF 300

TRIUMPH

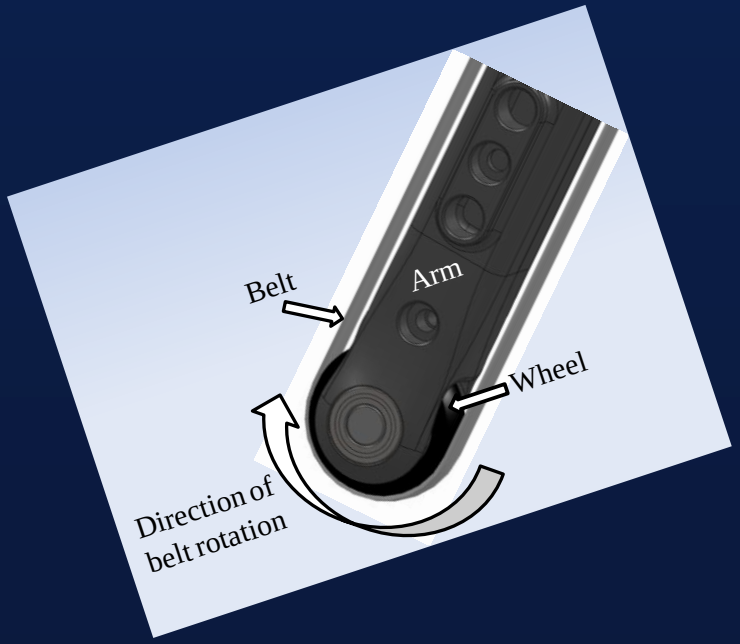
OPTIPRO

JOIN THE OPTIPRO REVOLUTION

UFF 500

UltraForm Finishing (UFF)

- 5-axis/6-axis CNC controller with simple to use GUI
- Wheel size range 8 to 100 mm in diameter
- Wheel nominal hardness range from 30 to 80 Shore A
- Bound/fixed abrasives or commercial polyurethane belts with slurry
- Capable of finishing a wide range of materials from optical glass to hard ceramics and metals to sub-micron form tolerances.



UFF






Measure Removal Function

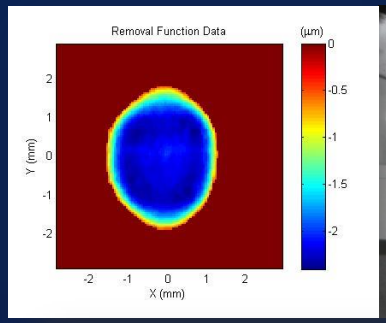
- Integrated STIL pen
- Onboard metrology

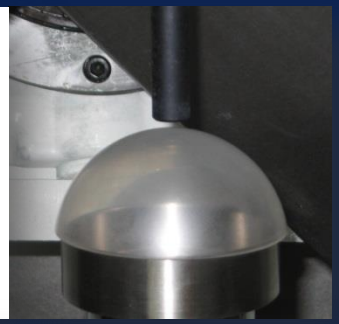
Input Initial Figure Error

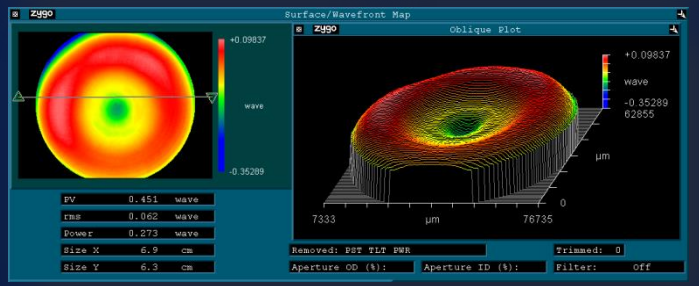
- Zygo Interferometer Input
- Profilometer Input

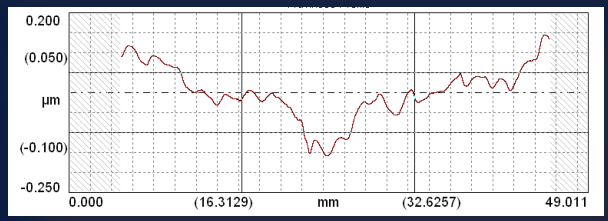
Optimize Polishing Tool Path

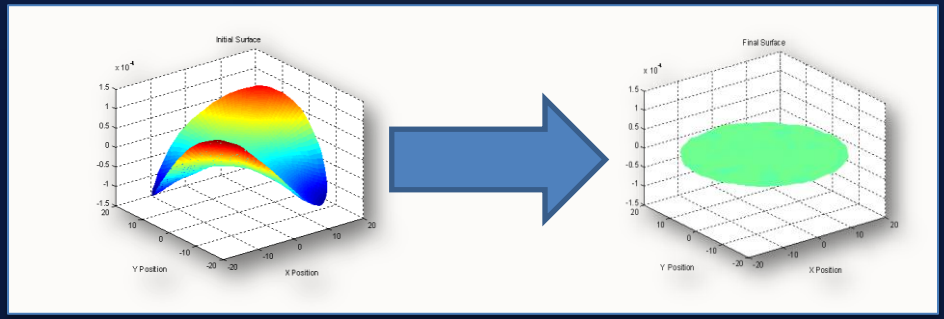
- Reduce figure error
- Fine control of polishing path







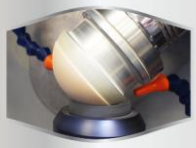




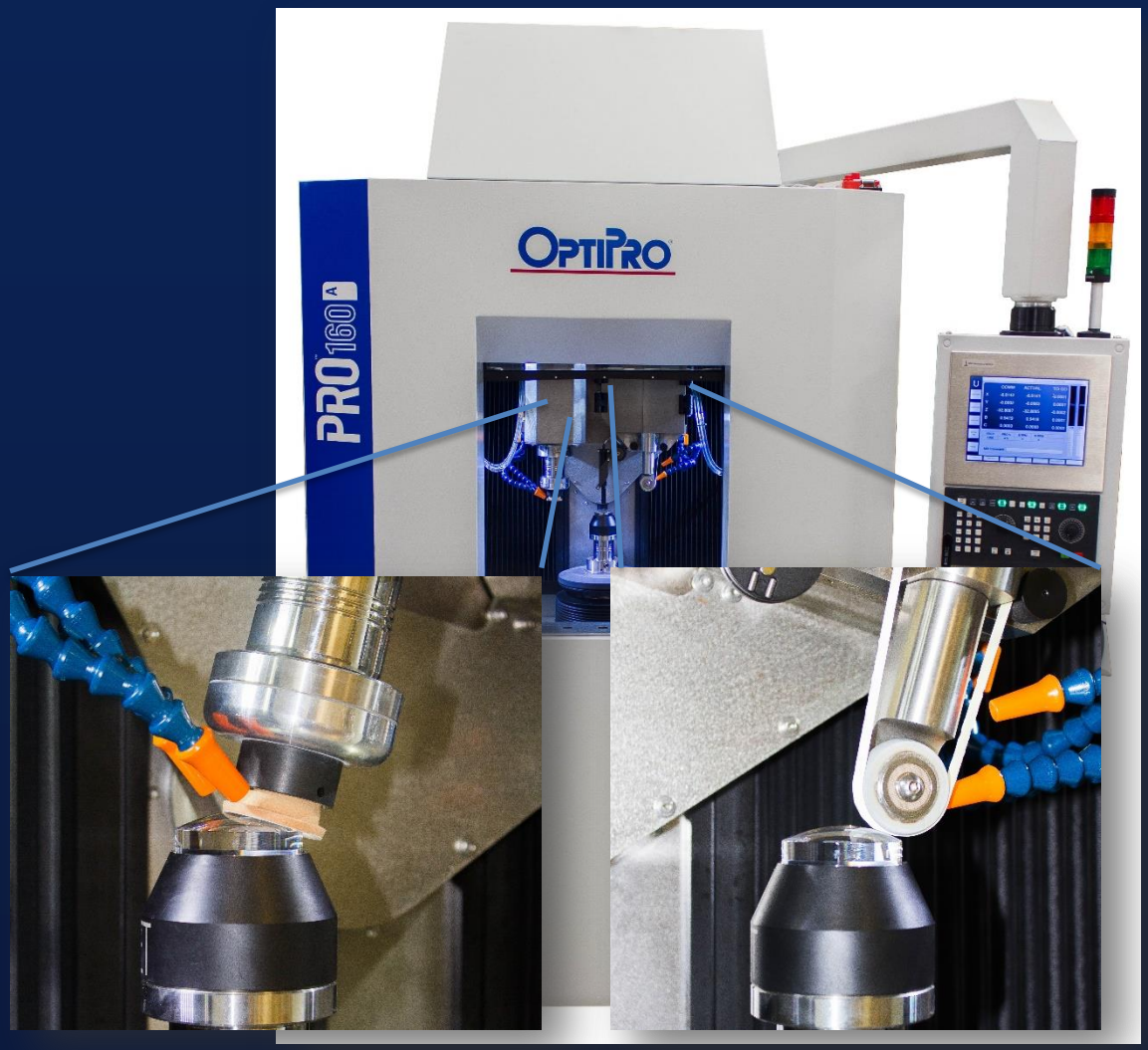
6-Axis UFF @ MSFC

- X,Y,Z linear axis
- A,B,C Rotary Axis
- Tool Rotation motion control
- Work Piece motion control
- Freeform capabilities
- Tool normal -> Surface
- Full CNC Control
- Optical Fabrication software
- Bound and loose abrasives
- Deterministic / corrective

