FABRICATION OF FREEFORM OPTICS & CONIC MIRROR MANDRELS

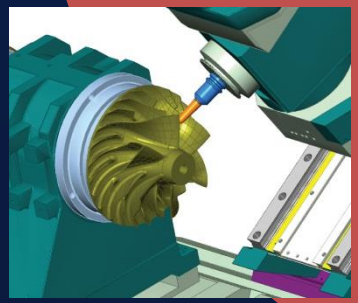
NASA Mirror Technology Days 2014
Albuquerque, New Mexico

OptiPro Systems, LLC
Ontario, NY 14519

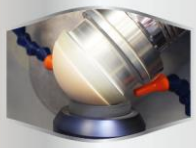
Presented by:

David Mohring

OptiPro Systems



SBIR Partners

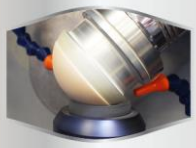





NASA

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

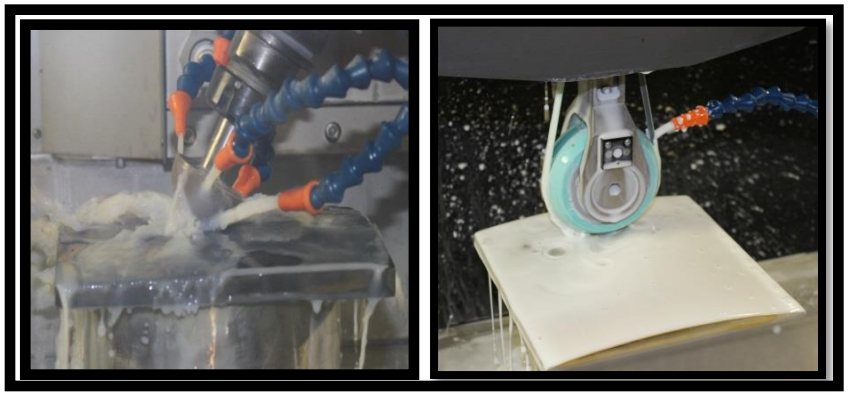
The UltraForm Finishing (6-Axis UFF) and the UltraSurf platforms developed by OptiPro Systems deterministically polish and measure complex aerodynamic and conformal mirror shapes made of difficult to manufacture glass, crystal and ceramic materials.

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 19, 2014

Outline

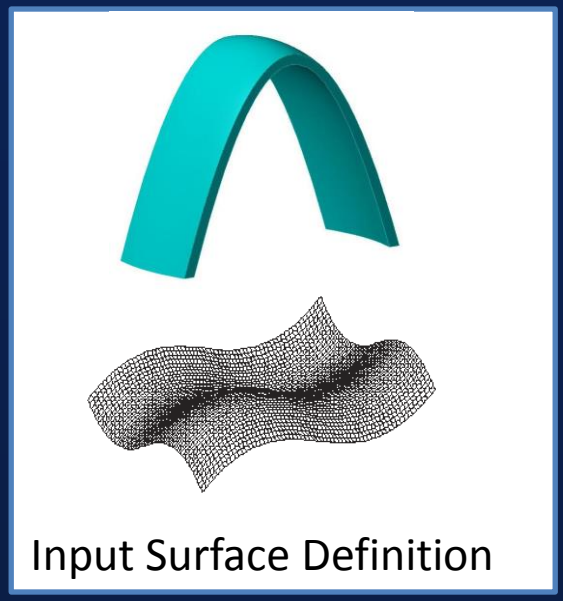
- Freeform Surface Definition
- Toolpath generation
- Grinding
- UFF Sub Aperture Polishing
- USF Polish Smoothing
- Surface Metrology
- Precision Platform Requirements
- CeFO

Freeform Applications

- AKA: Conformal Surfaces
- Reflective Light Mirrors
- X-Ray grazing incidence reflectors
- Off Axis Parabolic Mirrors
- IR telescope based on anamorphic mirrors
- Solar Energy

Input Surface Definition

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

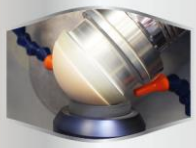


Input Surface Definition

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

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 $-3.0810743 \times 10^{-04}$

