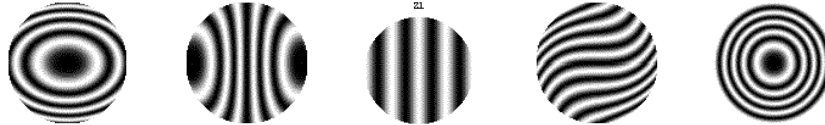College of Optical Sciences THE UNIVERSITY OF ARIZONA®

Interferometry and Optical Profilometry

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Outline

- 1. **Basic interference and measurement of surface shape**
- 2. **Phase-shifting interferometry**
- 3. **Optical profilometry**
- 4. **Starting a company**
- 5. **Foot scanner**
- 6. **Getting rid of problems with vibration**
- 7. **Starting another company**
- 8. **Concluding Remarks**

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Interference of Two Beams of Light

Resulting interference fringes
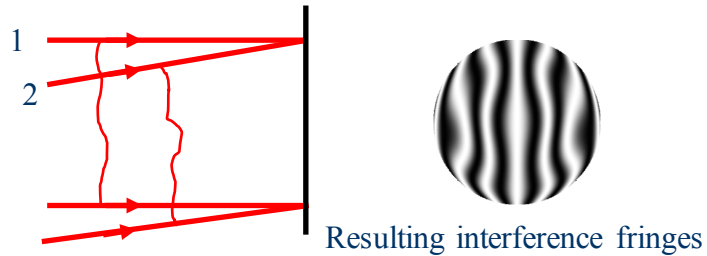
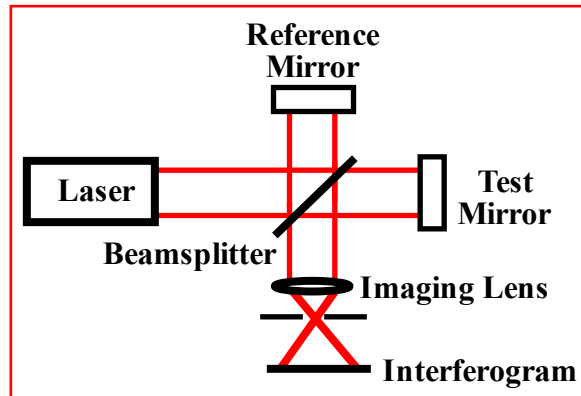Straight fringes if two beams match

Two-Beam Interference Fringes

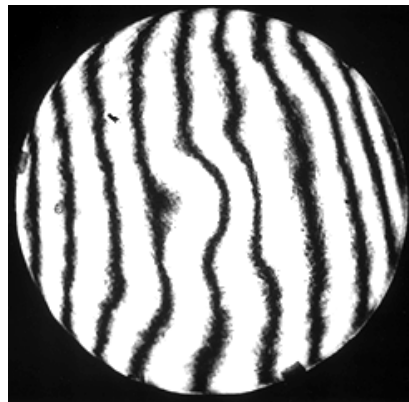$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\,Cos\left(\alpha_1 - \alpha_2\right)$$

$\alpha_1 - \alpha_2$ is the phase difference between the two interfering beams

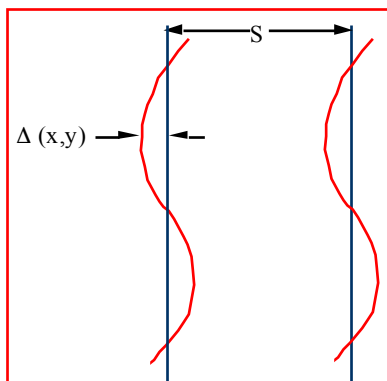$$\alpha_1 - \alpha_2 = \left(\frac{2\pi}{\lambda}\right)(\text{optical path difference})$$

Twyman-Green Interferometer (Flat Surfaces)

Typical Interferogram

$$\text{Surface height error} = \left(\frac{\lambda}{2}\right)\left(\frac{\Delta}{S}\right)$$
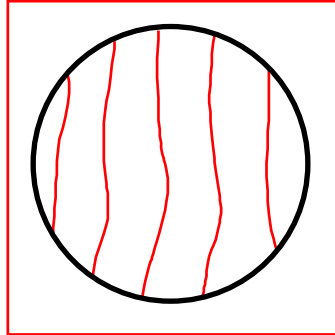
Technique for getting interferometric data into a computer

Typical Interferogram

Surface Error =
$(\lambda/2)\,(\Delta/S)$
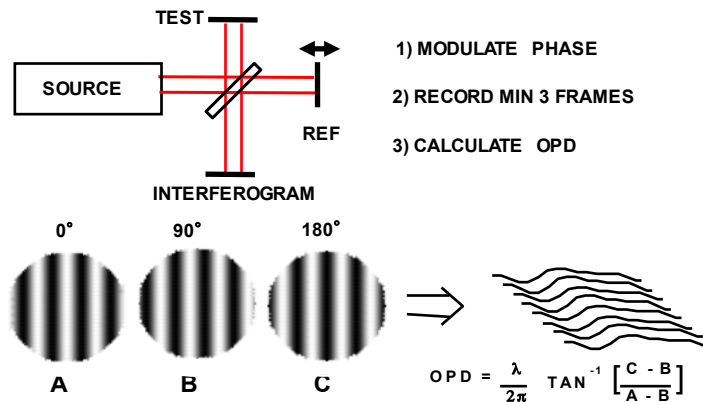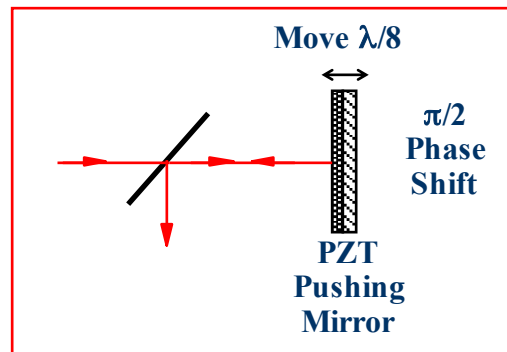
Classical Analysis

Measure positions of fringe centers.

Deviations from straightness and
equal spacing gives aberration.

