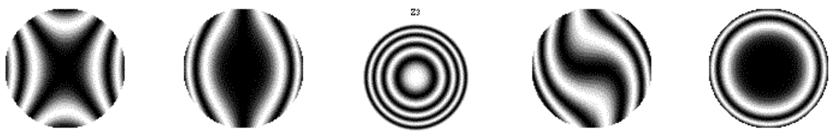
College of Optical Sciences THE UNIVERSITY OF ARIZONA®

Modern Optical Testing



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Outline

Part 1 - Basic Interferometers for Optical Testing

- Two Beam Interference
- Fizeau and Twyman-Green interferometers
- Basic techniques for testing flat and spherical surfaces
- Scatterplate and Smartt Interferometers
- Lateral Shearing Interferometers
- Typical Interferograms

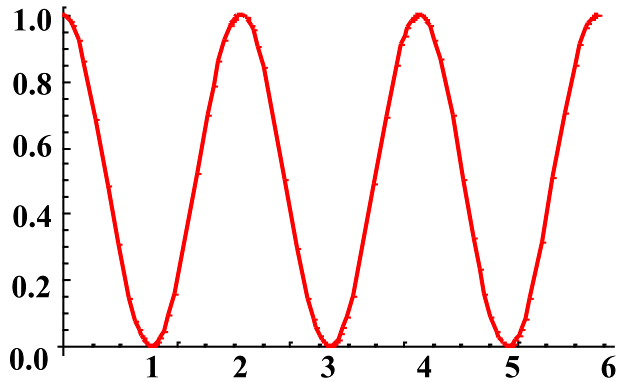
Two-Beam Interference Fringes

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

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

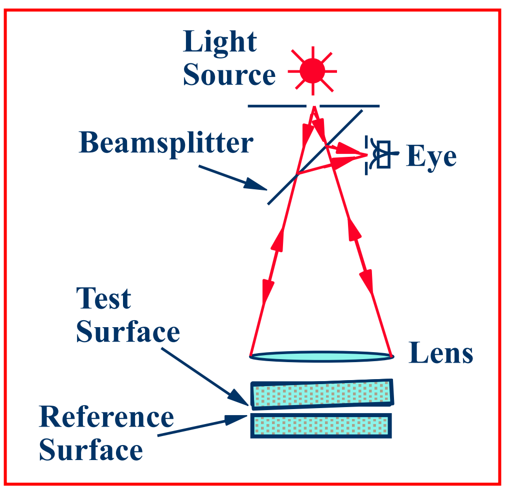
$$\alpha_1 - \alpha_2 = \left(\frac{2\pi}{\lambda}\right)(\text{optical path difference})$$

Sinusoidal Interference Fringes

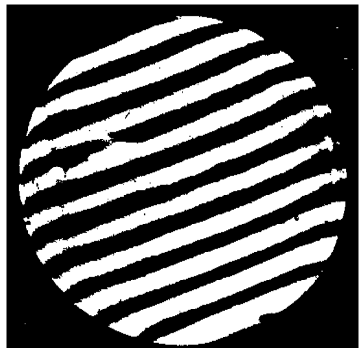


$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\alpha_1 - \alpha_2\right)$$

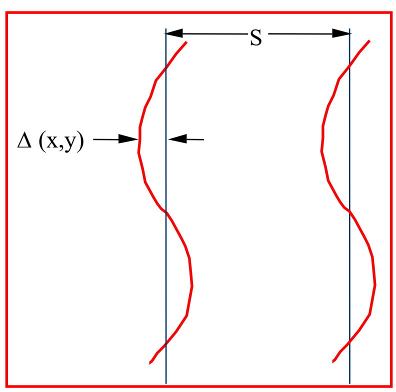
Pioneer Fizeau Interferometer - 1862



Typical Interferogram Obtained using Fizeau Interferometer

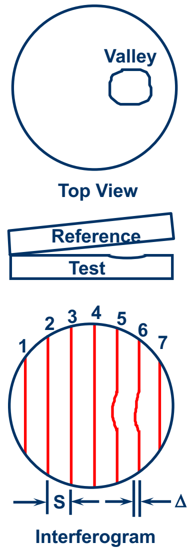


Relationship between Surface Height Error and Fringe Deviation



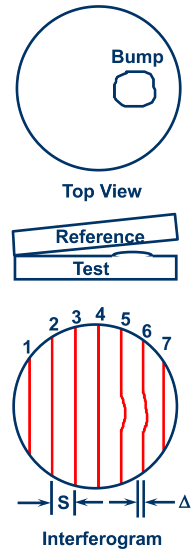
$$\text{Surface height error} = \left(\frac{\lambda}{2}\right)\left(\frac{\Delta}{S}\right)$$

Fizeau Fringes

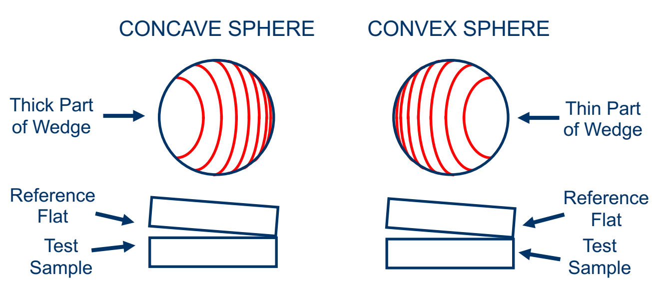


For a given fringe the separation between the two surfaces is a constant.

Height error = $(\lambda/2)(\Delta/S)$

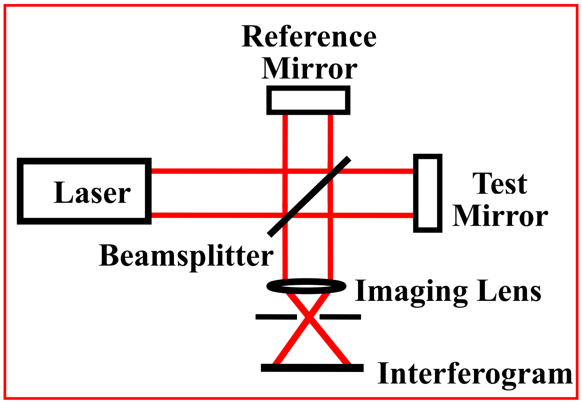


Fizeau Fringes for Concave and Convex Surfaces

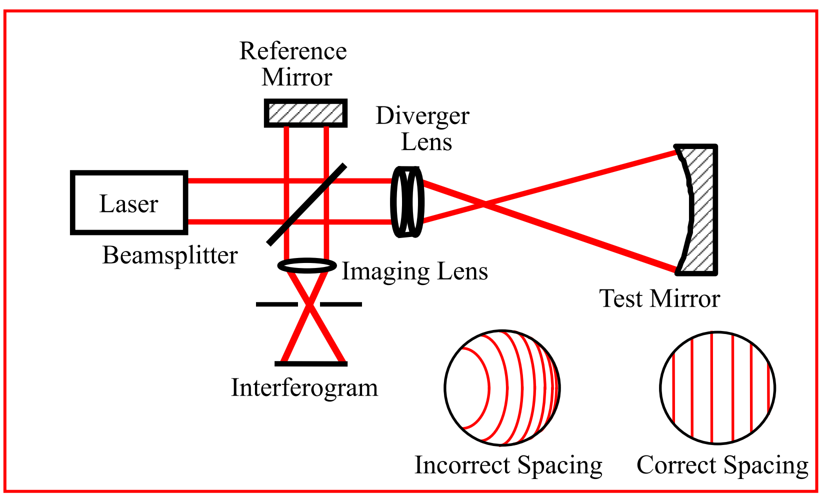


Twyman-Green Interferometer (Flat Surfaces)

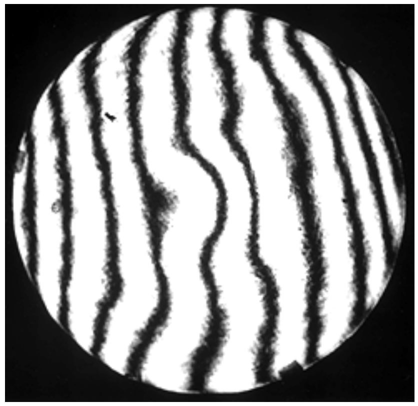
1918



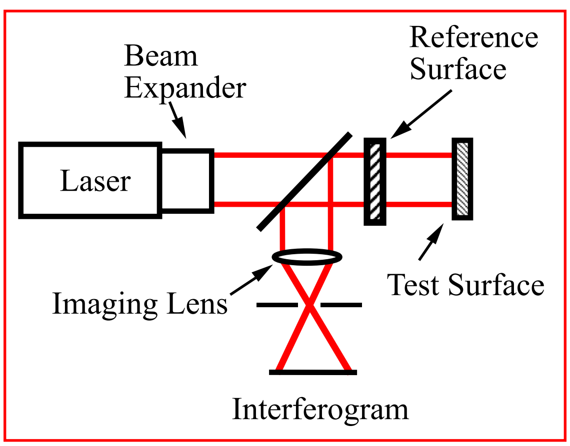
Twyman-Green Interferometer (Spherical Surfaces)



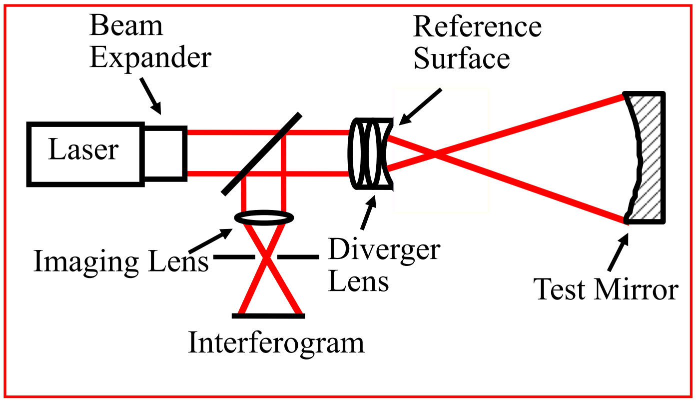
Typical Interferogram



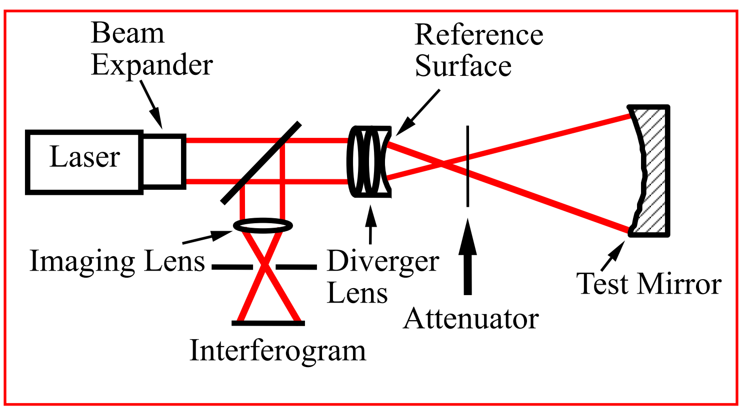
Fizeau Interferometer-Laser Source (Flat Surfaces)



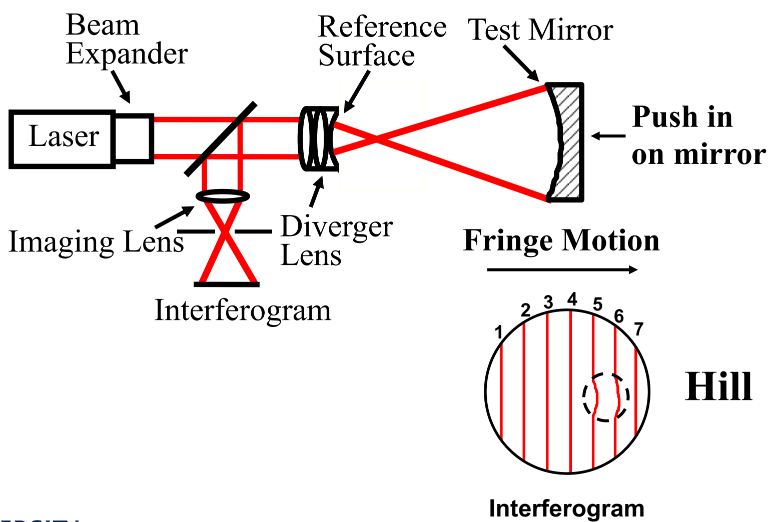
Fizeau Interferometer-Laser Source (Spherical Surfaces)



Testing High Reflectivity Surfaces



Hill or Valley?



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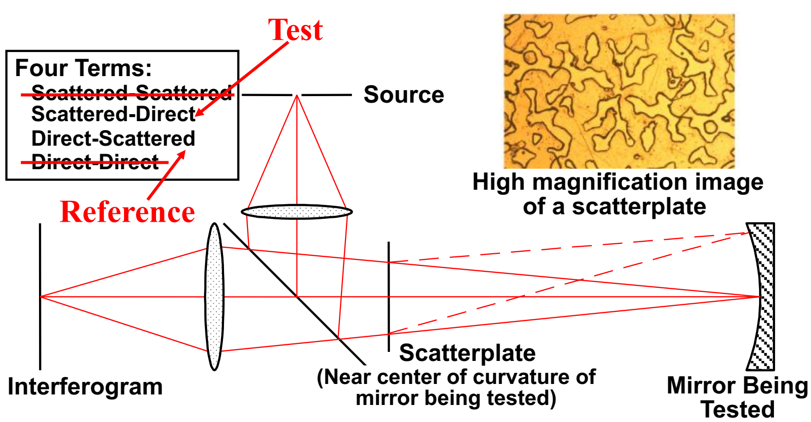
Scatterplate Interferometer



- Scatterplate has inversion symmetry
- Scatterplate is located at center of curvature of test mirror
- Direct-scattered and scattered-direct beams produce fringes

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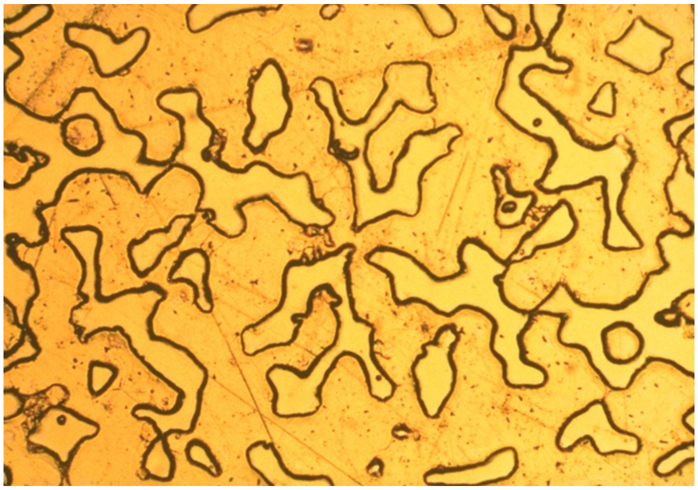
Microscopic Image of Scatterplate



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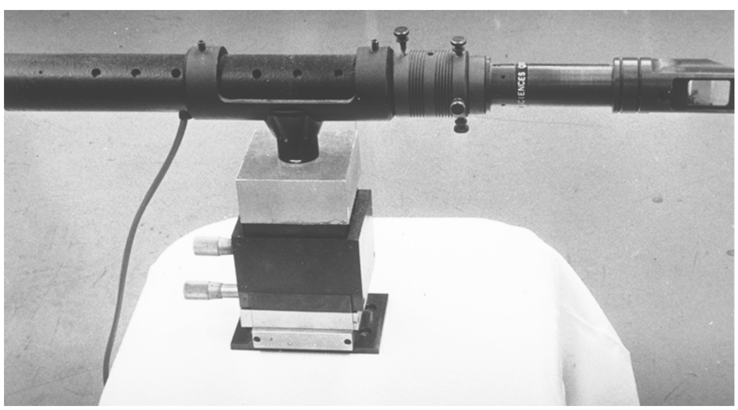
Scatterplate Interferometer



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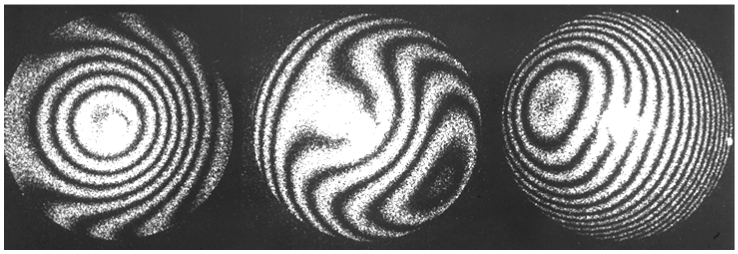
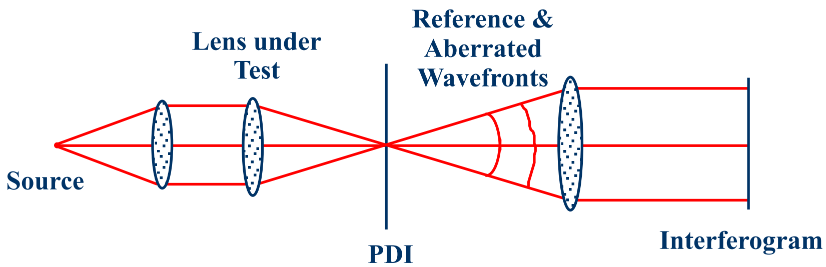
Scatterplate Interferograms

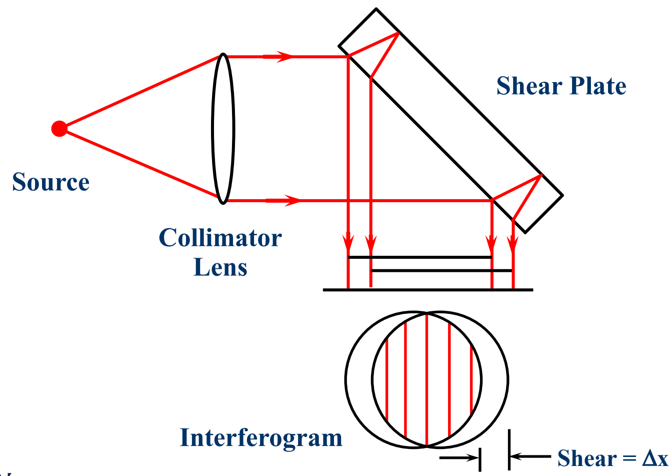


Smartt Point Diffraction Interferometer



Lateral Shear Interferometry

Measures wavefront slope



Lateral Shear Fringes

$\Delta W(x,y)$ is wavefront being measured

Bright fringe obtained when

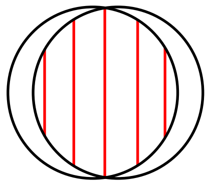
$$\Delta W(x+\Delta x, y) - \Delta W(x,y) = m\lambda$$

$$\left(\frac{\partial \Delta W(x,y)}{\partial x}_{\text{Average over shear distance}}\right)(\Delta x) = m\lambda$$