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

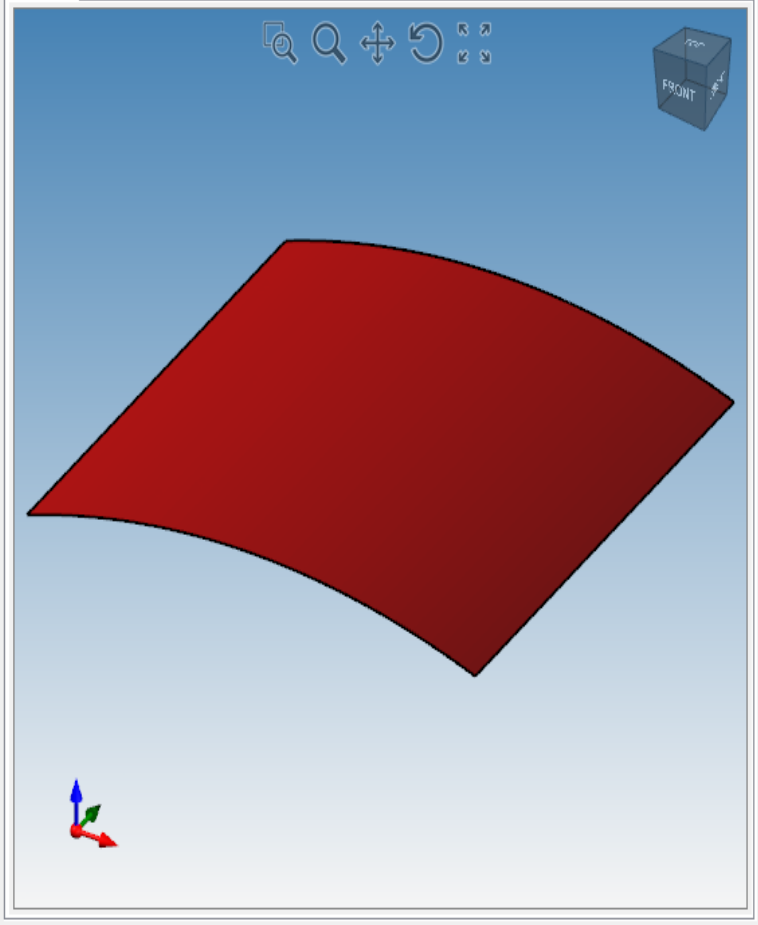
Input Equation

```
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

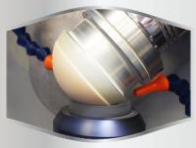
Convention for entering equations
1) All X's, Y's, and Z's must be capitalized.
2) All multiplication, division, or exponentiation involving multiple X and/or Y must be written using the following convention

Viewport | Surface Evaluation



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

Toolpath Generation



File Job Process Tool Manage View About

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

Lead In

Rapid In: 0 mm

Feed In: 0 mm

Axis: (•) X ( ) Y ( ) Z

Set Axes Positioning Order

X 1 Y 2 Z 3

A 1 B 4 C 5

Lead Out

Feed Out: 0 mm

Rapid Out: 0 mm

Axis: (•) X ( ) Y ( ) Z

Select Starting Position

( ) Negative X, Positive Y (•) Positive X, Positive Y

( ) Negative X, Negative Y ( ) Positive X, Negative Y

Axis Combination

3 Axis XYZ
5 Axis XYZAB
5 Axis XYZBC

Axis Align A: 0 mm

Axis Align B: 0.5 mm

Tool Length A: 0 mm

Tool Length B: 150 mm

C Axis Plate to Origin: 50 mm

B Zero Offset from Vertical: 0 deg

[ ] B Angle Compensation

B Angle Minimum: 90 deg