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Page 9

Phase-Shifting Interferometry

TEST

SOURCE

REF

INTERFEROGRAM

1) MODULATE PHASE

2) RECORD MIN 3 FRAMES

3) CALCULATE OPD

0°   90°   180°

A   B   C

$$OPD = \frac{\lambda}{2\pi}\ TAN^{-1}\left[\frac{C-B}{A-B}\right]$$

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Page 10

Phase-Shifting - Moving Mirror

Move λ/8

π/2 Phase Shift

PZT Pushing Mirror

Phase Stepping (Shifting) Interferometry Four-Step Method

phase shift

$$I(x,y) = I_{dc} + I_{ac} \cos[\phi(x,y) + \phi(t)]$$

measured object phase

$I_1(x,y) = I_{dc} + I_{ac} \cos [\phi(x,y)]$	$\phi(t) = 0 \quad (0°)$
$I_2(x,y) = I_{dc} - I_{ac} \sin [\phi(x,y)]$	$= \pi/2 \quad (90°)$
$I_3(x,y) = I_{dc} - I_{ac} \cos [\phi(x,y)]$	$= \pi \quad (180°)$
$I_4(x,y) = I_{dc} + I_{ac} \sin [\phi(x,y)]$	$= 3\pi/2 \quad (270°)$

$$Tan\left[\varphi(x,y)\right] = \frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}$$

Relationship between Phase and Height

$$\phi(x,y) = Tan^{-1}\left[\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right]$$

$$\text{Height Error}(x,y) = \frac{\lambda}{4\pi}\phi(x,y)$$

Phase-Measurement Algorithms

Three Measurements
$$\phi = ArcTan\left[\frac{I_3 - I_2}{I_1 - I_2}\right]$$

Four Measurements
$$\phi = ArcTan\left[\frac{I_4 - I_2}{I_1 - I_3}\right]$$

Schwider-Hariharan Five Measurements
$$\phi = ArcTan\left[\frac{2(I_4 - I_2)}{I_1 - 2I_3 + I_5}\right]$$

Carré Equation
$$\phi = ArcTan\left[\frac{\sqrt{[3(I_2 - I_3) - (I_1 - I_4)][(I_2 - I_3) - (I_1 - I_4)]}}{(I_2 + I_3) - (I_1 + I_4)}\right]$$

Optical profilometers

- **Non-Contact Optical Profilers**

- **White Light Interferometry**

- **Vertical Scanning Optical Profilers**

Interference Microscope Diagram

Detector Array

Digitized Intensity Data

Magnification Selector

Filters all but the red light from white light of halogen lamp

Beamsplitter

Filter

Illuminator

Translator

LightSource

Microscope Objective

Sample

Mirau Interferometer
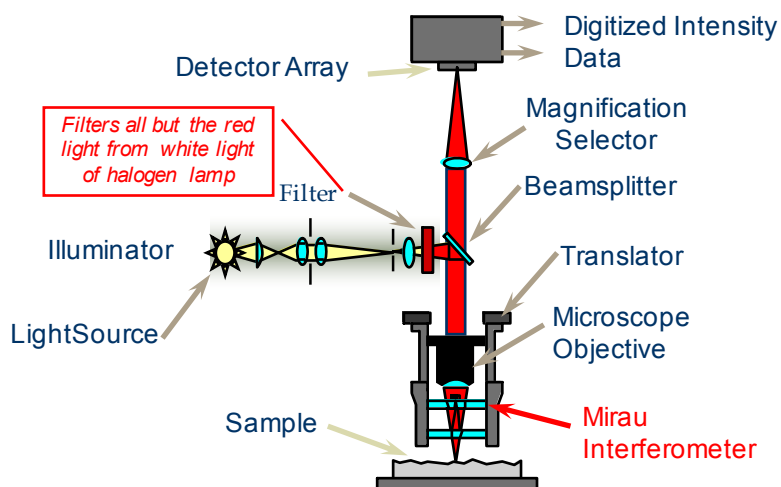
Mirau Interferometer

(10X, 20X, 50X)