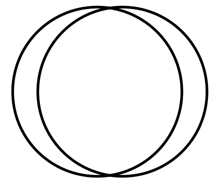
Measures average value of slope over shear distance

Collimation Measurement

No wedge in shear plate

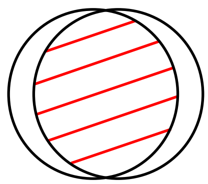


Not collimated

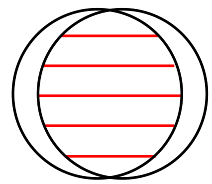


Collimated (one fringe)

Vertical wedge in shear plate



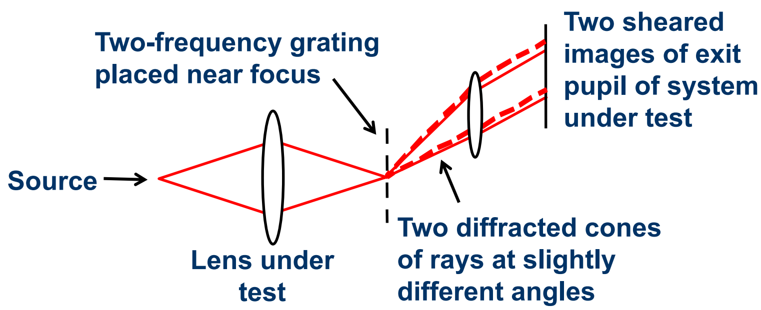
Not collimated



Collimated

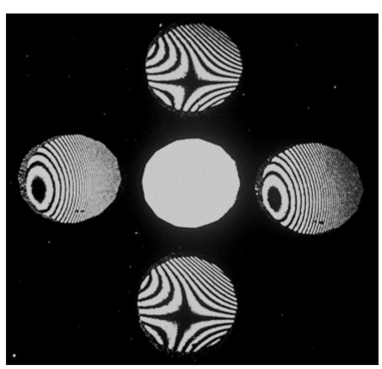
Typical Lateral Shear Interferograms

Lateral Shear Interferometer

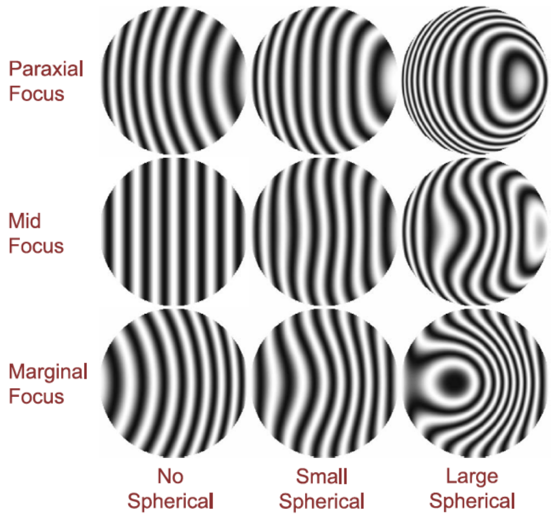


Measures slope of wavefront, not wavefront shape.

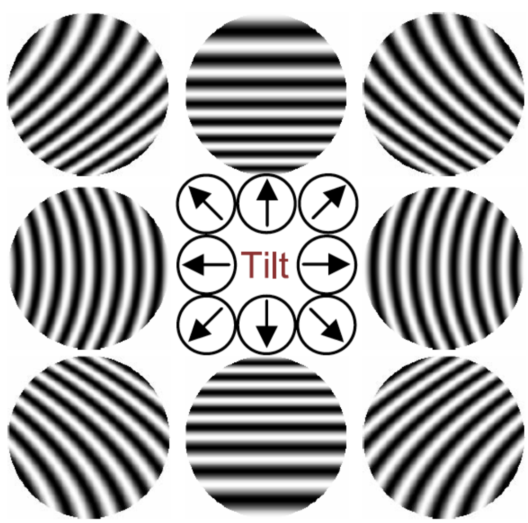
Interferogram Obtained using Grating Lateral Shear Interferometer



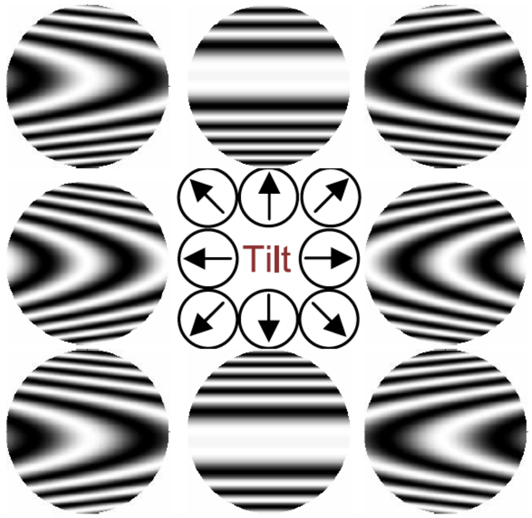
Interferograms - Spherical Aberration



Interferograms - Small Astigmatism, Sagittal Focus



Interferograms - Large Astigmatism, Sagittal Focus



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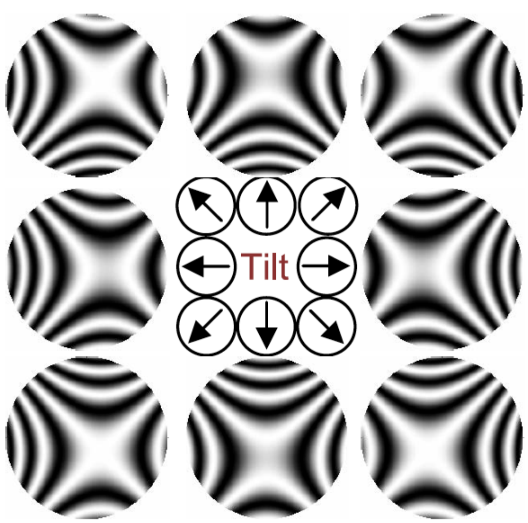
Interferograms - Large Astigmatism, Medial Focus



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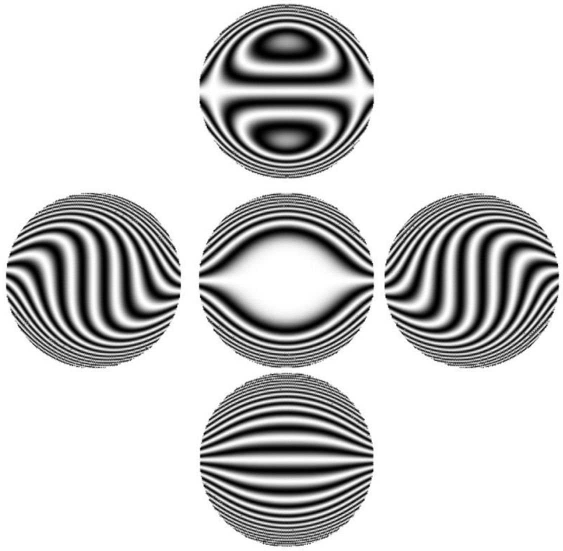
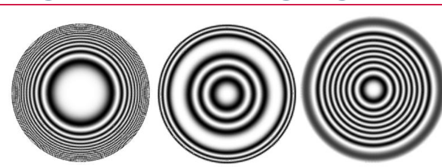
Interferograms - Large Coma, Varying Tilt

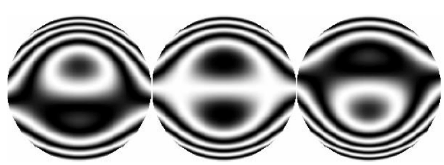


Interferograms - Changing Focus

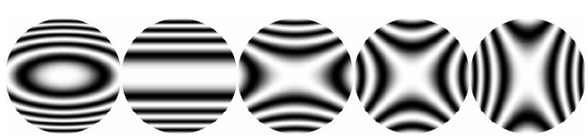
Spherical



Coma

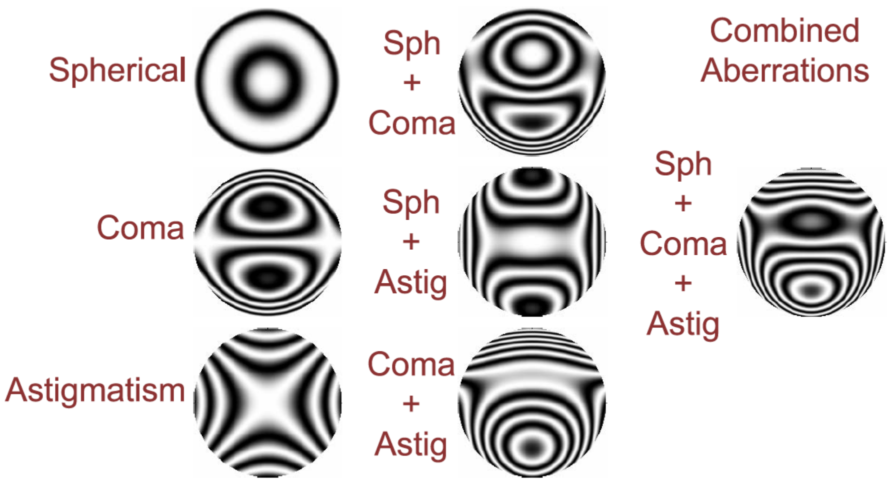


Astigmatism



Sagittal Medial

Interferograms - Combined Aberrations

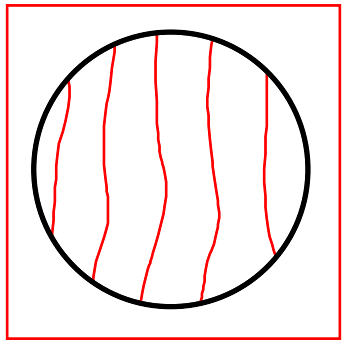


Part 2 - Phase-Shifting Interferometry

- **Classical analysis of interferograms**
- **Basic algorithms**
- **Removing phase ambiguities**
- **Single-shot phase-measurement interferometers**

Typical Interferogram

Surface Error =
(λ/2) (Δ/S)

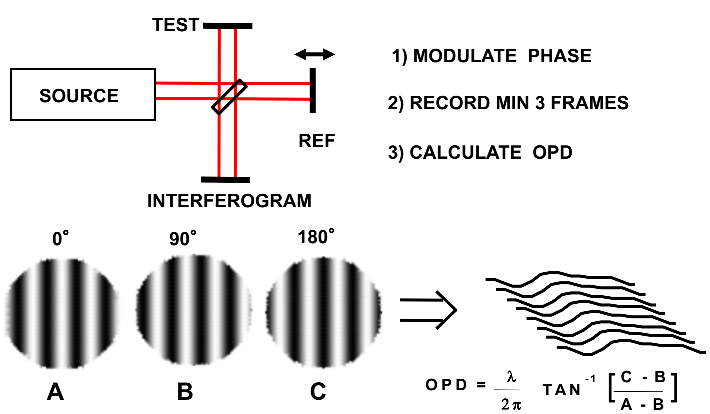


Classical Analysis

Measure positions of fringe centers.

Deviations from straightness and equal spacing gives aberration.

Phase-Shifting Interferometry

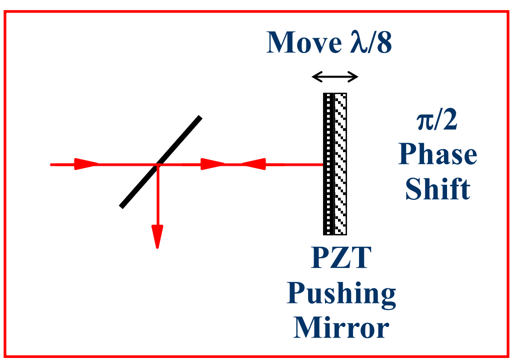


$$OPD = \frac{\lambda}{2\pi} \tan^{-1}\left[\frac{C - B}{A - B}\right]$$

Advantages of Phase-Shifting Interferometry

- High measurement accuracy (>1/1000 fringe, fringe following only 1/10 fringe)
- Rapid measurement
- Good results with low contrast fringes
- Results independent of intensity variations across pupil
- Phase obtained at fixed grid of points
- Easy to use with large solid-state detector arrays

Phase-Shifting - Moving 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

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

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

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

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

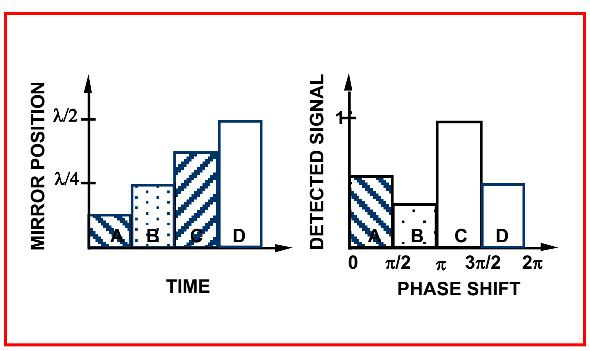
Schwider-Hariharan Five Measurements

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

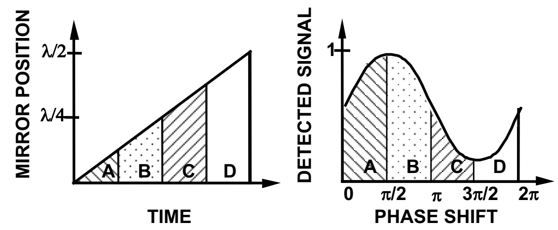
Carré Equation

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

Phase-Stepping Phase Measurement



Integrated-Bucket Phase Measurement



Integrating-Bucket and Phase-Stepping Interferometry

Measured irradiance given by

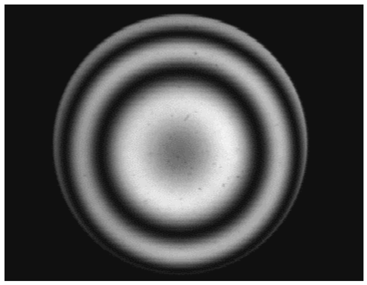
$$I_i = \frac{1}{\Delta}\int_{\alpha_i-\Delta/2}^{\alpha_i+\Delta/2} I_o\left\{1+\gamma_o Cos\left[\phi+\alpha_i(t)\right]\right\}d\alpha(t)$$

$$=\left\{1+\gamma_o Sinc\left[\frac{\Delta}{2}\right]Cos\left[\phi+\alpha_i\right]\right\}$$

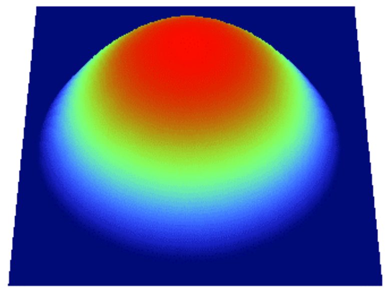
Integrating-Bucket $\Delta=\alpha$

Phase-Stepping $\Delta=0$

Typical Fringes For Spherical Surfaces



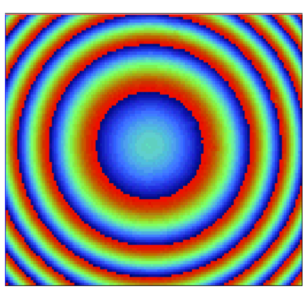
Fringes

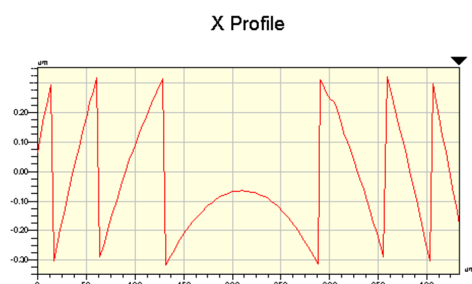


Phase map

Phase Ambiguities - Before Unwrapping

2 π Phase Steps





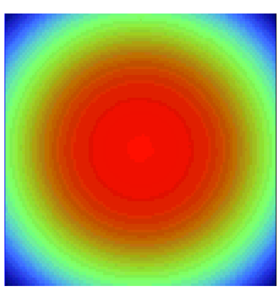
Removing Phase Ambiguities

- Arctan Mod 2π (Mod 1 wave)
- Require adjacent pixels less than π difference (1/2 wave OPD)
- Trace path
- When phase jumps by > π
  Add or subtract N2π

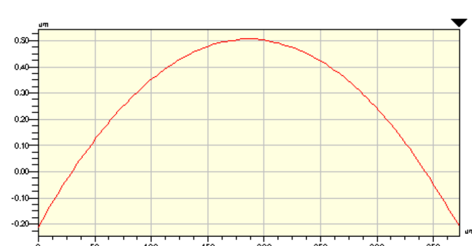
  Adjust so < π

Phase Ambiguities - After Unwrapping

Phase Steps Removed



X Profile

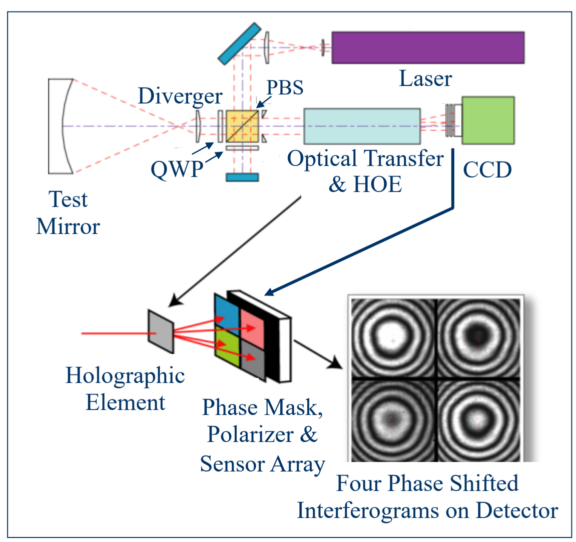


Error Due to Vibration

- 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.