B Angle Maximum: 90 deg

Select Compatible Machine

FiveAxisUFF
SixAxisUFF
Triumph
None

Tool Definition

File Job Process Tool Manage View About

DORIC ASPHERIC CYLINDER TEST UFF

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

Lead In

Rapid In 0 mm

Feed In 0 mm

Axis: X Y Z

Set Axes Positioning Order

X 1 Y 2 Z 3

A 1 B 4 C 5

Lead Out

Feed Out 0 mm

Rapid Out 0 mm

Axis: X Y Z

Select Starting Position

Negative X, Positive Y | Positive X, Positive Y

Negative X, Negative Y | Positive X, Negative Y

Axis Combination

3 Axis XYZ
5 Axis XYZAB
5 Axis XYZBC

Axis Align A 0 mm

Axis Align B 0.5 mm

Tool Length A 0 mm

Tool Length B 150 mm

C Axis Plate to Origin 50 mm

B Zero Offset from Vertical 0 deg

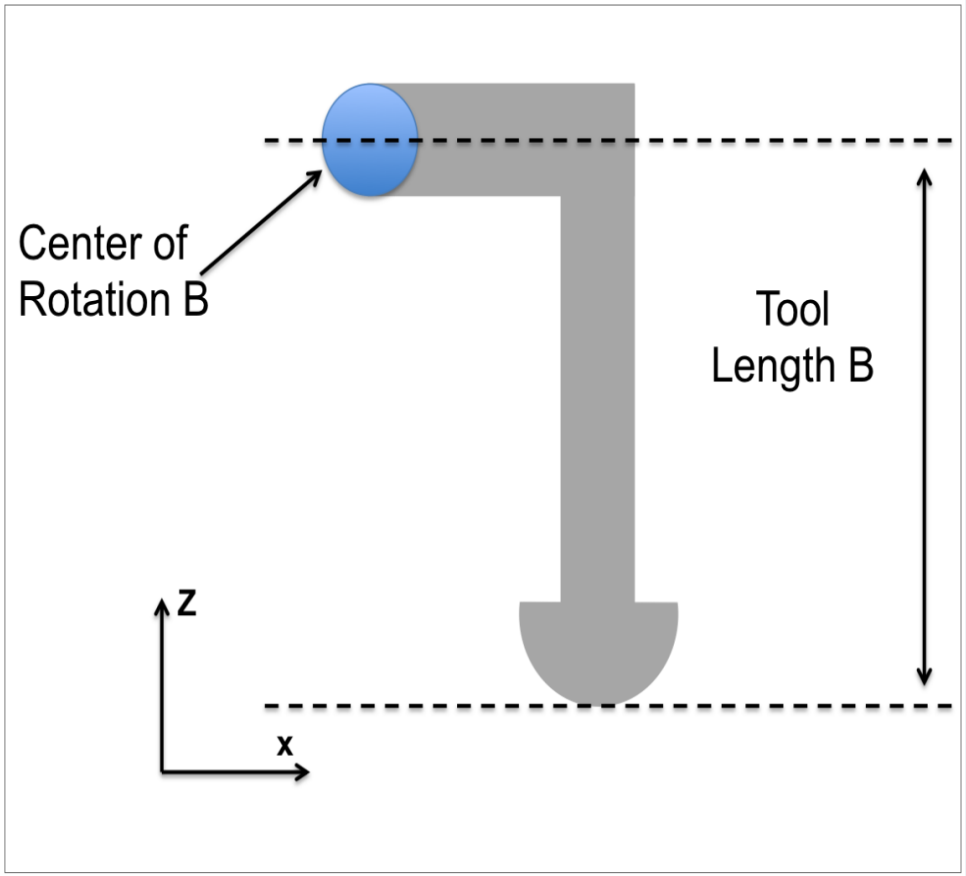
B Angle Compensation

B Angle Minimum 90 deg

B Angle Maximum 90 deg

Select Compatible Machine

FiveAxisUFF
SixAxisUFF
Triumph
None



Grinding Operation

- Bonded or plated diamond tools
- Spherical or toric
- Tool path is a raster motion (up to 5-axis)
- Metrology can make the process deterministic

Rough -> Fine Grind

- Surface Texture
- Mid Spatial Errors

(4-60 cycles /aperture)

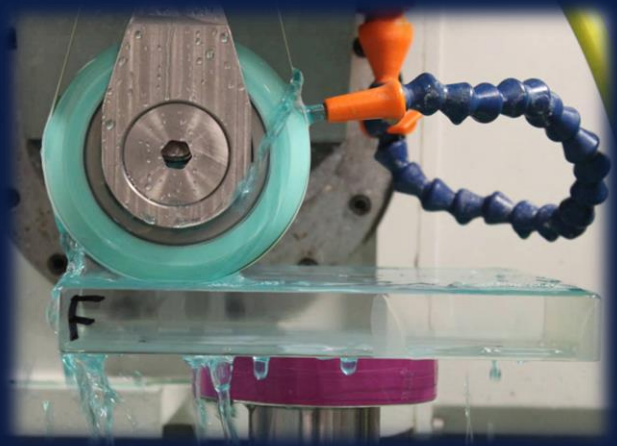
Metrology Data Input

