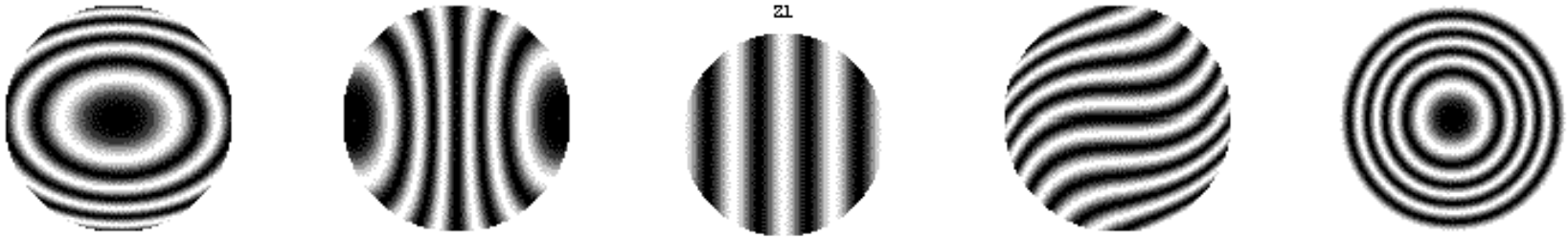
College of Optical Sciences THE UNIVERSITY OF ARIZONA®

Optical Testing and Testing Instrumentation



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Outline

- 1. Basic Interferometers for Optical Testing
- 2. Phase-Shifting Interferometry
- 3. Testing of Aspheric Surfaces
- 4. Measurement of Surface Microstructure
- 5. Concluding Remarks

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
- Typical Interferograms

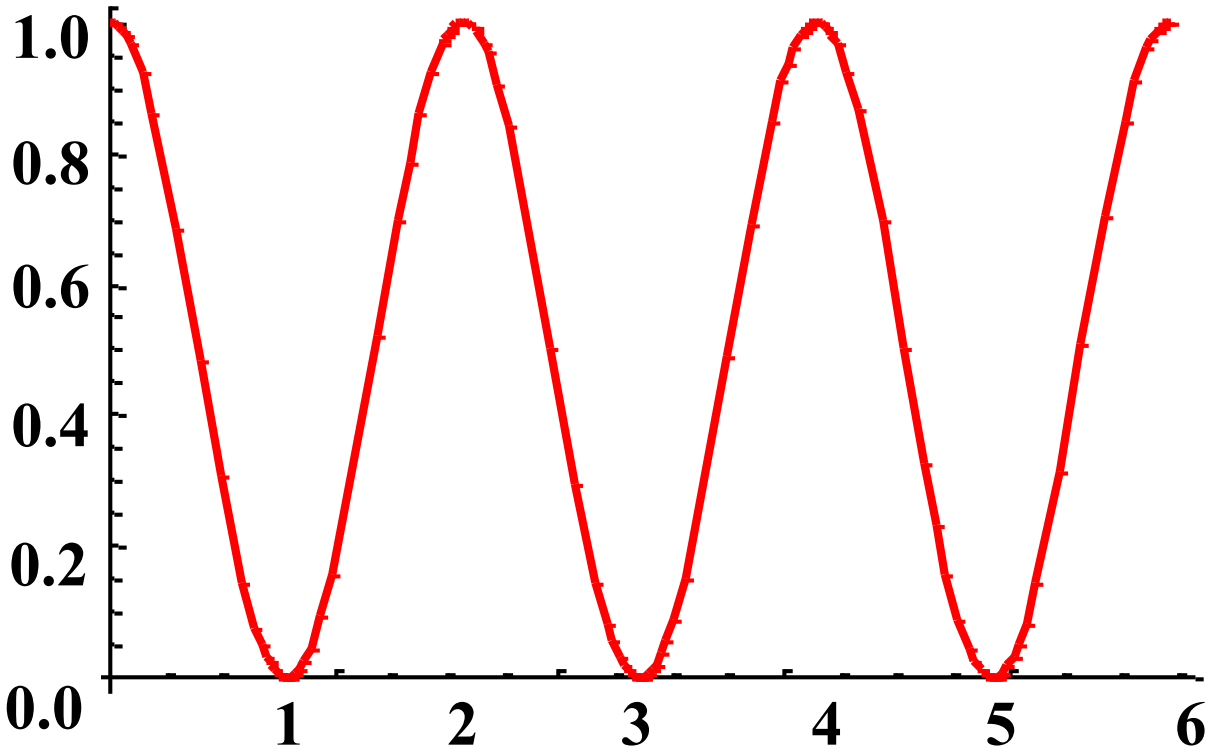
Two-Beam Interference Fringes

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

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

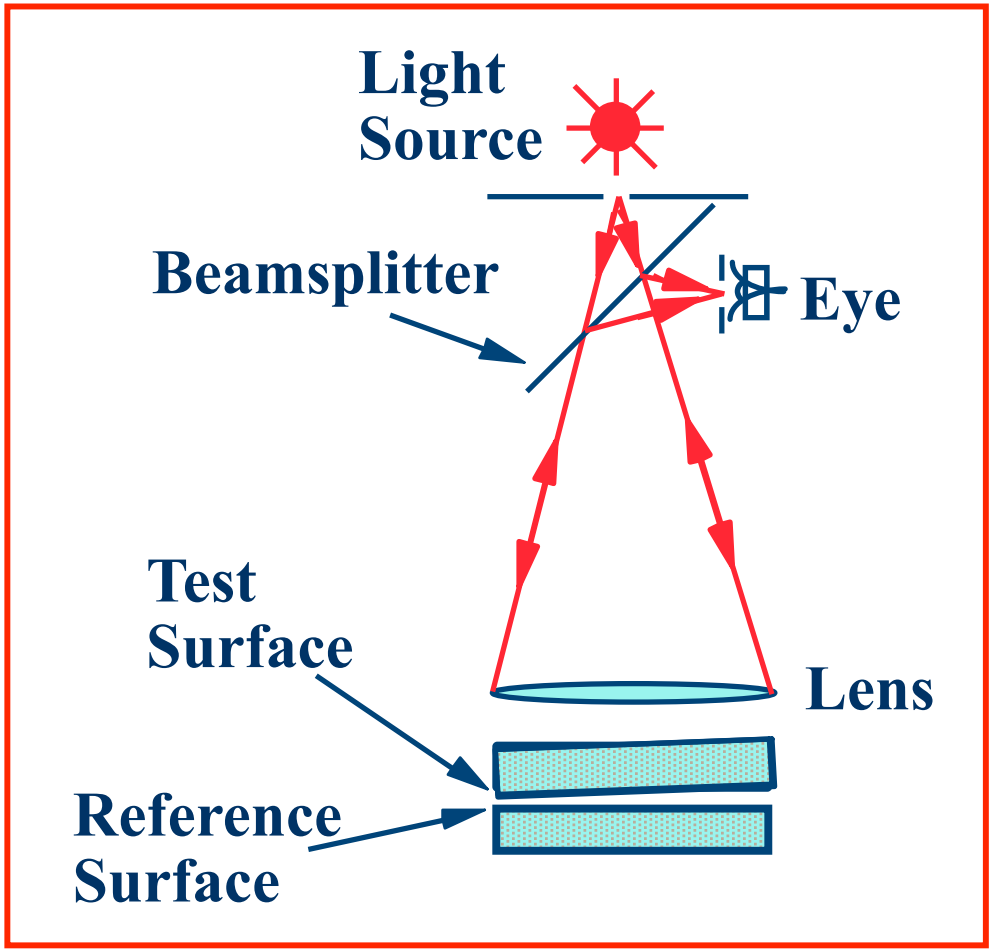
$$\alpha_1 - \alpha_2 = \left(\frac{2\pi}{\lambda}\right)(\text{optical path difference})$$

Sinusoidal Interference Fringes

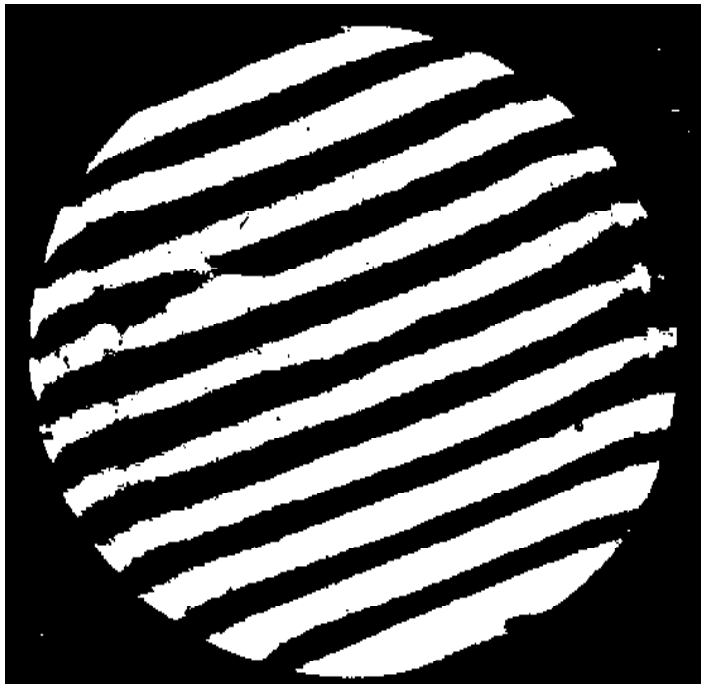


$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\alpha_1 - \alpha_2\right)$$

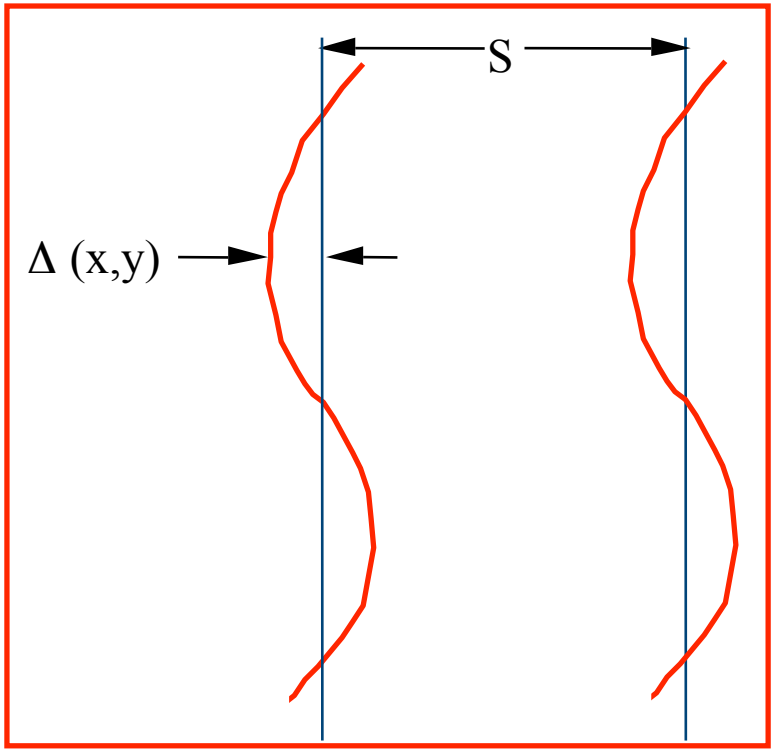
Pioneer Fizeau Interferometer - 1862



Typical Interferogram Obtained using Fizeau Interferometer

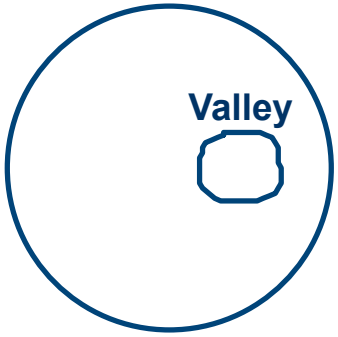


Relationship between Surface Height Error and Fringe Deviation

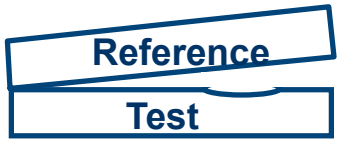


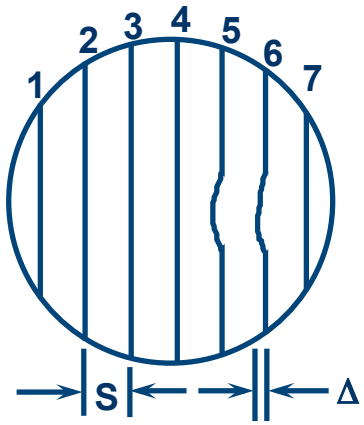
$$\text{Surface height error} = \left(\frac{\lambda}{2}\right)\left(\frac{\Delta}{S}\right)$$

Fizeau Fringes



Top View

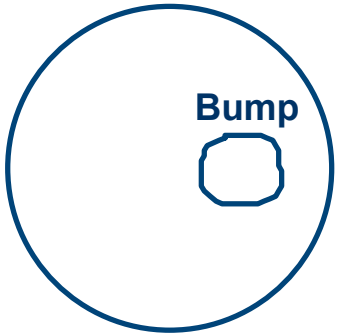




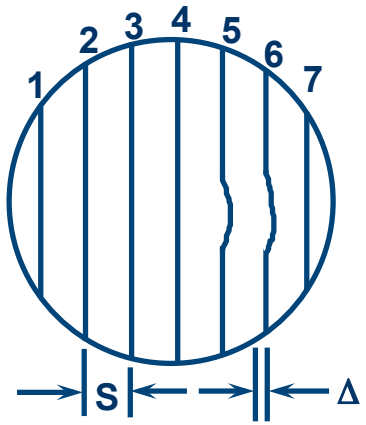
Interferogram

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

Height error = (λ/2)(Δ/S)