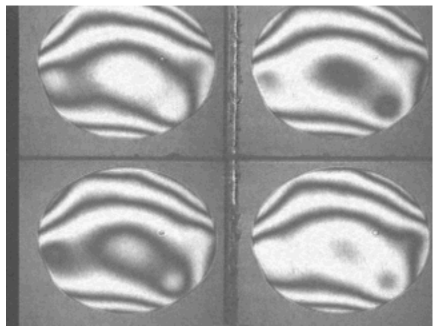
Single-Shot Phase-Measurement Interferometer

- **Twyman-Green**
  - Two beams have orthogonal polarization
- **4 Images formed**
  - Holographic element
- **Single Camera**
  - 1024 x 1024
  - 2048 x 2048
- **Polarization used to produce 90-deg phase shifts**



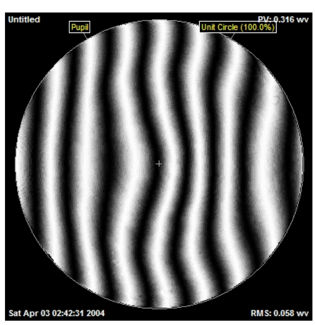
Dynamic Interferometry

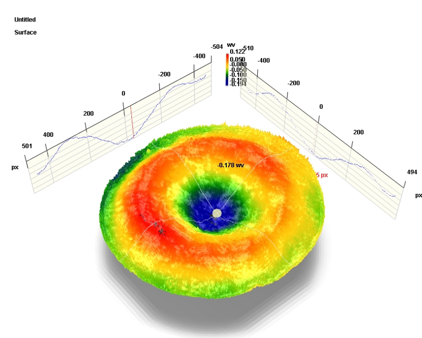
Fringes Vibrating



Phase relationship is fixed

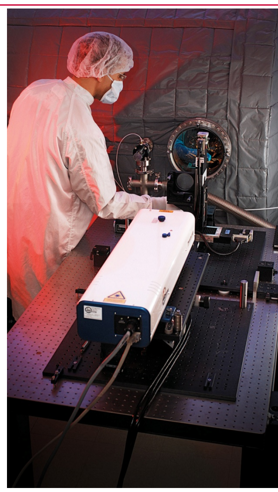
Measurement of 300 mm diameter, 2 meter ROC mirror



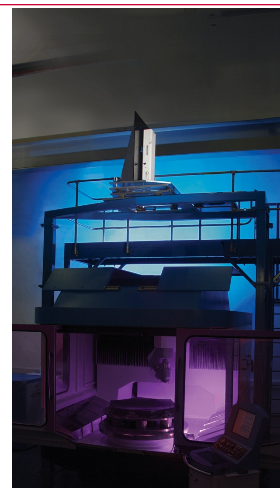


Mirror and interferometer on separate tables!

Testing of Large Optics



Testing in Environmental Chamber
(Courtesy Ball Aerospace)

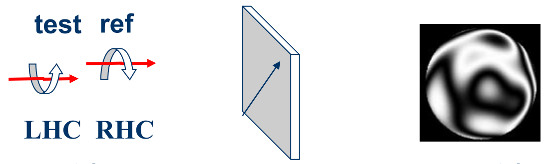


Testing on Polishing Machine
(Courtesy OpTIC Technium)

Pixelated Phase Sensor

- Compacted pixelated array placed in front of detector
- Single frame acquisition
  – High speed and high throughput
- Achromatic
  – Works from blue to NIR
- True Common Path
  – Can be used with white light

Use polarizer as phase shifter



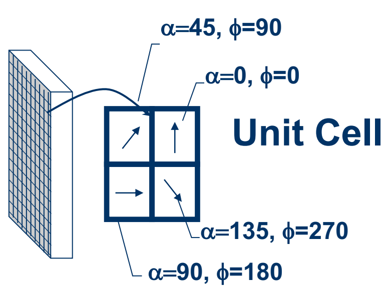
Circ. Pol. Beams ($\Delta\phi$) + linear polarizer $\rightarrow$ cos ($\Delta\phi + 2\alpha$)

Phase-shift depends on polarizer angle

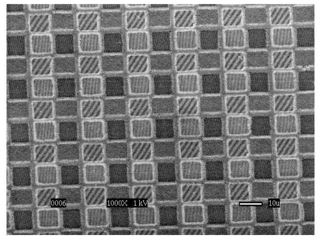
Reference: S. Suja Helen, M.P. Kothiyal, and R.S. Sirohi, "Achromatic phase-shifting by a rotating polarizer", Opt. Comm. 154, 249 (1998).

Array of Oriented Micropolarizers

Polarizer array Matched to detector array pixels



SEM of Patterned Polarizers

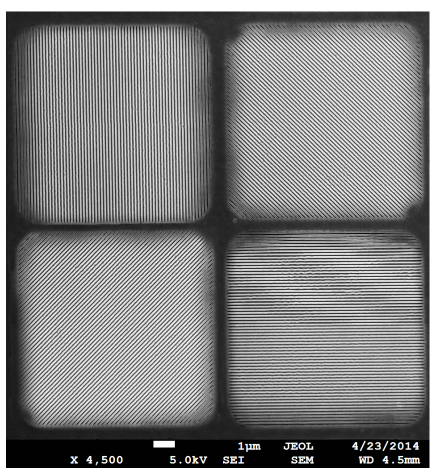


10 micron elements

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)**

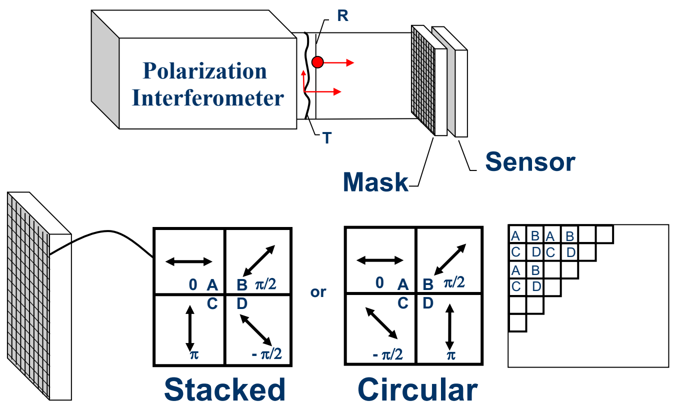
Array bonded directly to CCD

Electron micrograph of wire grid polarizers



20 um

Array of phase-shift elements unique to each pixel



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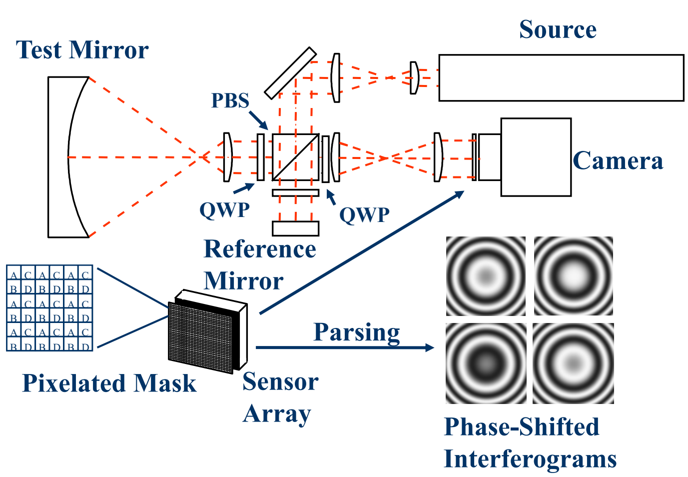
System Configuration



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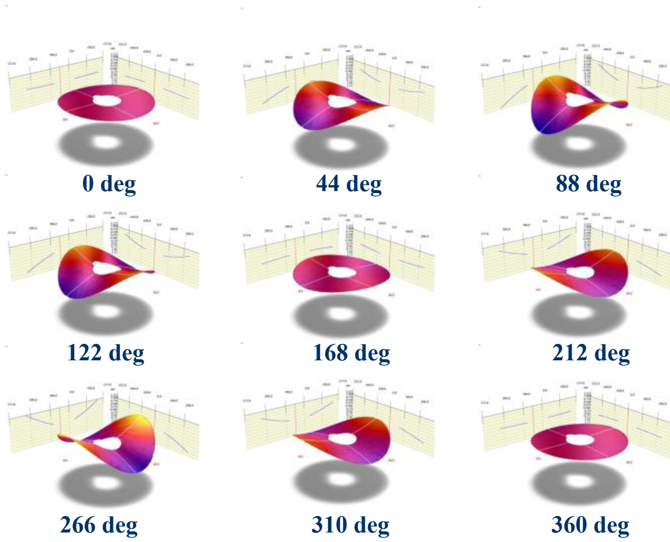
Phase Sweep at 408 Hz



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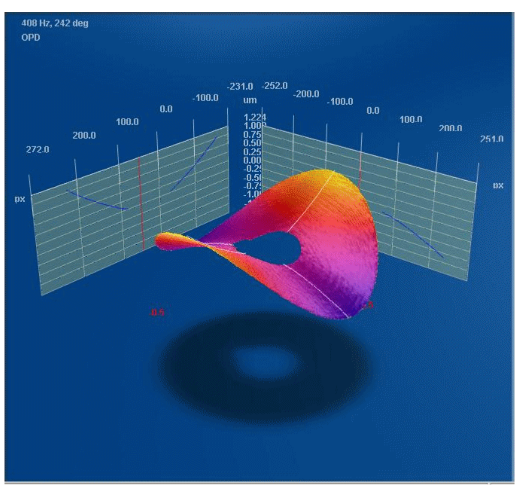
Al Mirror, 408 Hz



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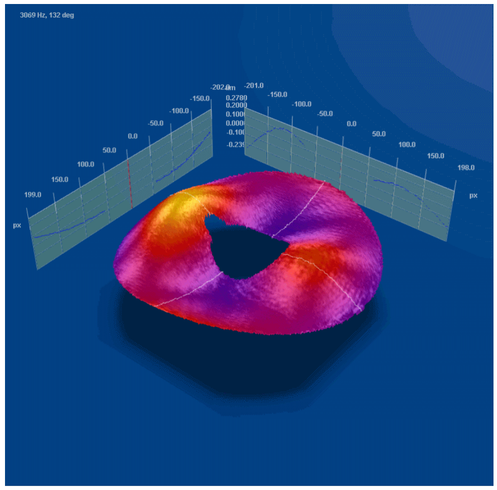
Al Mirror, 3069 Hz, Higher Order Mode



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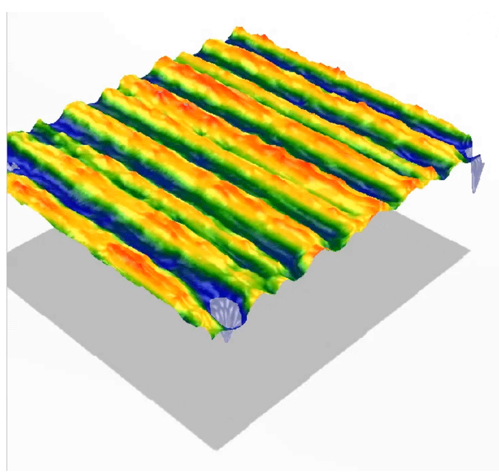
32 x 32 Element Deformable Mirror



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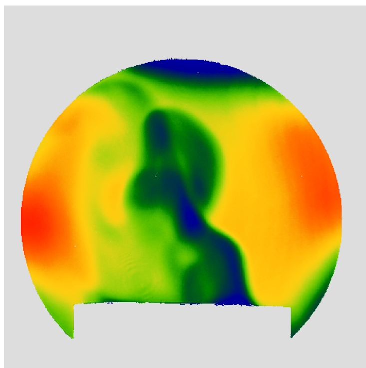
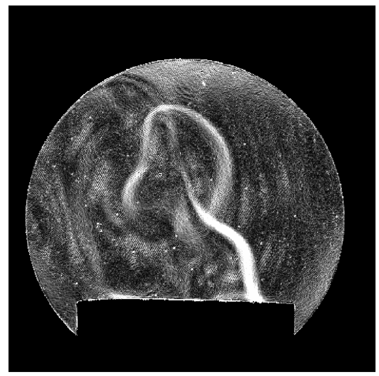
Heat Waves from Hot Coffee





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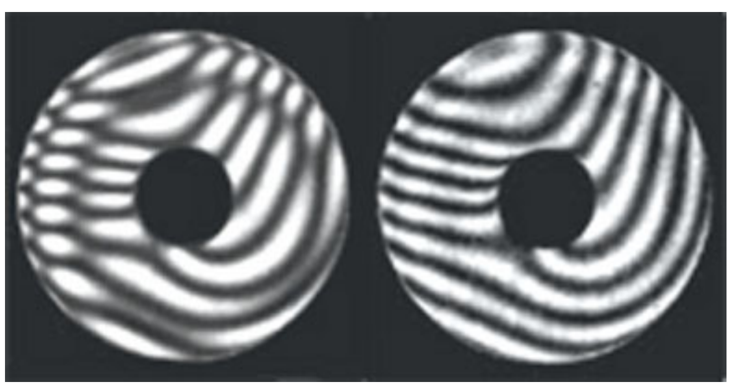
Interference Fringes Obtain Testing a Thin Glass Plate



a) Long coherence length source

b) Short coherence length source

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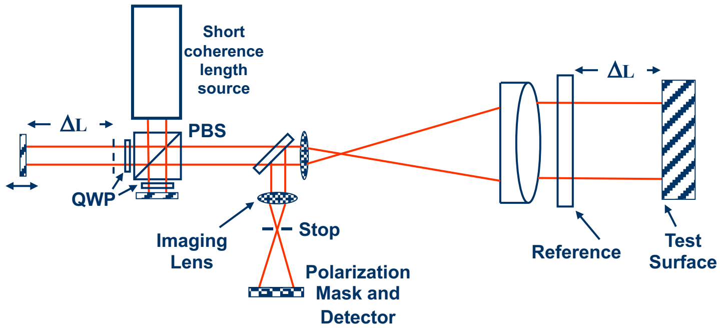
Simultaneous Phase-Shifting Fizeau – Short Coherence Length Source

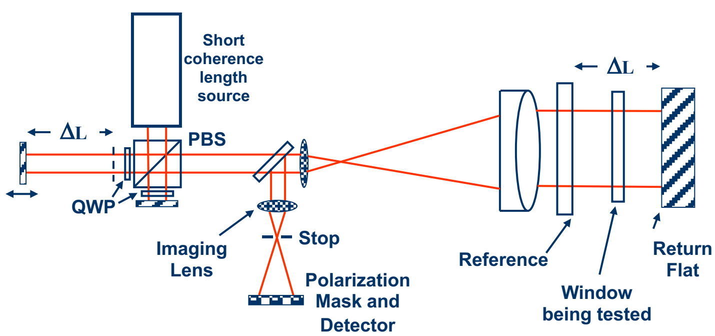


Interference pattern resulting from long path length source beam reflected off reference and short path length source beam reflected off test surface.

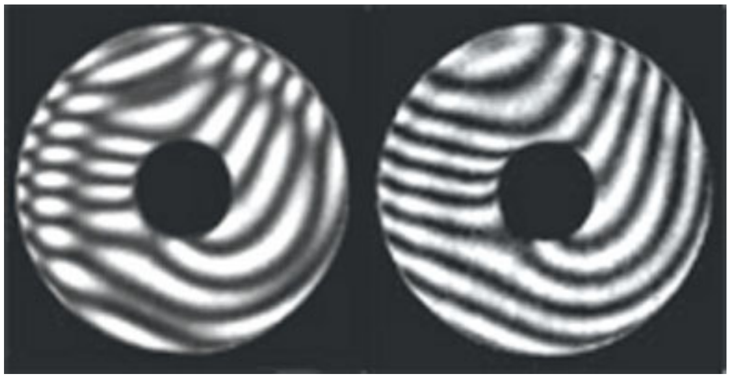
Test and reference beams have orthogonal polarization.

Fewer spurious fringes.

Testing Glass Sample - Short Coherence Length Source



Interference Fringes Obtain Testing a Thin Glass Plate



Long coherence length source Short coherence length source

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Conclusions – Single Shot Interferometer

- Vibration insensitive, quantitative interferometer
- Surface figure measurement (nm resolution)
- Snap shot of surface height
- Acquisition of "phase movies"

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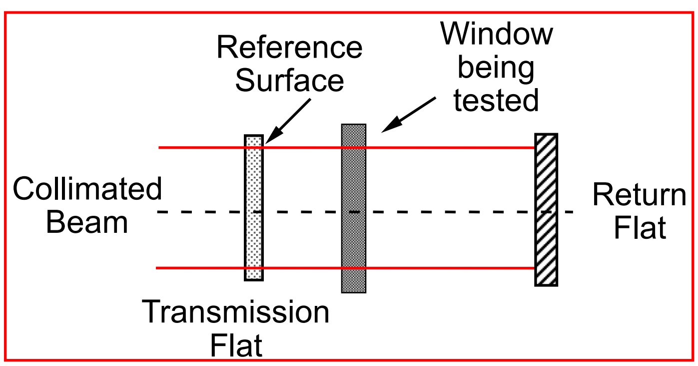
Part 3 - Specialized Optical Tests

- Testing windows, prisms, and corner cubes
- Measuring radius of curvature
- Measuring index inhomogeneity
- Testing cylindrical surfaces

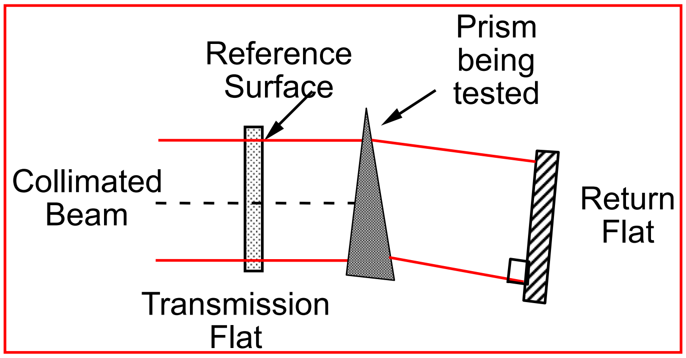
Testing Windows in Transmission



δt = window thickness variations

OPD measured = 2 (n-1) δt

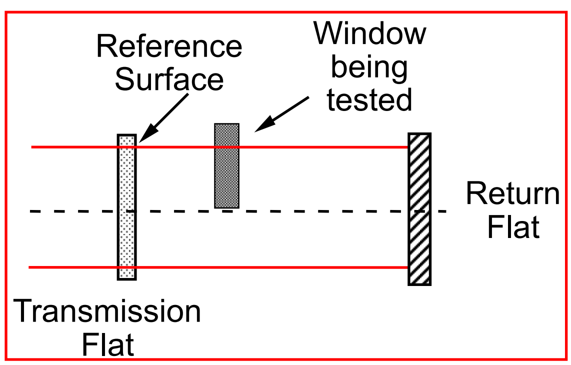
Testing Prisms in Transmission



δt = error in prism thickness

OPD measured $= 2\,(n-1)\,\delta t$

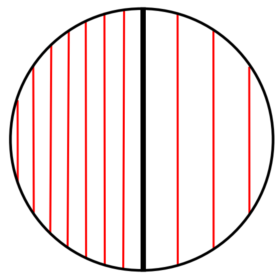
Measuring Window Wedge



Tilt difference between two interferograms gives window wedge.

Calculating Window Wedge

Tilt difference between two interferograms gives window wedge.