Microscope Objective

Reference

Beamsplitter

Sample

2016 – James C. Wyant
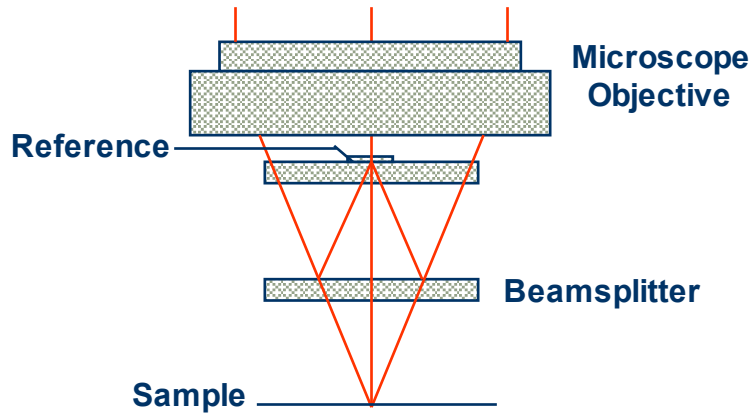
WYKO NT-2000

White Light Interferogram
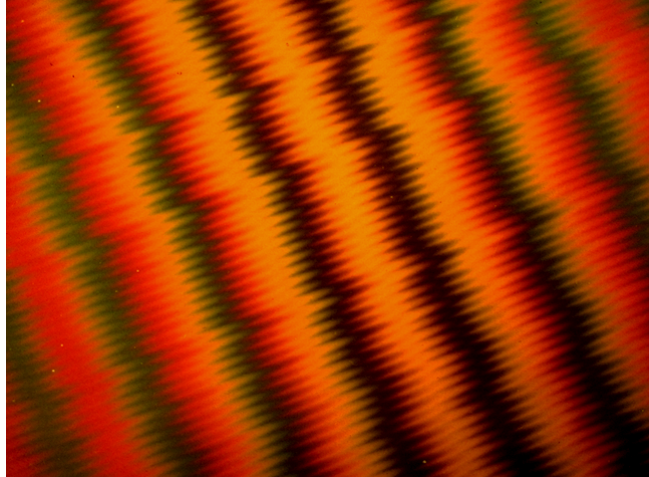
Profile of Diamond Turned Mirror
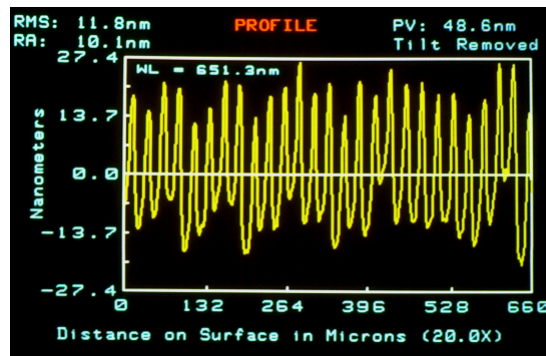
Diamond Turned Mirror
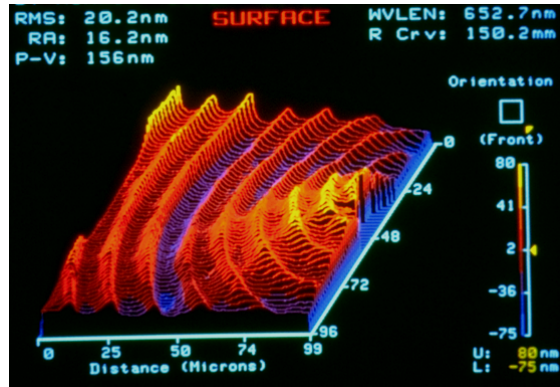
Grating
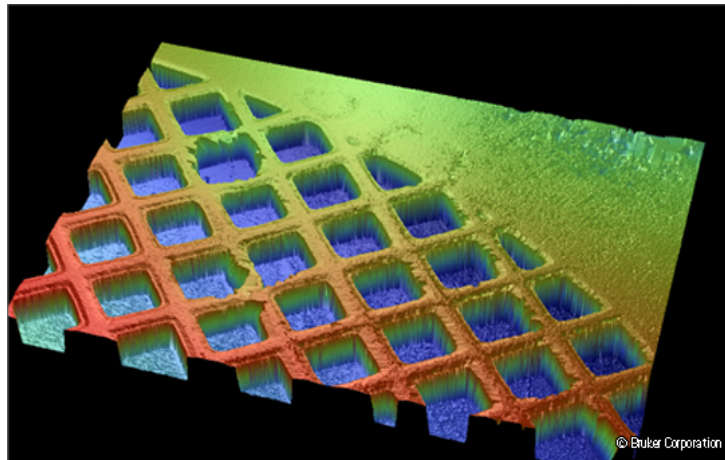
Ref: Bruker

Diamond Film
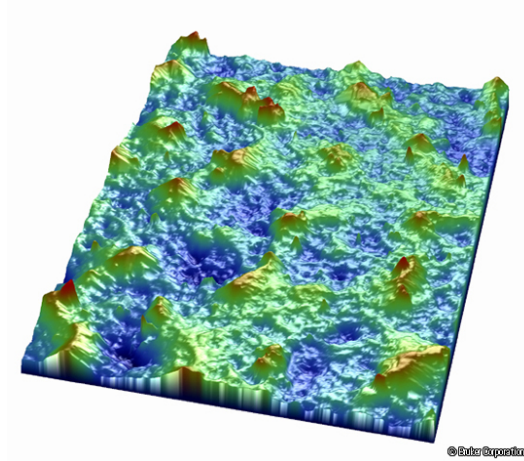
Ref: Bruker

How High is the Step?

Steps > λ/4 between adjacent detector pixels introduce integer half-wavelength height ambiguities

Step > λ/4   **Fringe Order ?**
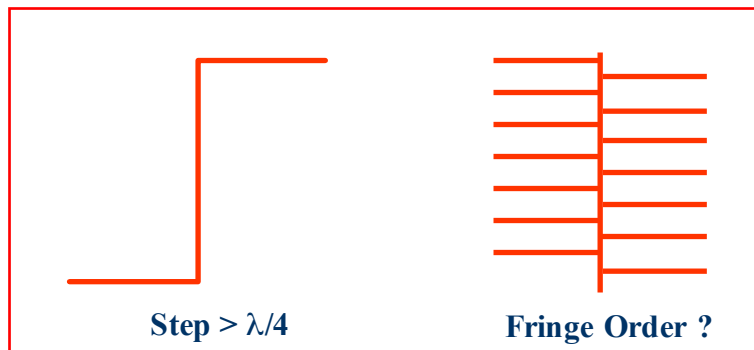
Interferograms of Diffraction Grating

Quasi-Monochromatic Light   **White Light**
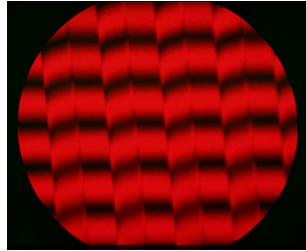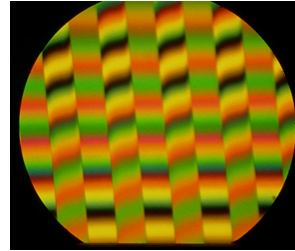
Profile

White Light Interference Fringes

- **Fringes form bands of contour of equal height on the surface with respect to the reference surface.**

- **Fringe contrast will be greatest at point of equal path length or "best focus."**

Interference Microscope Diagram

Digitized Intensity Data

Detector Array

Magnification Selector

Beamsplitter

Illuminator

Translator

Light Source

Microscope Objective

Mirau Interferometer

Sample
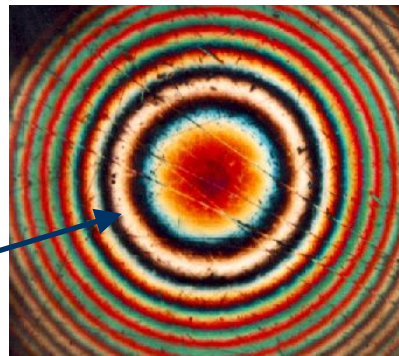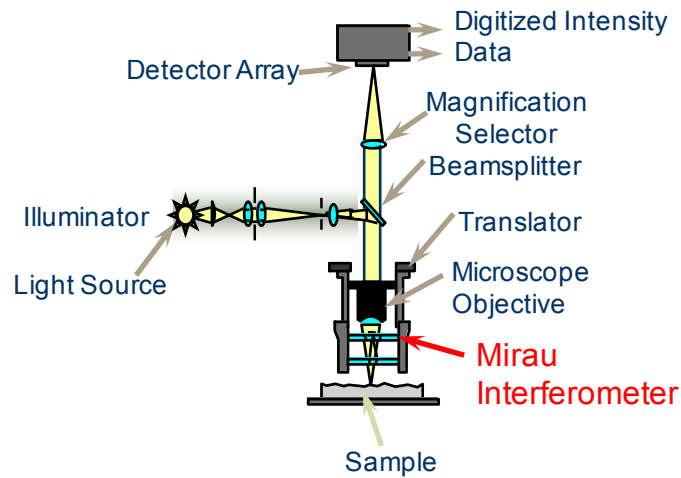
Irradiance Signal Through Focus