Top View



Interferogram

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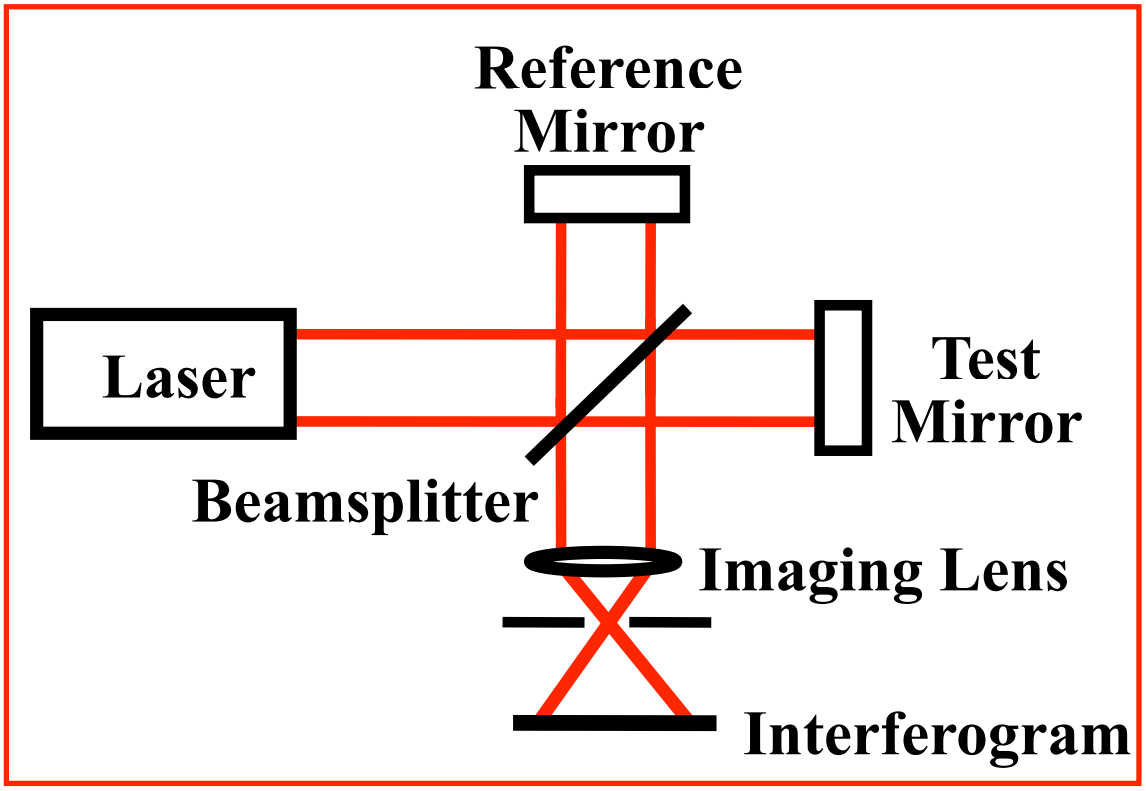
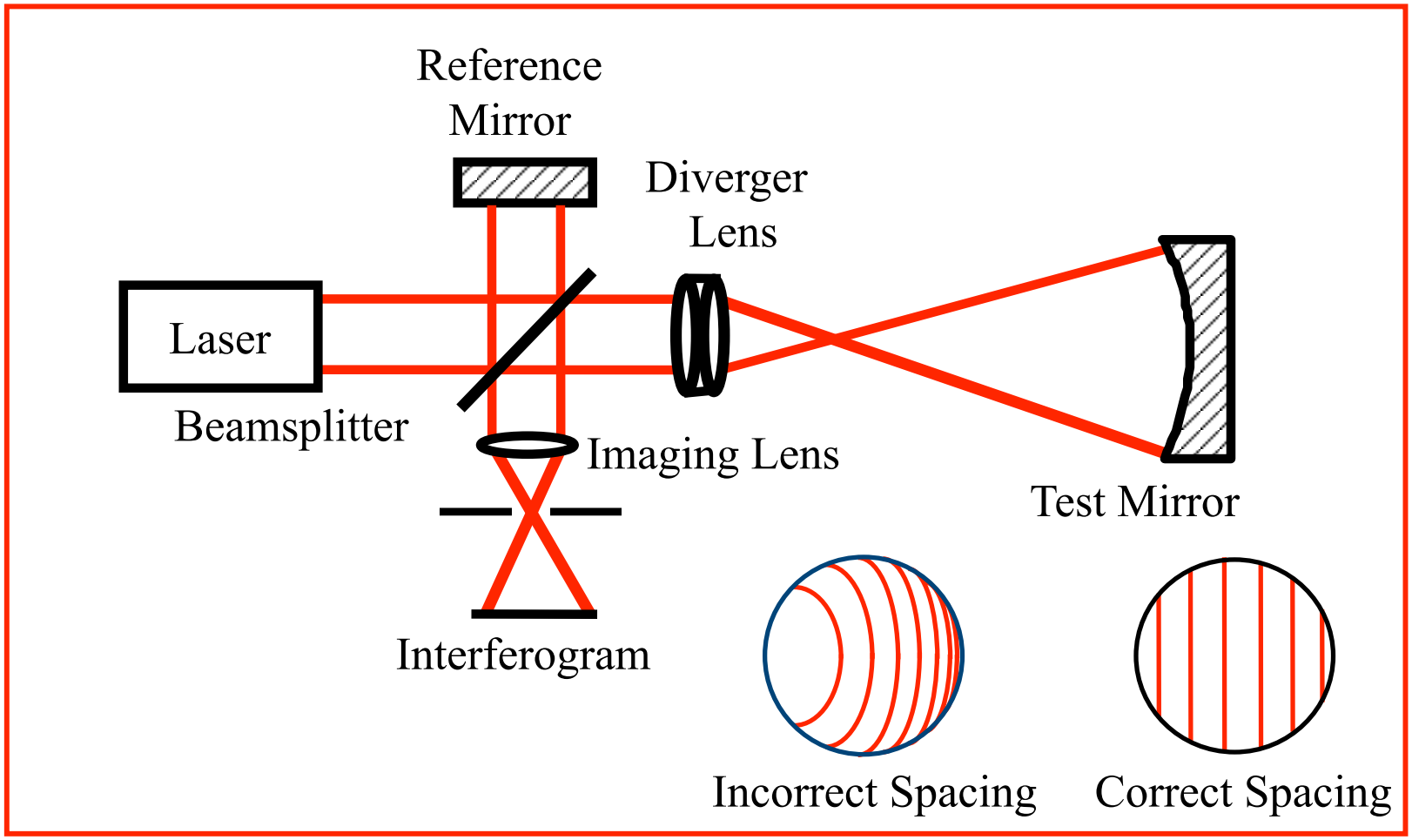
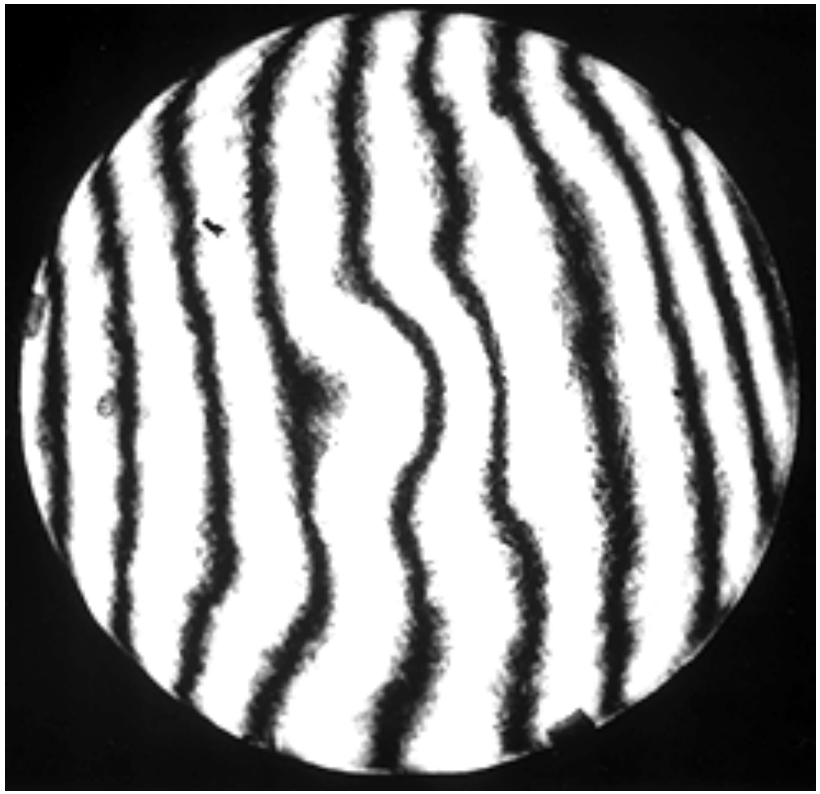
Twyman-Green Interferometer (Flat Surfaces)



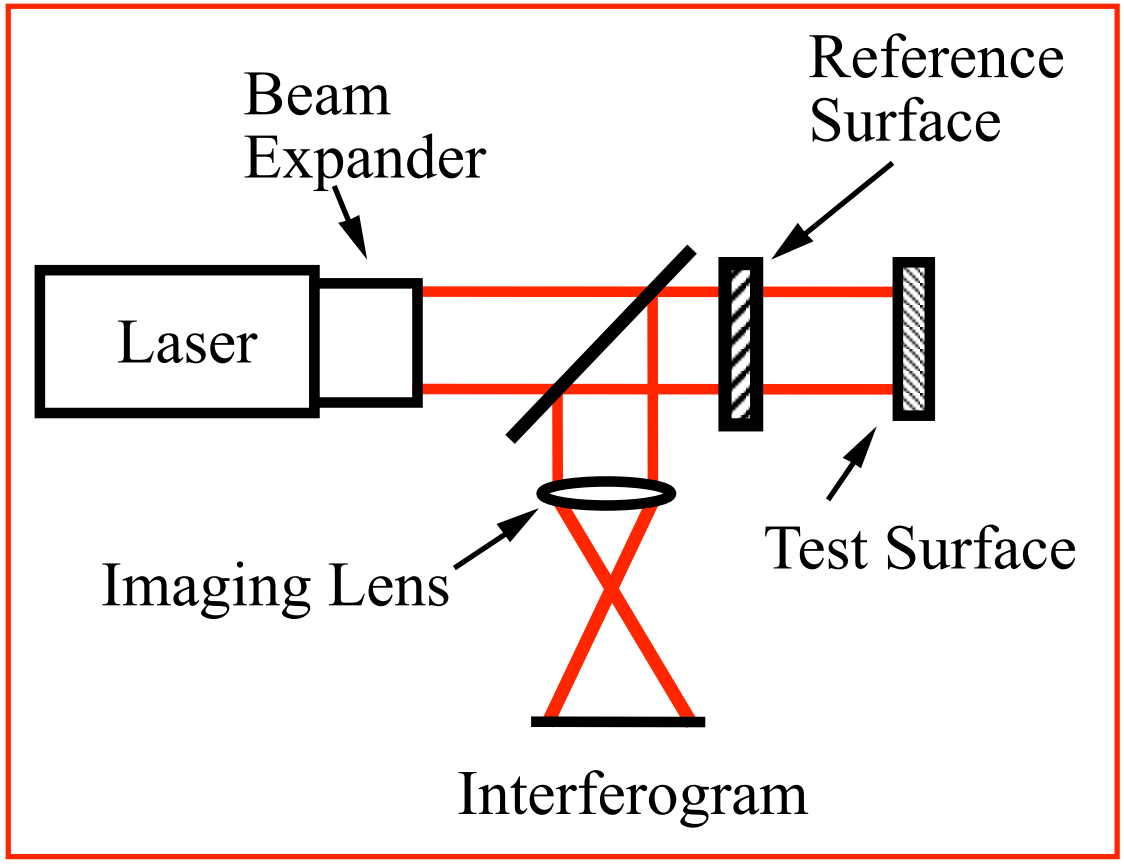
Twyman-Green Interferometer (Spherical Surfaces)



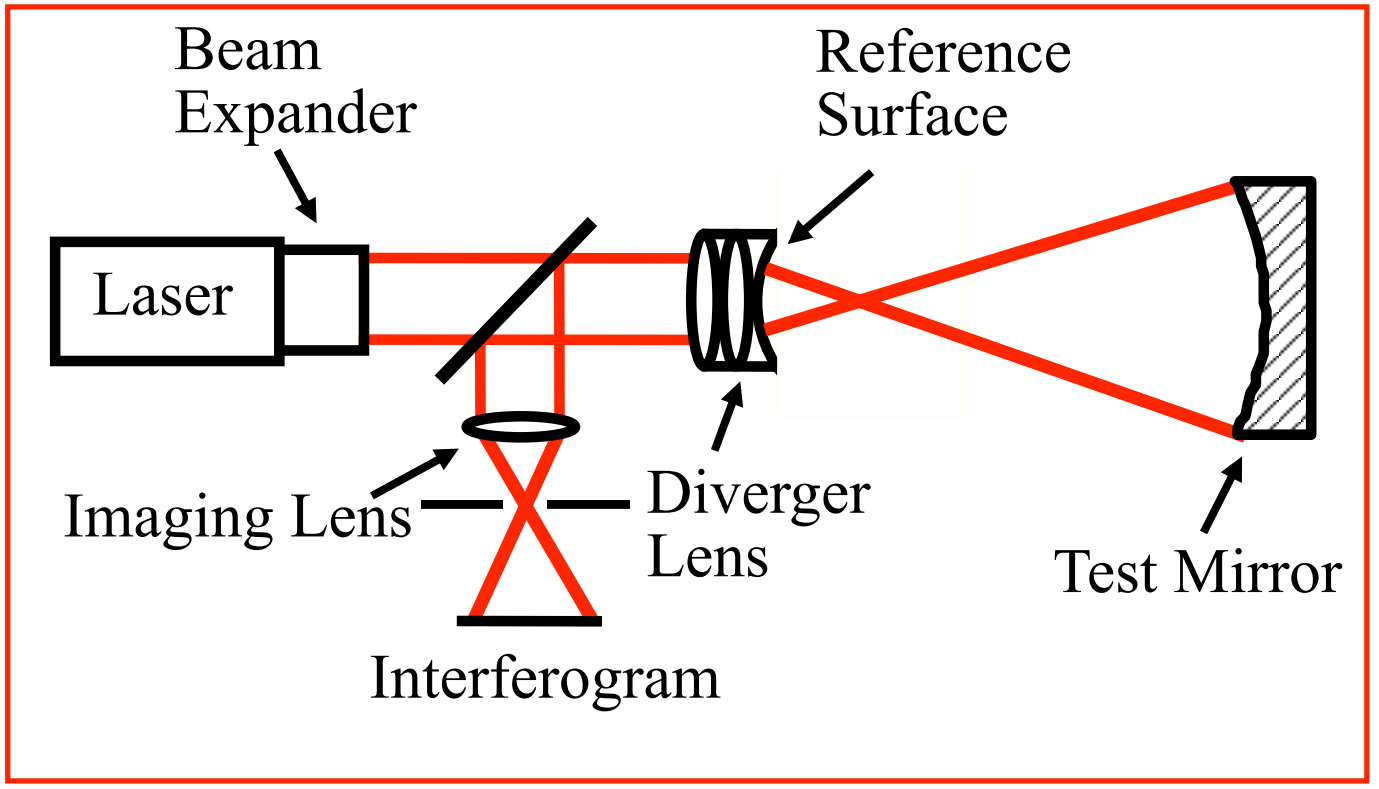
Typical Interferogram



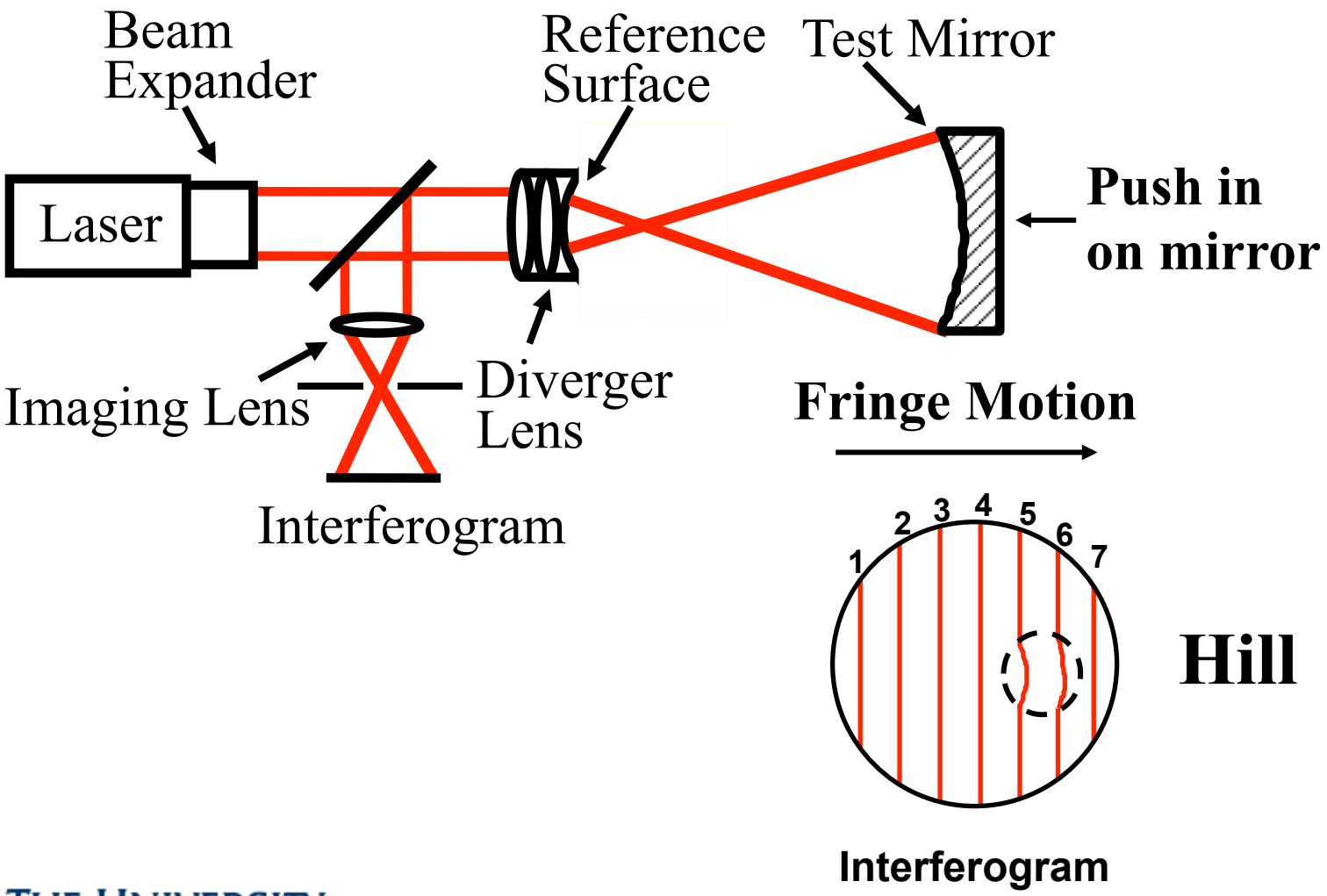
Fizeau Interferometer-Laser Source (Flat Surfaces)



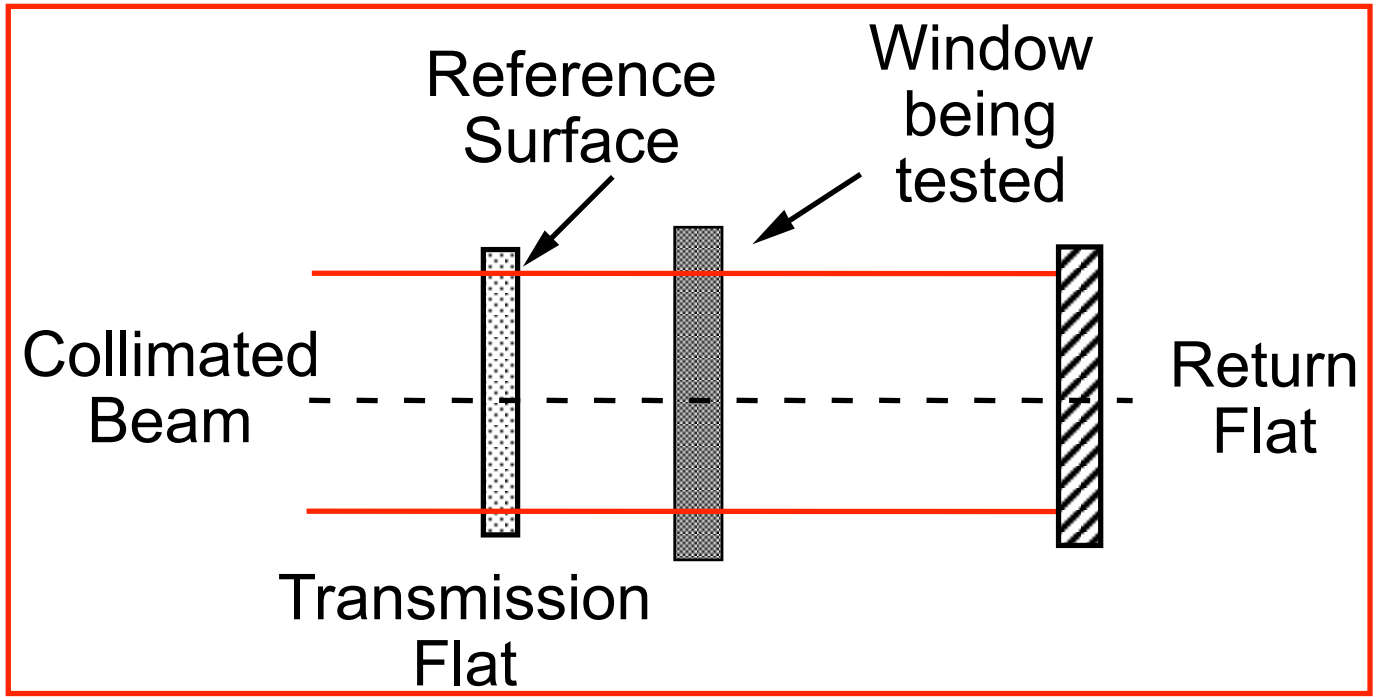
Fizeau Interferometer-Laser Source (Spherical Surfaces)



Hill or Valley?