α = window wedge

$$\alpha = \frac{\textbf{tilt difference}}{\textbf{2(n-1)}}$$

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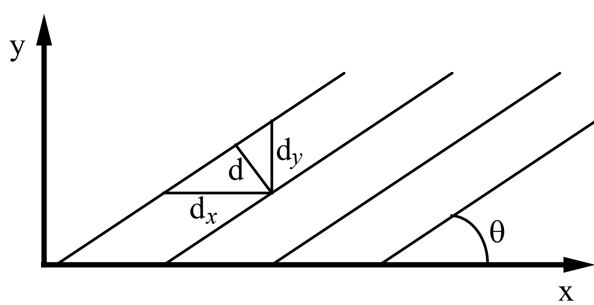
Calculation of Tilt



$d =$ fringe spacing $\quad \mathrm{d}_x = d/\sin(\theta) \quad \mathrm{d}_y = d/\cos(\theta)$

$$\beta = Tilt = \frac{\lambda}{d} \qquad \beta_x = \frac{\lambda}{d_x} \qquad \beta_y = \frac{\lambda}{d_y}$$

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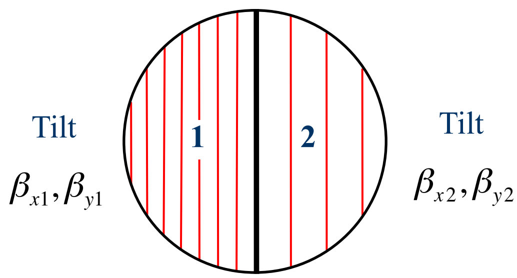
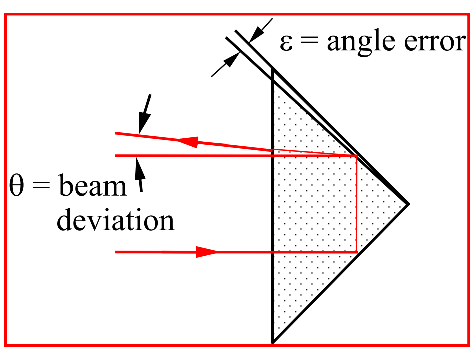
Calculation of Tilt Difference



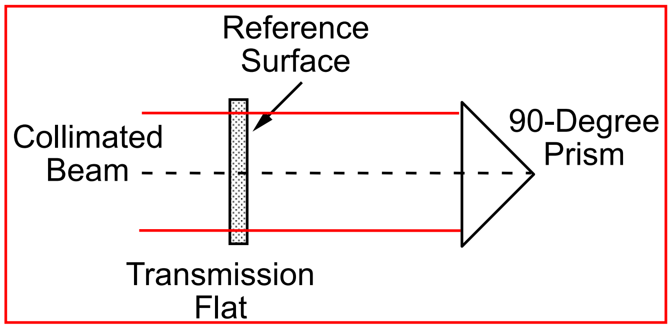
$$\text{Tilt Difference} = \sqrt{\left(\beta_{x1} - \beta_{x2}\right)^2 + \left(\beta_{y1} - \beta_{y2}\right)^2}$$

Angle Accuracy of 90-Degree Prisms



$$\varepsilon = \frac{\theta}{2n}$$

Testing 90-Degree Prisms (Single Pass)

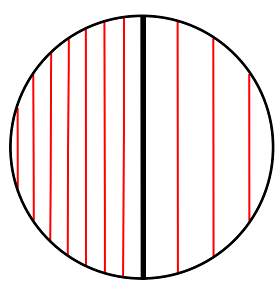


Tilt difference between two interferograms gives error in 90-degree angle.

Errors in collimated beam do not cancel.

Calculating Error in 90-Degree Prism (Single Pass)

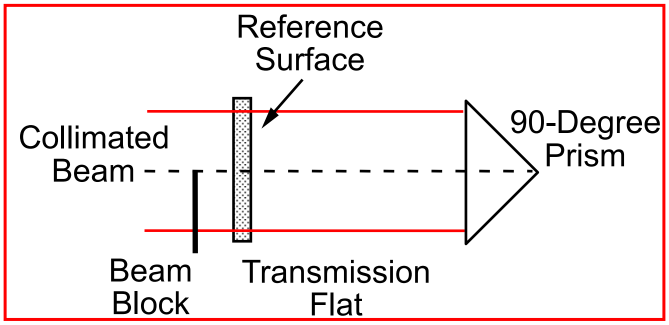
Tilt difference between two interferograms gives prism angle error.



ε = prism angle error

$$\varepsilon = \frac{\text{tilt difference}}{4n}$$

Testing 90-Degree Prisms (Double Pass)

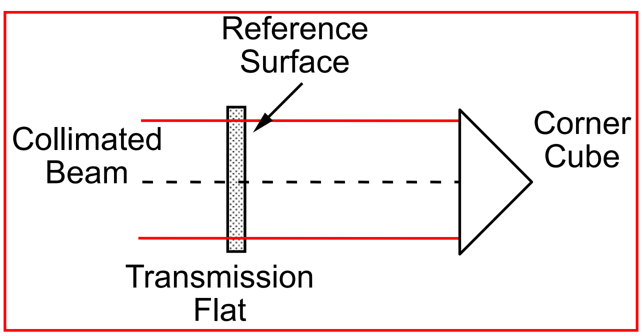


$$\varepsilon = \frac{\text{x tilt in interferogram}}{4n}$$

ε = prism angle error

Errors in collimated beam cancel.

Testing Corner Cubes (Single Pass)

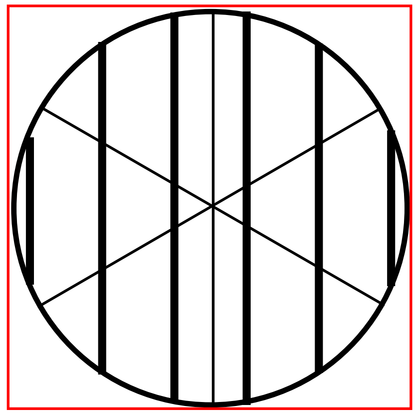


Errors in collimated beam do not cancel.

Interferogram for Perfect - Corner Cube (Single Pass)

6 interferograms obtained.

Straight fringes obtained for perfect corner cube.



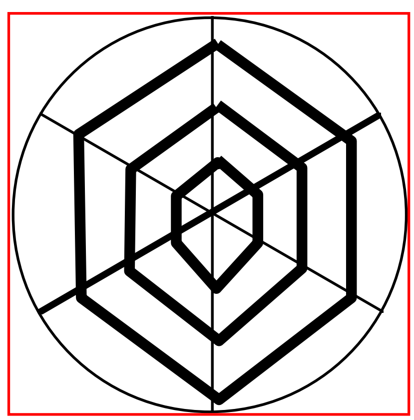
Analyzing Corner Cube Interferograms (Single Pass)

6 interferograms obtained.

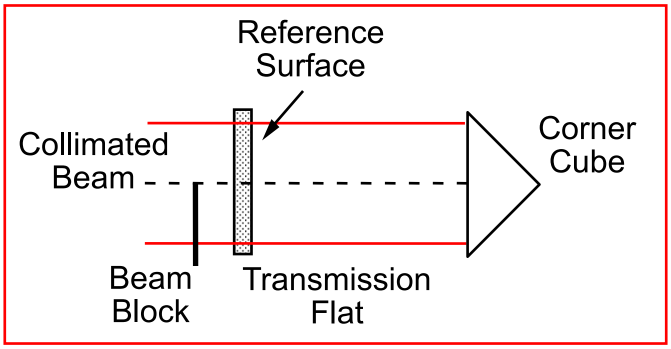
Tilt difference between any 2 interferograms gives one angle error in corner cube.

n is refractive index of corner cube.

Error = Tilt difference/(3.266 n)



Testing Corner Cubes (Double Pass)

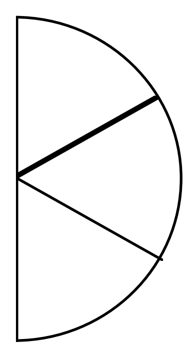


Errors in collimated beam cancel.

Interferogram for Perfect Corner Cube (Double Pass)

3 interferograms obtained

One fringe covers the entire interferogram

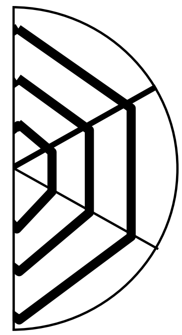


Analyzing Corner Cube Interferograms (Double Pass)

3 interferograms obtained.

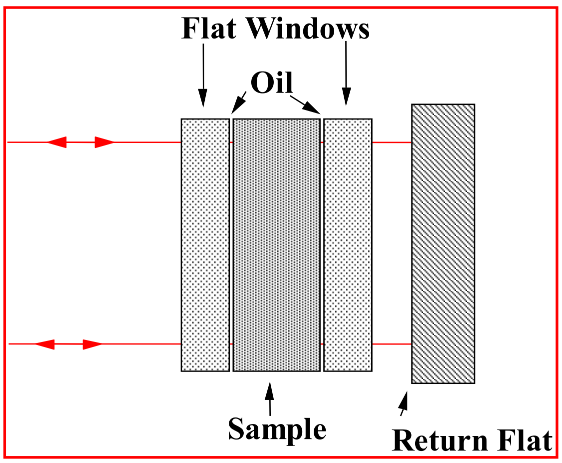
Tilt of each interferogram gives one angle error in corner cube.

n is refractive index of corner cube.

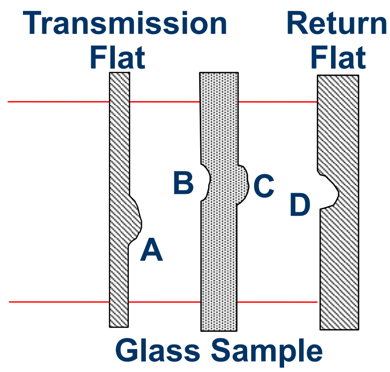


Error = Tilt/(3.266 n)

Measuring Index Inhomogeneity (Classical Technique)



Measuring Index Inhomogeneity Without Oil-On Plates



4 Measurements Required

Surface Errors in Test Optics and Glass Sample Cancel.

Measuring Index Inhomogeneity

1. **Measure light reflected from front surface of sample.**

   $$OPD_1 = 2(B-A)$$

2. **Measure light through sample and reflected off second surface.**

   $$OPD_2 = 2(B-A)+2n_o(C-B)+2\delta$$

3. **Measure through sample and reflected off return mirror.**

   $$OPD_3 = 2(B-A)+2n_o(C-B)+2(D-C)+2\delta$$

4. **Remove sample and measure cavity.**

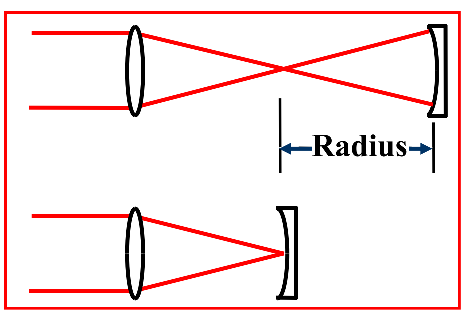
   $$OPD_4 = 2(D-A)$$

$$\delta = [n_o(OPD_3-OPD_4)-(n_o-1)(OPD_2-OPD_1)]/2$$
$$= (n-n_o)T$$

Index Inhomogeneity Test Results

RMS: 0.168 wv P-V: 0.711 wv wv: 632.8nm

Measuring Radius of Curvature



Two positions which give null fringe for spherical mirror.

Cylindrical Surface Test

- Need cylindrical wavefront
  - Reference grating: Off-axis cylinder
  - Cylinder null lens: Hard to make
- Direct measurement - No modifications to interferometer
- Concave and convex surfaces
- Quantitative - phase measurement

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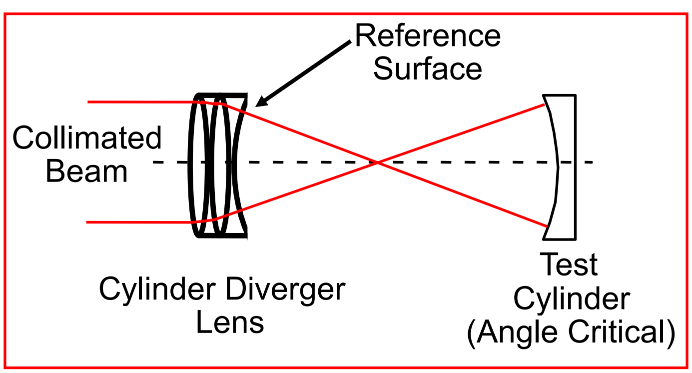
Cylinder Null Lens Test Setup



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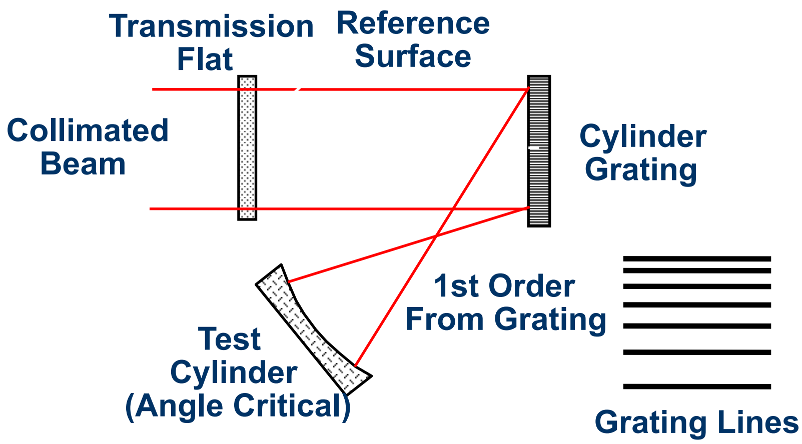
Cylinder Grating Test Setup



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Part 4 - Long Wavelength Interferometry

- Wavelengths of primary interest
- Test infrared transmitting optics
- Test optically rough surfaces

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Wavelengths of Primary Interest

- **1.06 microns**
  Reduced sensitivity
- **10.6 microns**
  Reduced sensitivity
  Test infrared transmitting optics
  Testing optically rough surfaces

1.06 Micron Source Interferometer

- **Diode Pumped Yag Laser**
  Excellent coherence properties
- **Normal Optics**
- **Normal CCD Camera**

Conventional interferometry techniques work well.

10.6 Micron Source Interferometer

- Carbon Dioxide Laser
  Excellent coherence properties
- Zinc Selenide or Germanium Optics
- Bolometer

Conventional interferometry techniques work well.

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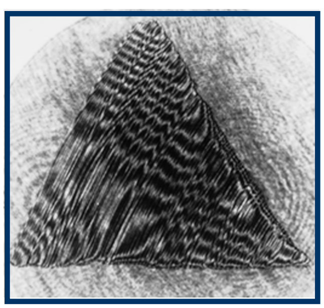
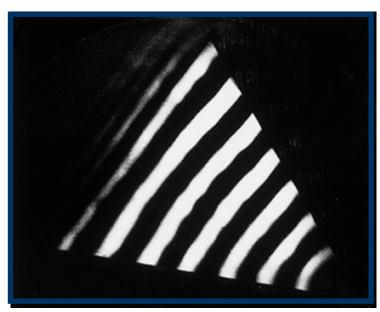
Reduced Sensitivity Testing



0.633 microns wavelength



10.6 microns wavelength

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Testing Rough Surfaces

Assume surface height distribution is Gaussian with standard deviation σ.

The normal probability distribution for the height, h, is

$$p(h) = \frac{1}{(2\pi)^{1/2}\sigma}\exp\left(-\frac{h^2}{2\sigma^2}\right)$$

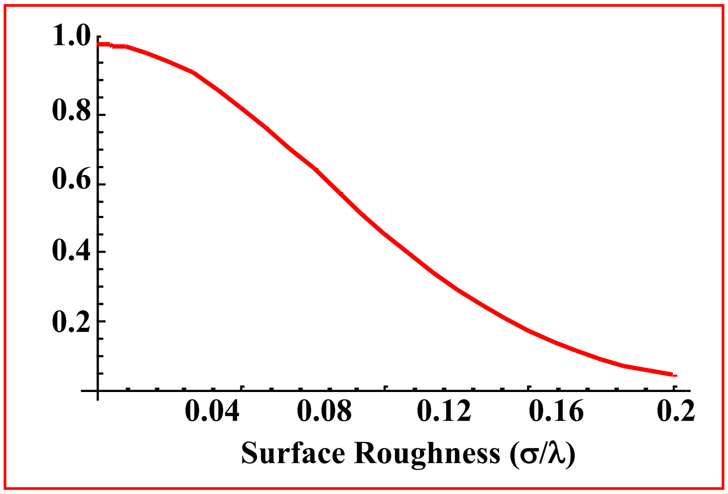
Fringe Contrast Reduction due to Surface Roughness

The fringe contrast reduction due to surface roughness is

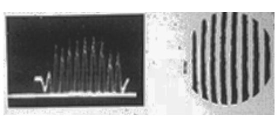
$$C = \exp\left(-8\pi^2\frac{\sigma^2}{\lambda^2}\right)$$

Reference: Appl. Opt. 11, 1862 (1980).