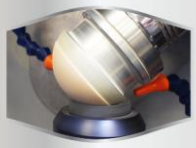
Deterministic Corrective Grind & Surface error spatial analysis

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

Polishing

- UltraWheel specifications
- Clearances
- Abrasives
- Toolpath orientation
- Irregularity
- Roughness
- Mid-Spatials

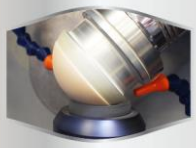




6-Axis UFF

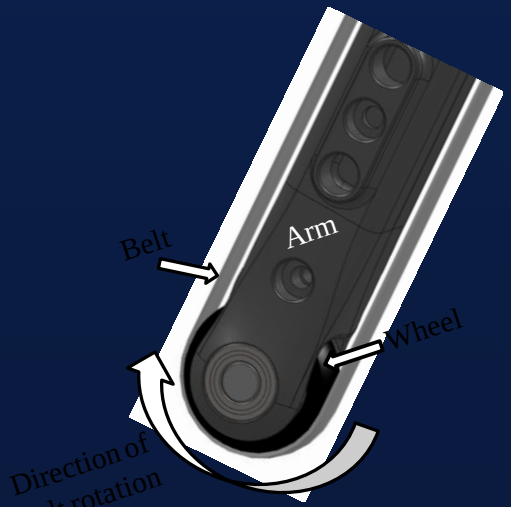
- X,Y,Z linear axis
- A,B,C Rotary Axis
- Tool Rotation motion control
- Work Piece motion control
- Freeform capabilities
- Tool normal -> Surface
- Full CNC Control
- Optical Fabrication software
- Bound and loose abrasives
- Deterministic / corrective



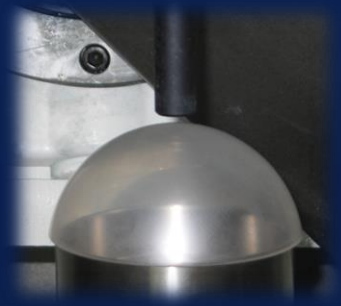
UltraForm Finishing (UFF)

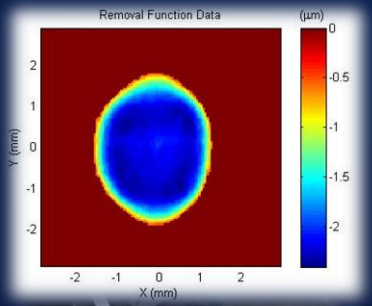
- 5-axis/6-axis CNC controller with simple to use GUI
- Wheel size range 8 to 100 mm in diameter
- Wheel nominal hardness range from 30 to 80 Shore A
- Bound/fixed abrasives or commercial polyurethane belts with slurry
- Capable of finishing a wide range of materials from optical glass to hard ceramics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



UltraForm Finishing (UFF) Process

Deterministic sub-aperture CNC polishing
10 to 300 mm optics: Flats, spheres, aspheres and freeforms