New 160A(sphere)

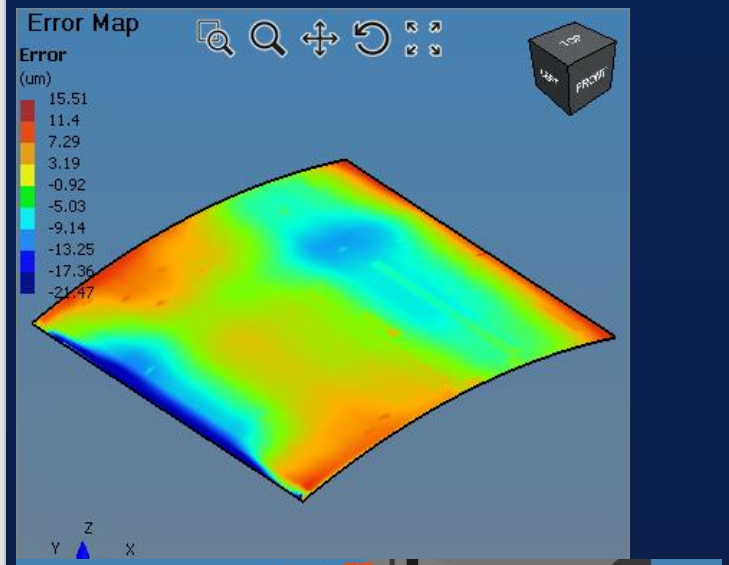


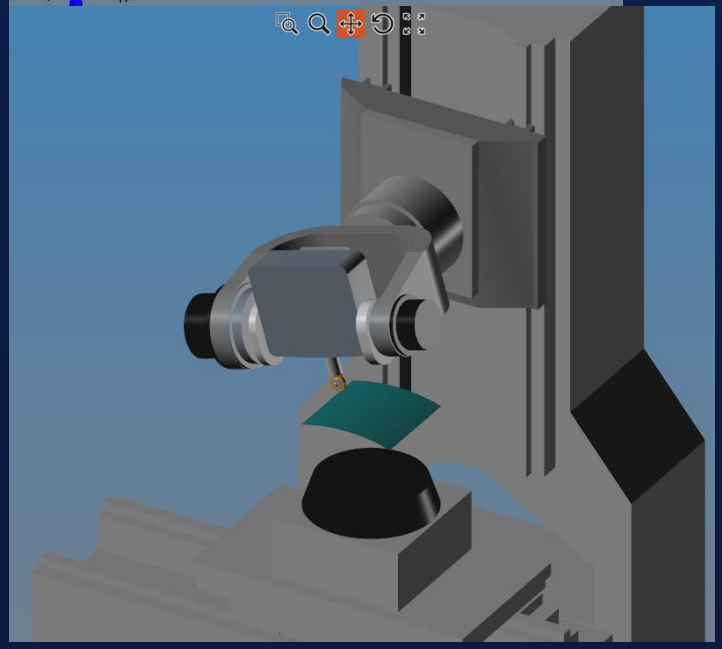


USF

- Prepare part for UFF correction
  - Lower stock removal will leave less signature
- Smooth MSF post UFF
  - Tool design allows for high compression in vertical direction and possesses great torsion stiffness
  - Tooling's compliant layer can be configured with different stiffness materials.
  - Ideal tool design for USF high-pressure, high-speed polishing setup

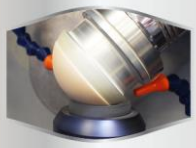
PROSurf Software





- Can generate corrective metrology based tool paths for both grinding and polishing
- Contains a built-in tool path animator as a visual aid for tool path verification

PROSurf Surface Definition



Edit Job

Name: NASA Secondary Mandrell

Type: Input Equation

Choose Aperture Type: Rectangular Circular

X Width: 253.89 mm

Y Width: 253.89 mm

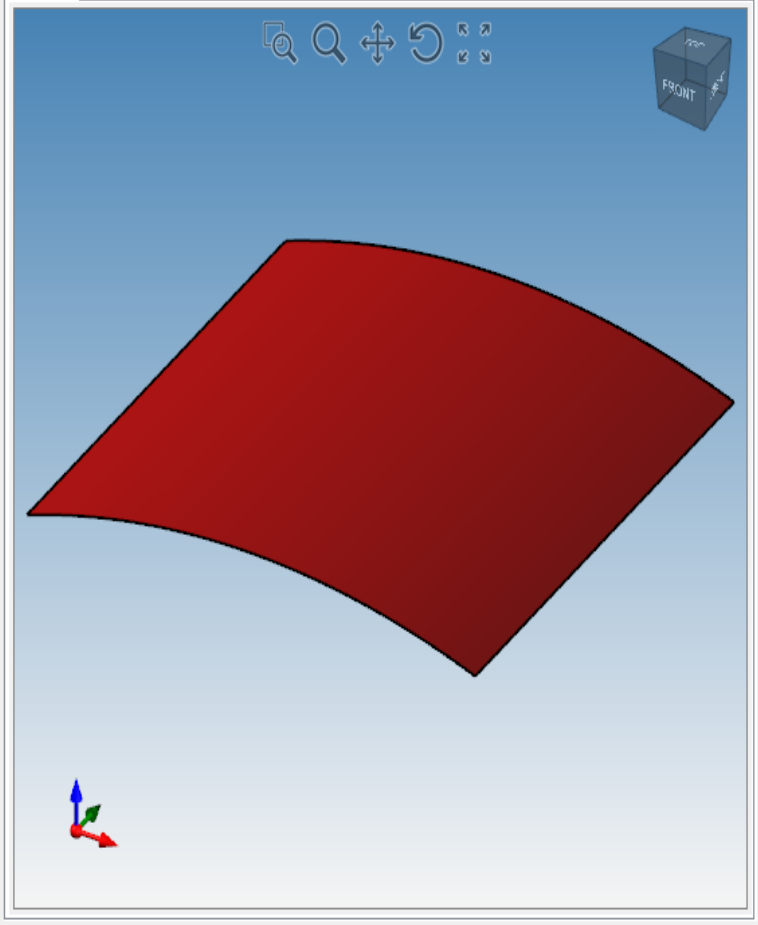
Input Equation

```
h0 = 425;
k = -3.844346977;
p = -3.0810743e-04;

rmat = sqrt(h0*h0 + 2*k*Y - p*Y.*Y);

Z = sqrt(rmat.^2 - X.^2);
```

Import Existing Equation | Plot Equation

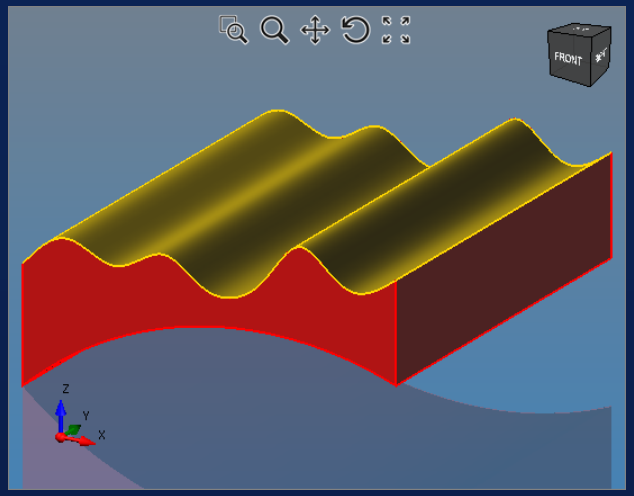
Convention for entering equations
1) All X's, Y's, and Z's must be capitalized.
2) All multiplication, division, or exponentiation involving multiple X and/or Y must be written using the following convention

Viewport | Surface Evaluation

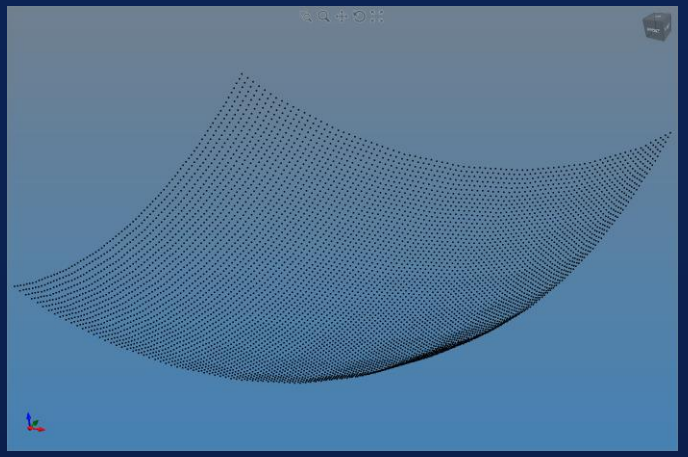


Change Default Directory | C:\Users\fwolfs\Documents\OptiPro\Freeform\Jobs | Flip Surface | OK | Cancel