$$I = I_0 \left[1 + \gamma(OPD)\cos(\phi + \alpha) \right]$$

Intensity

Coherence envelope

0

OPD
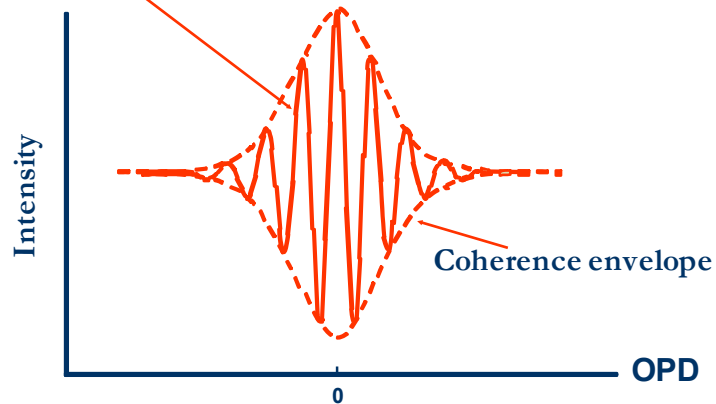
Vertical Scanning Interference Microscope

Focus Position A

Focus Position B

Focus Position C

Focus Position D

White Light Interferograms
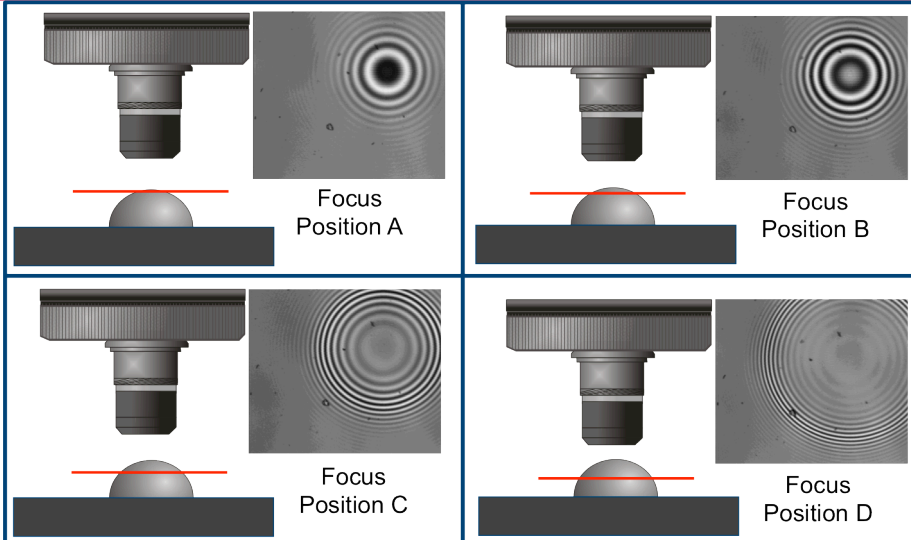
Focus Position A
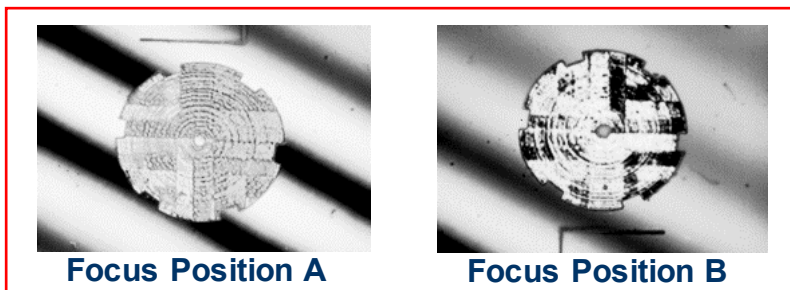
Focus Position B

As the scan moves different areas of the part being measured come into focus (have zero OPD or maximum contrast between fringes). A determination of the point of maximum contrast and knowledge of the scan position allows a reconstruction of the surface shape.

Step Measurement

Rt: 48.392 µm   SURFACE   Rq: 24.073 µm
MAG: 10.000   Ra: 24.074 µm
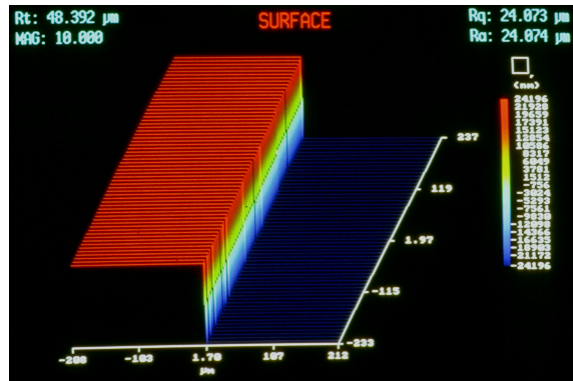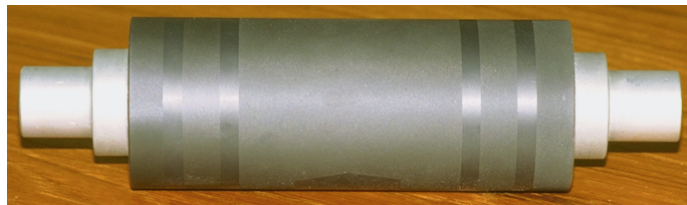
Print Roller