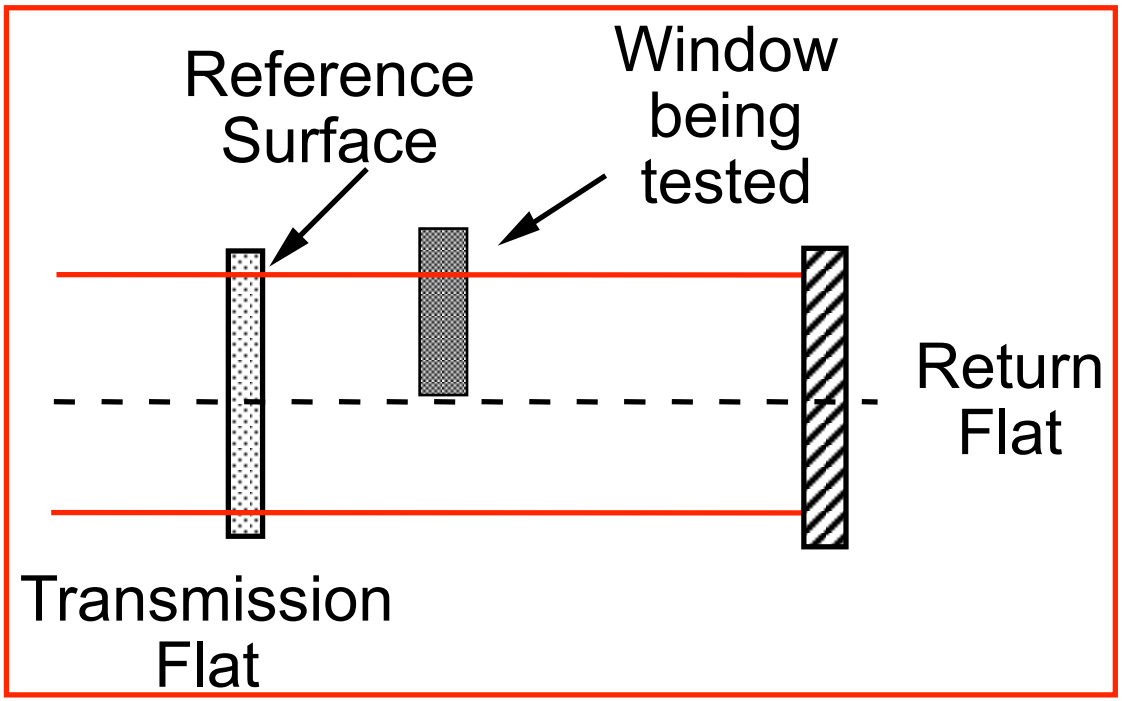
Testing Windows in Transmission



δt = window thickness variations

OPD measured = 2 (n-1) δt

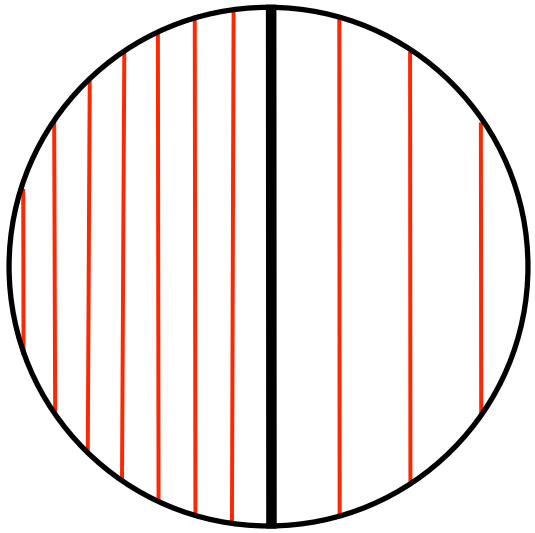
Measuring Window Wedge



Tilt difference between two interferograms gives window wedge.

Calculating Window Wedge

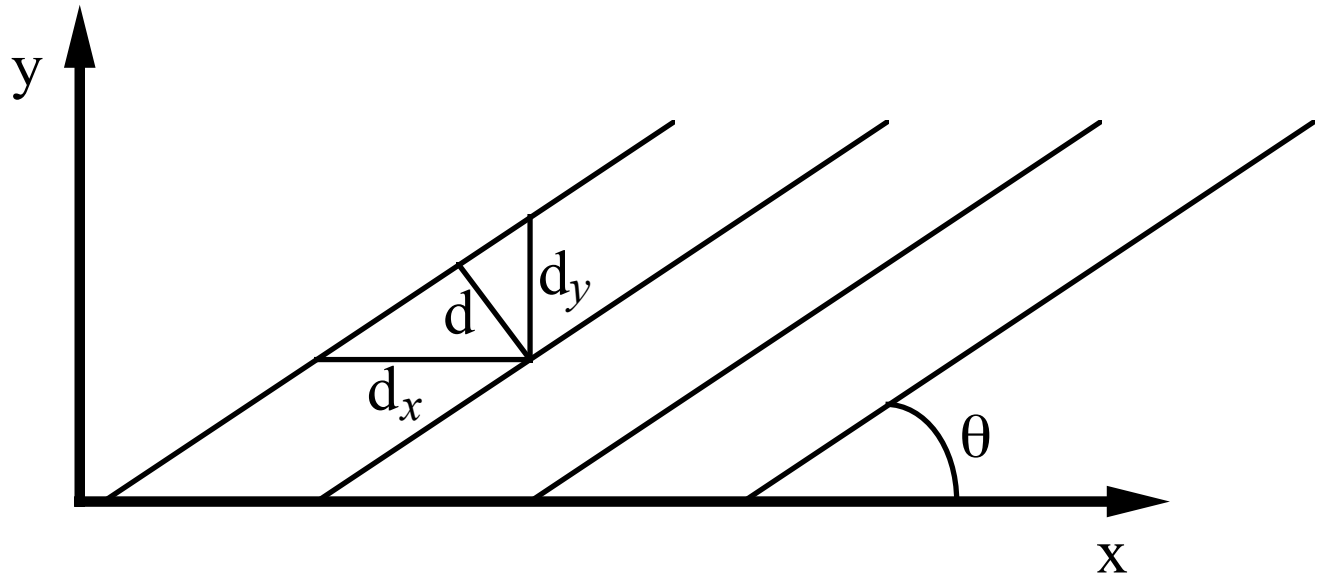
Tilt difference between two interferograms gives window wedge.



α = window wedge

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

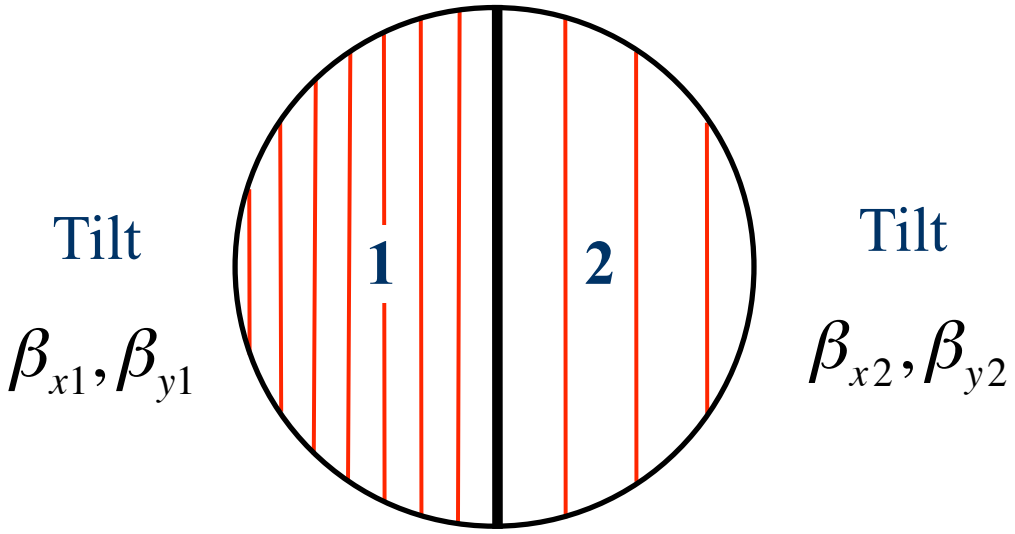
Calculation of Tilt



$d =$ fringe spacing $\quad d_x = d / \sin(\theta) \quad d_y = d / \cos(\theta)$

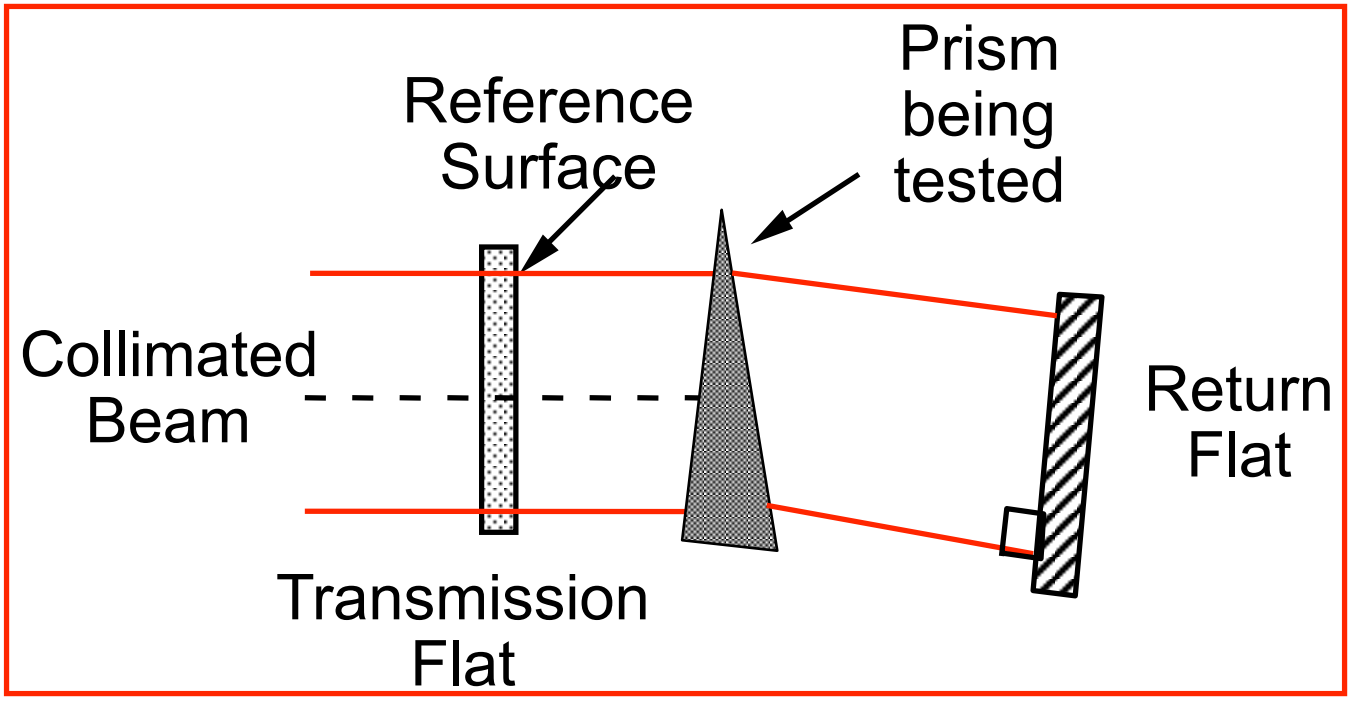
$$\beta = Tilt = \frac{\lambda}{d} \qquad \beta_x = \frac{\lambda}{d_x} \qquad \beta_y = \frac{\lambda}{d_y}$$

Calculation of Tilt Difference



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

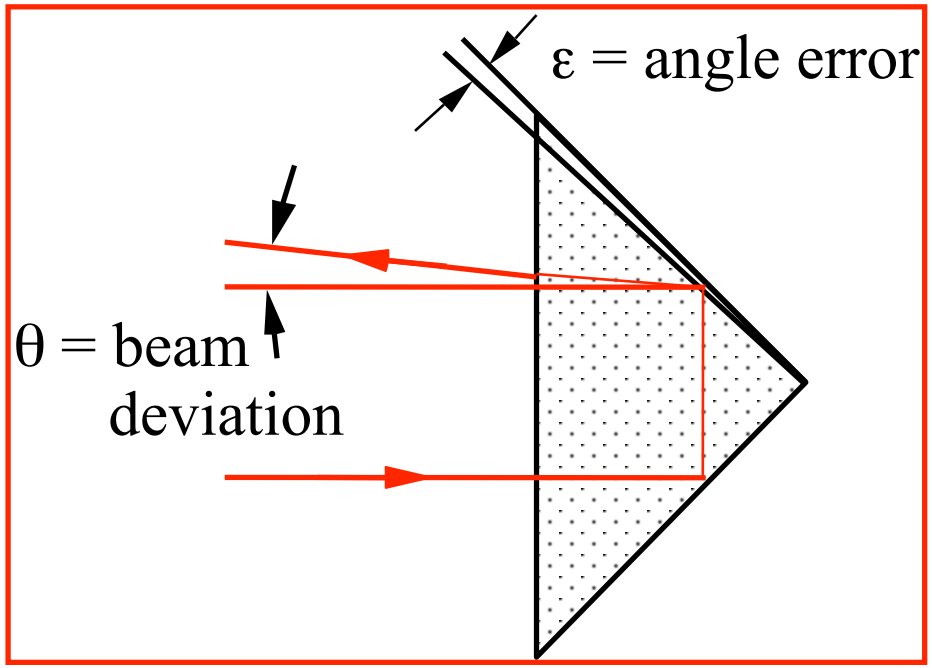
Testing Prisms in Transmission



δt = error in prism thickness

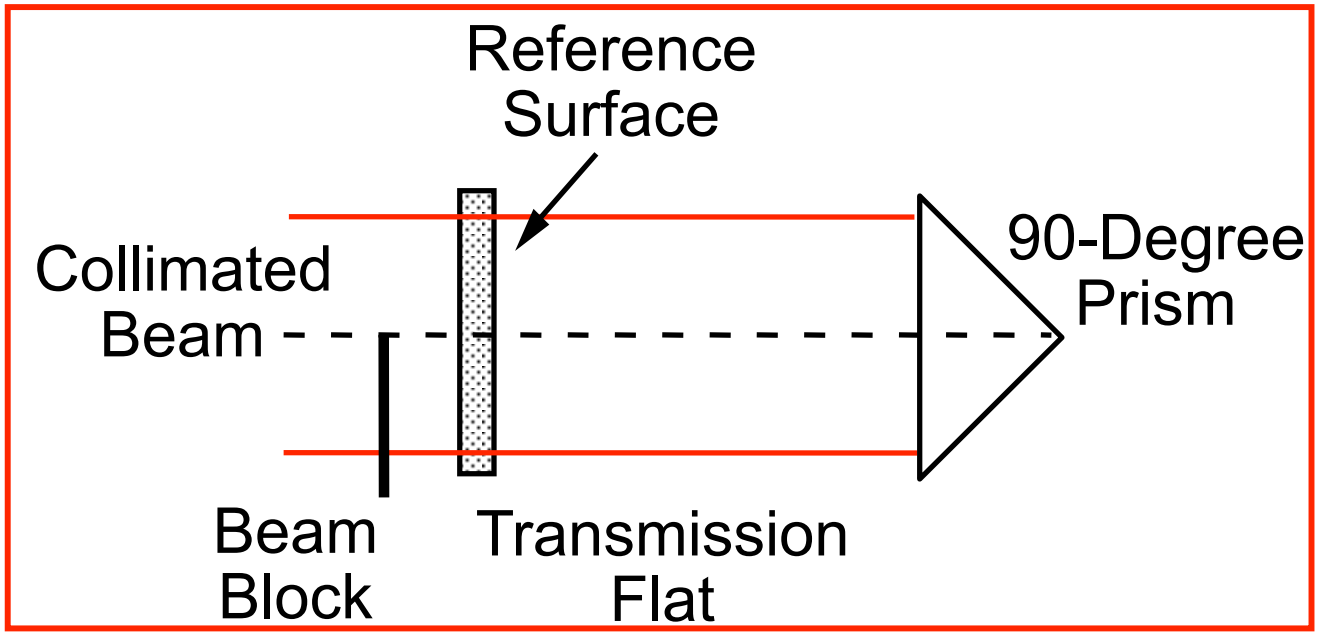
OPD measured = 2 (n-1) δt

Angle Accuracy of 90-Degree Prisms



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

Testing 90-Degree Prisms (Double Pass)