Measure Removal Function

- Integrated STIL pen
- Onboard metrology

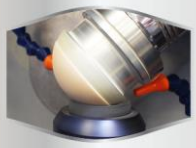
Input Initial Figure Error

- Zygo Interferometer Input
- Profilometer Input

Optimize Polishing Tool Path

- Reduce figure error
- Fine control of polishing path

Toolpath Tool Normal

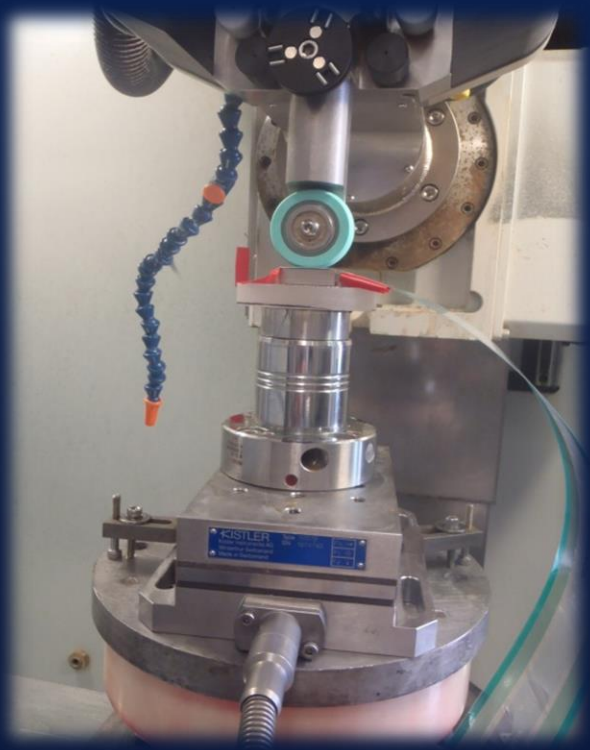





Force vs Compression

Goal: Derive the relationship between compression and resultant force for improved process understanding.

Tools: Force Dynamometer and a pressure mapping sensor.



Force vs. Compression Results

- Force vs. compression data
- Polynomial curve fit

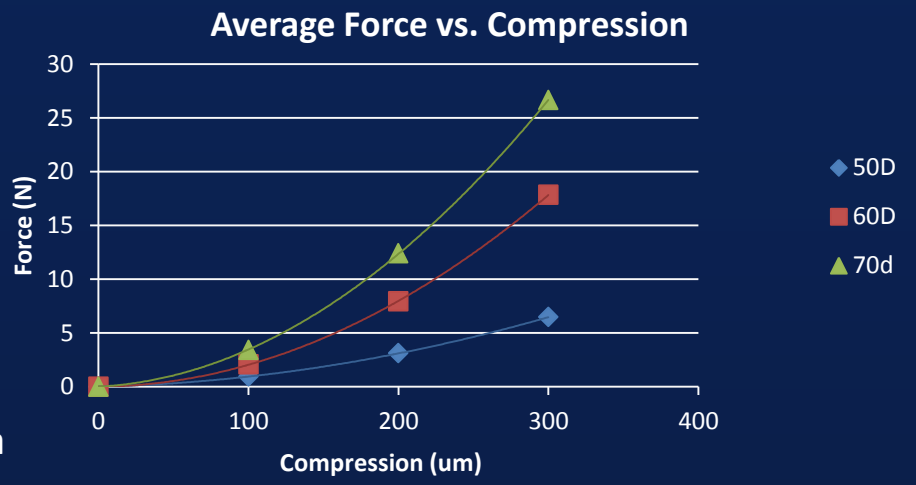


Figure 1: Pressure vs. Compression in discrete intervals averaged between both sensors and several runs. Wheels were ø40mm

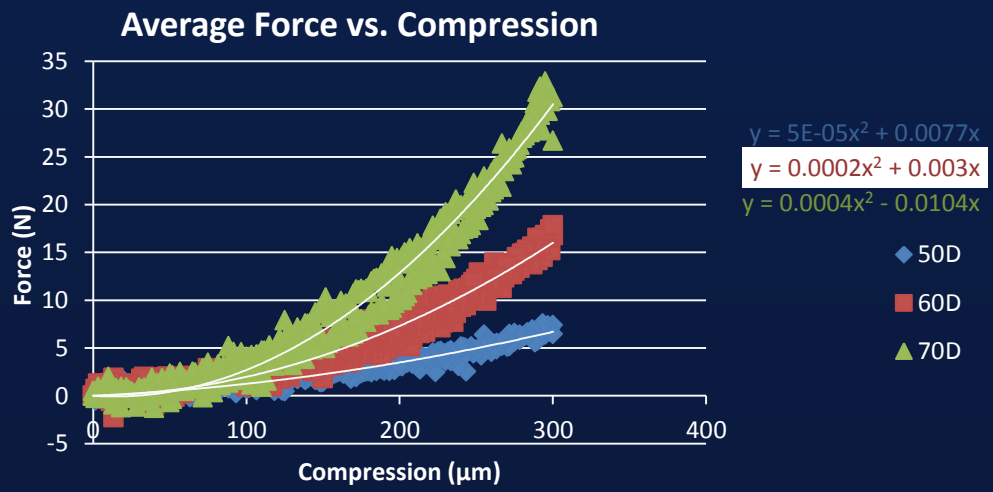


Figure 2: Pressure vs. Compression for a continuously increasing then decreasing compression . Data from the force dynamometer. Wheels were ø40mm

UltraSurf

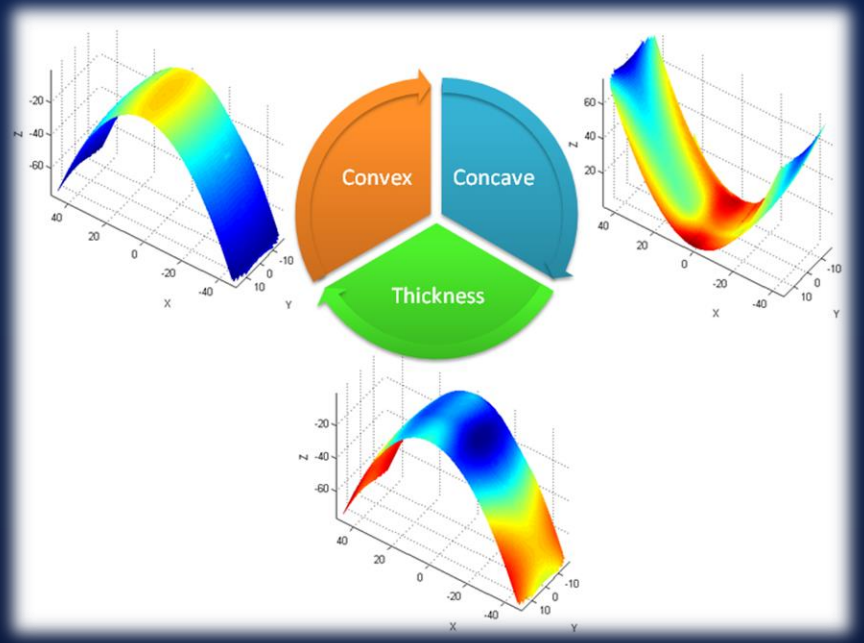
- 5-Axis Non-Contact Measuring System
- Scans With Various Non-Contact Probes
- All Air Bearing Axes
- Linear Motors
- Brushless DC Rotary Motors
- X,Y,C move the part
- Z,B move the probe