Shape Inputs/Definitions



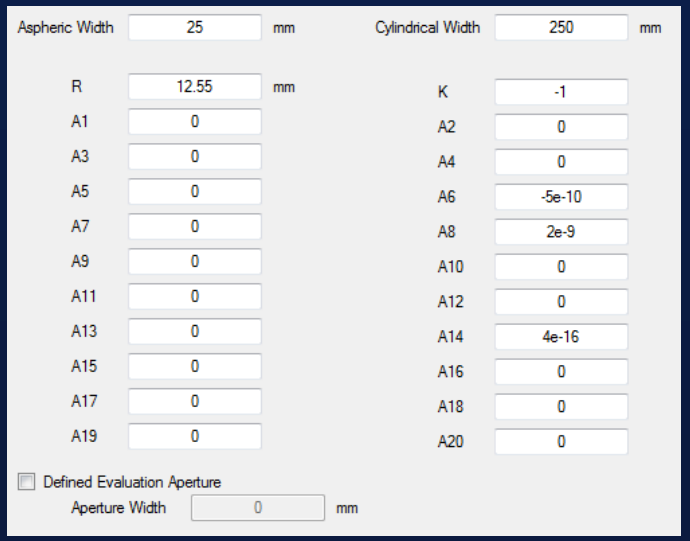
Solid Model (.igs files)



Point Cloud

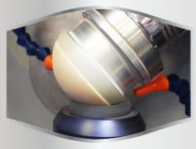
```
term1 = 4*(X/25).^2;
term2 = sin(X/20 + 30);
term3 = 3.*sin(Y/45);
term4 = (Y/8).^0.5;
Z = term1.*term2.*term3  + term4;
```

Mathematical Equations



Built-in Common Shapes

PROSurf USF Toolpath



PROSurf

File Job Process Tool Manage View About

SPINEL USF

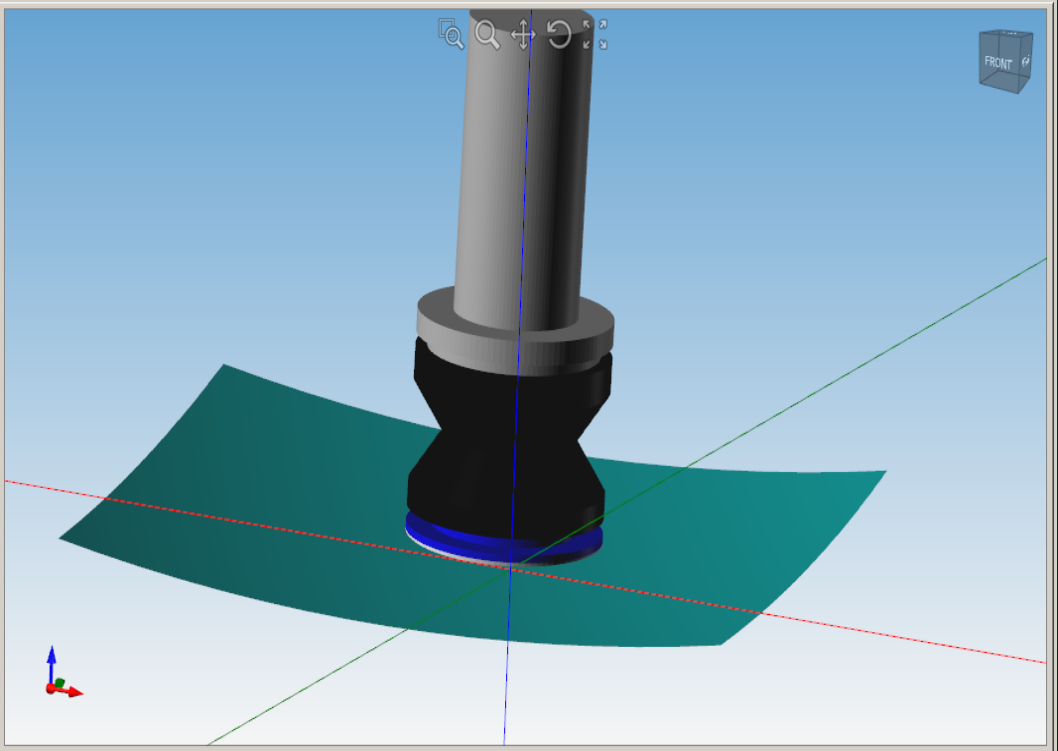
Processes | Tools | Orientation | Surface | Motion | Fixture | Correction | Tool Path

Coolant
Thru Tool Coolant
High Speed Cutting
C-Axis Brake

Work Coordinates G54
Safety Feed Rate 10
Spindle Rotation CW CCW
USF Spindle S1 S3

Write To Screen
Write To Disk
Write

```
(Tool Name: 50mm USF Pad)
(Tool Type: USFPad)
(X-eccentricity: 0 mm)
(Y-eccentricity: 0 mm)
(Tool Length B: 100 mm)
(Axis Align B: 0 mm)
(B angle compensation: off)
(Compression: 0 mm)
(Correction Type: grayOut)
(Gray Out Time: 0 min)
(Random Pause: On)
G01 F300  G7 G40 G90
G53 Z0.
G54
M16
M8

#HSC ON [FAST]
S1=120  M3
X-98.038
Y-52.215
Z11.756
B8.285
C69.358
X-98.038
G93 G01 X-98.038  F10
X-98.038 Y-52.215 Z11.756 B8.285 C69.358 F0
```



Machine On
Panels On
Slow Fast

Start

1:37 PM
3/30/2014

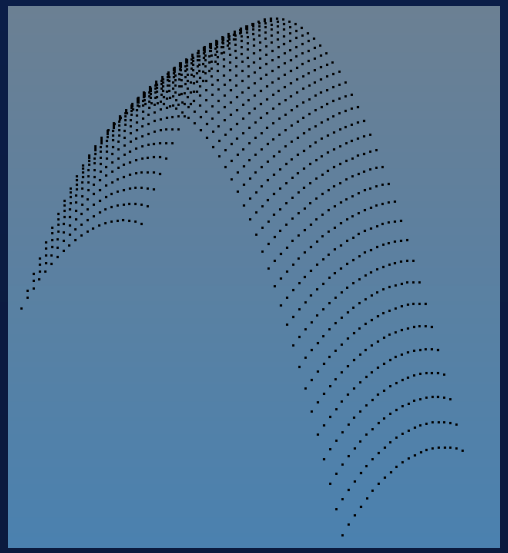
Rough -> Fine Grind

- Surface Texture
- Mid Spatial Errors

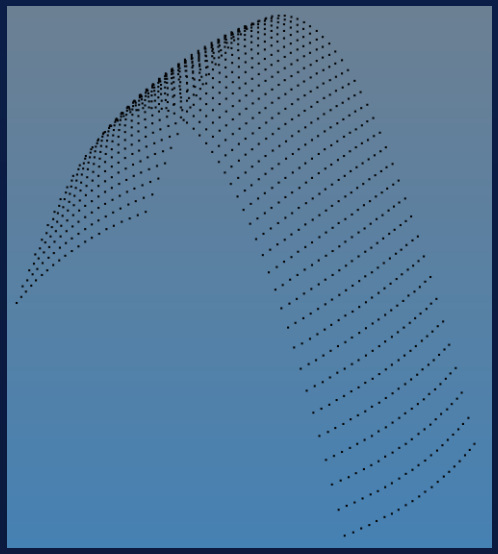
  (4-60 cycles /aperture)

Advanced Point Spacing

- Based on solutions for removing surface signatures from actual parts
- Even arc spacing, even curve spacing, cusp height minimization



Even Arc Spacing



Metrology Data Input

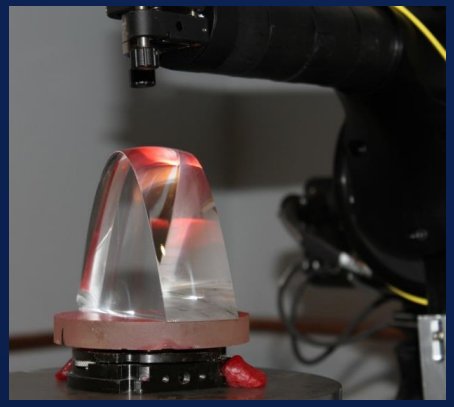
Deterministic Corrective Grind & Surface error spatial analysis

- Contact Profilometer multiple 2D scans
- Non-Contact scan
- On machine probe
- CMM

Freeform Metrology

UltraSurf

- Non-contact
- Not slope limited
- Can measure spheres, aspheres, and freeform optical components as well as optical thickness for meniscus shapes