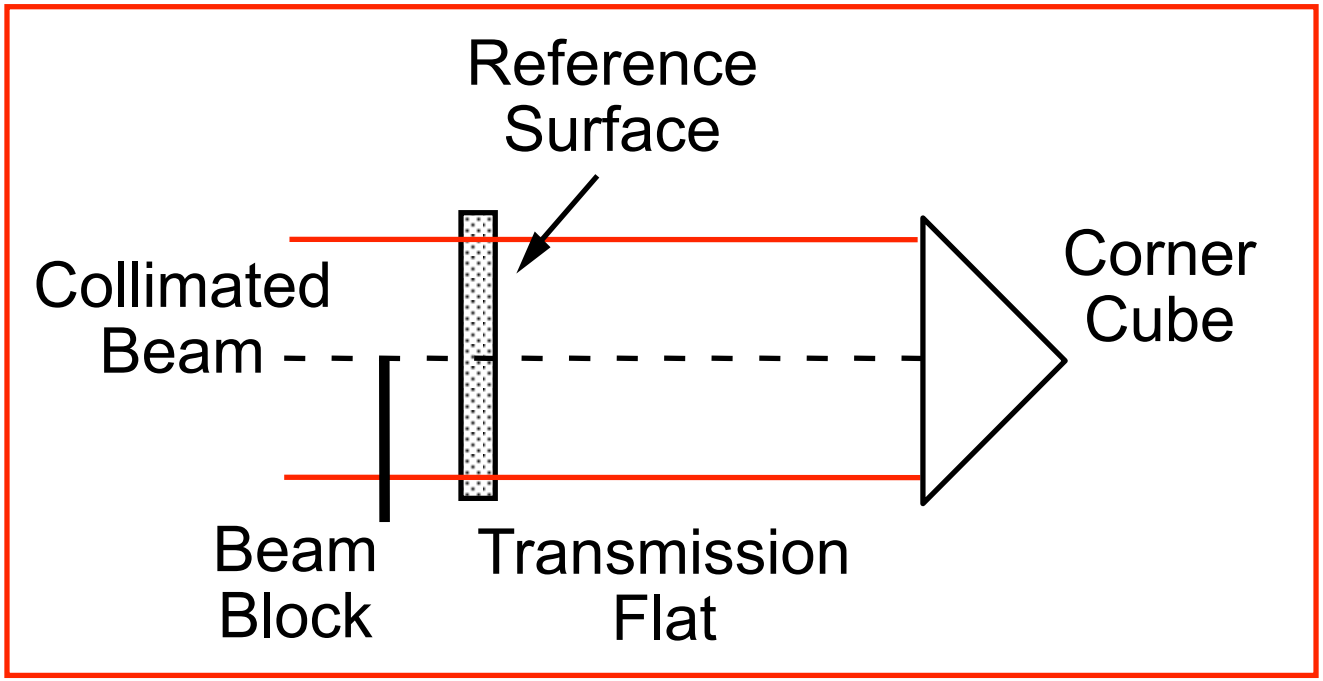


$$\varepsilon = \frac{\text{x tilt in interferogram}}{4n}$$

ε = prism angle error

Errors in collimated beam cancel.

Testing Corner Cubes (Double Pass)

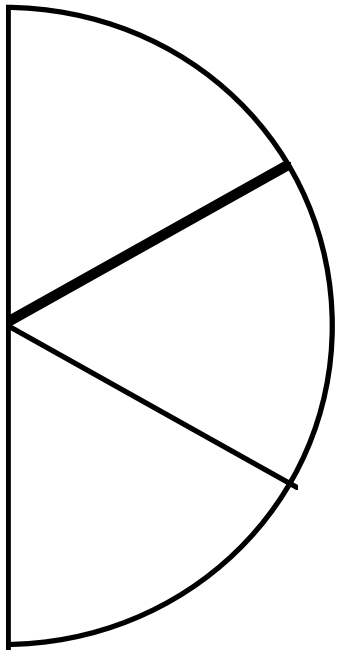


Errors in collimated beam cancel.

Interferogram for Perfect Corner Cube (Double Pass)

3 interferograms obtained

One fringe covers the entire interferogram

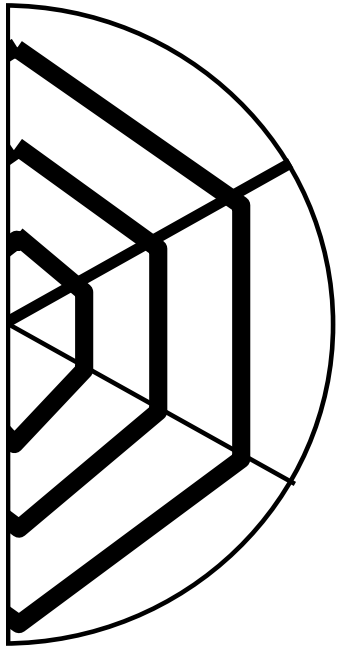


Analyzing Corner Cube Interferograms (Double Pass)

3 interferograms obtained.

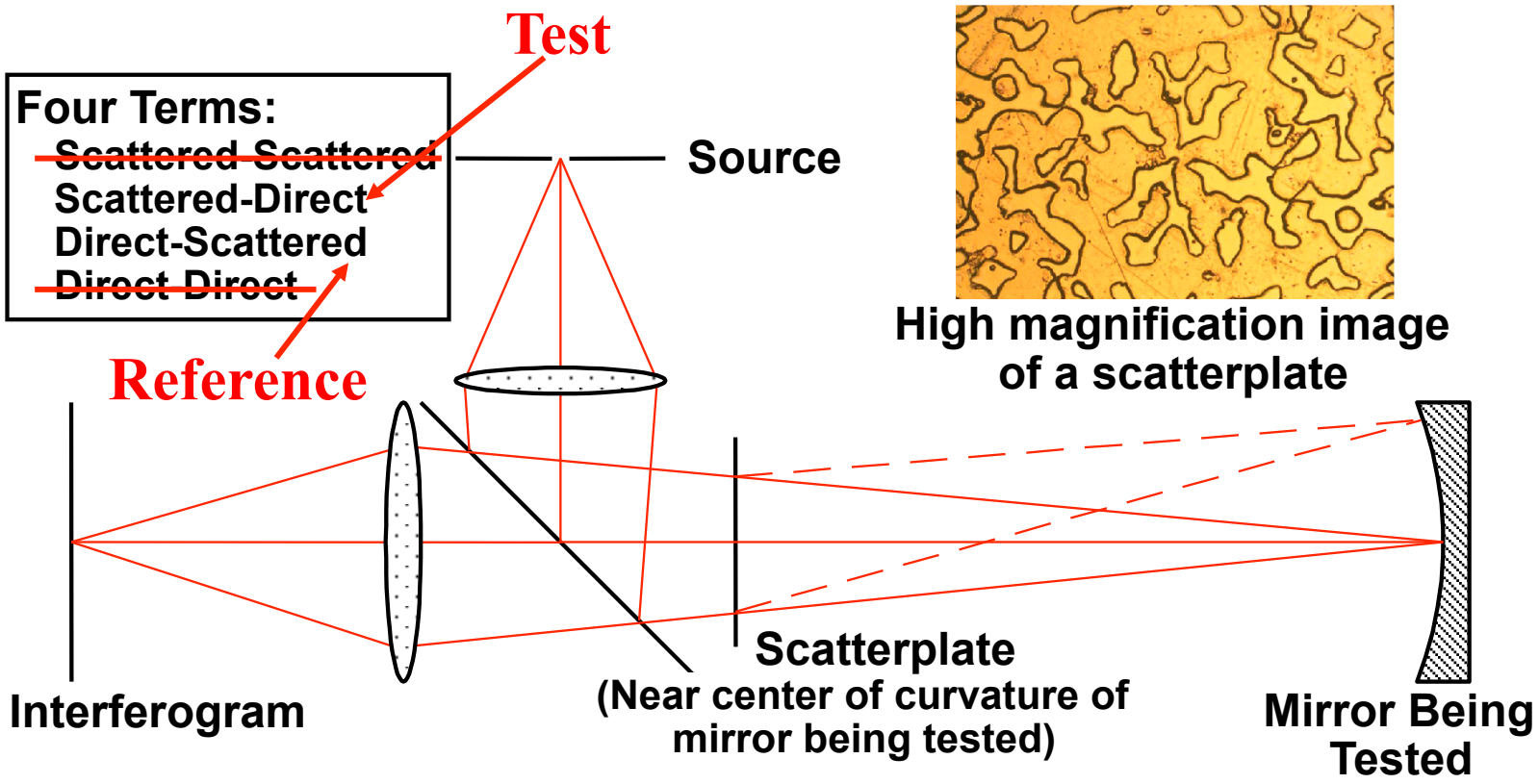
Tilt of each interferogram gives one angle error in corner cube.

n is refractive index of corner cube.



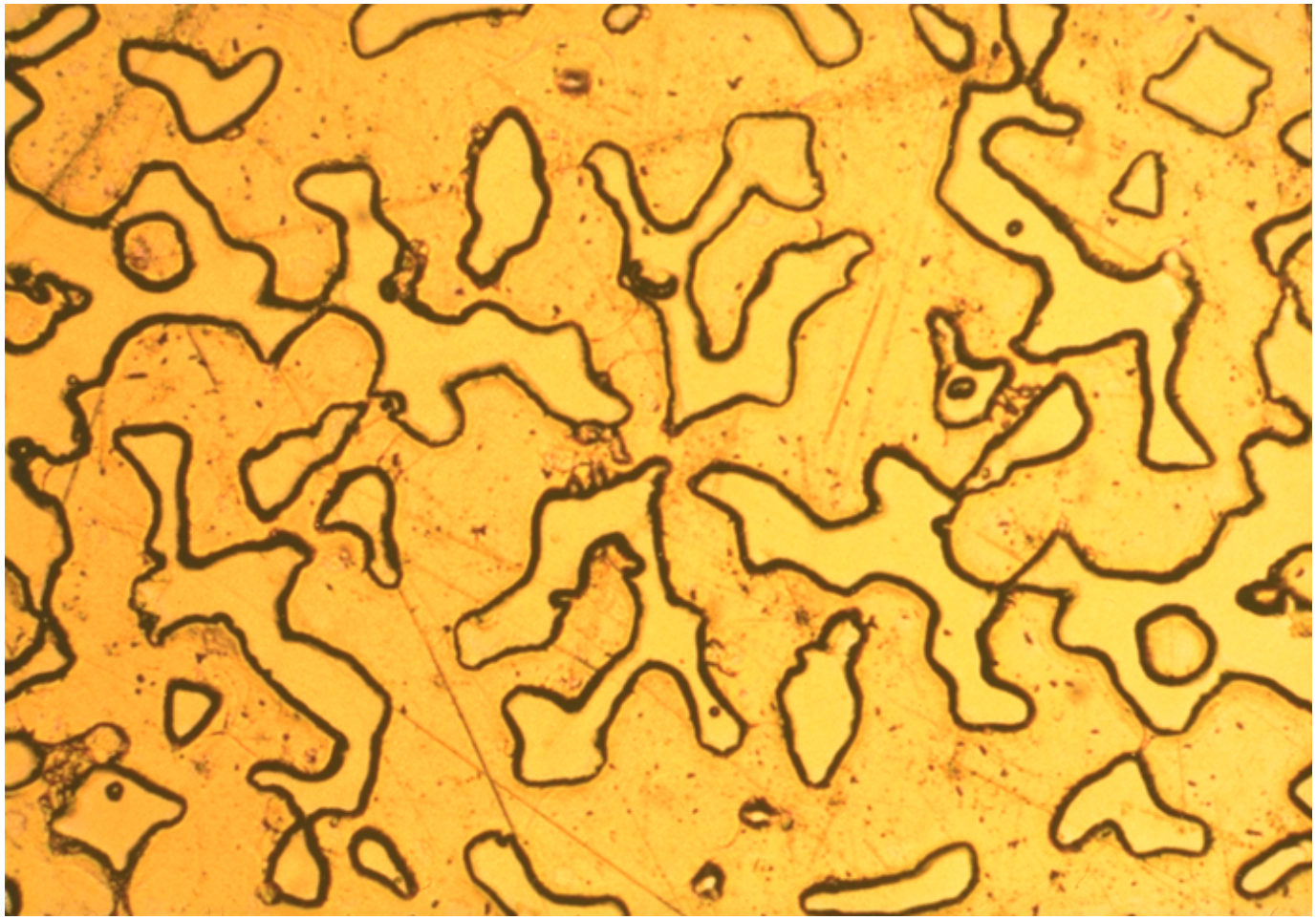
Error = Tilt/(3.266 n)

Scatterplate Interferometer

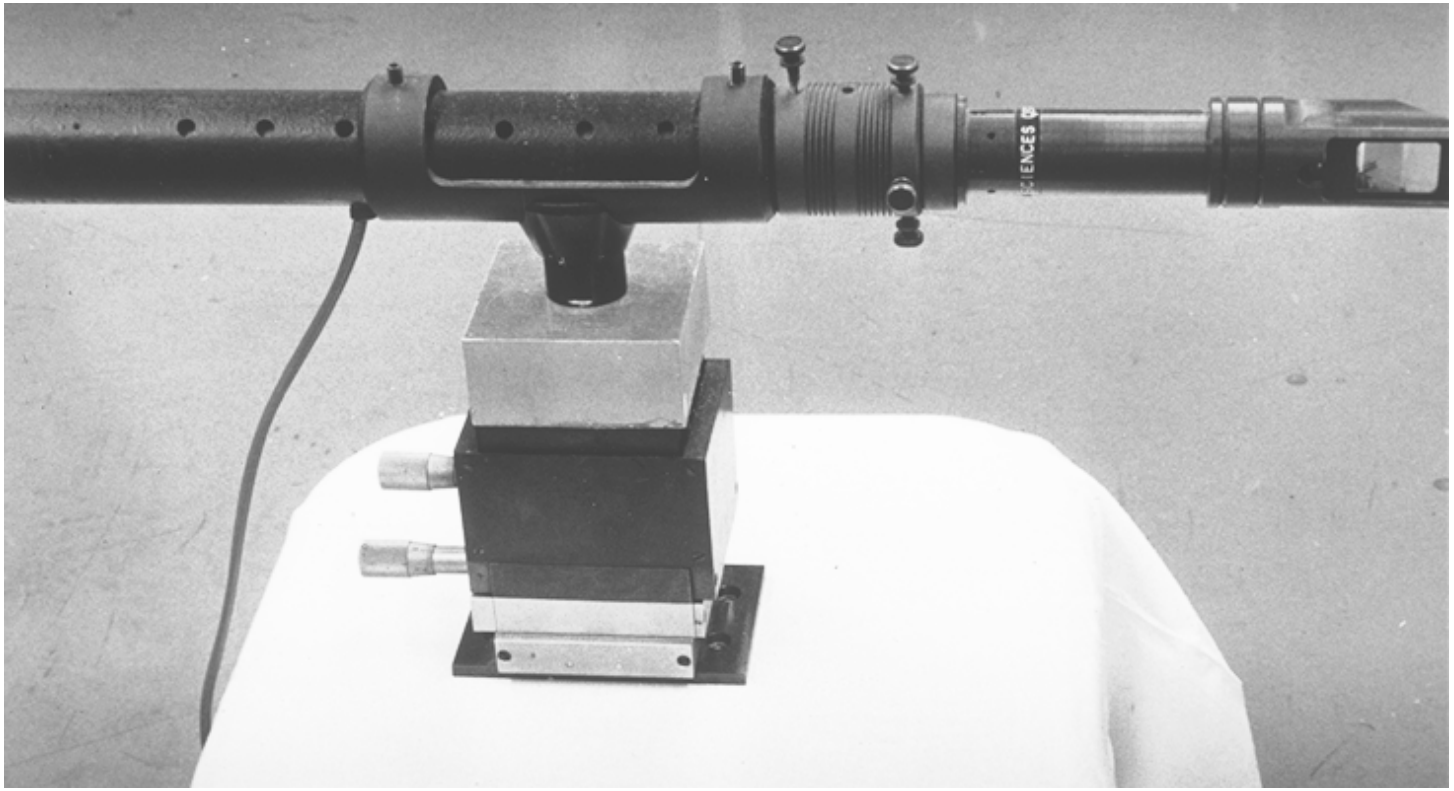


- Scatterplate has inversion symmetry
- Scatterplate is located at center of curvature of test mirror
- Direct-scattered and scattered-direct beams produce fringes