Axis:	X,Y,Z	B	C
Travel:	200 mm	360°	360°
Resolution:	5 nm	0.02 second	0.01 second
Max. Velocity:	20 mm/s	6 RPM	6 RPM

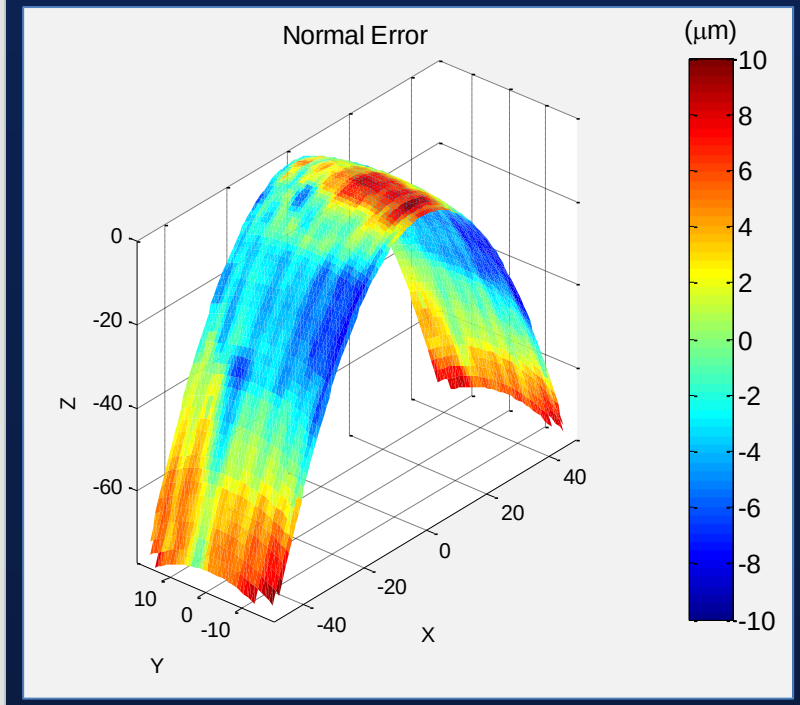
UltraSurf Measurements

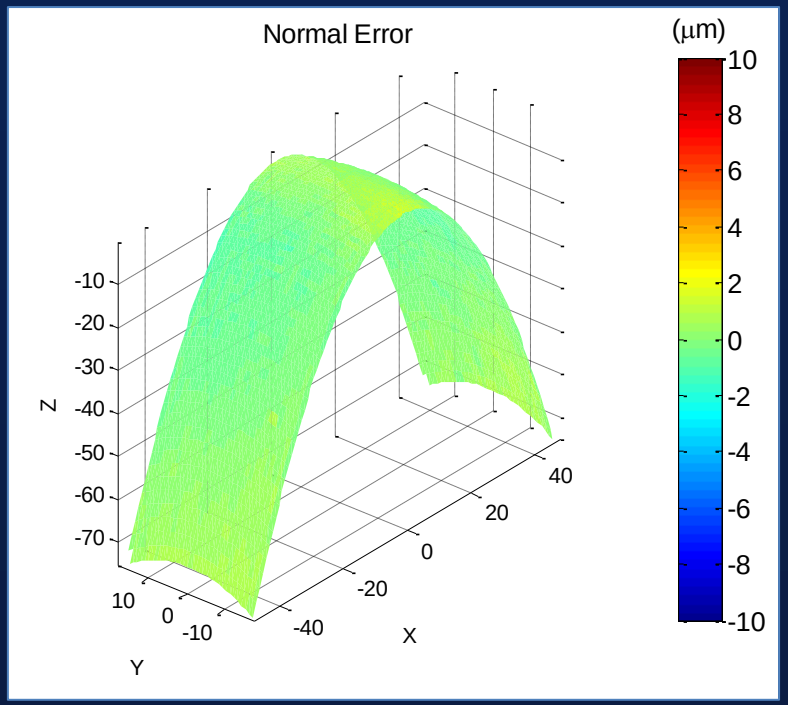
- Surface measurement
- Fixture measurement
- In process and final data
- Sensor flexibility

Depth of Field	20 µm	300 µm
Working Distance	0.6 mm	4.5 mm
Z Axis Resolution	1 nm	10 nm
Accuracy	10 nm	0.1 µm
Spot Diameter	1 µm	4 µm
Lateral Resolution	0.5 µm	2 µm
Numerical Aperture	0.69	0.5
Max Angular Slope (+/-)**	44º	30º



Freeform Metrology Results



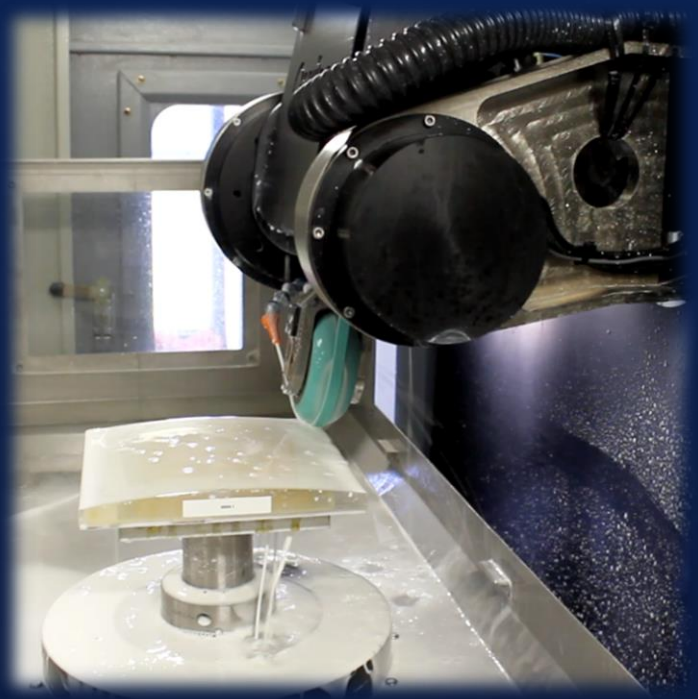


Before
PV : 25.5 µm
RMS : 3.97 µm

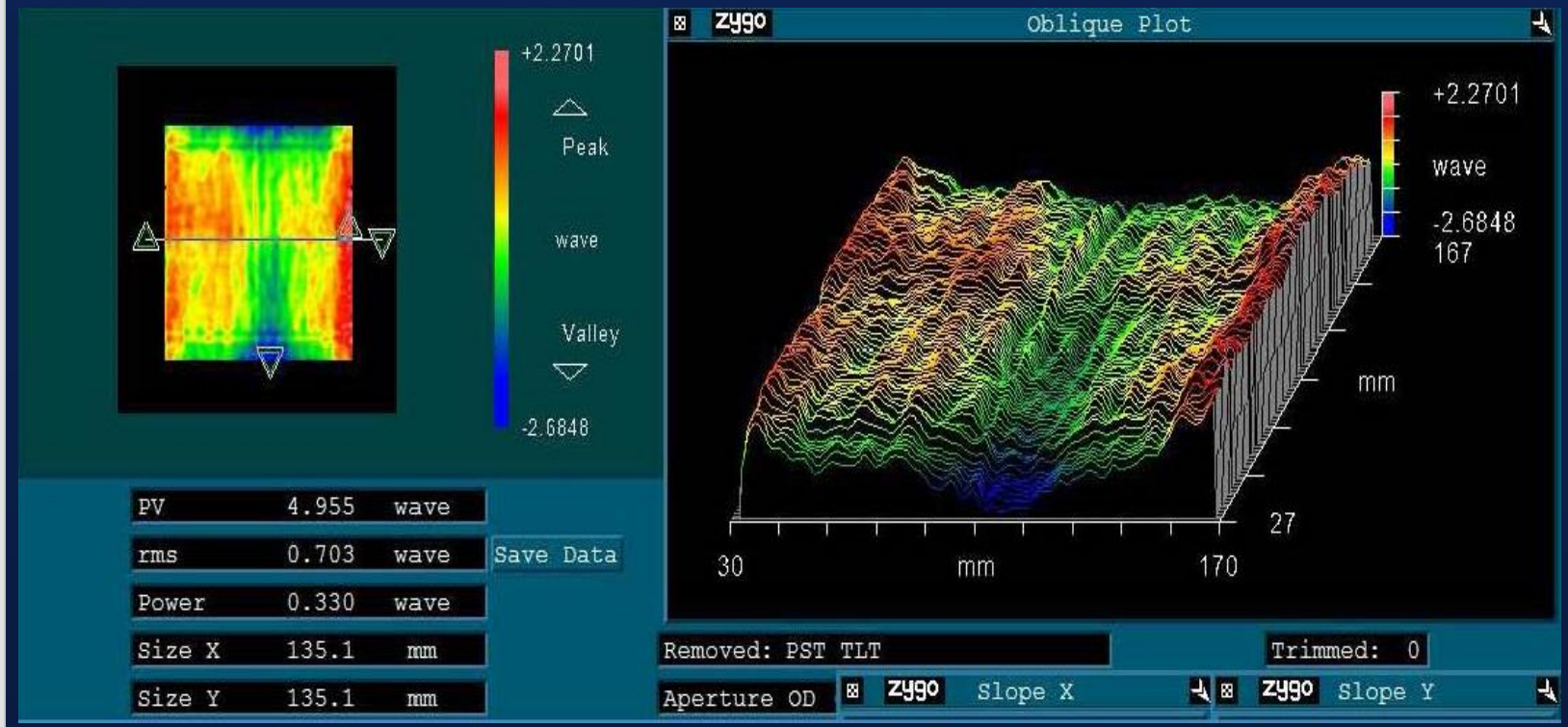
After
PV : 3.95 µm
RMS : 0.53 µm

6-Axis UFF Platform Updates

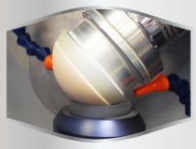
- Belt tracking
- UltraWheel change
- Tensioning apparatus
- Axis alignment tools
- Fixture datum
- Software



Freeform Metrology Results



PROSurf USF Toolpath



PROSurf

File Job Process Tool Manage View About

SPINEL USF

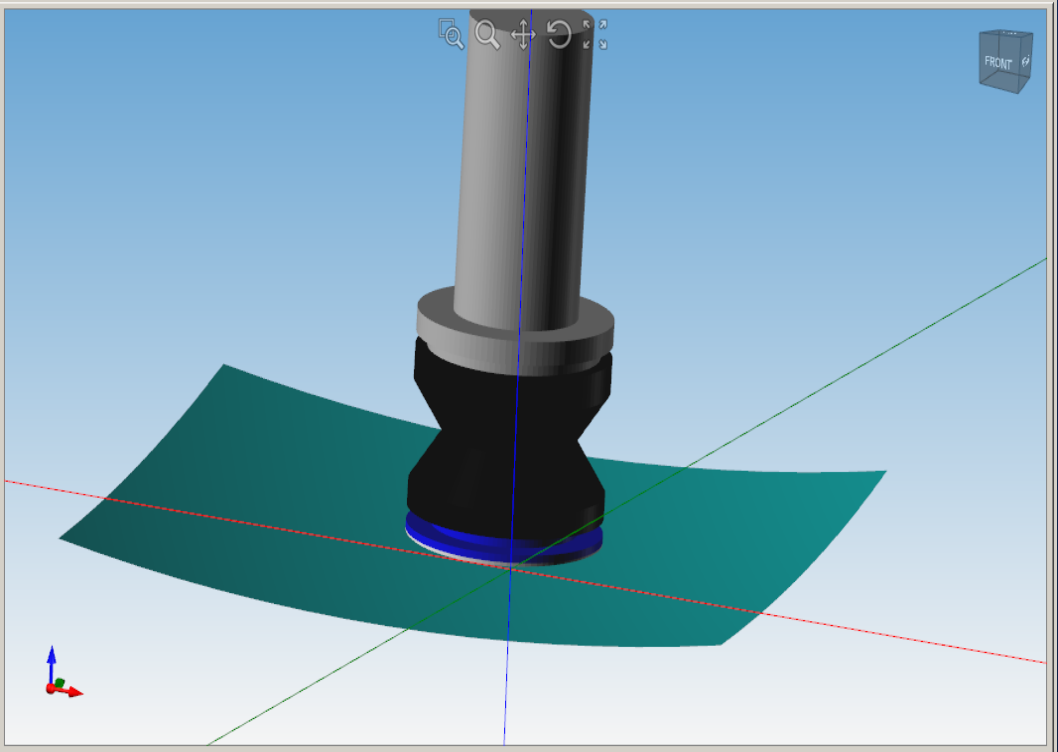
Processes | Tools | Orientation | Surface | Motion | Fixture | Correction | Tool Path

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
```