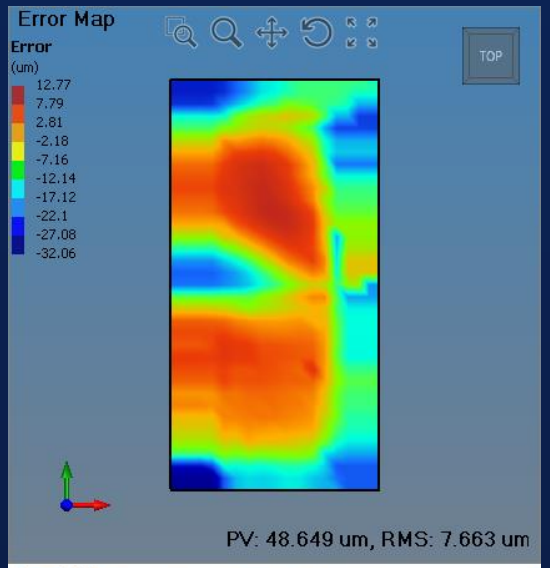


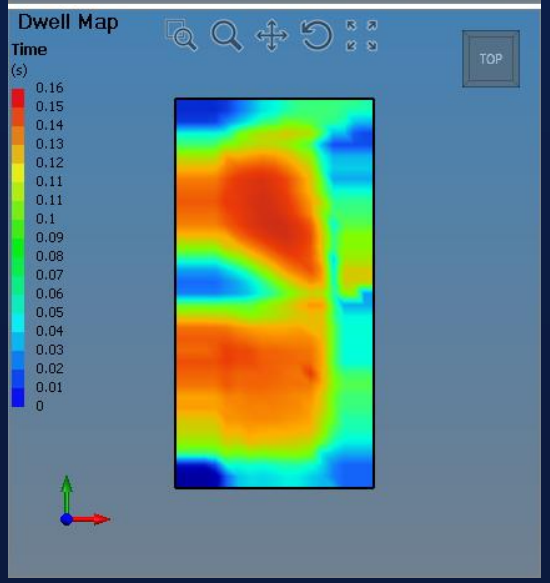
OptiTrace

- Scanning Stylus
- Equipped with optional Y/theta stages
- Y-axis can take multiple scans across an acylinder

Figure Correction

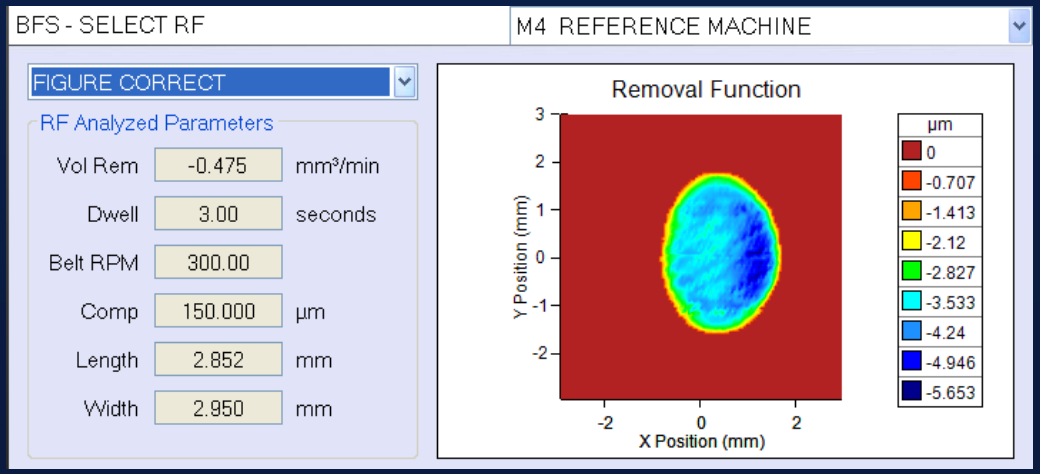
- Metrology driven tool paths for figure correction
- Grind Correction
  - Adjust the z-heights of the tool path based on metrology
- Polish Correction
  - Adjust dwell times based on relative amount of error
- Inputs
  - Dat, XYZ, Mod, CSV, OPM





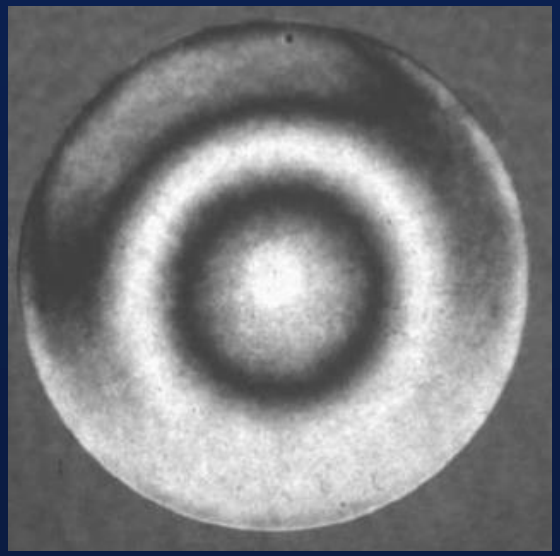
UFF

- Common parameters
  - Compression
    - 150 microns
  - Wheel durometer
    - Shore A 70D
  - Wheel diameter
    - 40mm
  - Wheel shape
    - 12.7mm nose radius
  - Belt speed
    - 300rpm
  - Belt type
    - CeO fixed abrasive

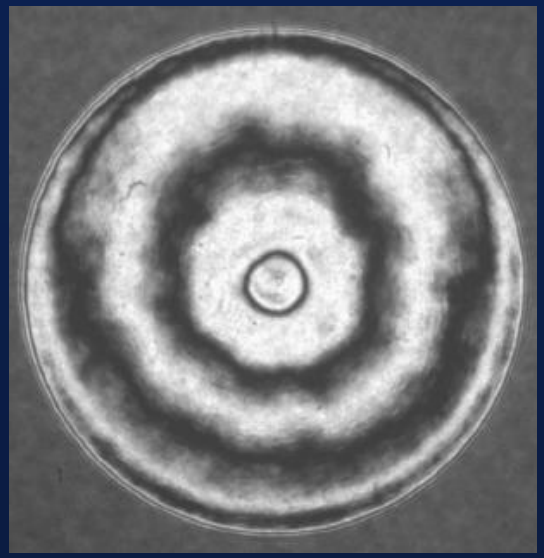


UFF-3D

- Common challenges
  - Slope error
  - Center artifact



Pre UFF
Smooth fringes



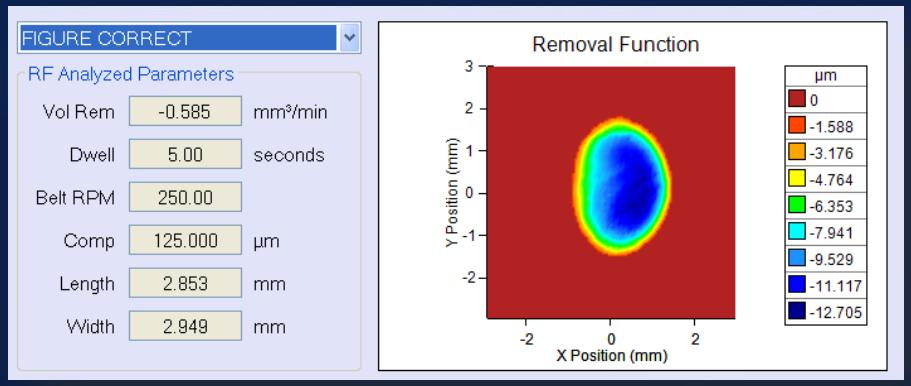
Post UFF
Noticeable spokes
Center artifact

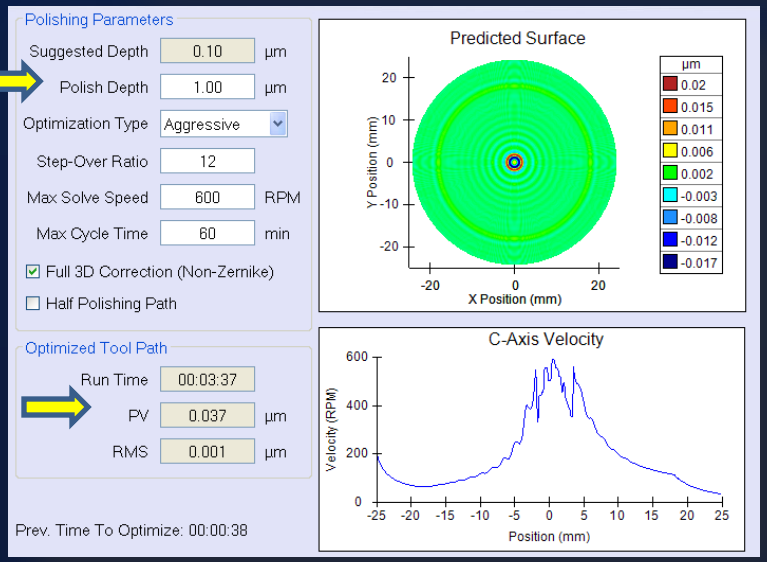
New URF utilization

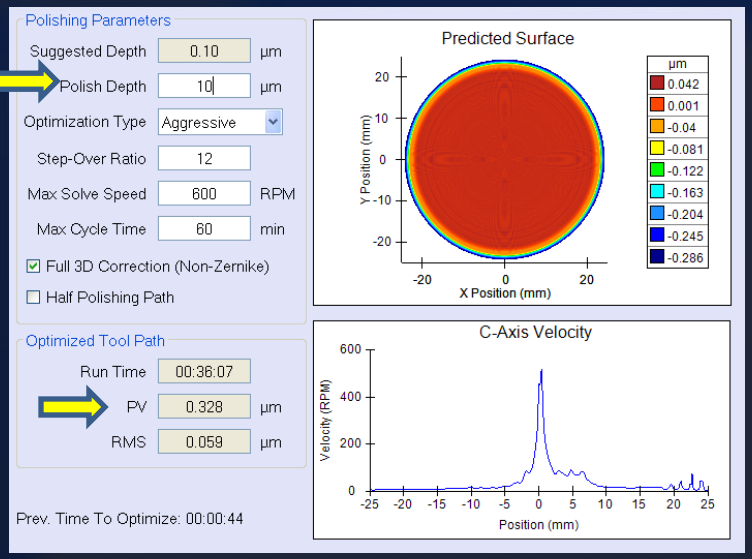
- Part preparation
  - High speed polished
  - 50mm BK7
  - Metrology
    - PRO Tower 6i
    - 1k camera
    - Max zoom
    - No filter
  - File manipulation
    - Convolution filter