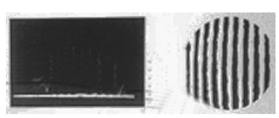
Fringe Contrast versus Surface Roughness - Theory



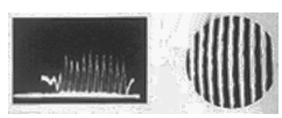
Interferograms Obtained for Different Roughness Surfaces



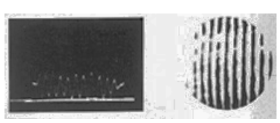
$\sigma = 0$ µm, C = 1.0



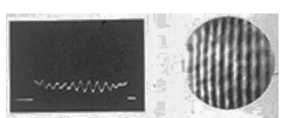
$\sigma = 0.32$ µm, C = 0.93



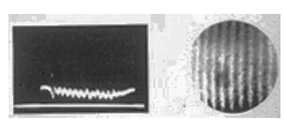
$\sigma = 0.44$ µm, C = 0.87



$\sigma = 0.93$ µm, C = 0.54

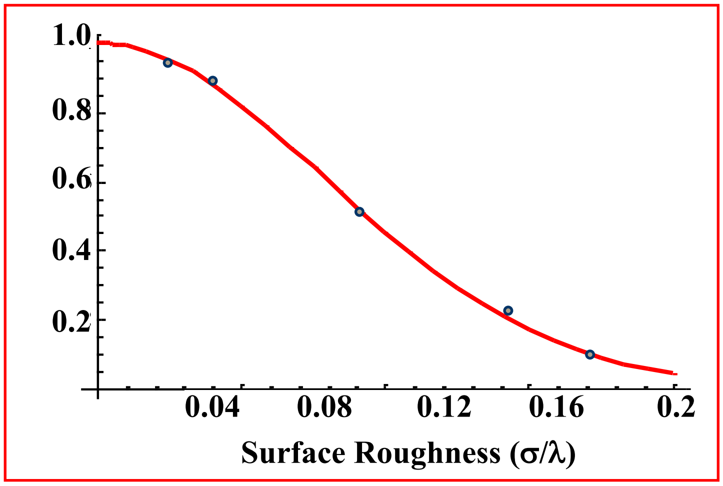


$\sigma = 1.44$ µm, C = 0.23



$\sigma = 1.85$ µm, C = 0.07

Fringe Contrast versus Surface Roughness - Theory and Experiment



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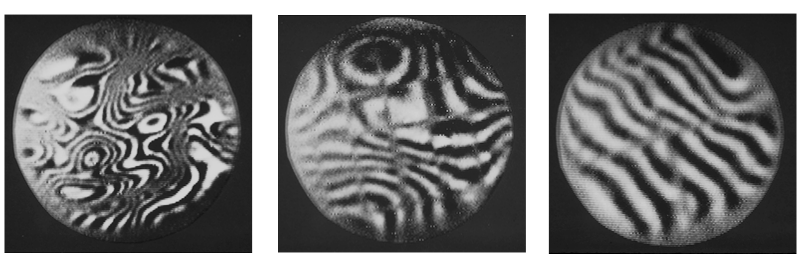
Infrared Interferograms of Off-Axis Parabolic Mirror in Chronological Order



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10.6 Micron Wavelength Interferometer

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Part 5 - Testing of Aspheric Surfaces

- Description of aspheric surfaces
- Techniques for testing aspheric surfaces
- Requirements for use of optical analysis software in optical testing
- Limitations of current aspheric testing techniques

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Aspheric Surfaces

Aspheric surfaces are of much interest because they can provide

- Improved performance
- Reduced number of optical components
- Reduced weight
- Lower cost

Conics

A conic is a surface of revolution defined by means of the equation

$$s^2 - 2rz + (k+1)z^2 = 0$$

Z axis is the axis of revolution. k is called conic constant. r is the vertex curvature.

$$s^2 = x^2 + y^2$$

Sag for Conic

$$z = \frac{s^2 / r}{1 + [1 - (k+1)(s/r)^2]^{1/2}}$$

$$s^2 = x^2 + y^2$$

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Sag for Asphere

$$z = \frac{s^2 / r}{1 + [1 - (k+1)(s/r)^2]^{1/2}} + A_4 s^4 + A_6 s^6 + \ldots$$

$$s^2 = x^2 + y^2$$

k is the conic constant

r is the vertex radius of curvature

A's are aspheric coefficients

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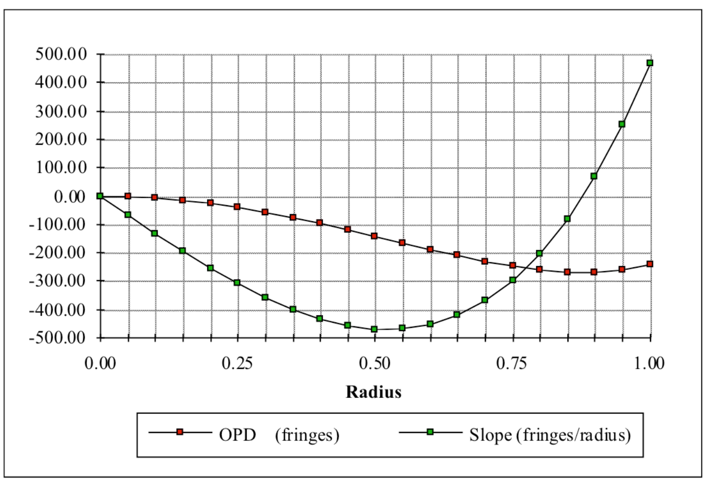
Difficulty of Aspheric Test

Slope of aspheric departure determines difficulty of test

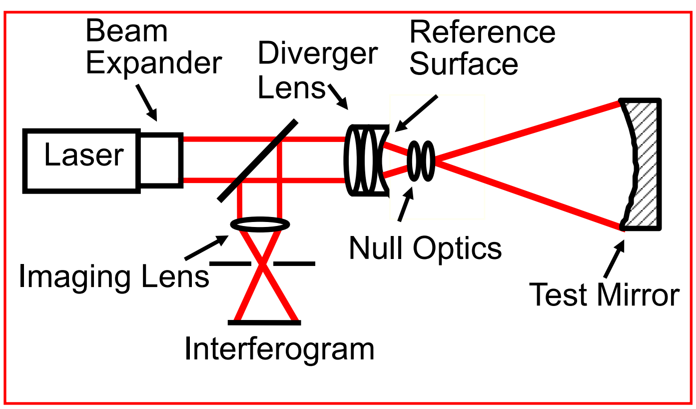
Wavefront Departure and Slope versus Radius



Aspheric Testing Techniques

- **Null Tests - Perfect optics give straight equally spaced fringes**
  - Conventional null optics
  - Computer generated holograms
- **Non-null Tests - Even perfect optics do not give straight equally spaced fringes**
  - Deflectometry (SCOTS)
  - Shack-Hartmann
  - Lateral shear interferometry
  - Radial shear interferometry
  - High-density detector arrays
  - Sub-Nyquist interferometry
  - Long-wavelength interferometry
  - Two-wavelength holography
  - Two-wavelength interferometry
  - Tilted wave interferometry
  - Stitching interferograms
  - Scanning interferometry

Conventional Null Optics



Hubble Pictures (Before and After the Fix)

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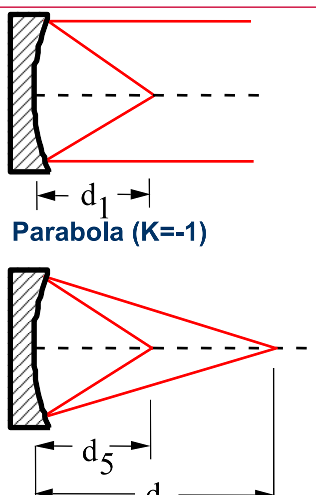
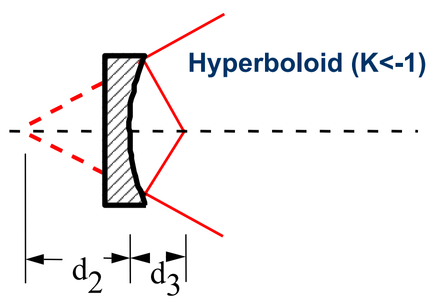
Null Tests for Conics





$$d_1 = r/2$$

$$d_2, d_3 = \frac{r}{K+1}\left(\sqrt{-K} \pm 1\right)$$

$$d_4, d_5 = \frac{r}{K+1}\left(1 \pm \sqrt{-K}\right)$$

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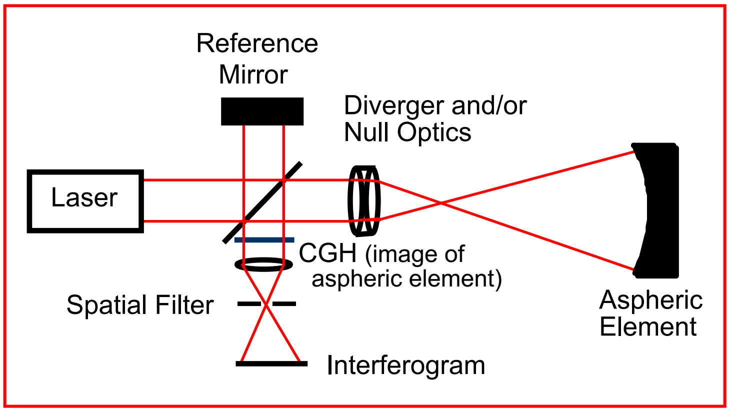
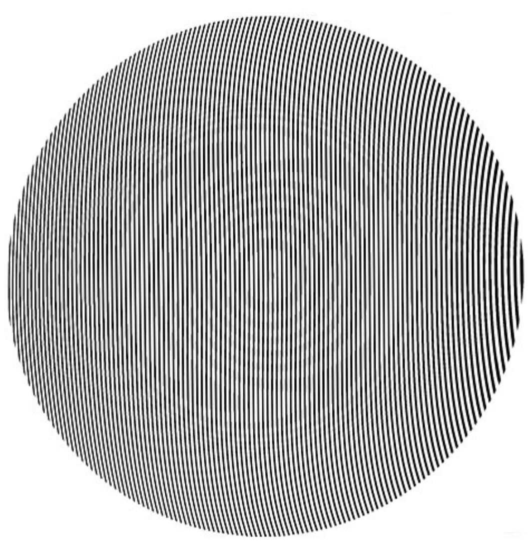
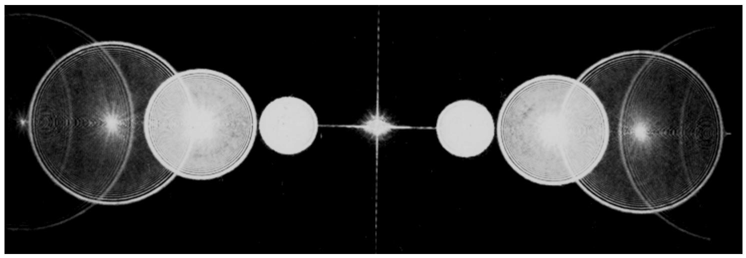
CGH Interferometer



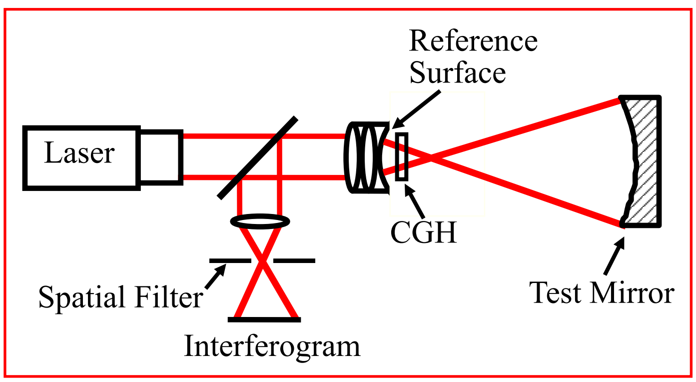
Computer Generated Hologram



Light in Spatial Filter Plane



CGH Used as Null Lens



- Can use existing commercial interferometer
- Double pass through CGH, must be phase etched for testing bare glass optics
- Requires highly accurate substrate

Error Source

- Pattern distortion (Plotter errors)
- Substrate surface figure
- Alignment Errors

Pattern Distortion

- The hologram used at m^{th} order adds *m* waves per line;
- CGH pattern distortions produce wavefront phase error:

$$\Delta W(x,y) = -m\lambda \frac{\varepsilon(x,y)}{S(x,y)}$$

ε(x,y) = grating position error in direction perpendicular to the fringes;

S(x,y) = localized fringe spacing;

For m = 1, phase error in waves = distortion/spacing

0.1 µm distortion / 20 µm spacing -> λ/200 wavefront

Plotters

- **E-beam**
  - Critical dimension – 1 micron
  - Position accuracy – 50 nm
  - Max dimensions – 150 mm
- **Laser scanner**
  - Similar specs for circular holograms

Solving Substrate Distortion Problems

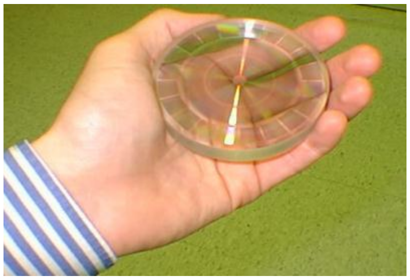
- Use direct laser writing onto custom substrates
- Use amplitude holograms, measure and back out substrate
- Use an optical test setup where reference and test beams go through substrate

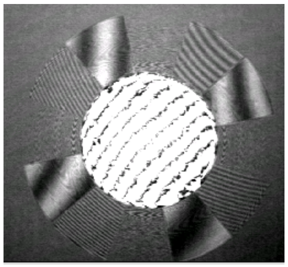
Alignment Errors

- Lateral misalignment gives errors proportional to slope of wavefront
- Errors due to longitudinal misalignment less sensitive if hologram placed in collimated light
- Alignment marks (crosshairs) often placed on CGH to aid in alignment
- Additional holographic structures can be placed on CGH to aid in alignment of CGH and optical system under test

Use of CGH for Alignment

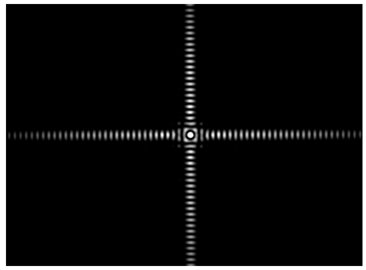
Commonly CGH's have patterns that are used for aligning the CGH to the incident wavefront.





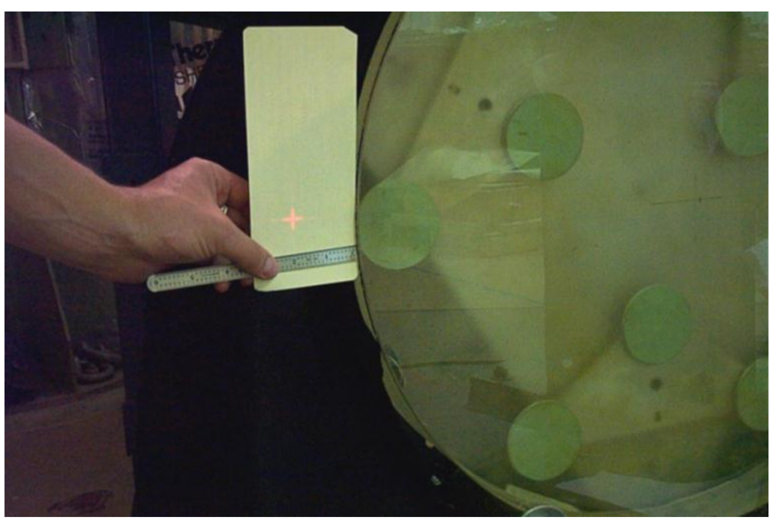
Using multiple patterns outside the clear aperture, many degrees of freedom can be constrained using the CGH reference.

Projection of Fiducial Marks

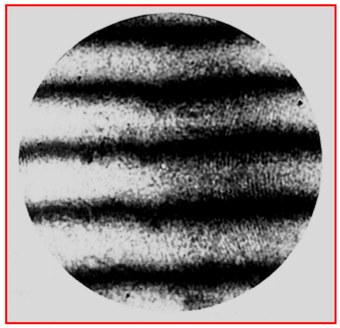


- The positions of the crosshairs can be controlled to micron accuracy
- The patterns are well defined and can be found using a CCD
- Measured pattern at 15 meters from CGH. Central lobe is only 100 μm FWHM

CGH Alignment for Testing Off-Axis Parabola



Holographic test of refractive element having 50 waves of third and fifth order spherical aberration



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Deflectometry (SCOTS Test)

- Hartmann test in reverse
- Measures slope
- Accuracies in the range of 100 – 200 nrad (rms) have been achieved

- Ref: Su, Parks, Wang, Angel, and Burge, "Software configurable optical test system: a computerized reverse Hartmann test", Appl. Opt, 49(23), 4404-4412, (2010).
- Ref: Su, Wang, Burge, Kaznatcheev, and Idir, "Non-null full field X-ray mirror metrology using SCOTS: a reflection deflectometry approach", Opt. Express 20(11), 12393-12406 (2012).
- Ref: Häusler, Faber, Olesch, and Ettl, "Deflectometry vs. Interferometry", Proc. SPIE. 8788, Optical Measurement Systems for Industrial Inspection VIII 87881C (May 13, 2013) doi: 10.1117/12.2020578.

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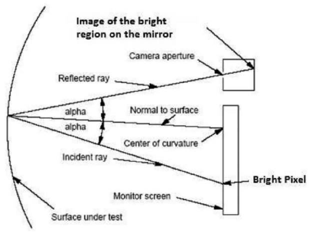
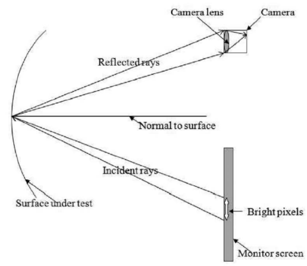
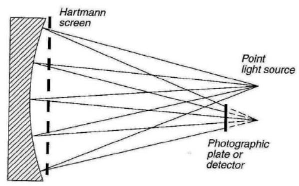
Deflectometry and Hartmann Test





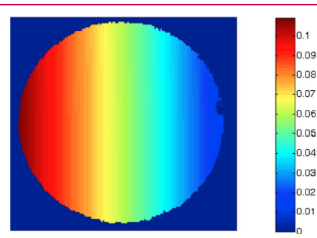
Geometry of Deflectometry



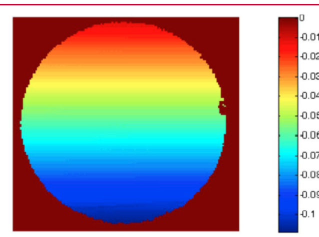
HartmannTest

Use line source to measure either x-slope or y-slope. Sinusoidal fringes can be used instead of line and phase-shifting techniques can be used.

Measurement of Off-Axis Parabola

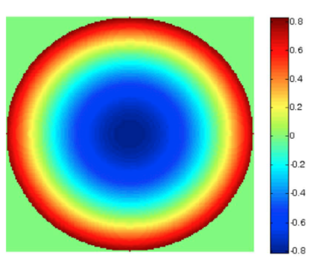


X-slope

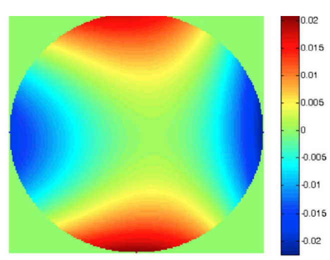


Y-slope

Radians



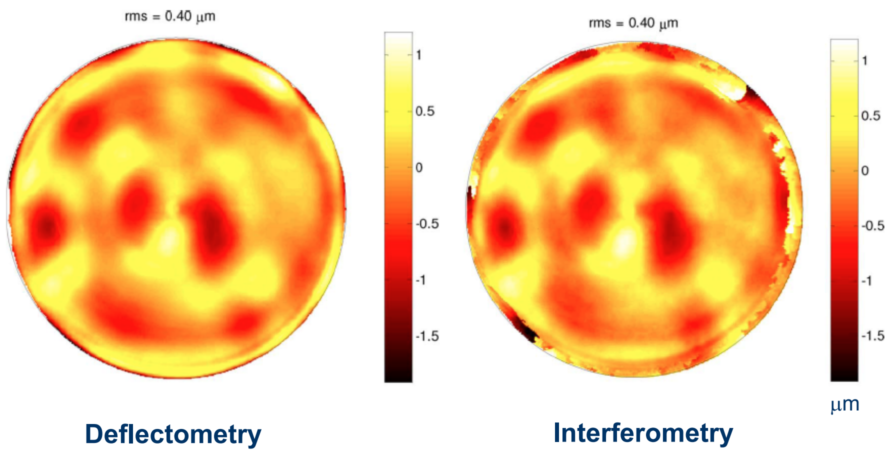
Surface



Surface Departure

mm

8.4 m Giant Magellan Telescope

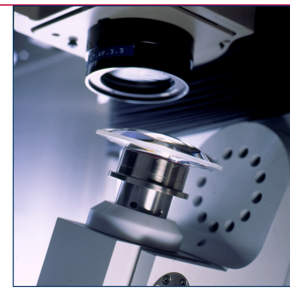


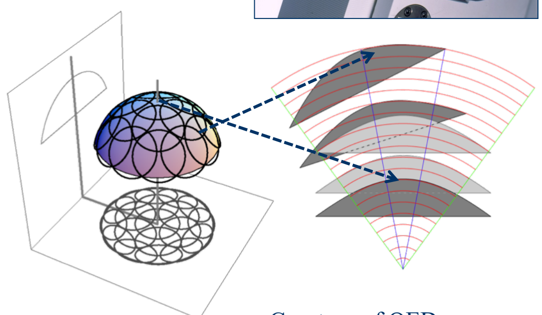
Stitching Interferograms

- Perform sub-aperture test of aspheric and stitch together interferograms.
- Trade-off between overlap between interferograms and number of interferograms required.
- Much easier to describe than to obtain accurate results.