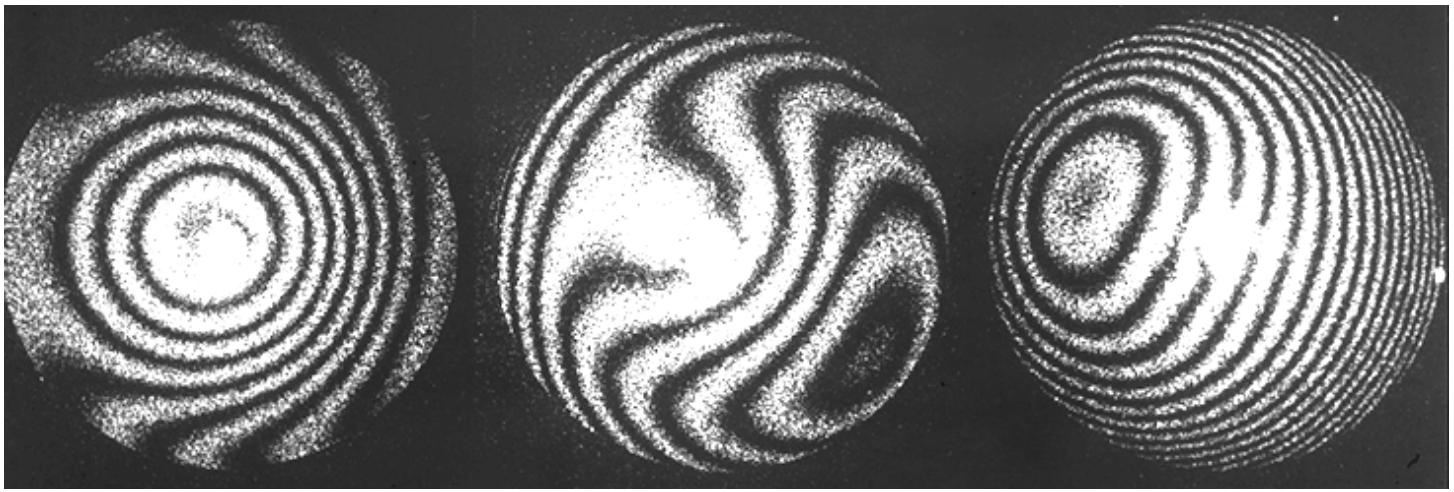
Microscopic Image of Scatterplate



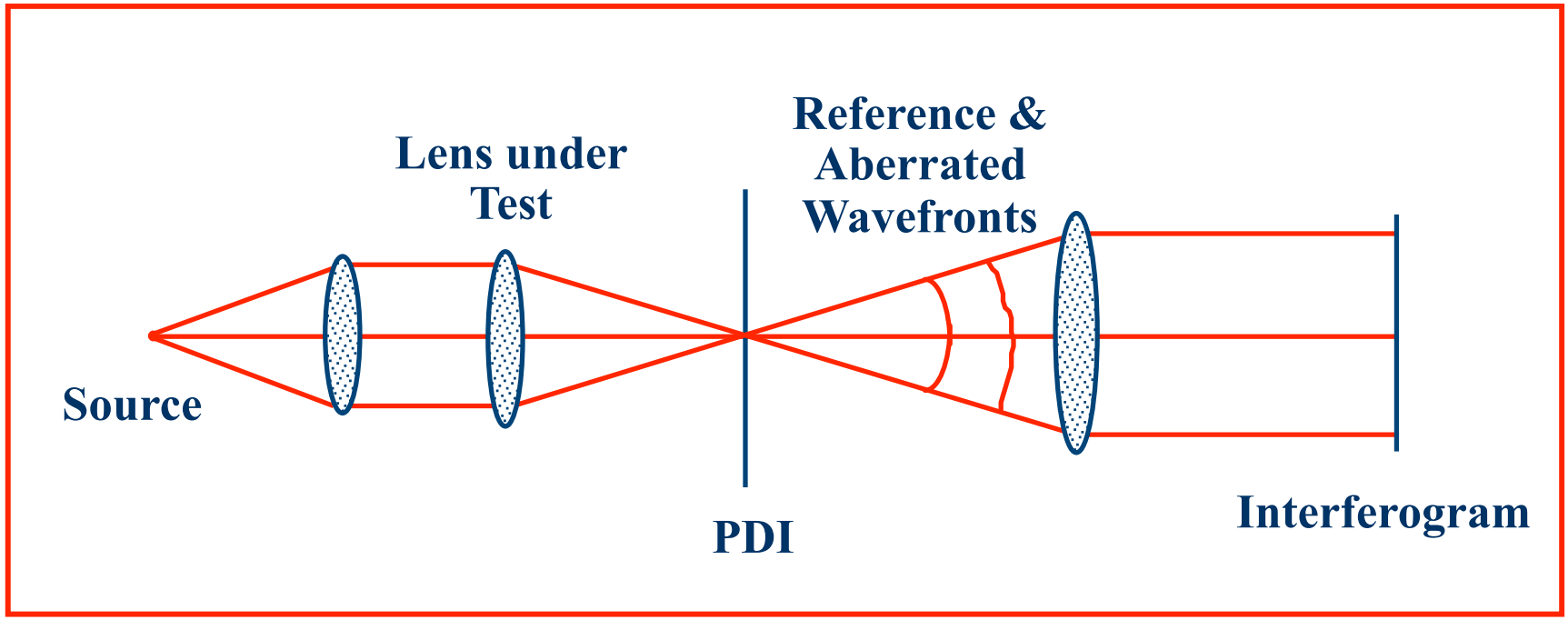
Scatterplate Interferometer



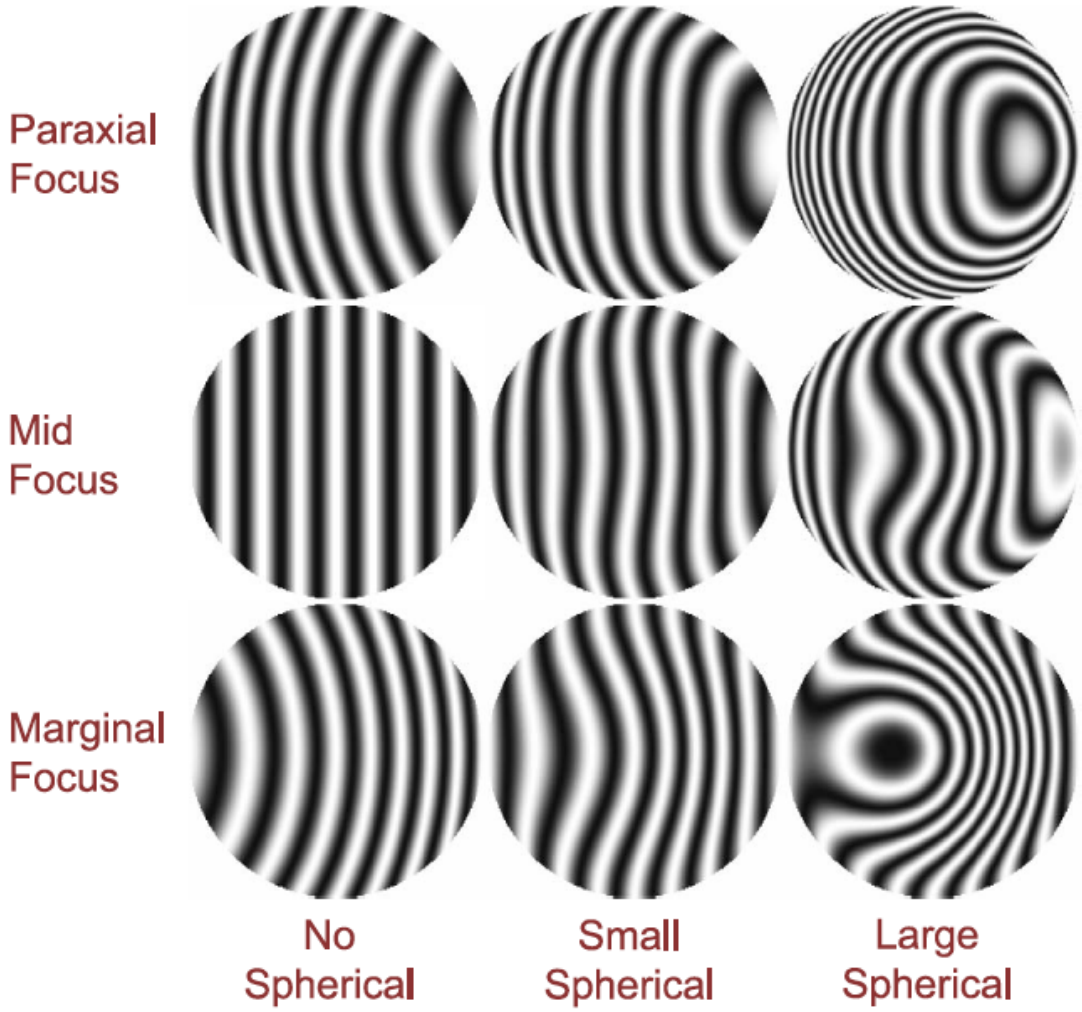
Scatterplate Interferograms



Smartt Point Diffraction Interferometer



Interferograms
Spherical Aberration



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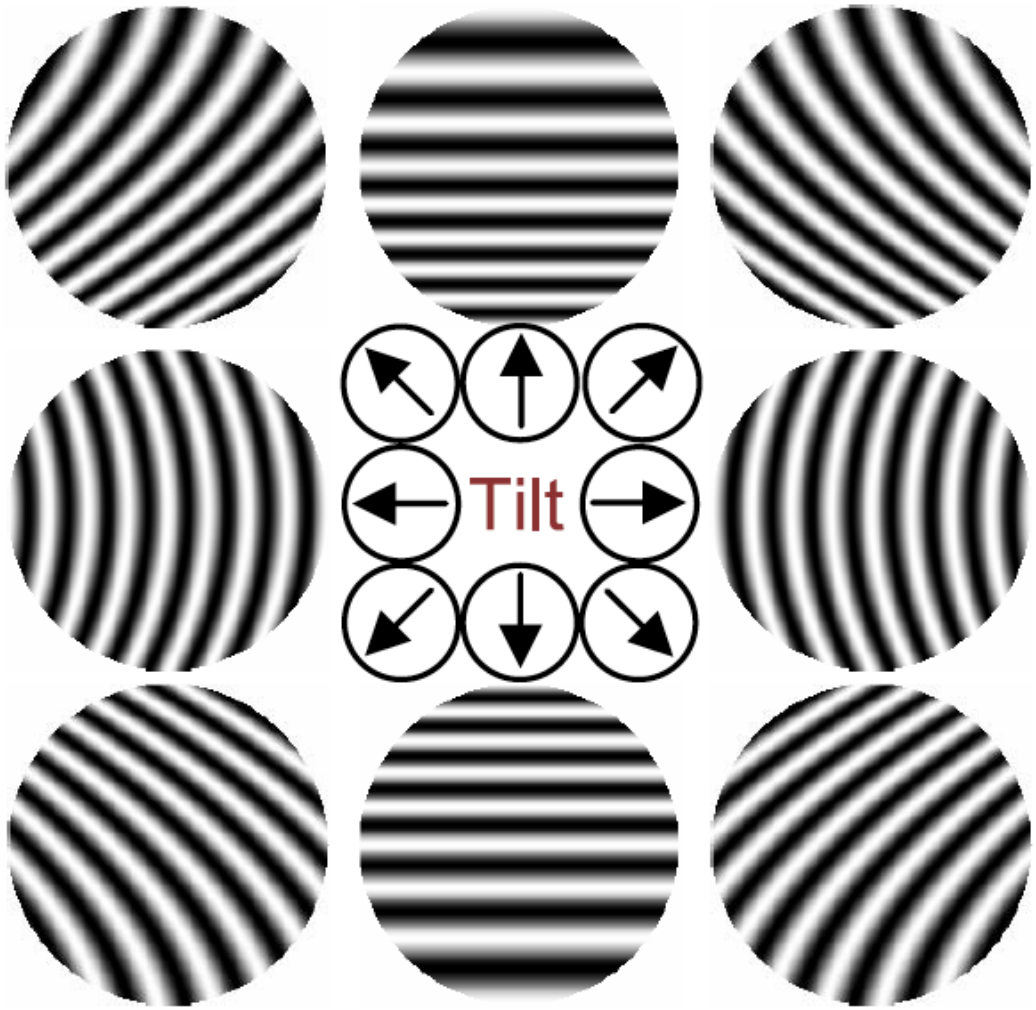
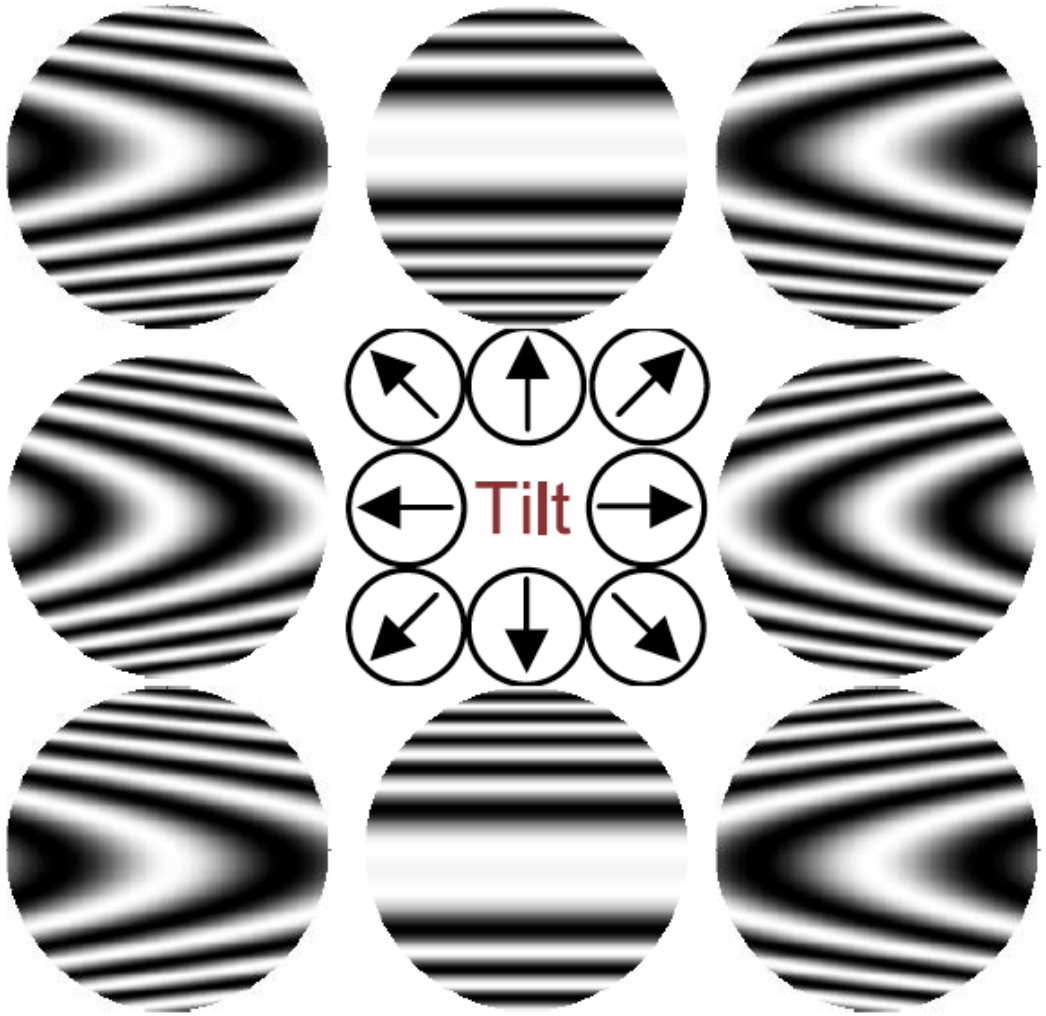
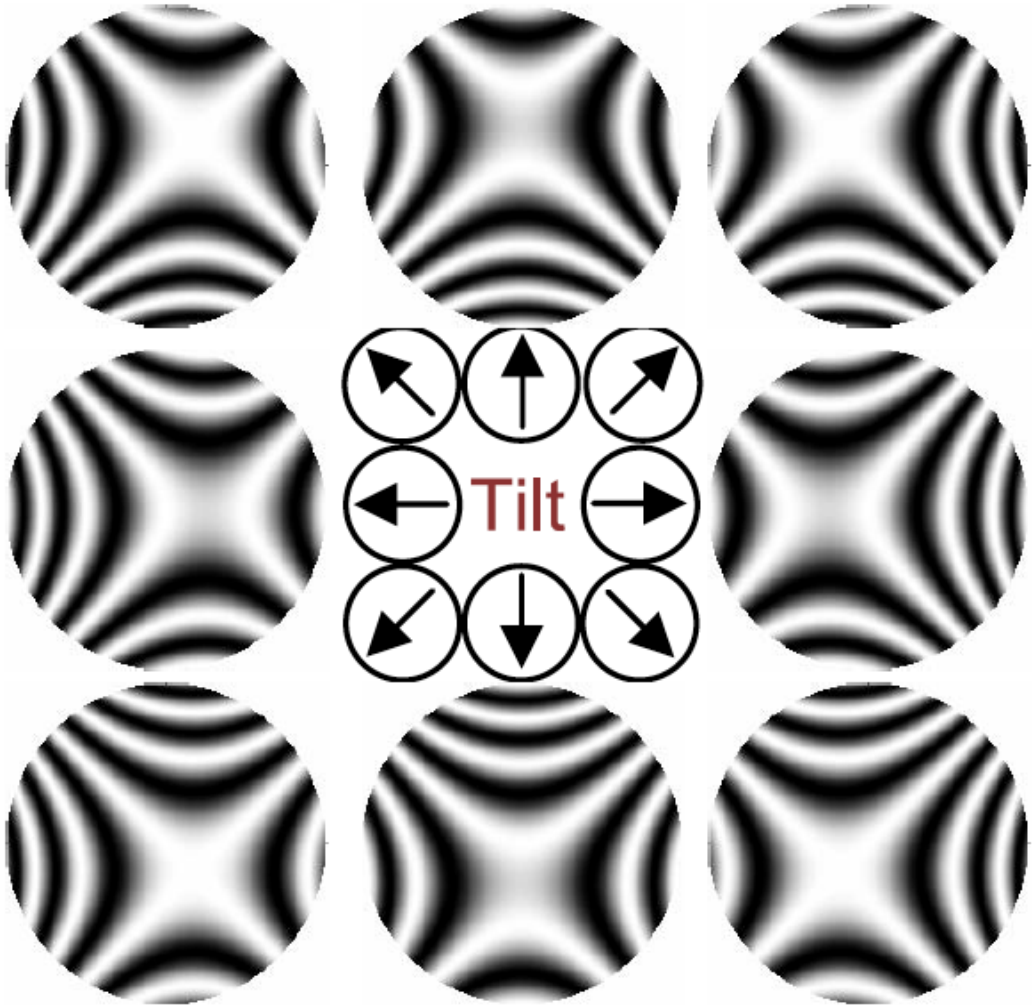
Interferograms
Small Astigmatism, Sagittal Focus