URF Testing

- Stock removal influences final results



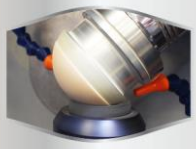




URF Testing

- URF's shape & removal rate
  - Compression
  - Belt speed
  - Wheel stiffness
    - Direction the rubber deforms under compression
    - Higher durometer means higher force
    - Belt wrap
    - Wheel
    - Bearing

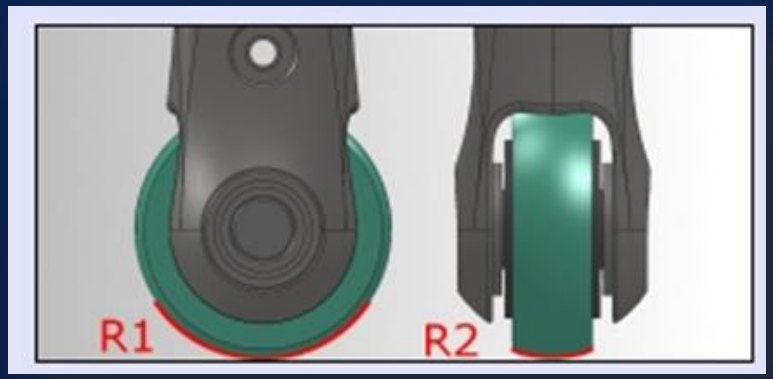
URF Testing

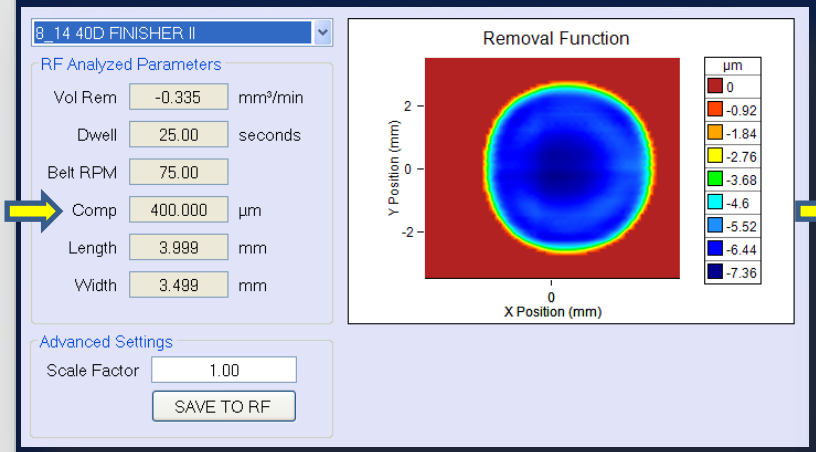



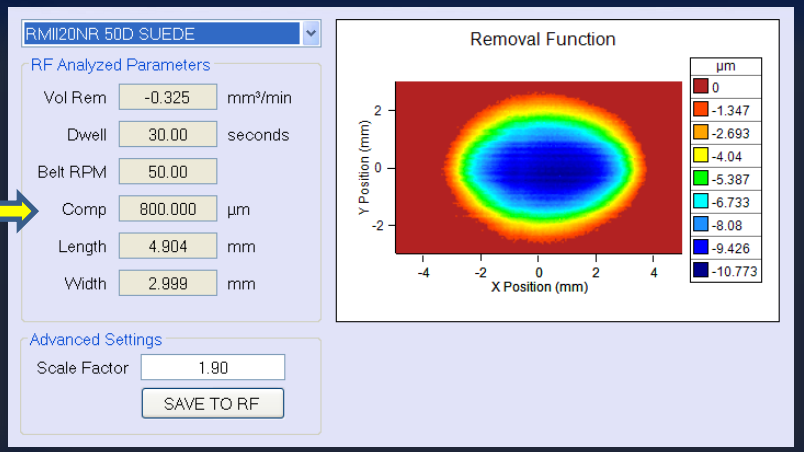


What affects the URF's shape & rate

- Compression
  - Elliptical URF
  - Round URF's
- Ultra Wheel nose radius



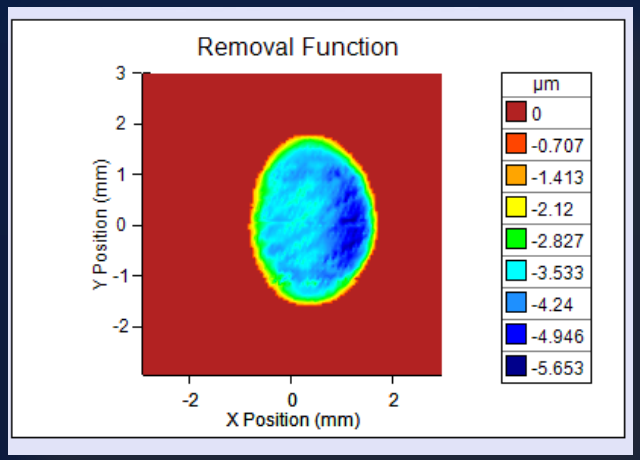


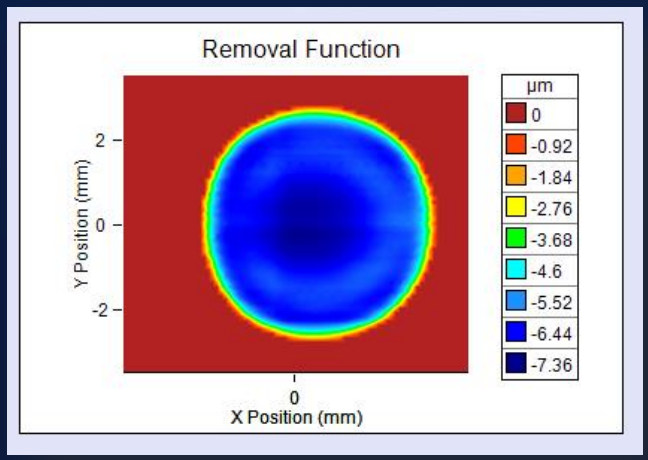


URF Improvements

- Old Parameter set
  - Compression
    - 150 microns
  - Wheel durometer
    - Shore A 70D
  - Wheel diameter
    - 40mm
  - Wheel shape
    - 12.7mm nose radius
  - Belt speed
    - 300rpm
  - Belt type
    - CeO fixed abrasive

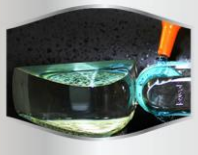
- New Parameters Set
  - Compression
    - *400 microns*
  - Wheel durometer
    - *Shore A 40D*
  - Wheel diameter
    - 40mm
  - Wheel shape
    - *6mm nose radius*
  - Belt speed
    - 70rpm
  - Belt type
    - CeO fixed abrasive