Subaperture Stitching Interferometry (SSI®)

- What is it?
  - 6-axis motion system
  - "Standard" interferometer
  - Automatic collection of multiple subaperture measurements
  - **Magnified**, **locally nulled** sub-apertures **reduce "aspheric" fringe density**
  - Compensation of systematic errors
- SSI extends standard interferometry
  - **Fast** & **Large** parts
  - Aspheres (up to ~200 λ)
- And also can *improve*:
  - **Accuracy** & **Resolution**

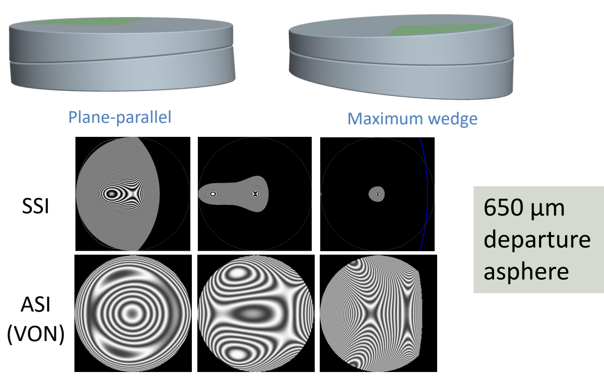


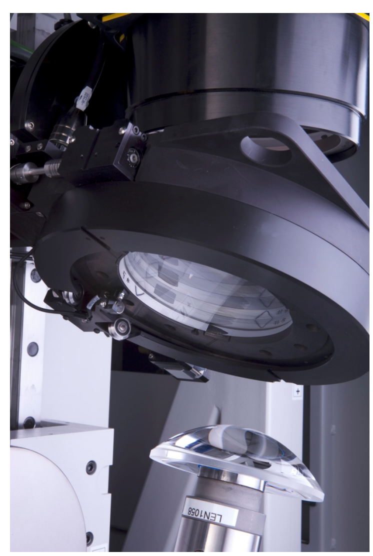


Courtesy of QED

Extending the SSI to ASI®

- Variable Optical Null (VON) extends aspheric departure capture range
- Counter-rotating optical wedges
  - Varying the wedge angle and tilt produces astigmatism & coma

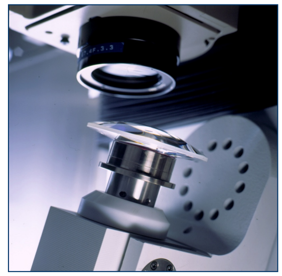


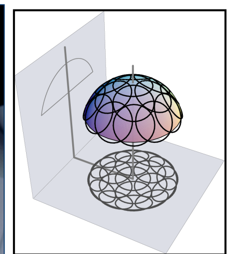


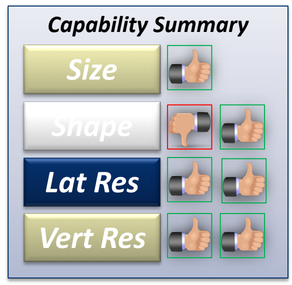
Courtesy of QED

SSI/ASI: *Summary*

- What is it good for?
  - Flexible – no dedicated nulls
  - High departure
  - Large NA or CA
  - High vertical resolution
  - High lateral resolution
  - Compensation of systematic errors
- What are its key limitations?
  - Inflection points
  - High slope deviations
  - 3rd order spherical uncertainty

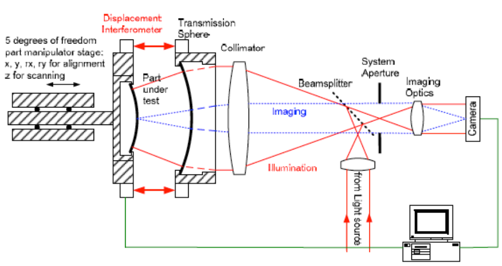


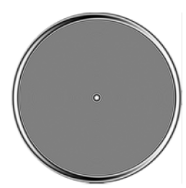




Courtesy of QED

Zygo Verifire Multi-Zone Aspheric Tester





- **Measure 6 to 200 sub-measurements of concentric zones.**
- **Measure distance of every zone from from center point of spherical reference surface.**
- **Measure distance to apex of part.**
- **Stitching of overlapping apertures not required.**
- **The results represents surface-deviation in normal direction.**

Reference: M. F. Kuechel, "Interferometric measurement of rotationally symmetric aspheric surfaces," in "Proc. SPIE 7389, Optical Measurement Systems for Industrial Inspection VI, 738916," (2009).

Verifire Asphere Spec (from Zygo brochure)

Aspheric Shape[7]	Axially symmetric concave or convex shape with specular surface and a measurable apex
Departure from asphere design	Up to 10 µm
Departure from vertex sphere R0	Approximately 800 µm
Part Diameter[8]	1 mm to 130 mm

Simple Repeatability[2,3]	≤1 nm (λ/600) RMS
Surface Measurement Repeatability[2,4]	≤5 nm (λ/125) RMS
Height Resolution	0.08 nm
Cycle Time[5]	2 - 8 minutes (typical)

Lens Analysis Software

- **Must know precisely how optics in test setup change aspheric wavefront.**
- **Must know effects of misalignments, so errors due to misalignments can be removed.**

Basic Limitations of Aspheric Testing

- Must get light back into the interferometer
- Must be able to resolve the fringes
- Must know precisely the optical test setup

This is the most serious problem

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Part 6 - Measurement of Surface Microstructure

- Non-Contact Optical Profilers
- White Light Interferometry
- Vertical Scanning Optical Profilers

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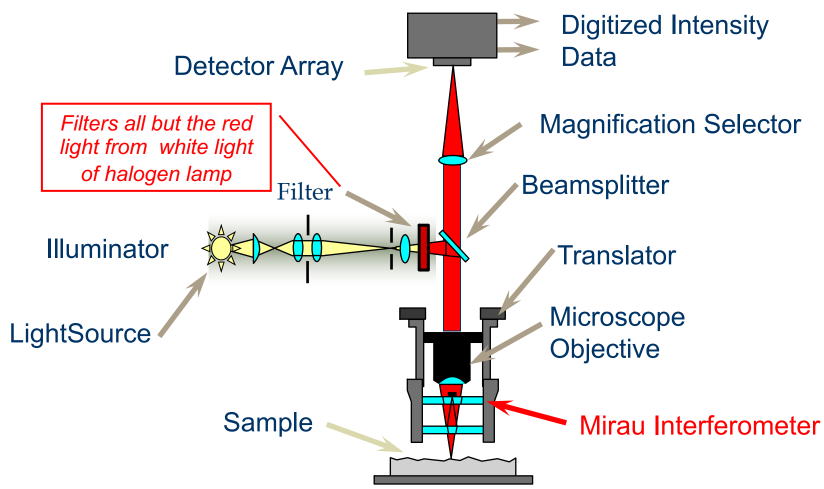
Non-Contact Optical Profilers for Measurement of Surface Microstructure

- Non-contact measurement
- 2D or 3D surface topography
- Visual qualitative surface inspection
- Vertical resolution suitable for super-polished optics
- Fast measurement and analysis

Advantages of White Light over Laser Light

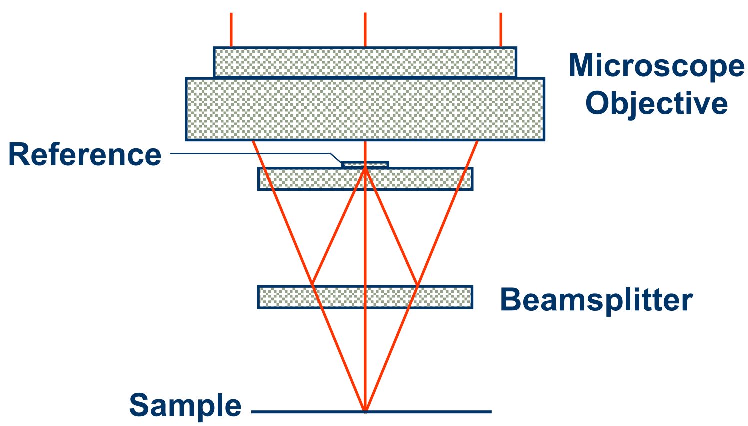
- Lower noise
  - No spurious fringes
- Multiple wavelength operation
  - Measure large steps
- Focus easy to determine

Interference Microscope Diagram

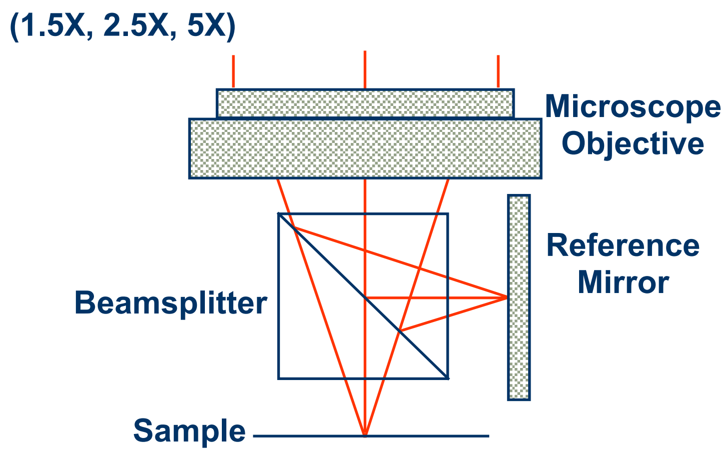


Mirau Interferometer

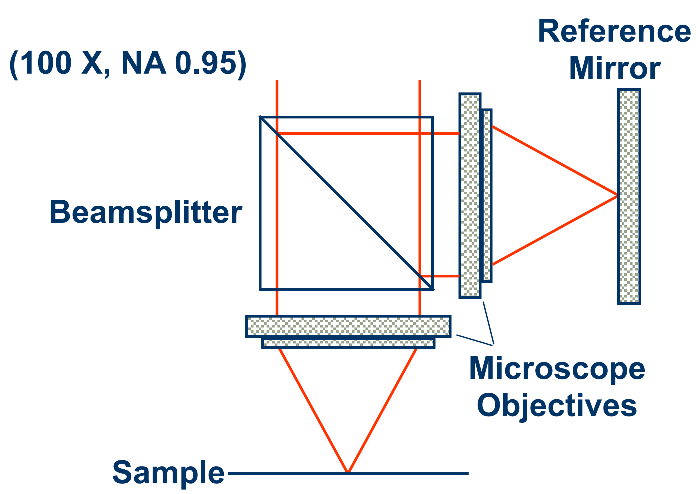
(10X, 20X, 50X)



Michelson Interferometer



Linnik Interferometer

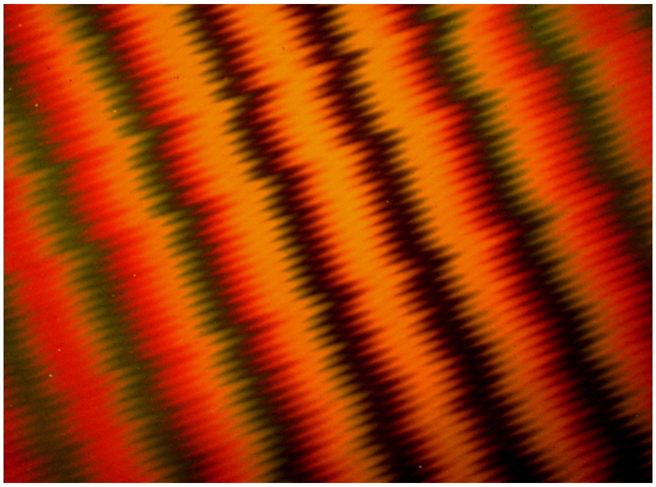


Interference Objectives

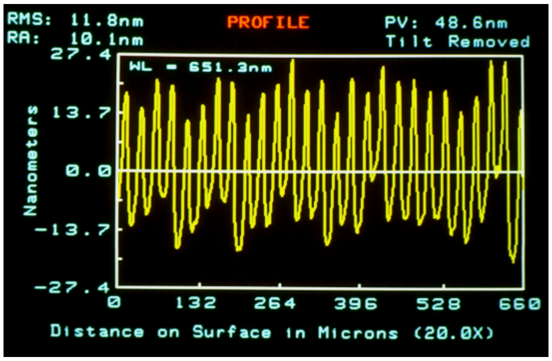
- **Mirau**
  - Medium magnification
  - Central obscuration
  - Limited numerical aperture
- **Michelson**
  - Low magnification, large field-of-view
  - Beamsplitter limits working distance
  - No central obscuration
- **Linnik**
  - Large numerical aperture, large magnification
  - Beamsplitter does not limit working distance
  - Expensive, matched objectives

Optical Profiler

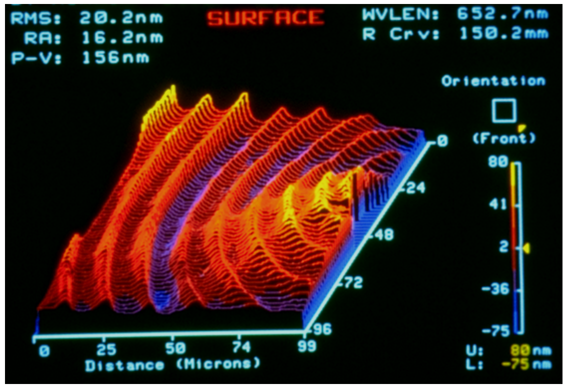
White Light Interferogram



Profile of Diamond Turned Mirror



Diamond Turned Mirror



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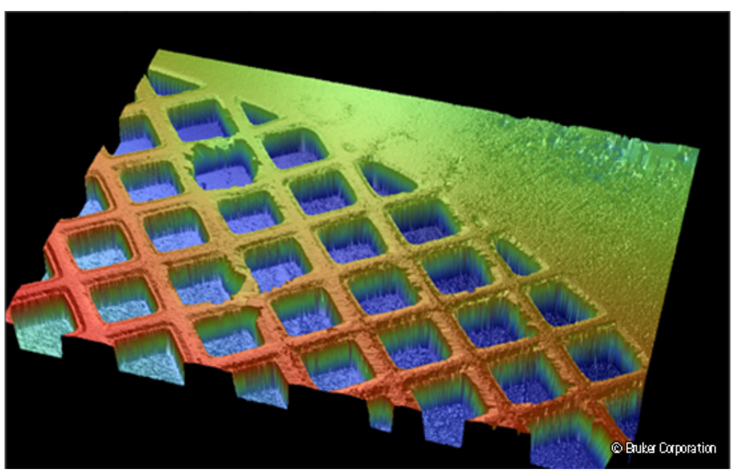
Grating



Ref: Bruker

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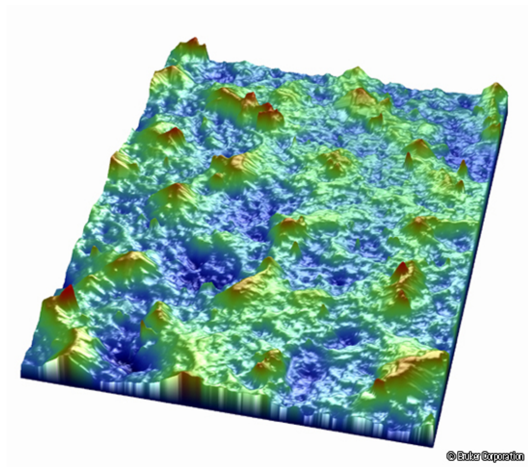
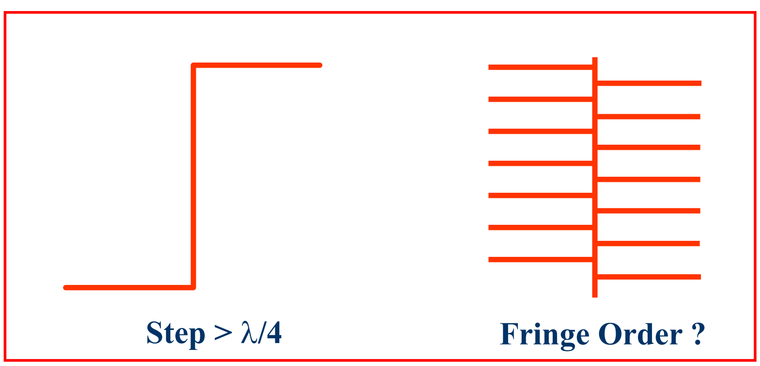
Diamond Film



Ref: Bruker

How High is the Step?

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

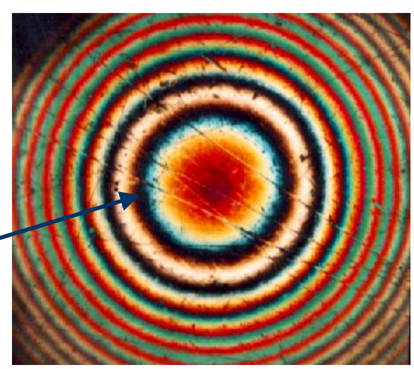


White Light Interferometry

- Eliminates ambiguities in heights present with monochromatic interferometry
- Techniques old, but use of modern electronics and computers enhance capabilities and applications

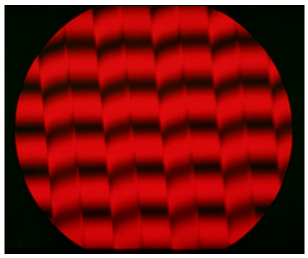
White Light Interference Fringes

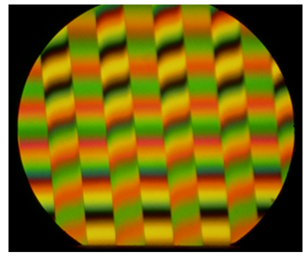
- Fringes form bands of contour of equal height on the surface with respect to the reference surface.
- Fringe contrast will be greatest at point of equal path length or "best focus."