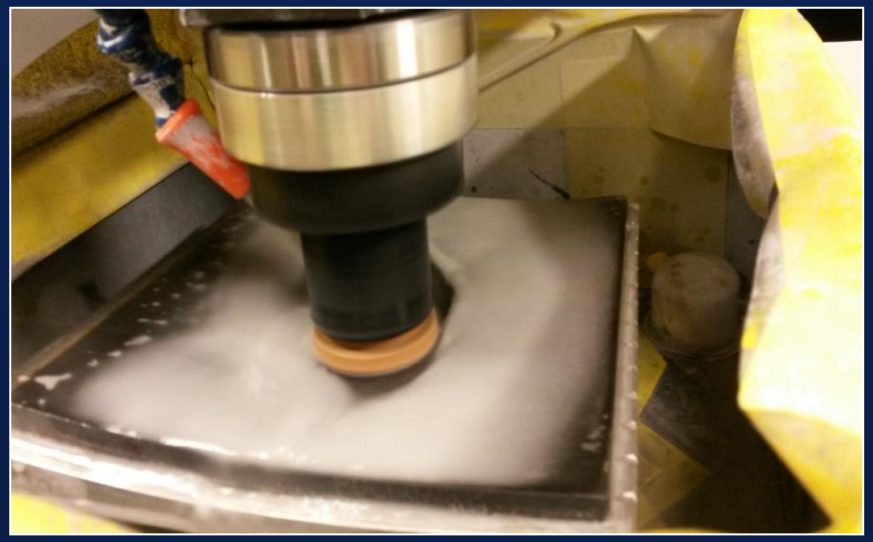
Machine On
Panels On
Slow Fast

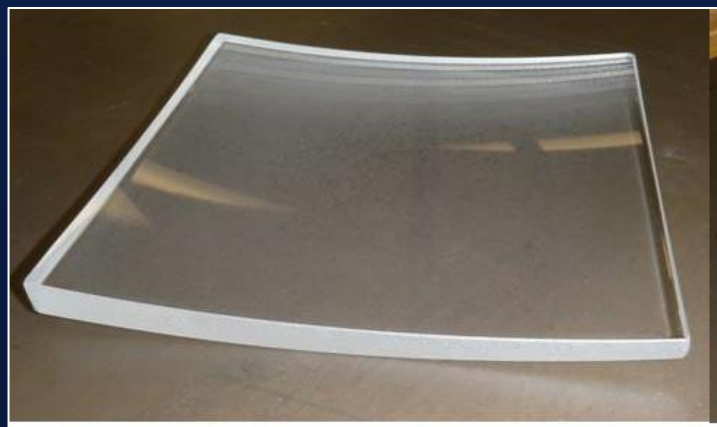
Start

1:37 PM
3/30/2014

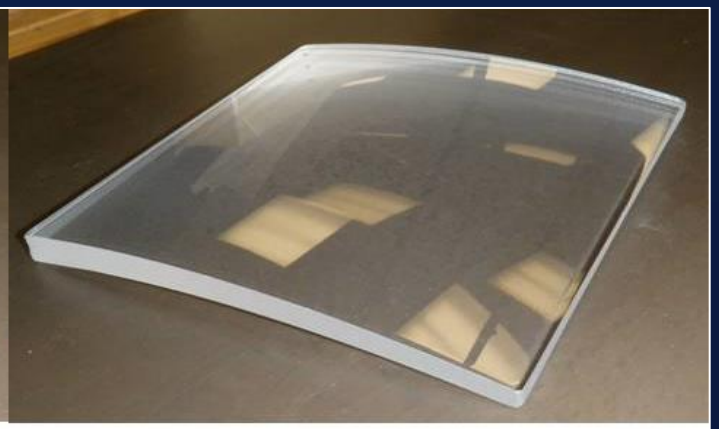
UltraSmooth Finishing (USF)

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





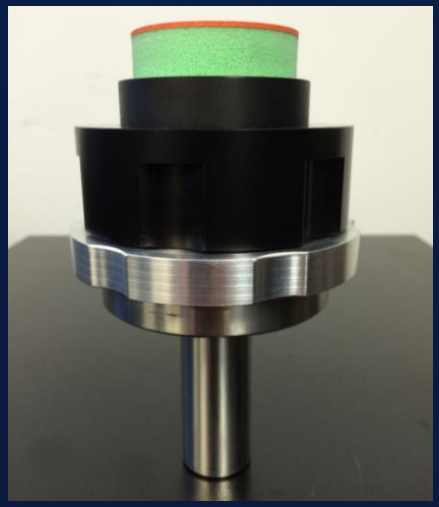
Concave Surface



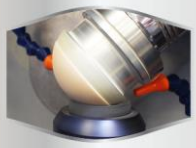
Convex Surface

USF Tooling Design

- Quick change
- Backing durometer
- PolyPad Patterns
- Slurry central feed
- Cost Reduction