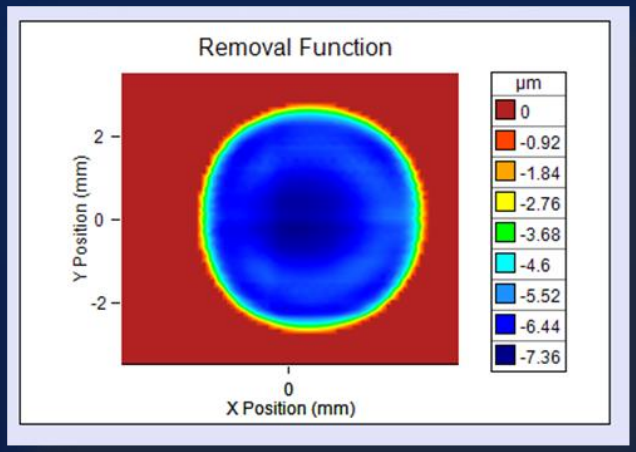


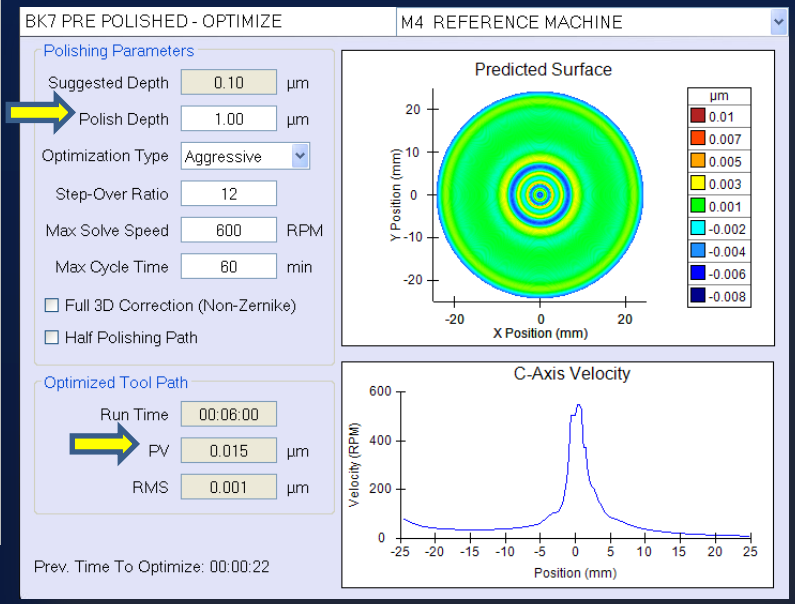


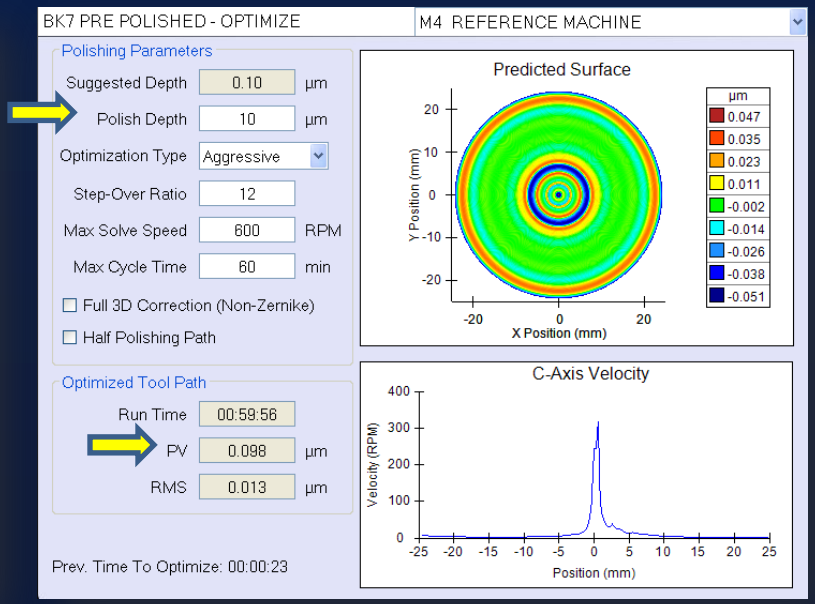
URF Improvements





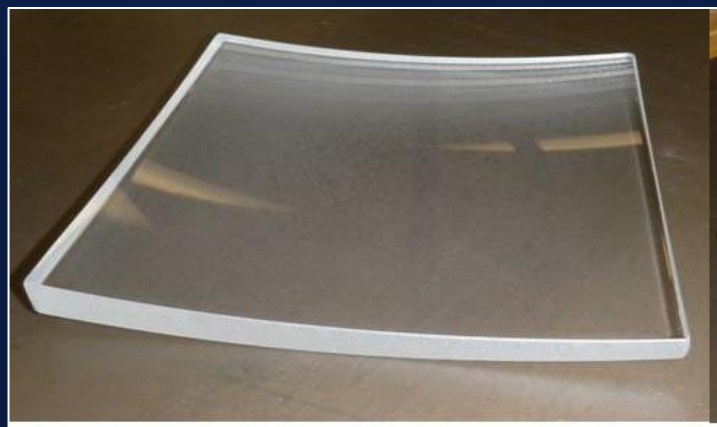





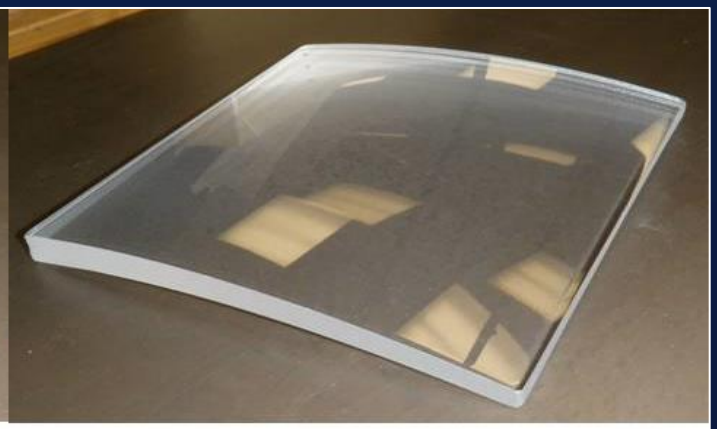


UltraSmooth Finishing (USF)

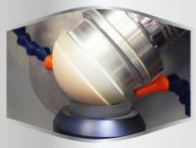
- Abrasives
- Toolpath orientation
- Irregularity
- Roughness
- Mid-Spatials