Interferograms of Diffraction Grating

Quasi-Monochromatic Light | **White Light**

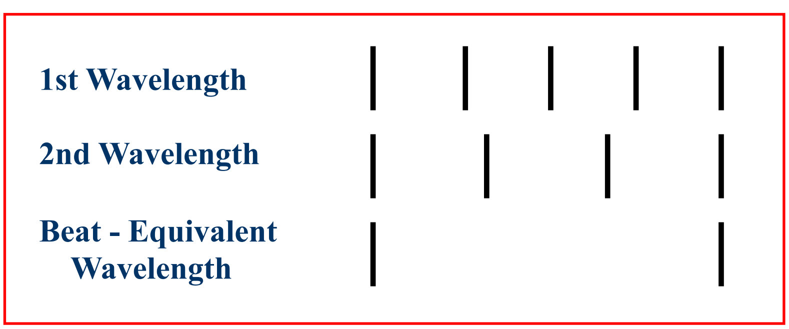




Profile

Two Wavelength Measurement

- Measure Beat Frequency
- Long Effective Wavelength



Two Wavelength Calculation

Equivalent Wavelength $$\lambda_{eq} = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|}$$

Equivalent Phase $$\varphi_{eq} = \varphi_1 - \varphi_2$$

No height ambiguities as long as height difference between adjacent detector pixels < equivalent wavelength / 4

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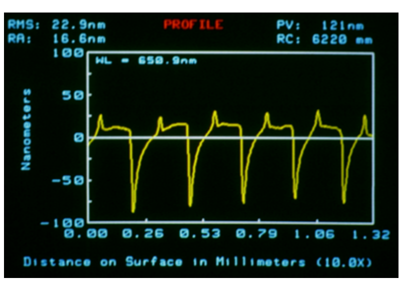
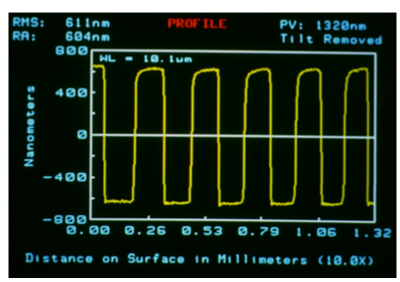
Diffraction Grating Measurement

Single wavelength (650 nm)



Equivalent wavelength (10.1 microns)



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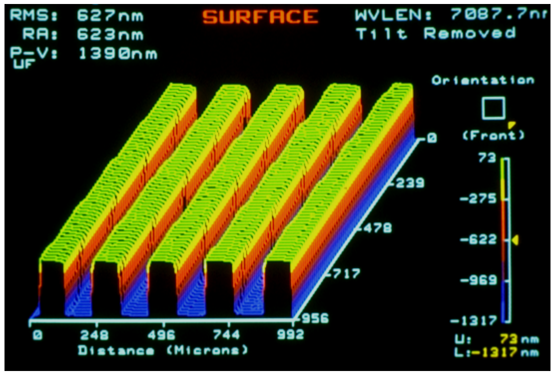
3-D Two-Wavelength Measurement (Equivalent Wavelength, 7 microns)



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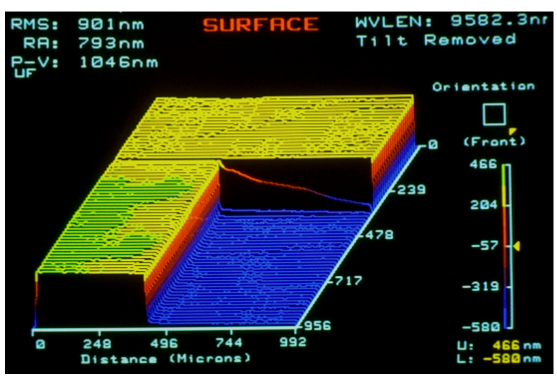
Two-Wavelength Measurement of Step



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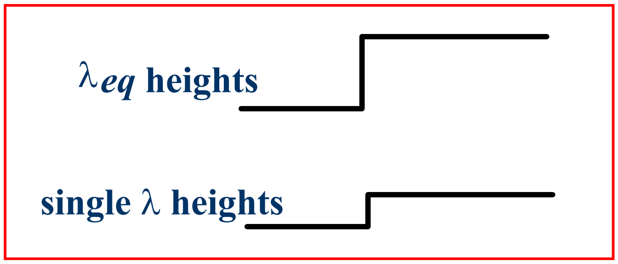
Wavelength Correction

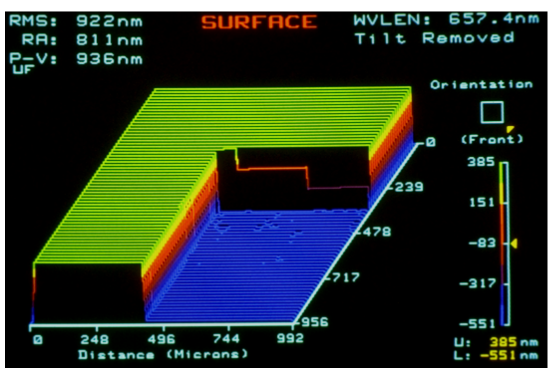
Compare

- Heights calculated using equivalent wavelength
- Heights calculated using single wavelength



Add N x λ/2 to heights calculated using single wavelength so difference < λ/4

Wavelength Correction Measurement of Step



Principles of Vertical Scanning Interferometry

- **A difference between the reference and test optical paths causes a difference in phase.**
- **Best fringe contrast corresponds to zero optical path difference.**
- **Best focus corresponds to zero optical path difference.**

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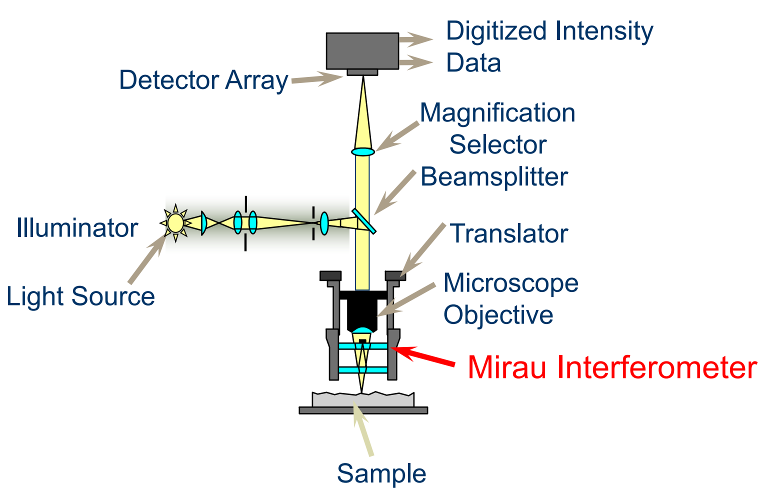
Interference Microscope Diagram



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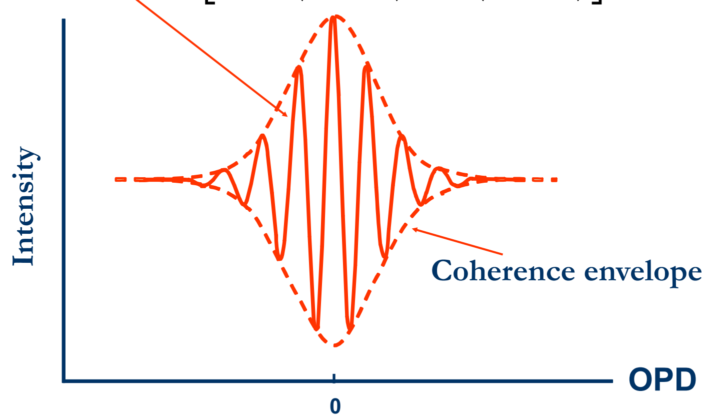
Irradiance Signal Through Focus

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



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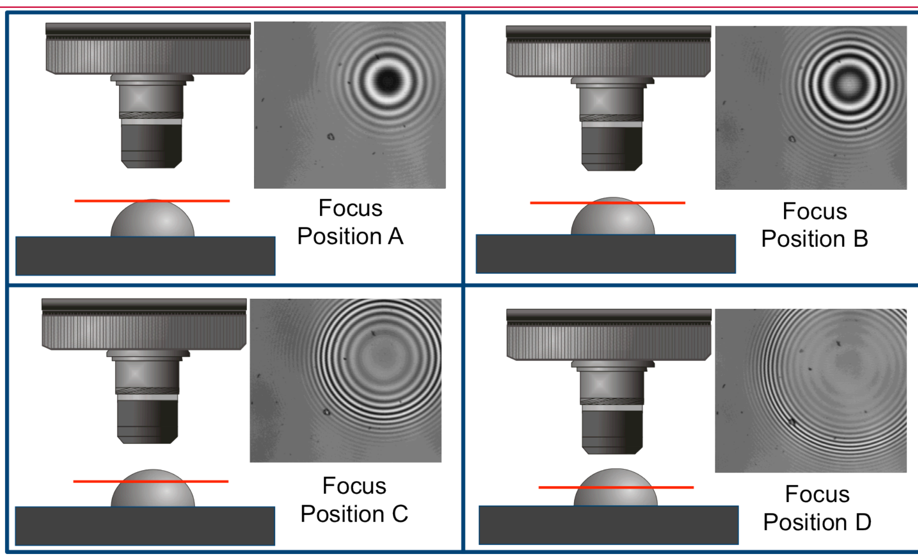
Vertical Scanning Interference Microscope



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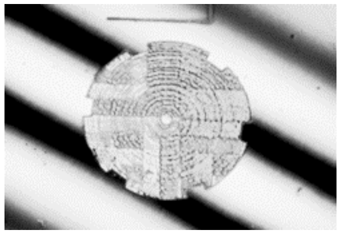
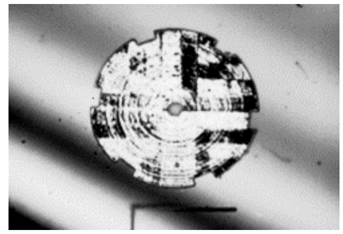
White Light Interferograms

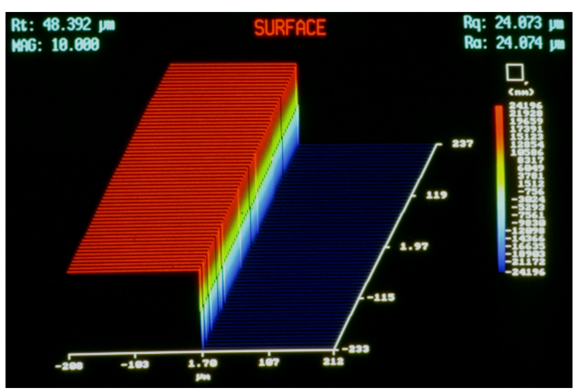

Focus Position A


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).

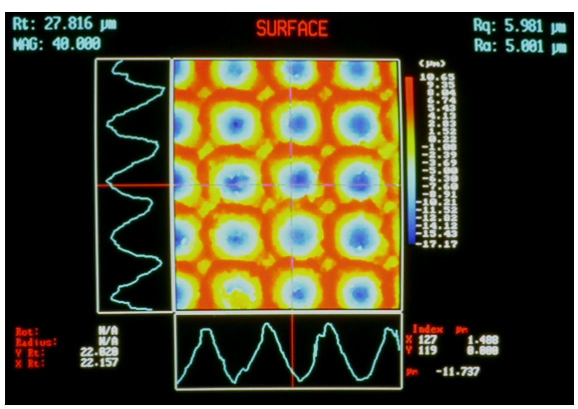
A determination of the point of maximum contrast and knowledge of the scan position allows a reconstruction of the surface shape.

Step Measurement

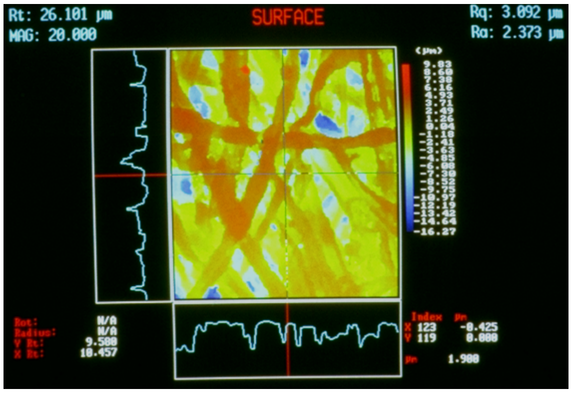


Print Roller

Print Roller Measurement



Paper Measurement



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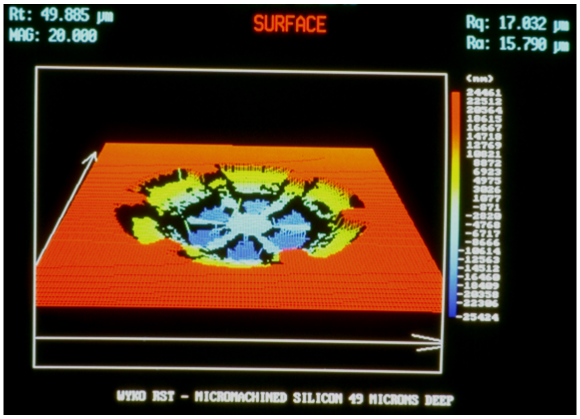
Micromachined Silicon Measurement



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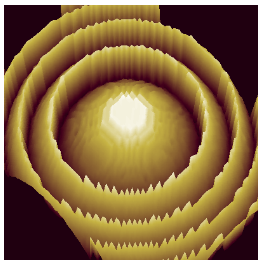
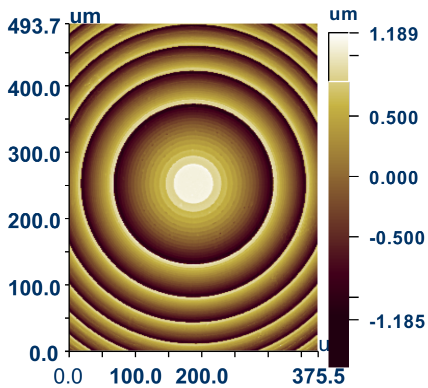
Binary Optic Lens

Surface Stats:
RMS: 561.30 nm
PV: 2.37 um





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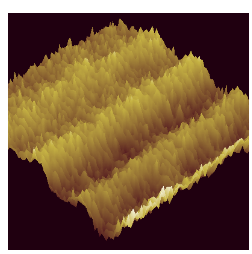
Chatter Seen on Camshaft

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



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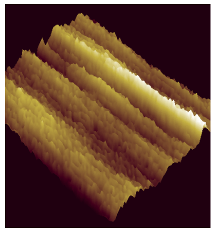
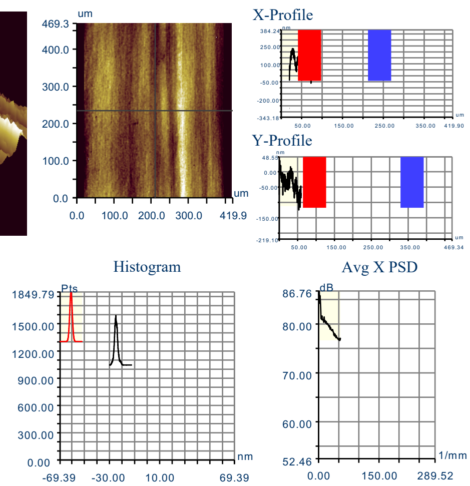
Heart Valve





Data Statistics
Rt: 1.419 um
Ra: 87.391 nm
Rq: 113.942 nm

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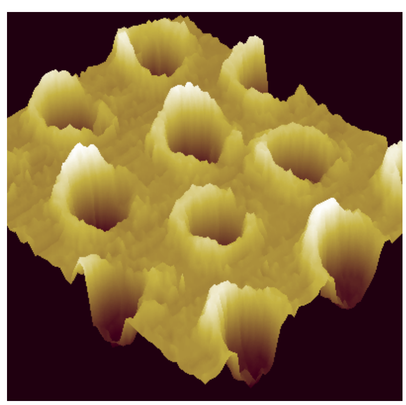
Pits in Metal

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



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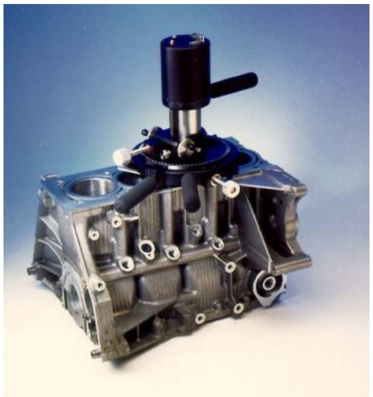
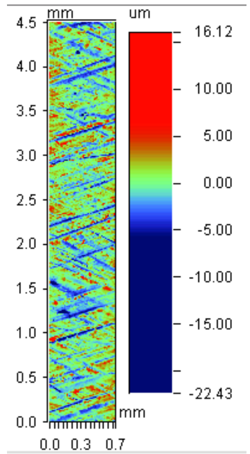
Six Stitched Data Sets of Inside of Engine Bore



Insight 2000 measuring inside of engine bore



Ra = 1.69 µm, Rz = 27.87 µm, and Rt = 38.54 µm

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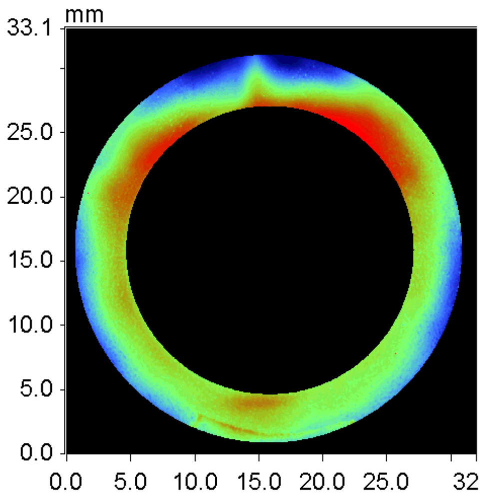
Stitched Measurement - Fuel Cap



VSI mode

Surface statistic

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

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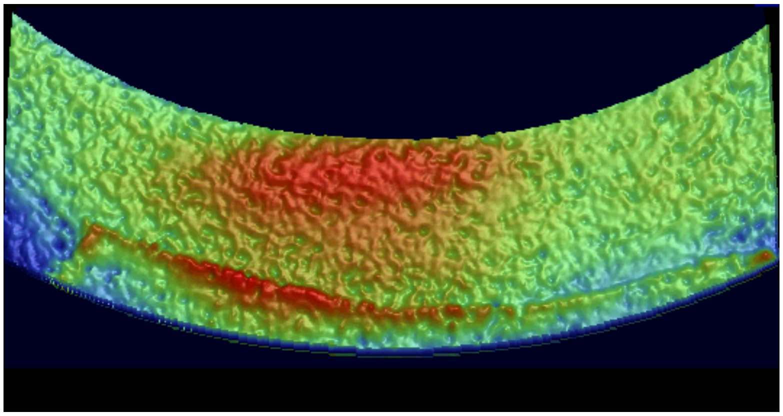
Sub-Region of Stitched - Fuel Cap