Print Roller Measurement
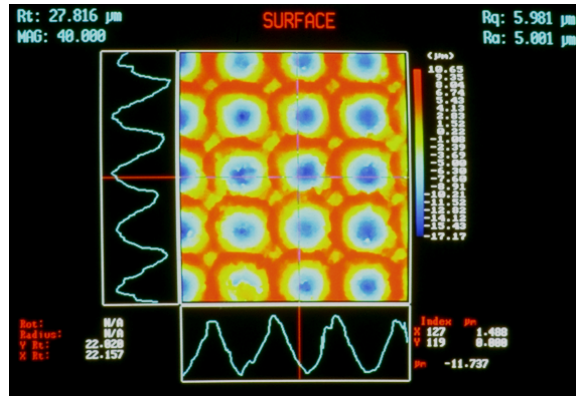
Paper Measurement
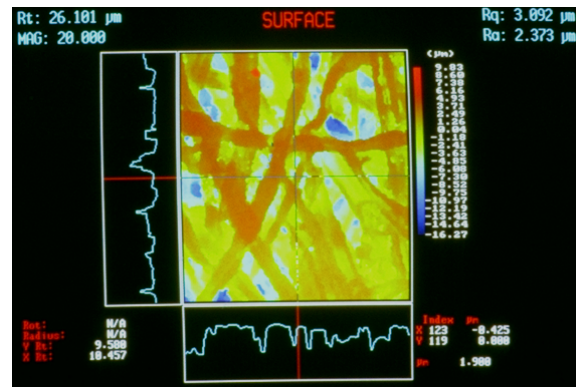
Micromachined Silicon Measurement

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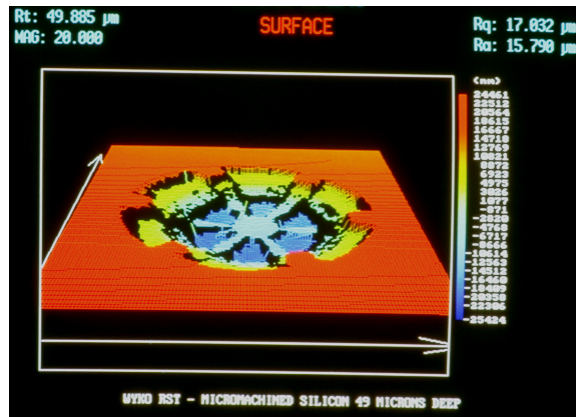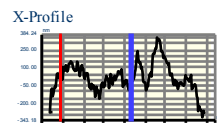
Binary Optic Lens

Surface Stats:
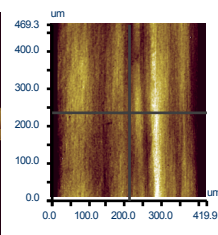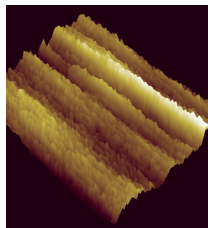**RMS: 561.30 nm**
PV: 2.37 um

2016 – James C. Wyant
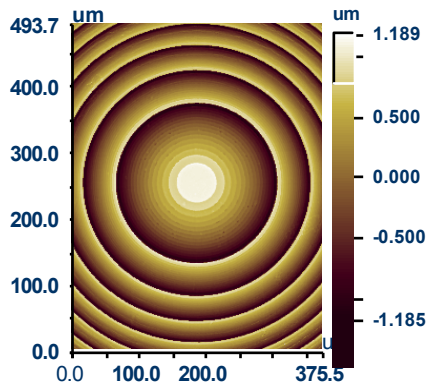
Chatter Seen on Camshaft

Surface Stats:
Rq: 872.06 nm
Ra: 693.90 nm
Rt: 7.47 um
Terms Removed:
Cylinder & Tilt

Heart Valve

X-Profile

Y-Profile

Histogram

Avg X PSD
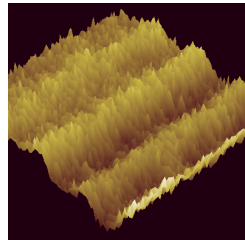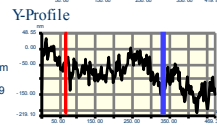
Data Statistics
Rt: 1.419 um
Ra: 87.391 nm
Rq: 113.942 nm
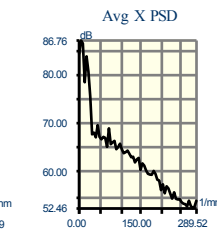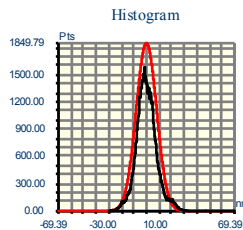
Pits in Metal

Size: 248 X 239
Sampling: 1.70 um

Surface Stats:
Rq: 5.07 um
Ra: 3.44 um
Rt: 31.05 um
Terms Removed:
Tilt
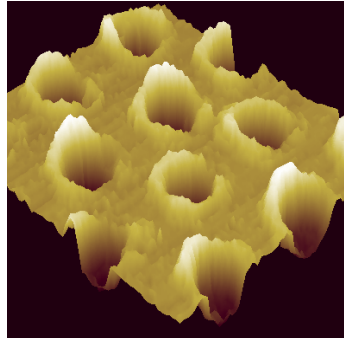
Six Stitched Data Sets of Inside of Engine Bore
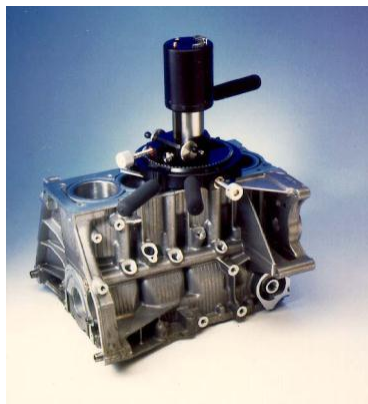
Insight 2000 measuring inside of engine bore
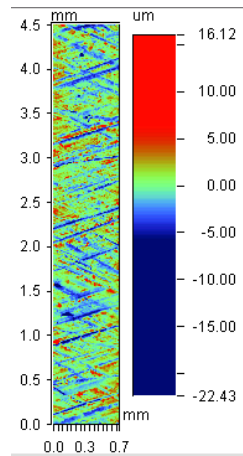
Ra = 1.69 µm, Rz = 27.87 µm, and Rt = 38.54 µm