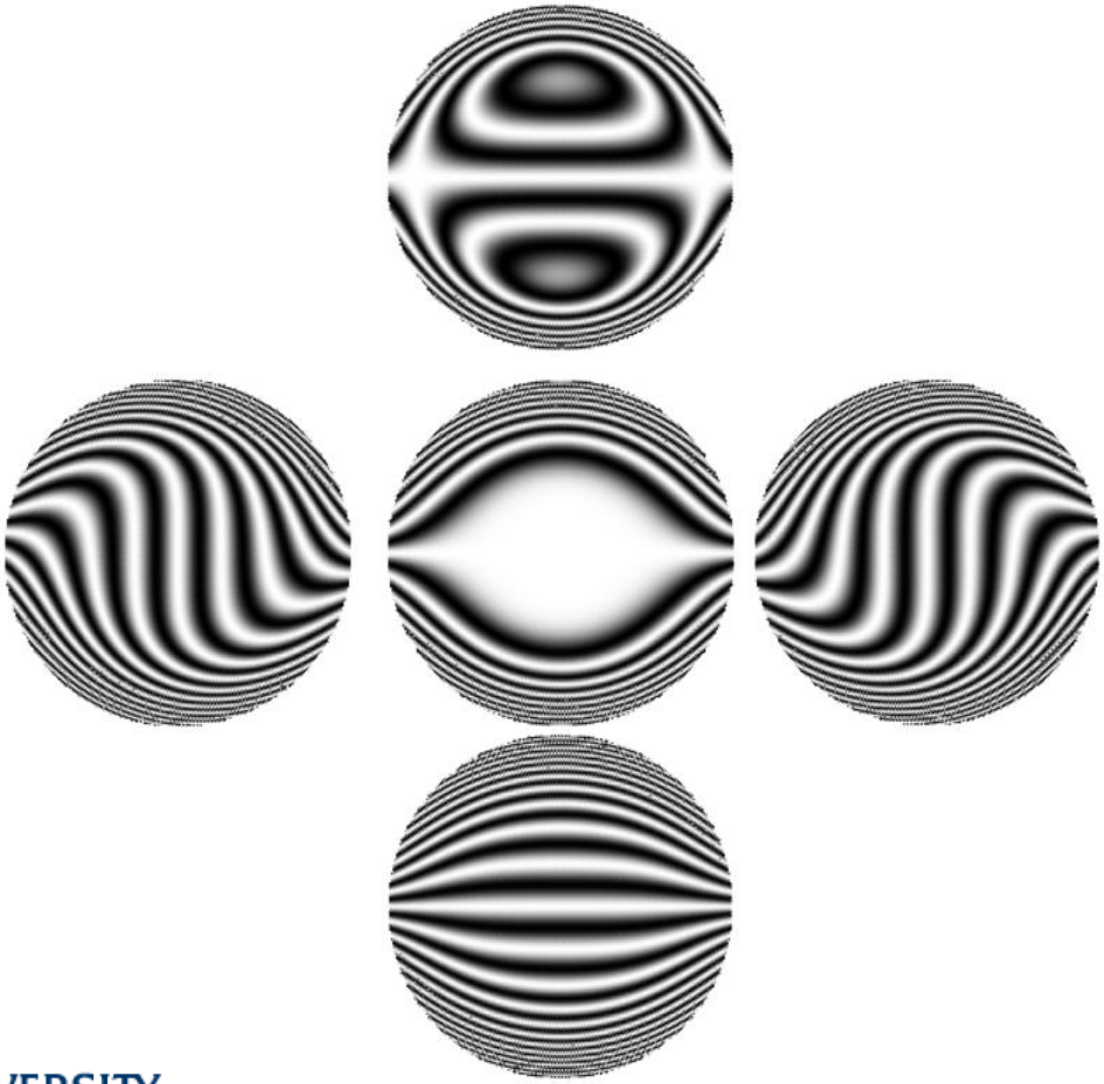
Interferograms
Large Astigmatism, Sagittal Focus



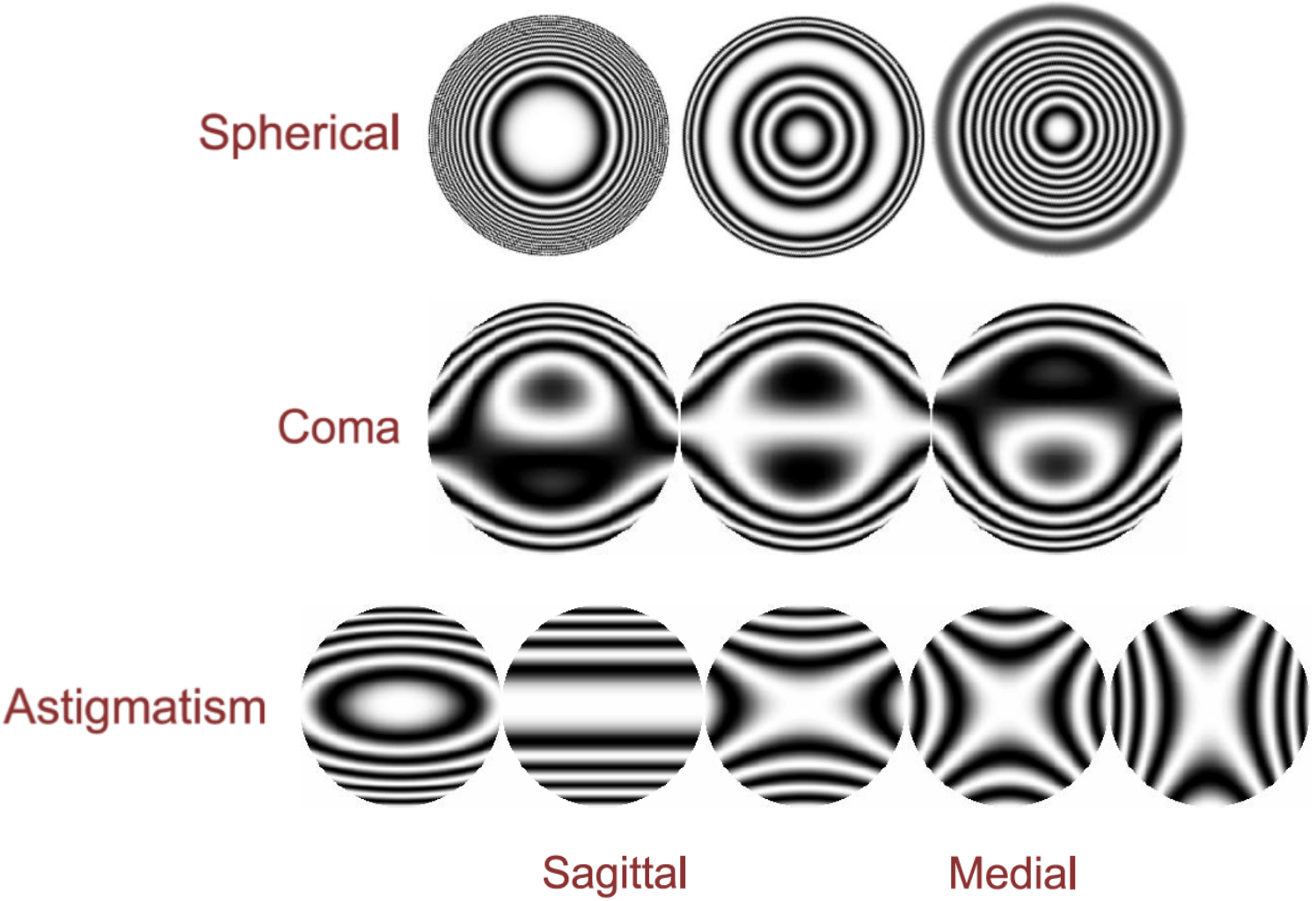
Interferograms
Large Astigmatism, Medial Focus



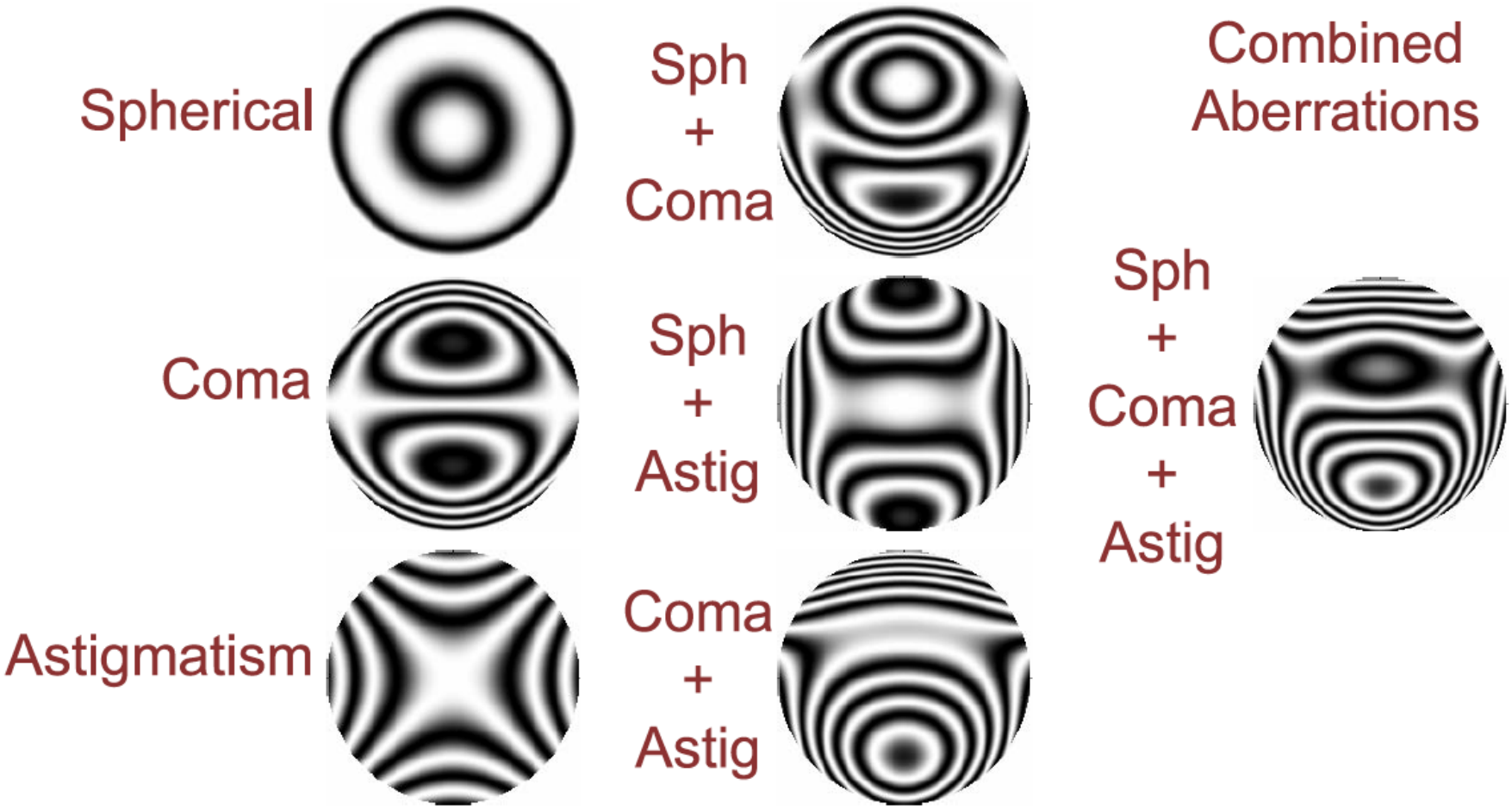
Interferograms
Large Coma, Varying Tilt



Interferograms
Changing Focus



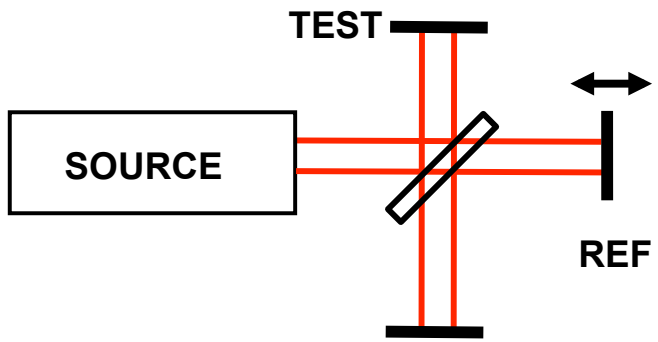
Interferograms
Combined Aberrations



Part 2
Phase-Shifting Interferometry

- Basic algorithms
- Removing phase ambiguities
- Simultaneous Phase-Measurement Interferometers