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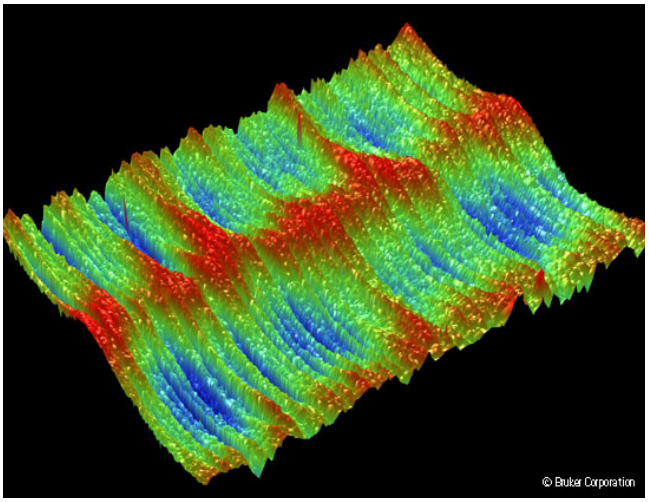
Chatter on Camshaft



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Ref: Bruker

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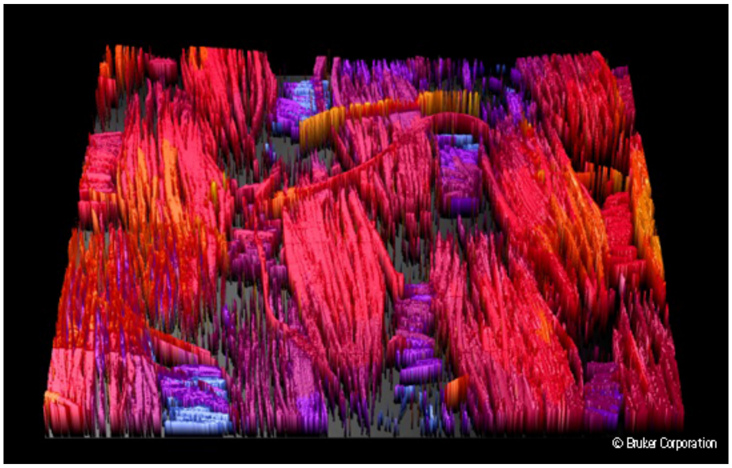
Woven Cloth



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Ref: Bruker

Part 7 - Absolute Measurements

- Absolute measurement of flats
- Absolute measurement of spheres
- Absolute measurement of surface roughness

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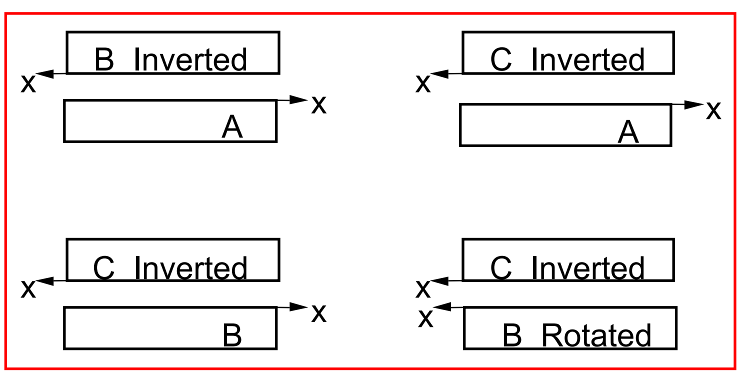
Absolute Surface Shape Measurement

- Removing system aberrations & reference surface effects
- Improves measurement accuracy
- Tests for
  - Flats
  - Spheres
  - Surface roughness

Measurements Required for Three-Flat Test



Three-Flat Test Equations

Make 4 Measurements

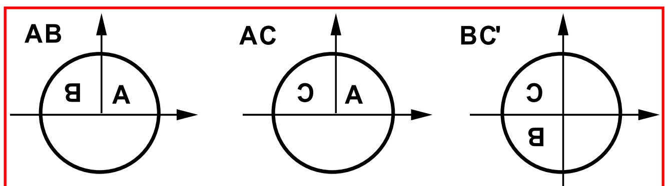
$$G_{AB}(x,y) = f_A(x,y) + f_B(-x,y)$$

$$G_{AC}(x,y) = f_A(x,y) + f_C(-x,y)$$

$$G_{BC}(x,y) = f_B(x,y) + f_C(-x,y)$$

$$G_{BC'}(x,y) = f_B(-x,-y) + f_C(-x,y)$$

Three-Flat Test - X Line

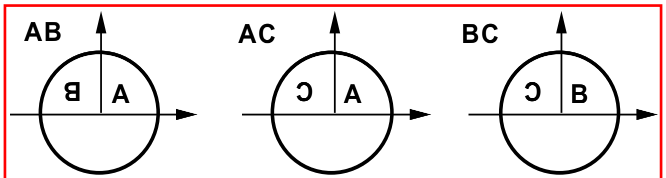


$$f_A(x,0) = \frac{G_{AB}(x,0) + G_{AC}(x,0) - G_{BC'}(x,0)}{2}$$

$$f_B(x,0) = \frac{G_{AB}(x,0) - G_{AC}(x,0) + G_{BC'}(x,0)}{2}$$

$$f_C(x,0) = \frac{- G_{AB}(x,0) + G_{AC}(x,0) + G_{BC'}(x,0)}{2}$$

Three-Flat Test - Y Line

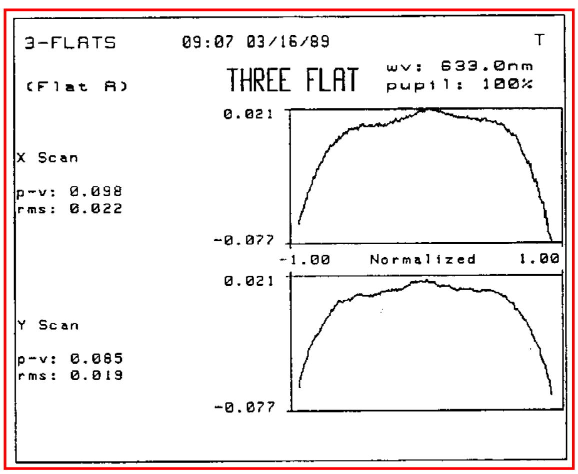


$$f_A(0,y) = \frac{G_{AB}(0,y) + G_{AC}(0,y) - G_{BC}(0,y)}{2}$$

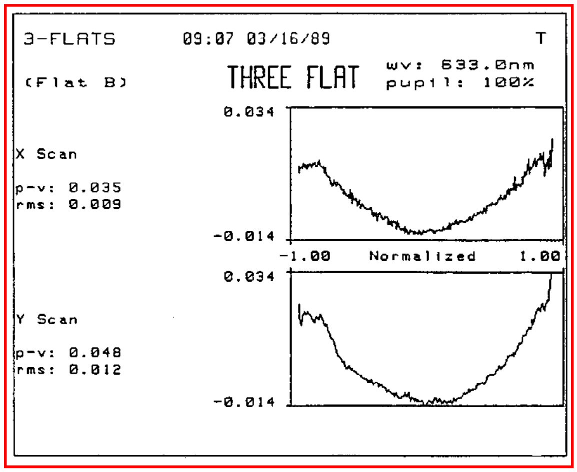
$$f_B(0,y) = \frac{G_{AB}(0,y) - G_{AC}(0,y) + G_{BC}(0,y)}{2}$$

$$f_C(0,y) = \frac{- G_{AB}(0,y) + G_{AC}(0,y) + G_{BC}(0,y)}{2}$$

Three-Flat Test - Flat A



Three-Flat Test - Flat B



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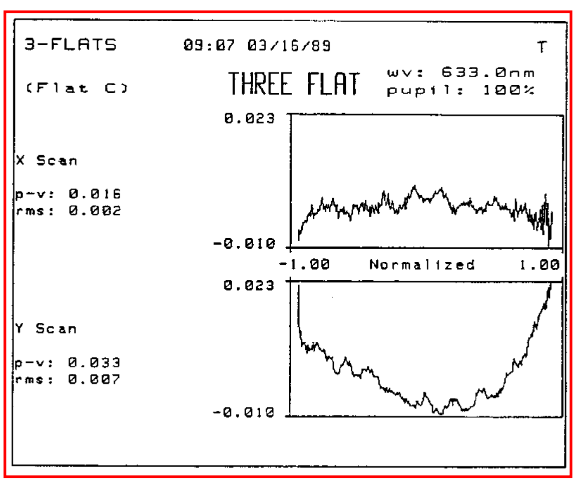
Three-Flat Test - Flat C



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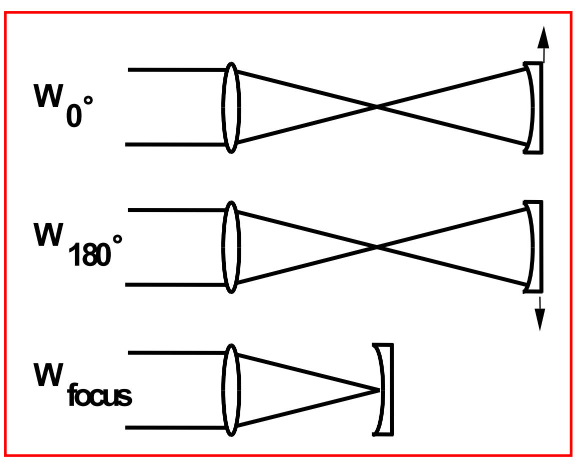
Absolute Sphere Testing

- Separate interferometer errors from errors in spherical mirror being tested.
- Three measurements required.

Absolute Sphere Testing (Measurements Required)



Absolute Sphere Testing (Equations)

$$W_{focus} = W_{ref} + \frac{1}{2}\left[W_{div} + \overline{W}_{div}\right]$$

$$W_{0^o} = W_{surf} + W_{ref} + W_{div}$$

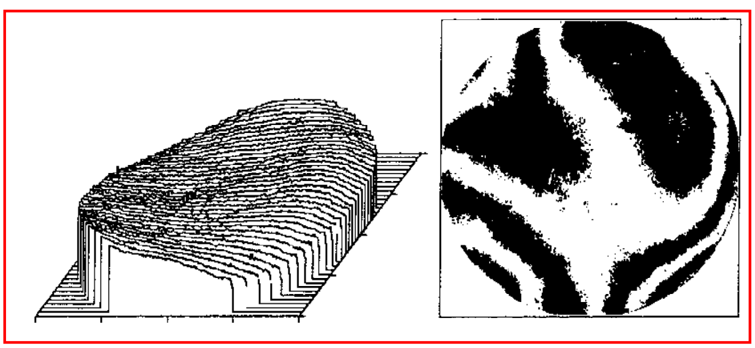
$$W_{180^o} = \overline{W}_{surf} + W_{ref} + W_{div}$$

COMBINE 3 MEASUREMENTS

$$W_{surf} = \frac{1}{2}\left[W_{0^o} + \overline{W}_{180^o} - W_{focus} - \overline{W}_{focus}\right]$$

Single Measurement of Sphere

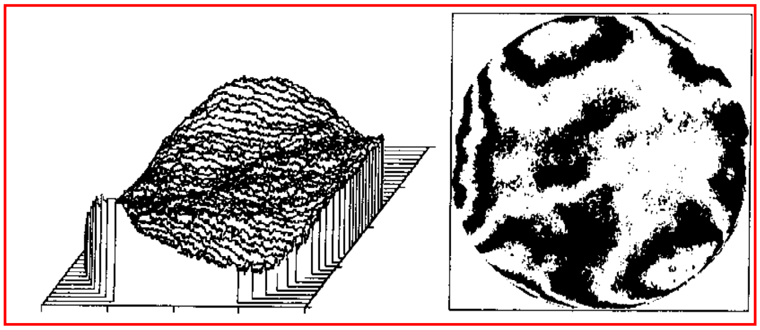
TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.014 WAVES
P-V = 0.121 WAVES



FIZEAU INTERFEROMETER, F/1.1 REF. SPHERE

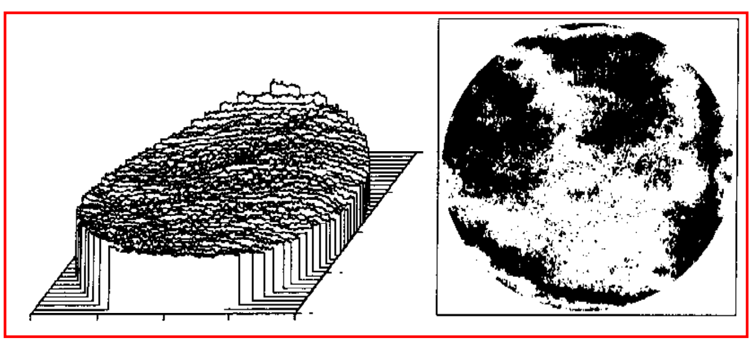
Flat at Focus f/1.1 Diverger

TILT, POWER, COMA REMOVED
INTERVAL = 0.05
RMS = 0.027 WAVES
P-V = 0.243 WAVES



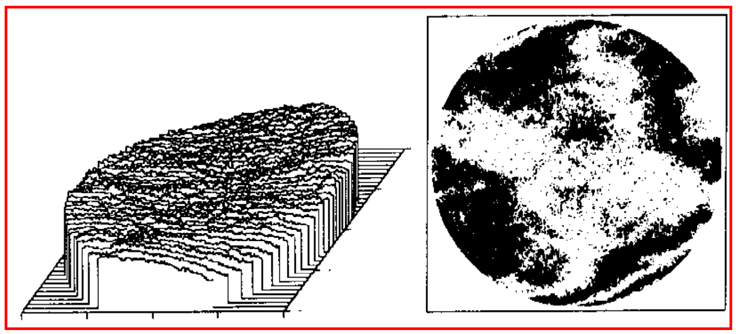
Absolute Reference

TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.010 WAVES
P-V = 0.084 WAVES



Absolute Measurement of Sphere

TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.011 WAVES
P-V = 0.081 WAVES



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Absolute Surface Roughness Measurement Assumptions

- Surface height is random
- Statistics do not vary over surface
- Each measurement = Test + Reference
- Test and reference uncorrelated

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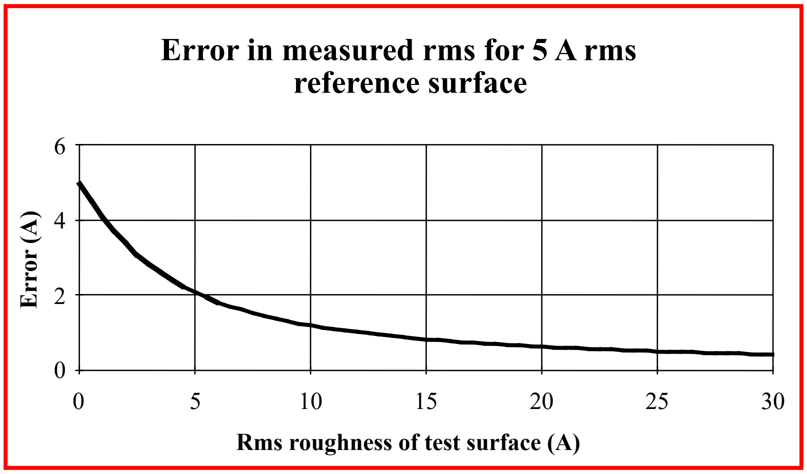
Effect of Reference Surface on Measurement



Subtraction of Errors due to Reference Surface

- Perfect mirror
- Generate reference
- Absolute rms measurement

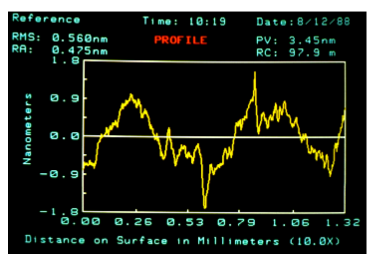
Generate Reference

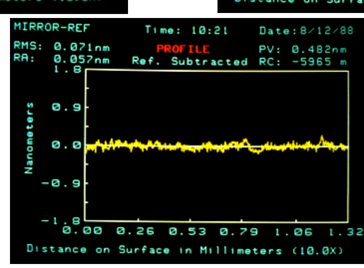
- Average many measurements
- Move random surface > correlation length between measurements
- Effects of random surface reduce as square root of number of measurements

Generate Reference and Subtract

Surface + Reference

Reference





Surface (0.071 nm)

Absolute RMS Measurement

- Make 2 measurements where surface moved > correlation length between measurements
- Subtract measurements and divide by square root of 2
- Reference cancels and obtain
- RMS of test surface

$$Diff = Test_1 + (-Test_2)$$
$$RMS_{Test} = \frac{1}{\sqrt{2}} RMS_{Diff}$$

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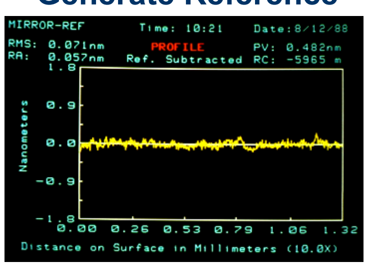
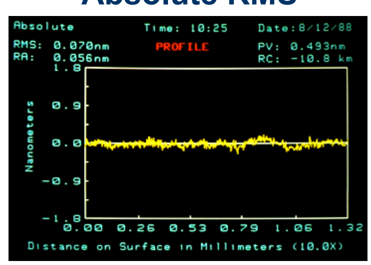
Generate Reference and Absolute RMS Comparison

Generate Reference



RMS = 0.071 nm

Absolute RMS



RMS = 0.070 nm

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Part 8 – Concluding Remarks

- Limitations of Direct Phase Measurement Interferometers
- Most Important to Remember
- References

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Limitations of Direct Phase Measurement Interferometers

- Accuracy generally limited by environment
  - Vibration
  - Turbulence
- Measurement of surface roughness less limited by environment because path differences small
- Single-shot phase-measurement interferometers greatly reduce the effects of vibration and turbulence effects can be averaged out.

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Remember

- If you make optics you have to be able to test the optics because you cannot make optics any better than you can test.
- If you purchase optics you need to test the optics you buy to make sure the optics meet the specs.
- If you let the supplier know you are going to test the optics when you receive them you will get better optics.

References

D. Malacara, Ed., Optical Shop Testing

W. Smith, Modern Optical Engineering

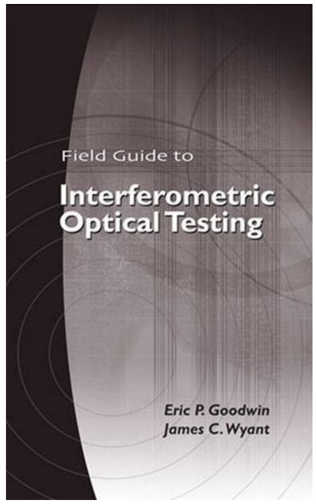
Kingslake, Thompson, Shannon, and Wyant, Ed. Applied Optics and Optical Engineering, Vols. 1-11

Goodwin and Wyant, Field Guide to Interferometric Optical Testing

Optical Society of America
OSA Publishing

SPIE
Digital Library

Field Guide to Interferometric Optical Testing (Published by SPIE)



Thank you for taking the short course!