Stitched Measurement - Fuel Cap
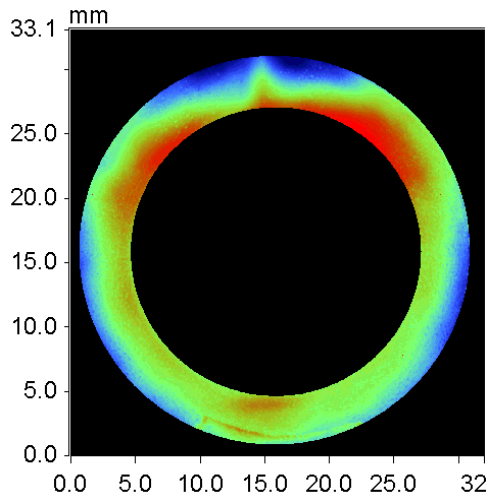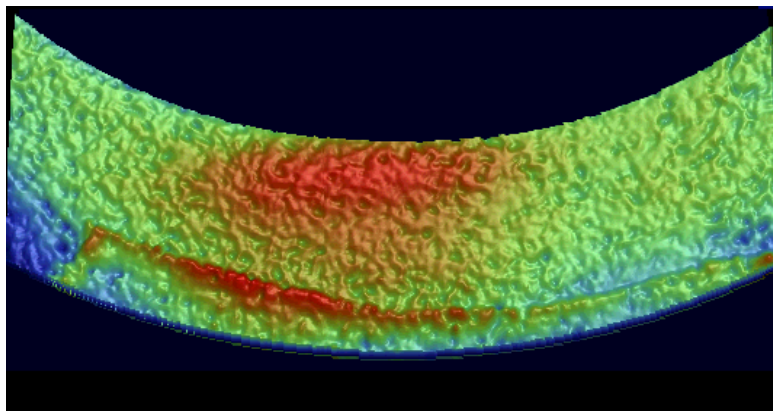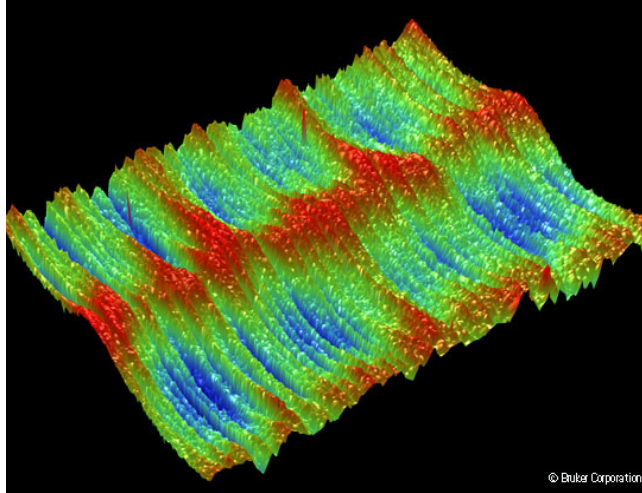

**VSI
mode**

Surface statistic

Ra=26.32 microns
Rq=32.72 microns
Rt=246.42 microns
array size 1251x1107
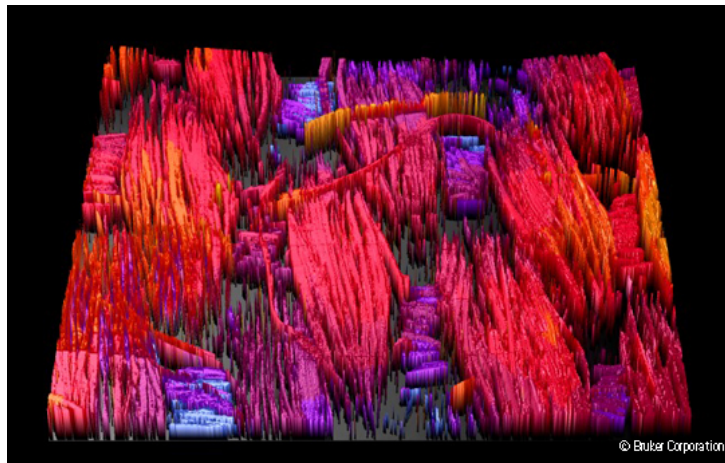sampling 25.5 microns

Sub-Region of Stitched - Fuel Cap

Chatter on Camshaft

© Bruker Corporation

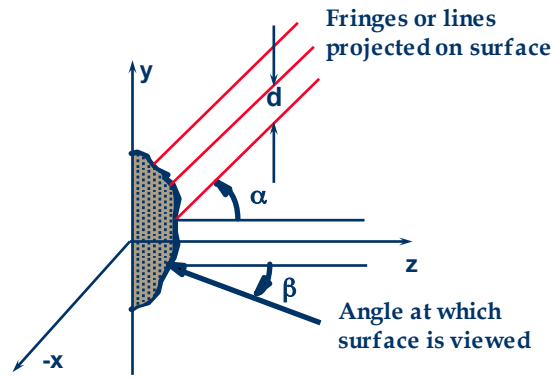THE UNIVERSITY OF ARIZONA.

Ref: Bruker
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Woven Cloth

© Bruker Corporation

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Ref: Bruker
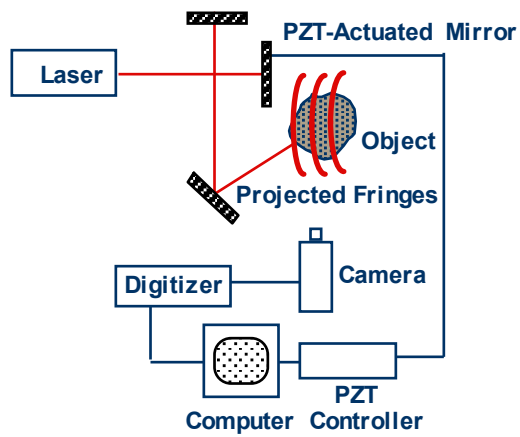2016 – James C. Wyant

WYKO — Projected Fringe Contouring

Fringes or lines projected on surface

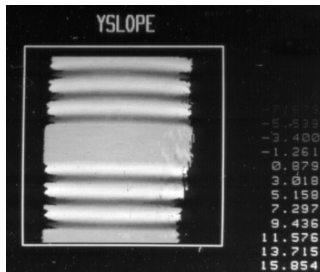$$\lambda_{eq} = \frac{2d}{\tan(\alpha) + \tan(\beta)}$$