Concave Surface

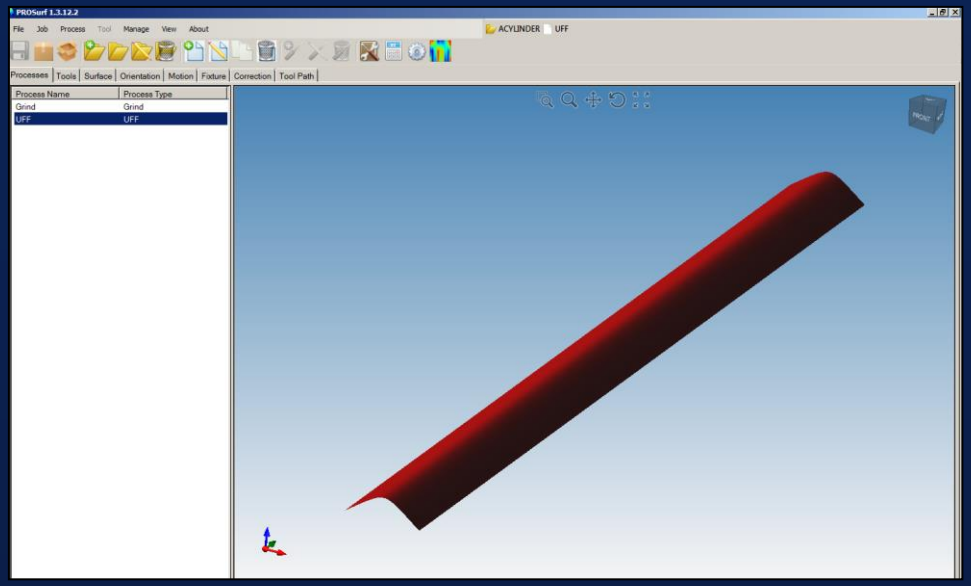


Convex Surface



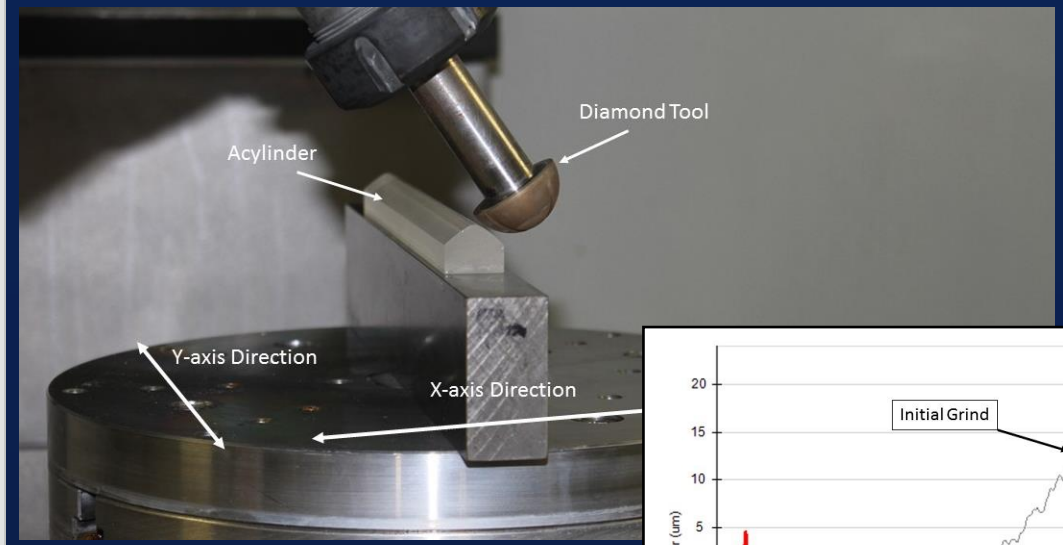
Acylinder ProSurf

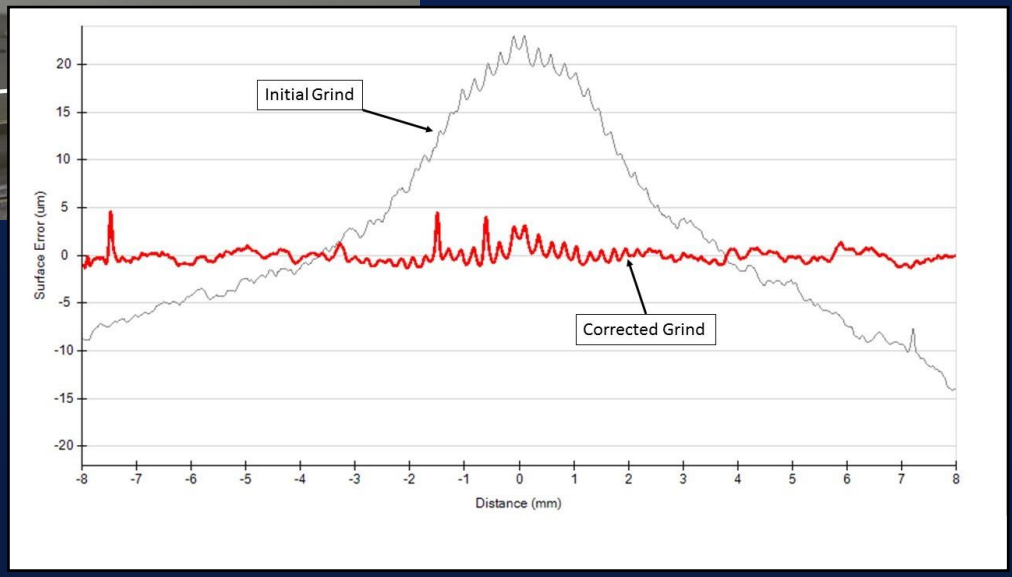


- Schott F2 Glass
- Dimensions 16x16x200 mm

Tool	Diamond Size (micron)	Concentration	Bond	Depth of cut/Pass (mm)	Feed rate (mm/min)
Rough	65	75	Bronze	1.0	
Fine	15	75	Bronze	0.05	
Coolant : UltraCool 5000, 5% concentration					

Acylinder Grind

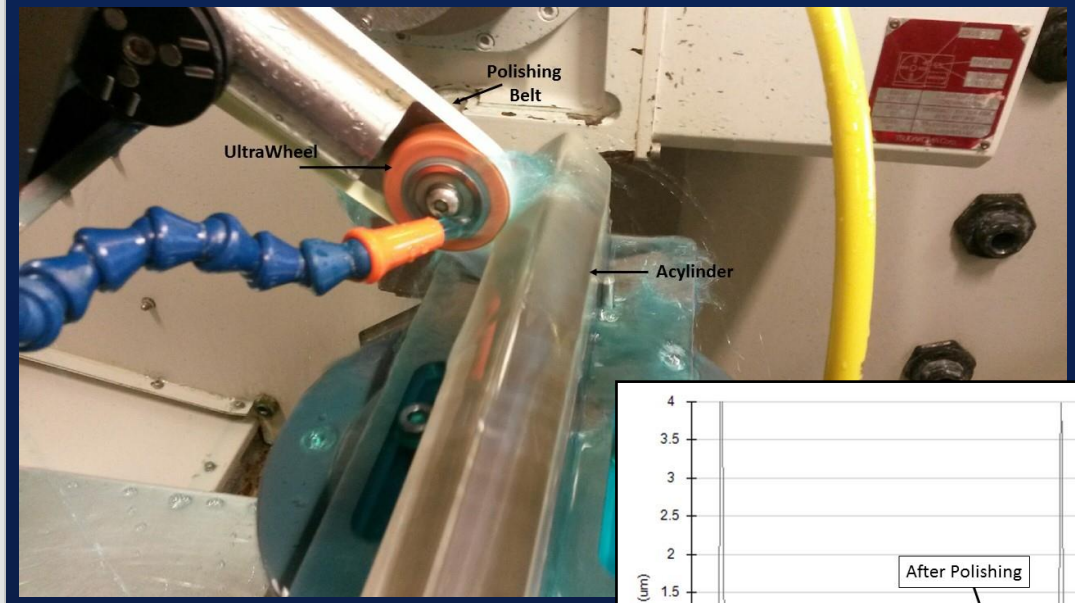


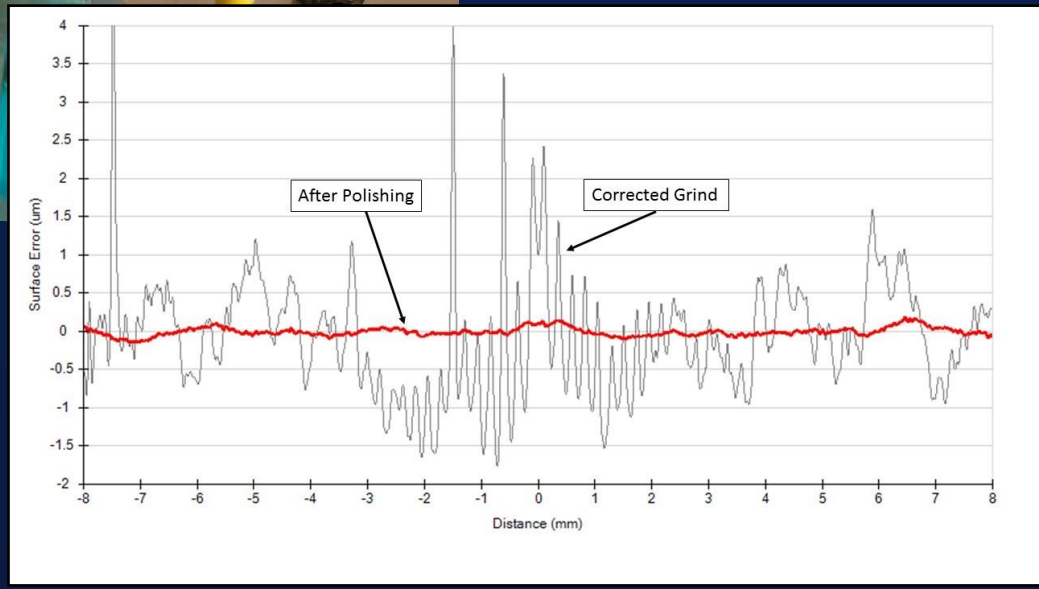


Cut	PV (microns)	RMS (microns)
Initial	44.3	10.7
Corrected Grind	6.98	0.886

Data measured on a OptiTrace 5000, 1mm stylus, $\lambda c = 0.080$mm filter

Acylinder Polish

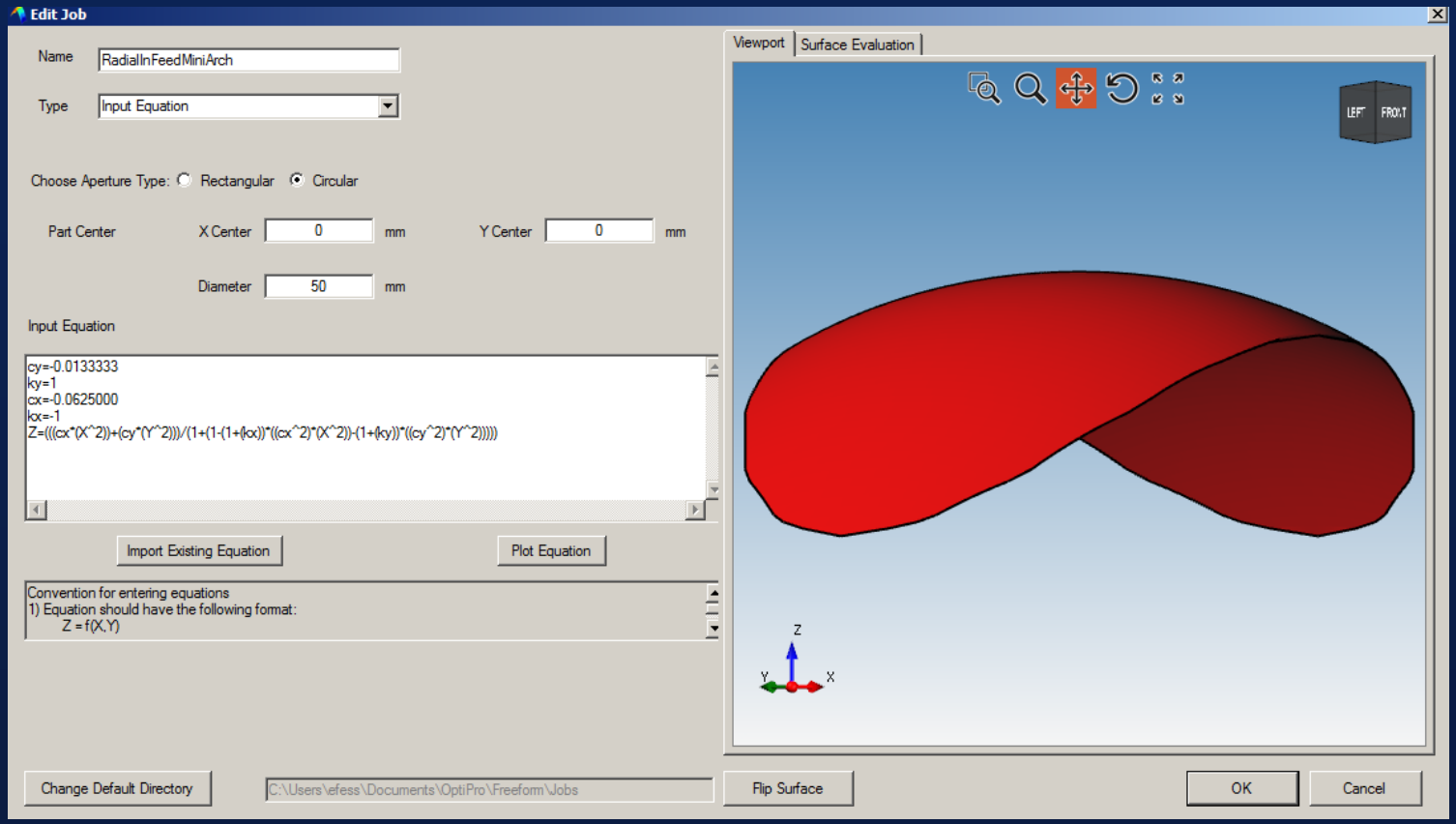




	PV (microns)	RMS (microns)
Final Figure	0.442	0.068

Roughness: 2nm rms

Anamorphic Asphere



Part was defined by the anamorphic asphere equation. It had ~4 mm of sag in one direction and over 20 mm of sag in the perpendicular direction. The material use was bk-7.