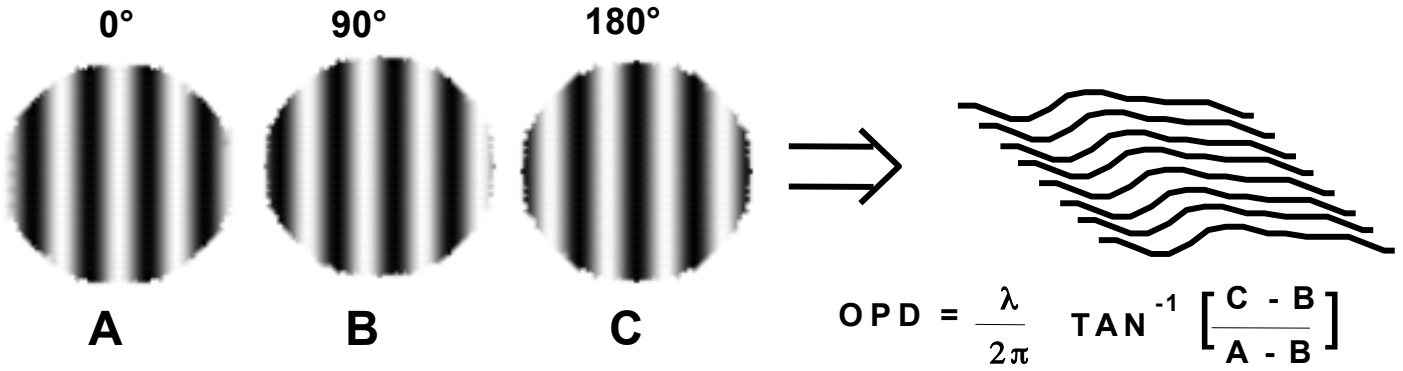
Phase-Shifting Interferometry



1) MODULATE PHASE

2) RECORD MIN 3 FRAMES

3) CALCULATE OPD

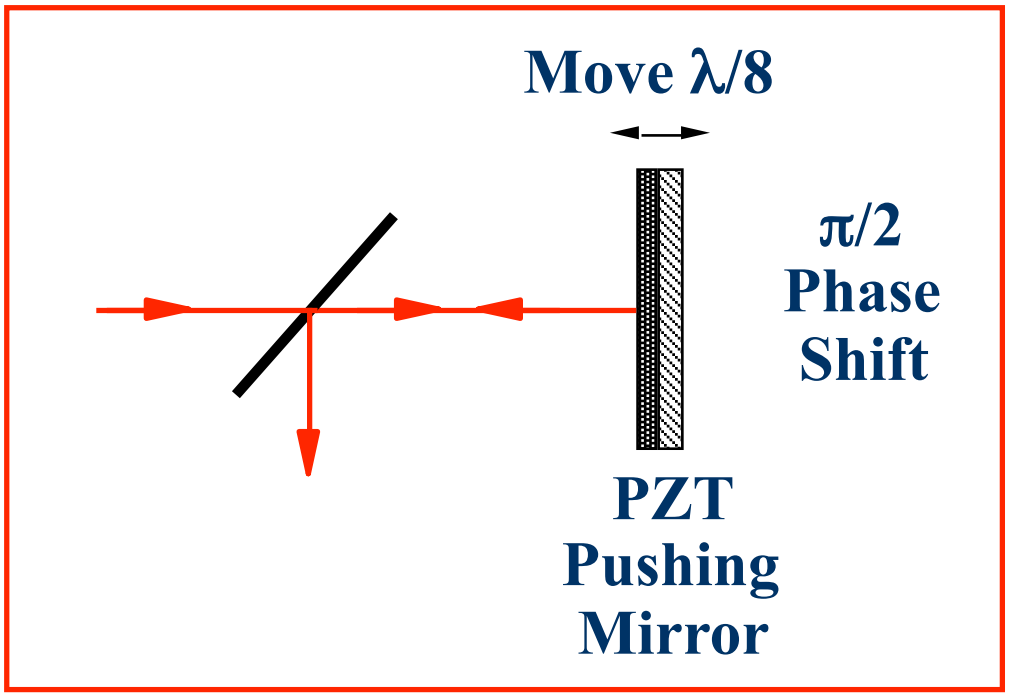


$$OPD = \frac{\lambda}{2\pi} \, TAN^{-1}\left[\frac{C - B}{A - B}\right]$$

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



Four-Step Method

phase shift

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

measured object phase

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

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

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

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

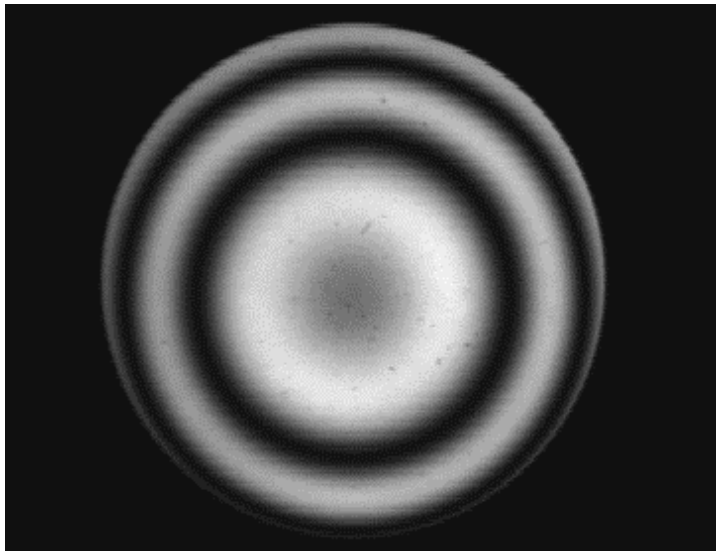
Schwider-Hariharan Five Measurements

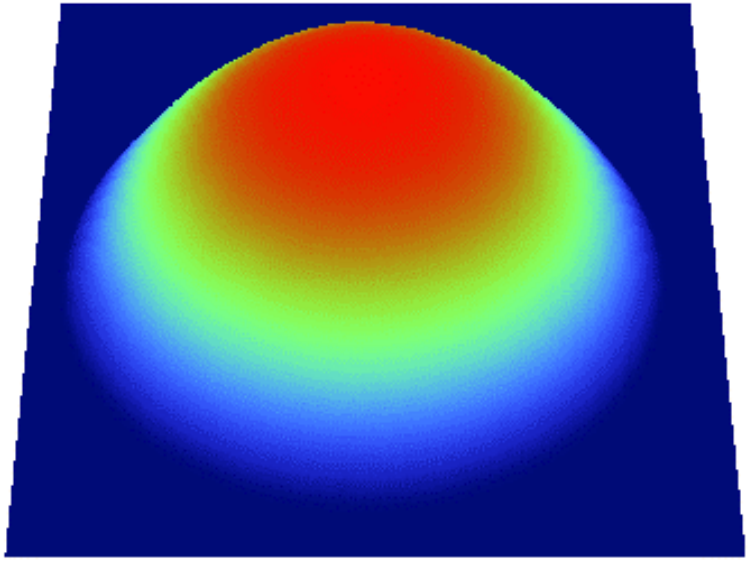
$$\phi = ArcTan\left[\frac{2(I_4 - I_2)}{I_1 - 2I_3 + I_5}\right]$$

Carré Equation

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

Typical Fringes
For Spherical Surfaces



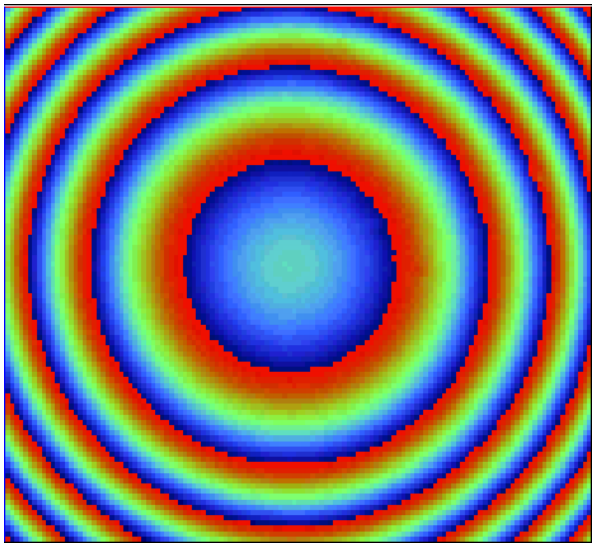


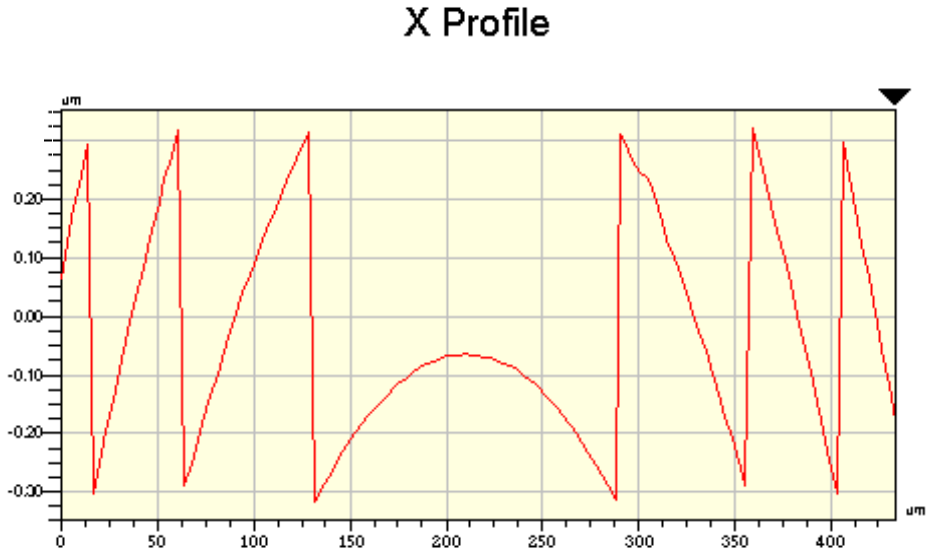
Fringes

Phase map

Phase Ambiguities - Before Unwrapping

2 π Phase Steps





Removing Phase Ambiguities

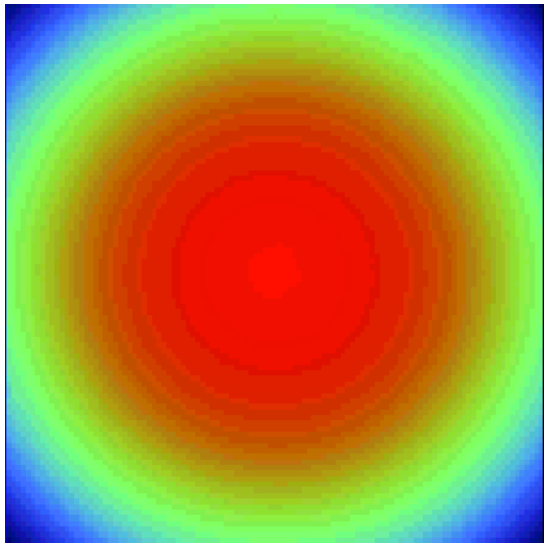
- Arctan Mod 2π (Mod 1 wave)
- Require adjacent pixels less than π difference (1/2 wave OPD)

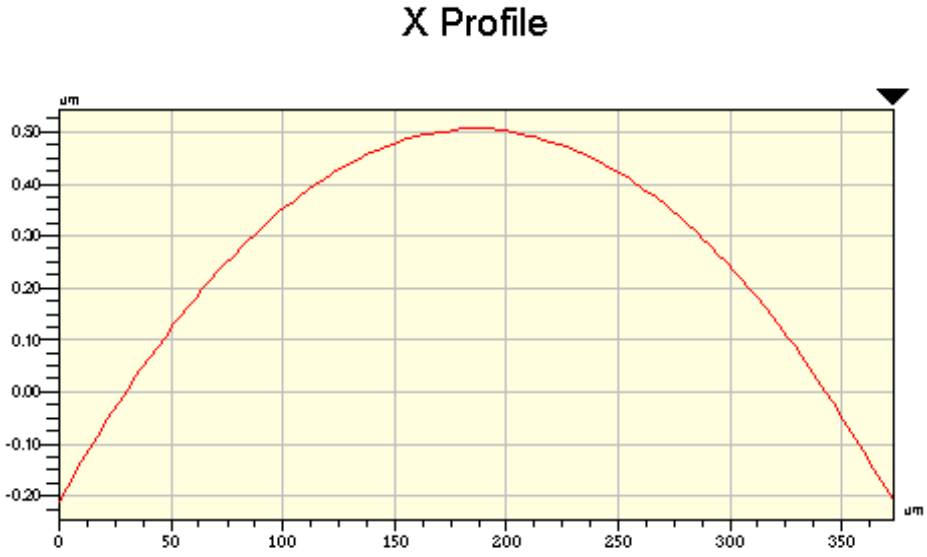
- Trace path
- When phase jumps by $>\pi$
  Add or subtract $N2\pi$

  Adjust so $<\pi$

Phase Ambiguities - After Unwrapping

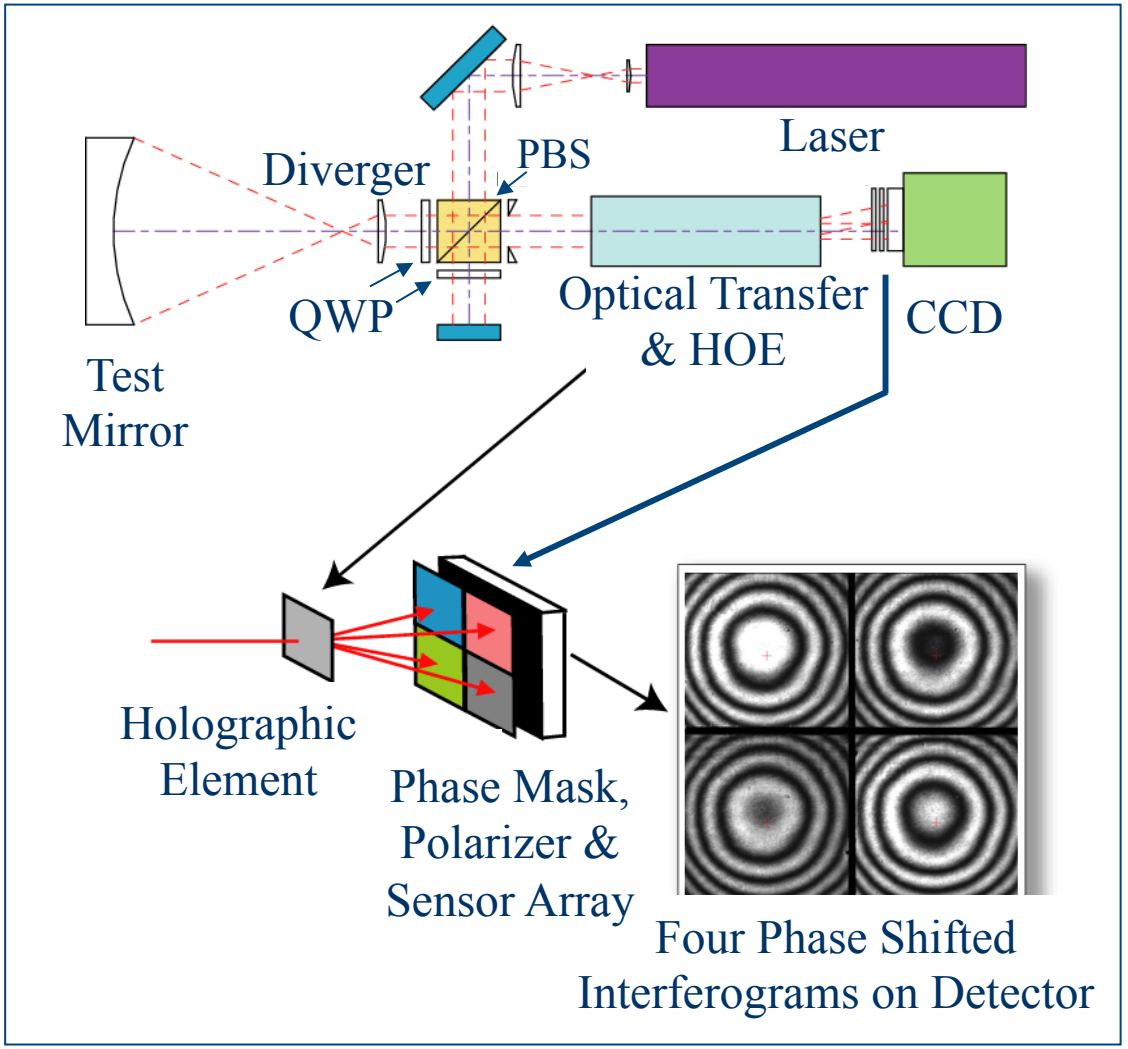
Phase Steps Removed





Simultaneous 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**



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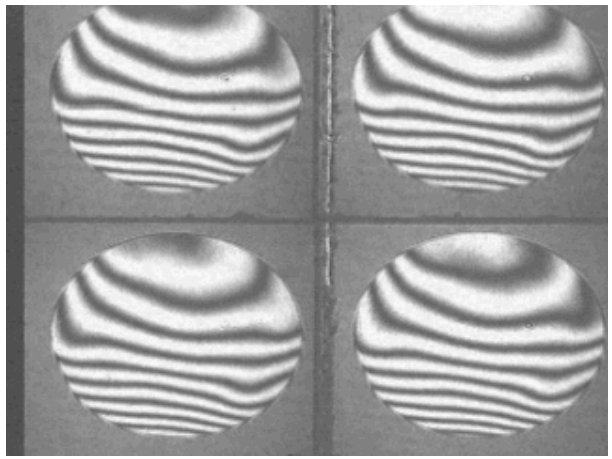
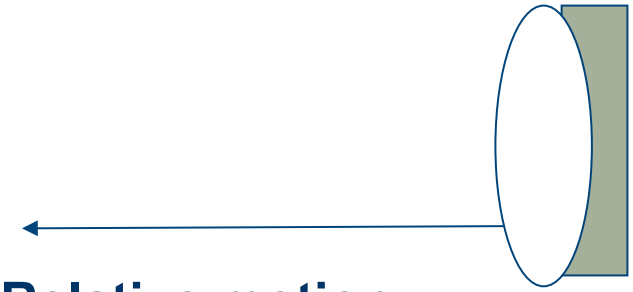
Effects of vibration