Angle at which surface is viewed

WYKO — Projected Fringe Contouring Setup

PZT-Actuated Mirror

Laser

Object

Projected Fringes

Camera

Digitizer

PZT Controller

Computer

Can
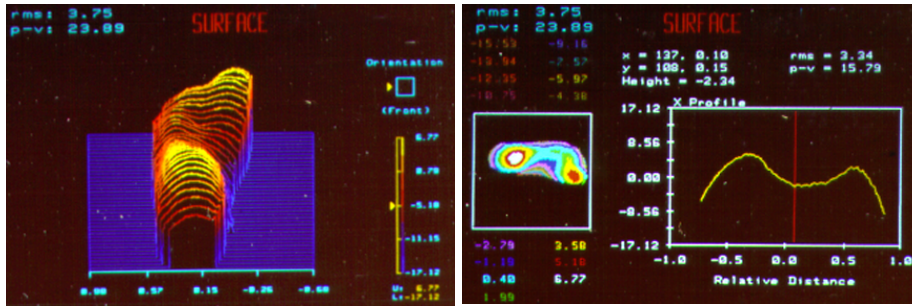

Hand

WYKO Foot
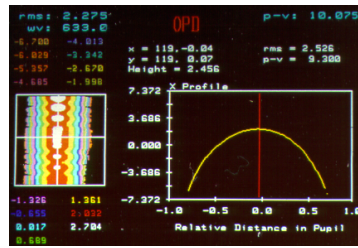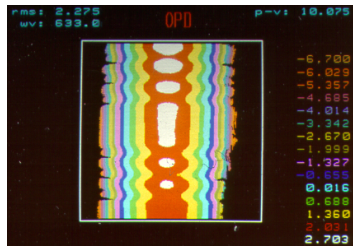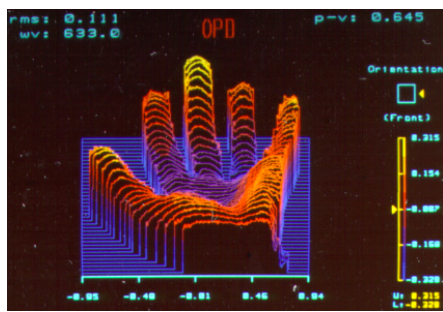
WYKO Foot Scanner

WYKO WYKO 6000

WYKO Bump Measurement System

Doing Companies is a Disease

Error Due to Vibration

- **Probably the most serious impediment to wider use of PSI is its sensitivity to external vibrations.**
- **Vibrations cause incorrect phase shifts between data frames.**
- **Error depends upon frequency of vibration present as well as phase of vibration relative to the phase shifting.**

Use polarizer as phase shifter

test ref

LHC RHC
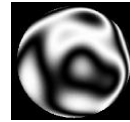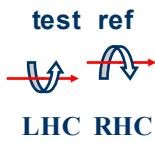
Circ. Pol. Beams ($\Delta\phi$) + linear polarizer $\longrightarrow$**cos ($\Delta\phi + 2\alpha$)**
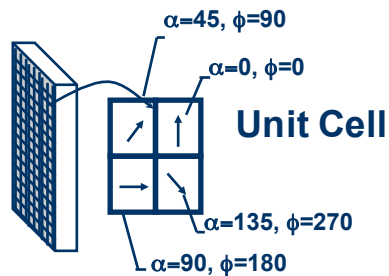
Phase-shift depends on polarizer angle

Reference: S. Suja Helen, M.P. Kothiyal, and R.S. Sirohi, "Achromatic phase-shifting by a rotating polarizer", Opt. Comm. 154, 249 (1998).
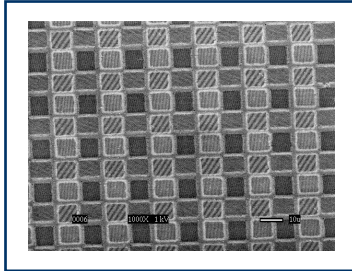

Array of Oriented Micropolarizers

Polarizer array Matched to detector array pixels

$\alpha=45$, $\phi=90$

$\alpha=0$, $\phi=0$

Unit Cell

$\alpha=135$, $\phi=270$

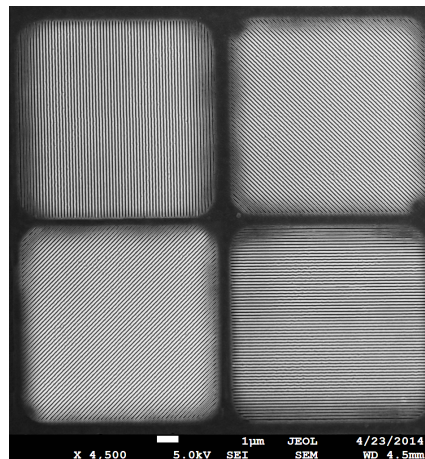$\alpha=90$, $\phi=180$

SEM of Patterned Polarizers

10 micron elements

Photolithography used to pattern polarizers
- **Ultra-thin (0.1 - 0.2 microns)**
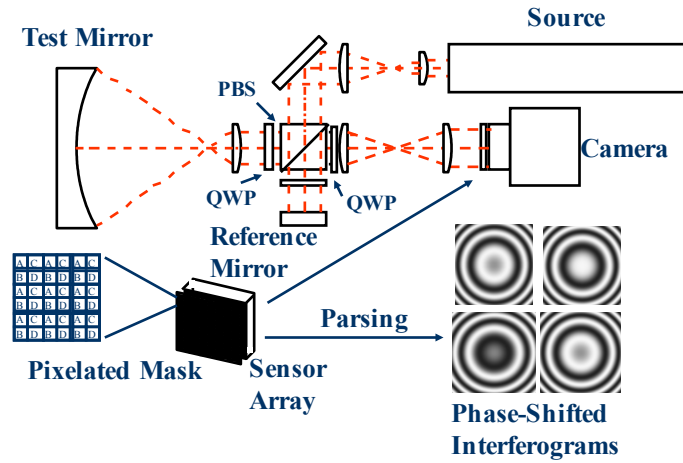- **Wide acceptance angle (0 to 50 degrees)**
- **Wide chromatic range (UV to IR)**

Array bonded directly to CCD

2016 – James C. Wyant

Electron micrograph of wire grid polarizers

20 um

2016 – James C. Wyant

System Configuration

Test Mirror

Source

PBS

Camera

QWP   QWP

Reference Mirror

Pixelated Mask   Sensor Array

Parsing

Phase-Shifted Interferograms

2016 – James C. Wyant

Dynamic Interferometry

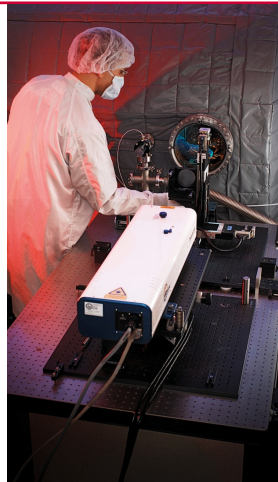**Fringes Vibrating**
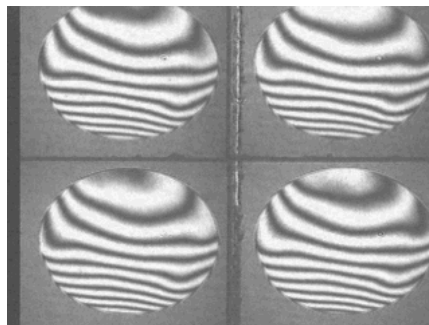
Phase relationship is fixed