Processing on UFF

Finished on UFF with CeO2 belt for removal of grinding damage and figure correction.

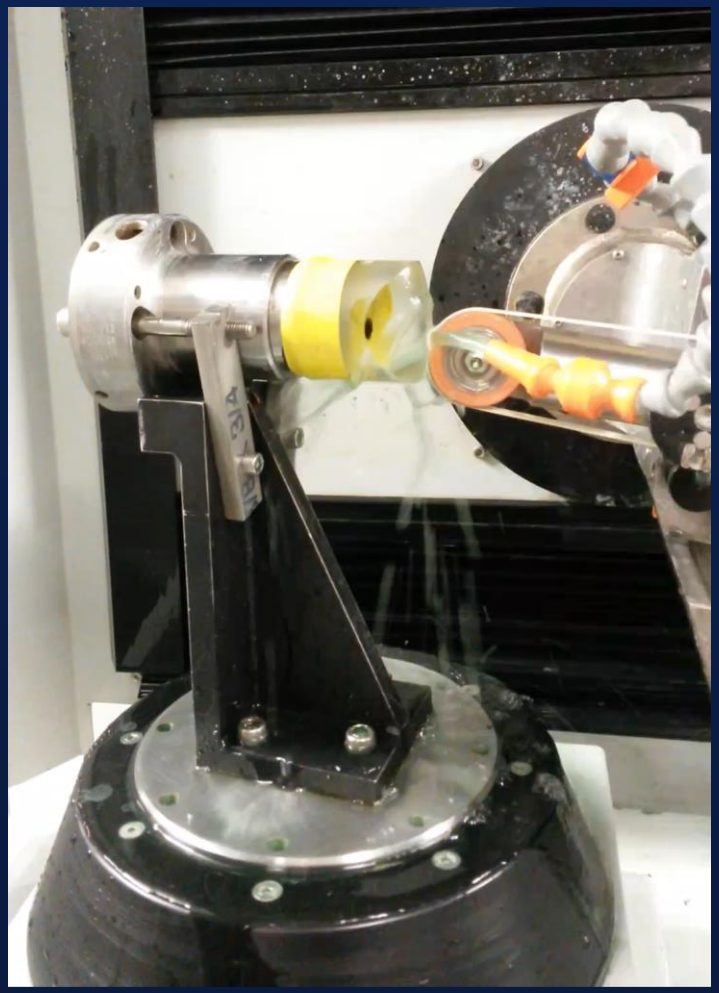
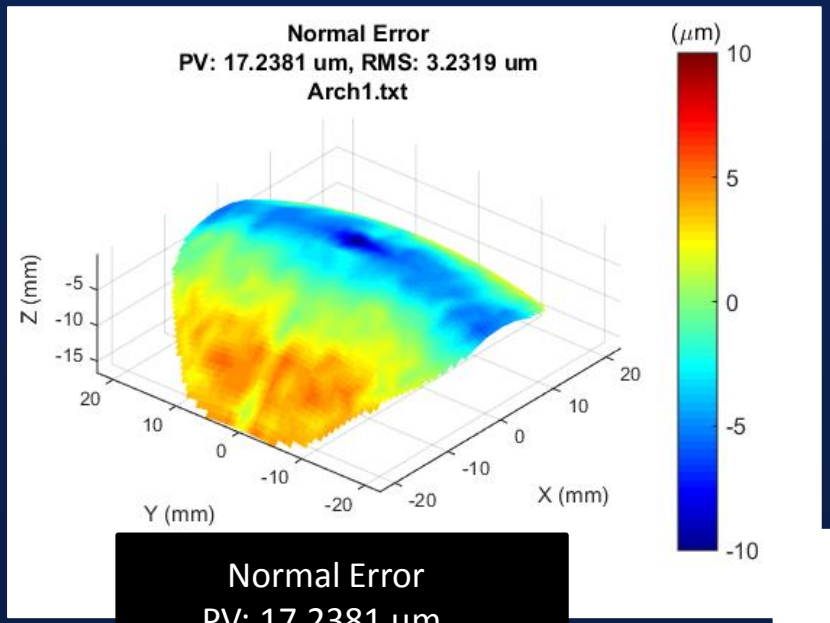
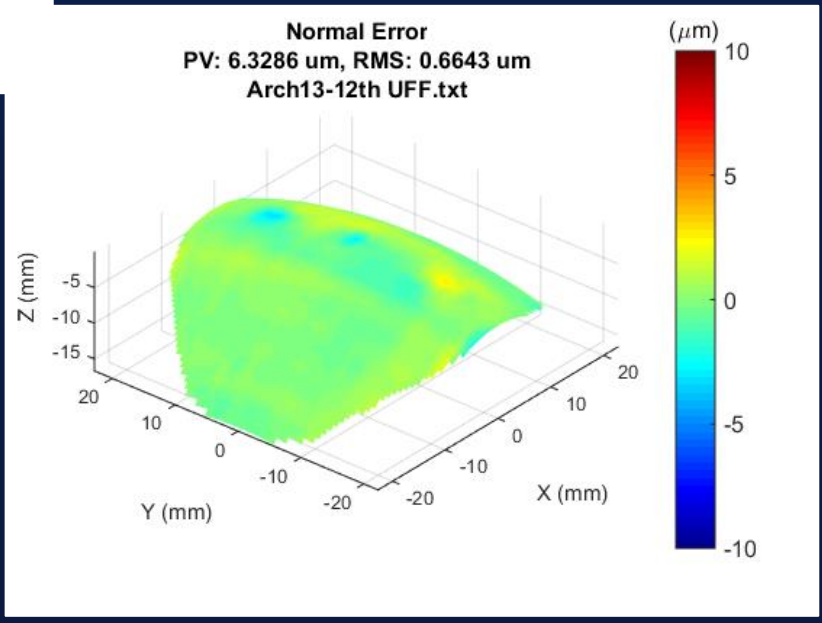


Figure correction Results

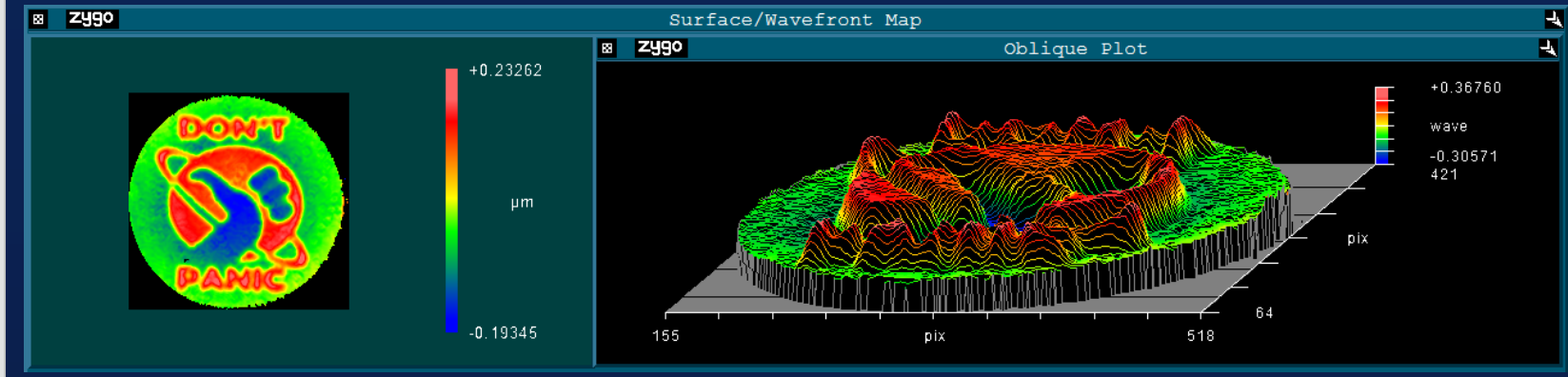


Normal Error
PV: 17.2381 µm,
RMS: 3.2319 µm

Normal Error
PV: 5.6598 µm, RMS: 0.5464



Thank You



The Hitchhiker's guide to the galaxy

- There are many challenges to manufacturing acylinder and freeform optical components, but Don’t Panic!
- OptiPro continues to develop technologies in Grinding, UFF, UltraSurf, and ProSurf to deterministically fabricate precise complex optical surfaces.

National Science Foundation
WHERE DISCOVERIES BEGIN

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