Optitrace 2D Scan

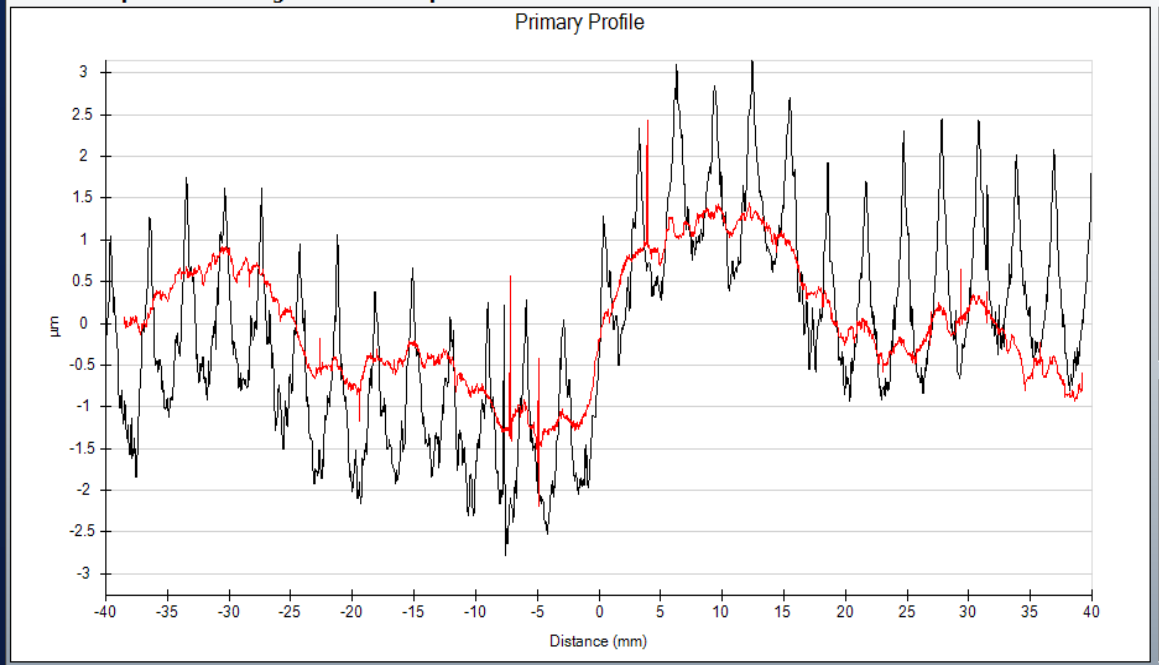





OptiTrace

File View Remove Form Filter Mask Export Advanced

Trace Inspection Change Bounds Gap Fill: Off



Profile Control

- 8AC 3
- ISAC 2

P W R S

Shift Distance mm

Reset Shift

Analysis Settings

Form Removed	LSQArc
Radius - Convex	529.97642 mm
λc:	0.800 mm
λs:	0.000 µm
Slope Window	--- mm
Clear Aperture	--- mm

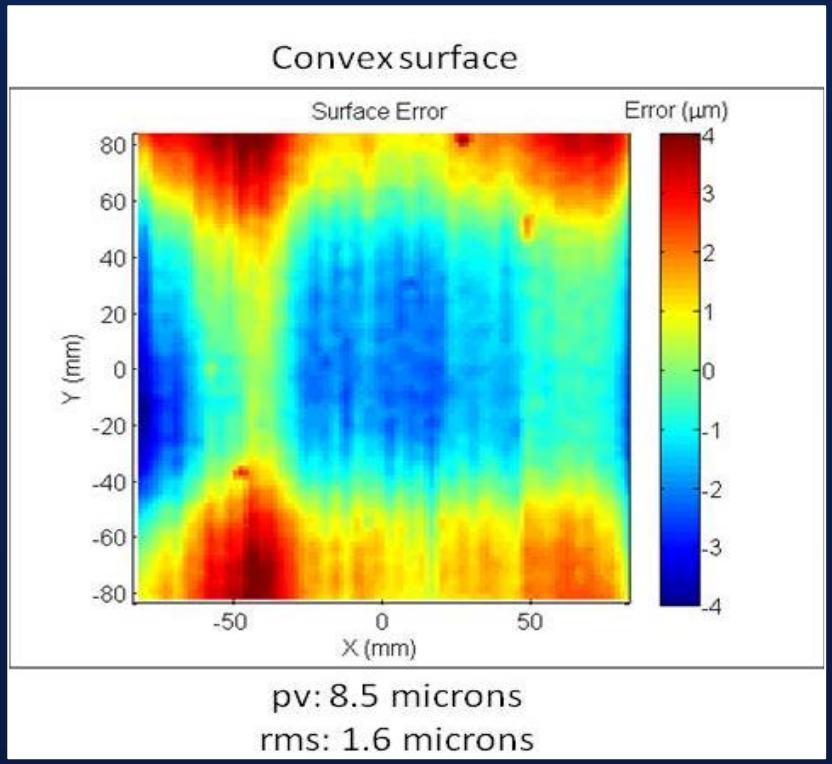
	Primary (µm)	Waviness (µm)	Roughness (µm)	Slope (µm / mm)
PV:	**5.475**	2.892	3.543	2.892
RMS:	**0.731**	0.727	0.058	0.727
AVG:	**0.614**	0.611	0.030	0.611

	X (mm)	Y (um)

OPTIPRO The *Machines* Behind Precision Optics

UltraSurf 3D Scan

- 175mm x 175mm
- Raster Ground
- USF Polish Data
- UFF Correction input



Optical Polishing/Finishing Machines

PRO 80P ePX 200

PRO 80 UFF UFF 300

TRIUMPH

JOIN THE OPTIPRO REVOLUTION

UFF 500

OptiPro Systems
585-265-0160

Optical Metrology Equipment

OptiTrace 5000

UltraSurf 4X/5X

PRO Tower 4i/6i

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Center for Freeform Optics (CeFO)

CeFO is a joint Industry-University cooperative research center funded primarily through Industry members

Vision: Compact, affordable, and performant optical systems will permeate precision technologies of the future.

Mission: The mission of the Center for Freeform Optics (CeFO) is to advance research and education in the science, engineering, and applications of systems based on freeform optics through a dedicated, continuing industrial partnership based on shared value, and promotion of technical advantage leading to a competitive economic advantage for CeFO members.

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