2016 – James C. Wyant

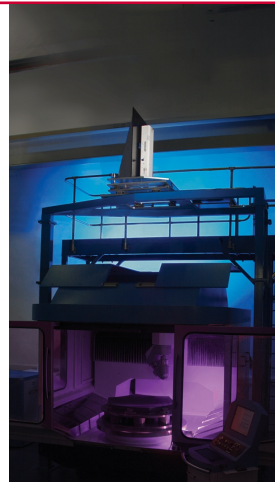# Measurement of 300 mm diameter, 2 meter ROC mirror
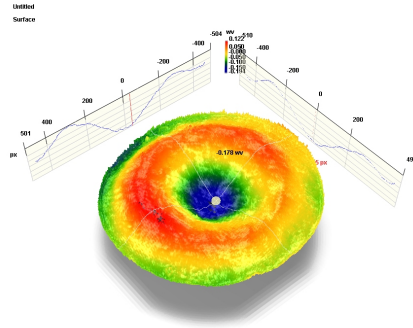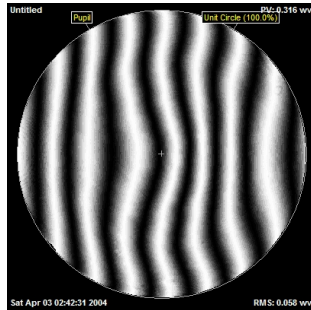
Mirror and interferometer on separate tables!
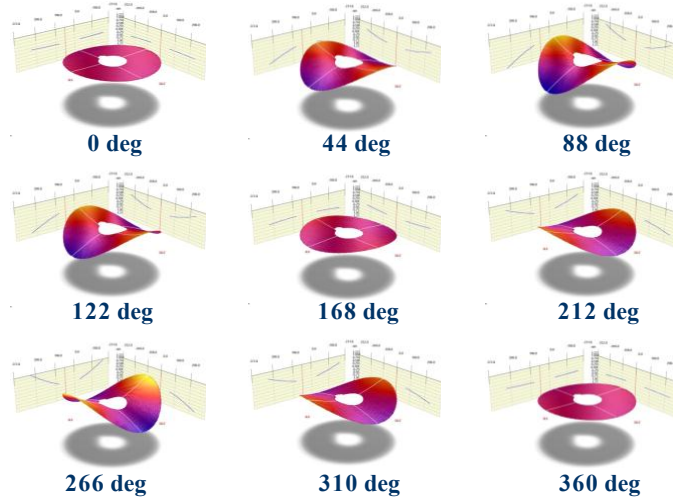

Testing of Large Optics

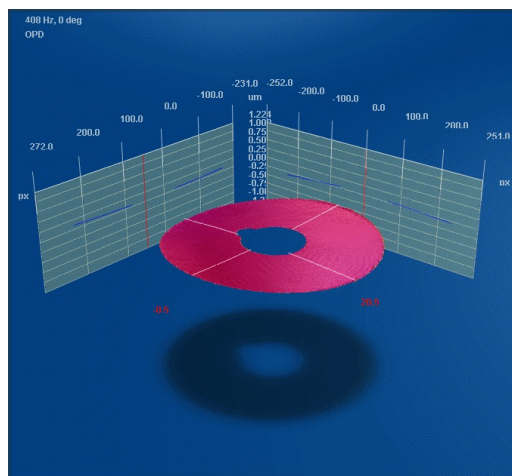**Testing in Environmental Chamber**
(Courtesy Ball Aerospace)

Testing on Polishing Machine
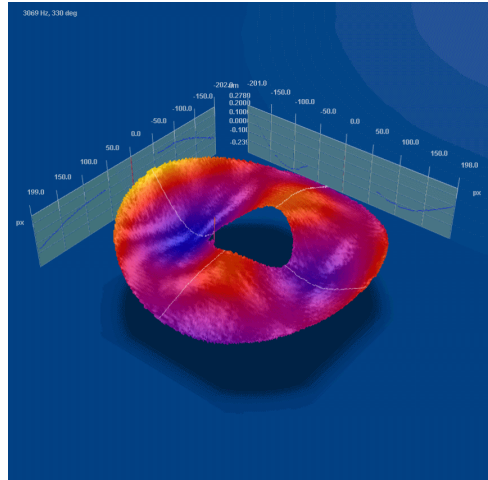(Courtesy OpTIC Technium)
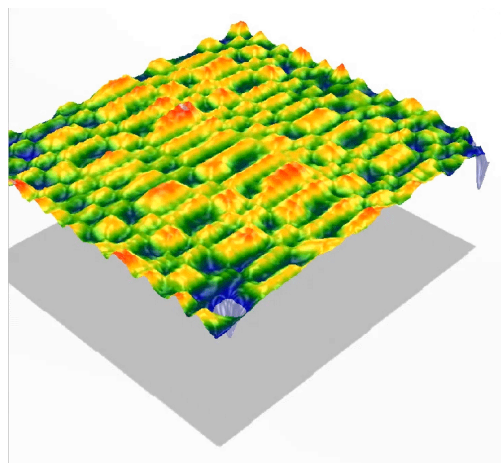
Phase Sweep at 408 Hz

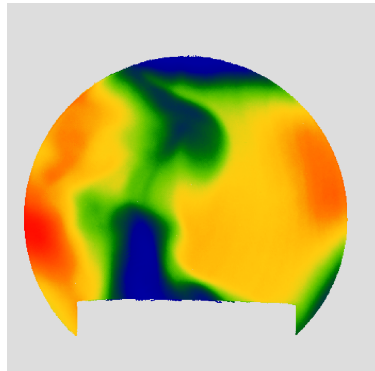## Al Mirror, 408 Hz

Al Mirror, 3069 Hz, Higher Order Mode

2016 – James C. Wyant

32 x 32 Element Deformable Mirror

2016 – James C. Wyant

Heat Waves from Hot Coffee

OPD

Slope

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Thank for listening!

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