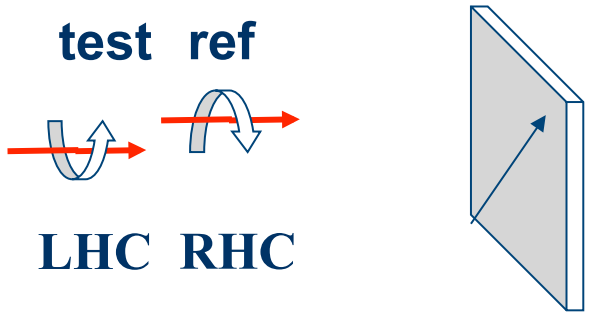


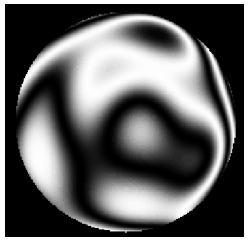


Relative motion between PhaseCam and test object

Phase relationship is fixed

Use polarizer as phase shifter



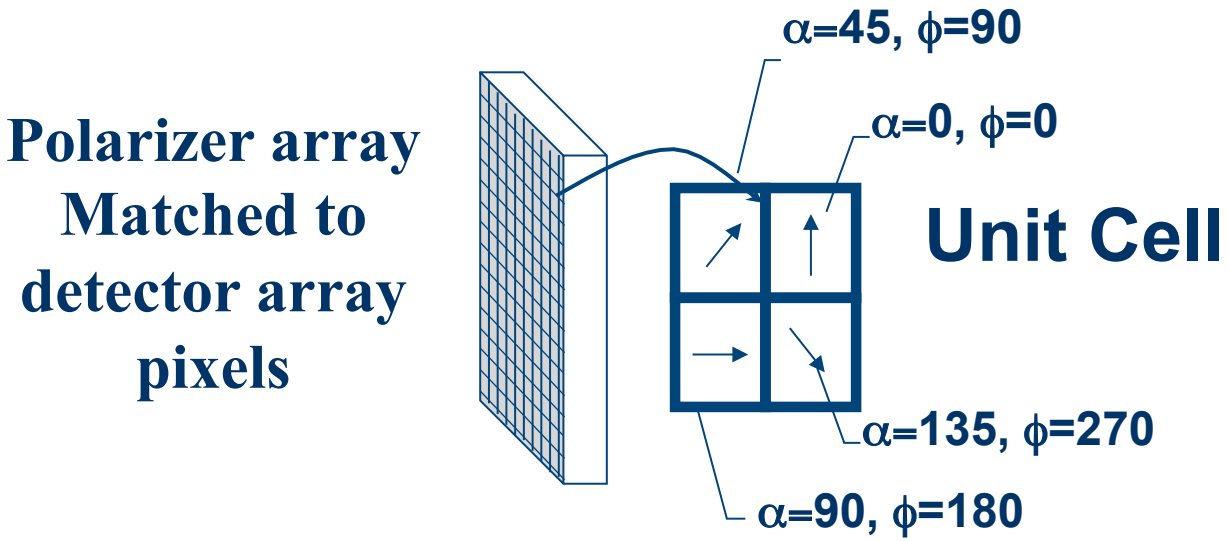


Circ. Pol. Beams ($\Delta\phi$) + linear polarizer $\rightarrow$ cos ($\Delta\phi + 2\alpha$)

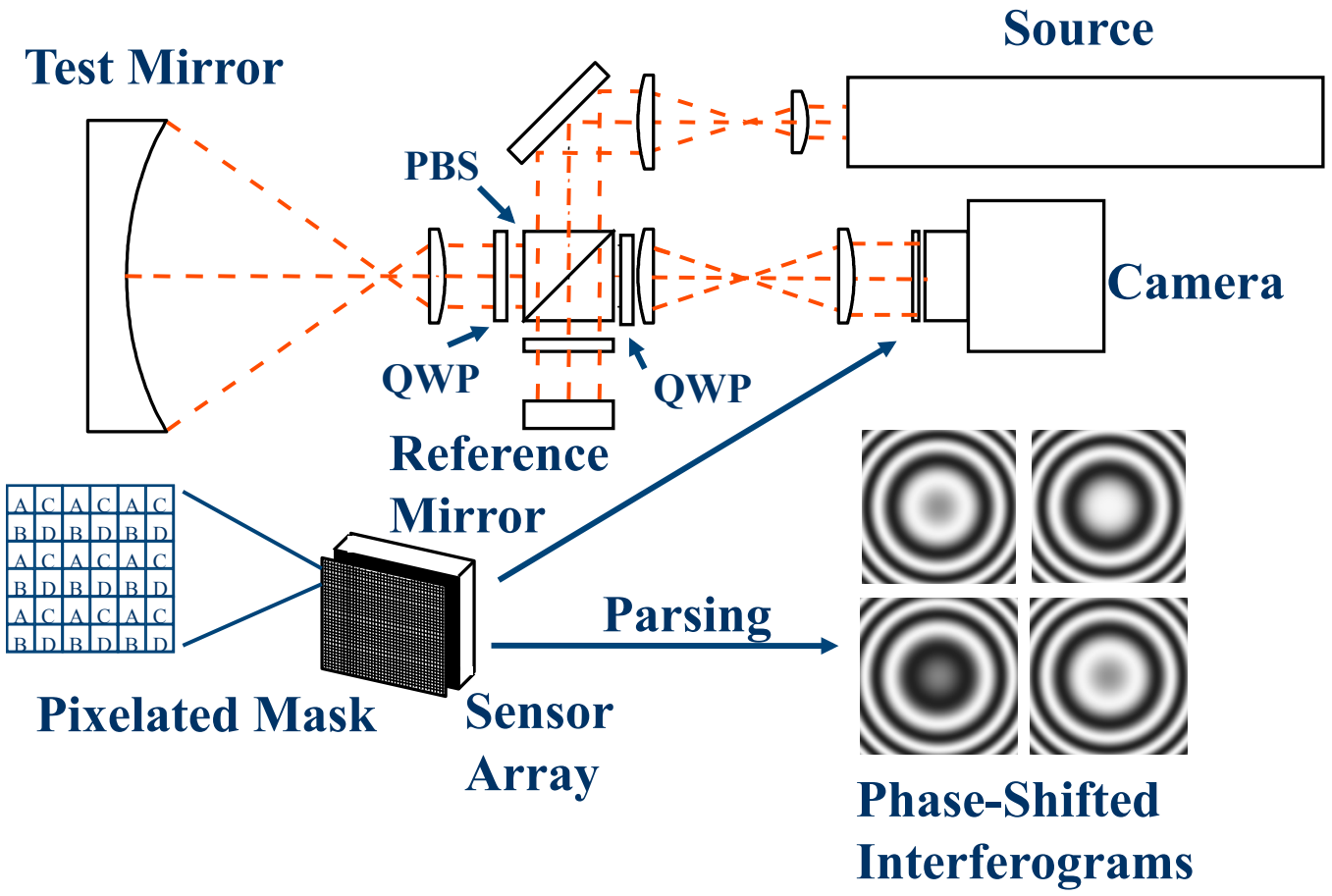
Phase-shift depends on polarizer angle

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

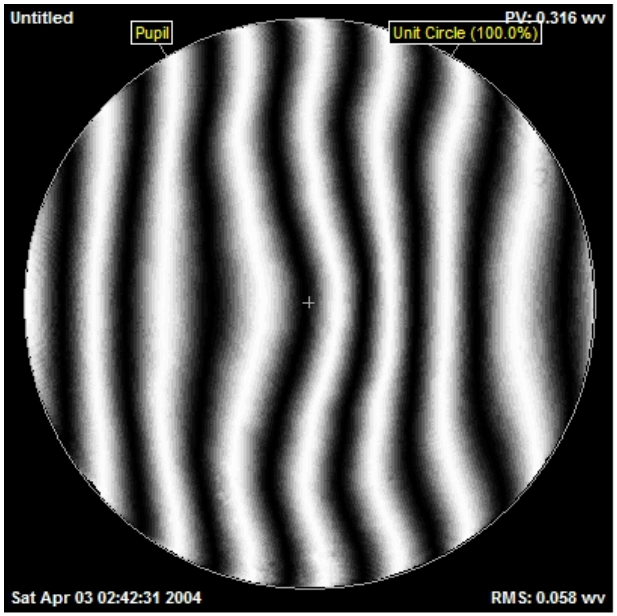
Array of Oriented Micropolarizers

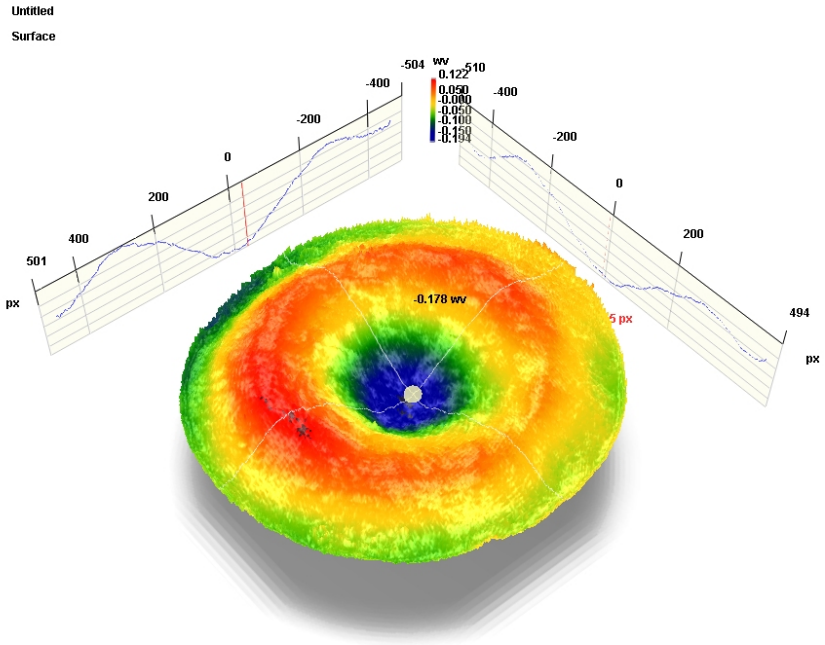


System Configuration



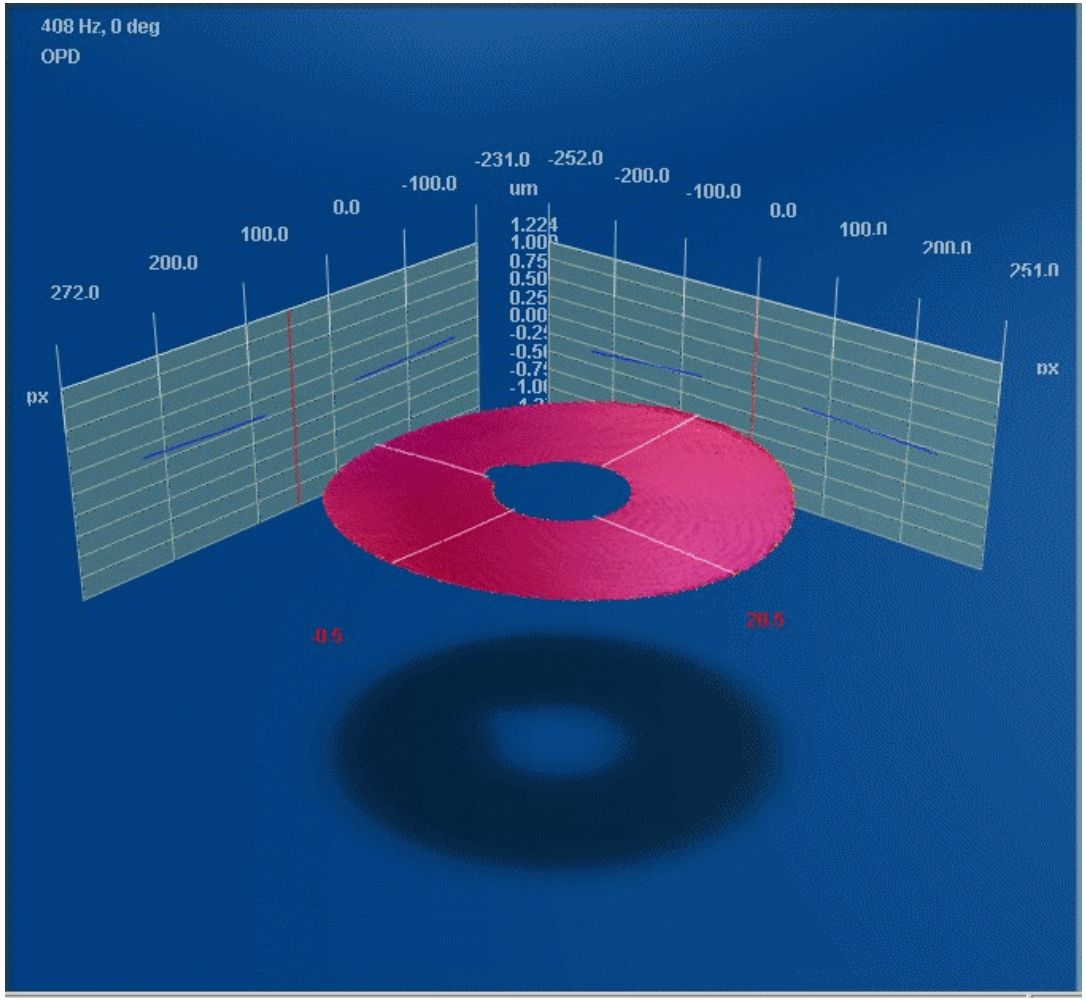
Measurement of 300 mm diameter, 2 meter ROC mirror





Mirror and interferometer on separate tables!

Modal Movie - Disk Vibration



Al mirror, 408 Hz

Conclusions – Single Shot Interferometer

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

Part 3
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

Aspheric Surfaces

Aspheric surfaces are of much interest because they can provide

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

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

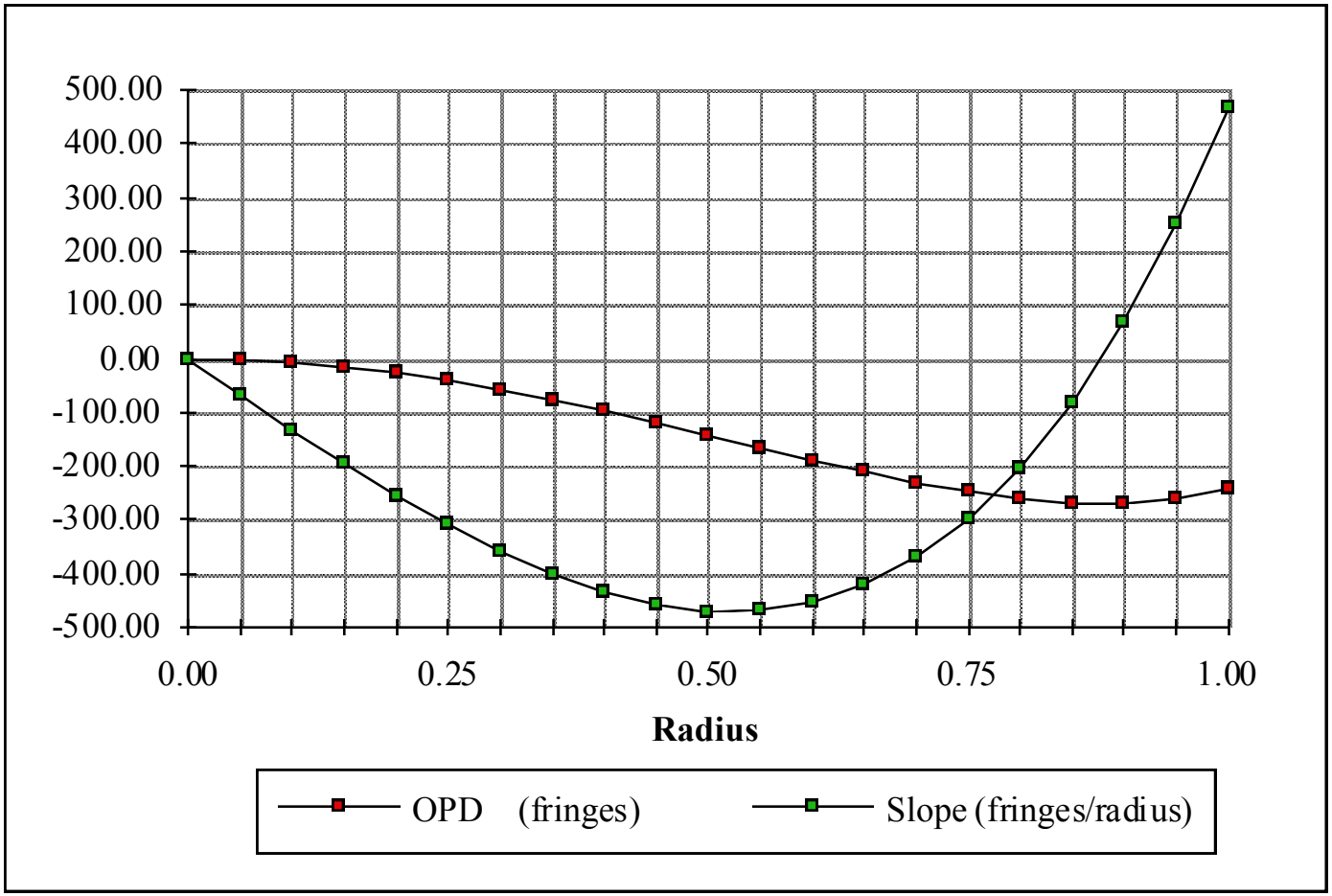
r is the vertex radius of curvature

A's are aspheric coefficients

Difficulty of Aspheric Test

Slope of aspheric departure determines difficulty of test

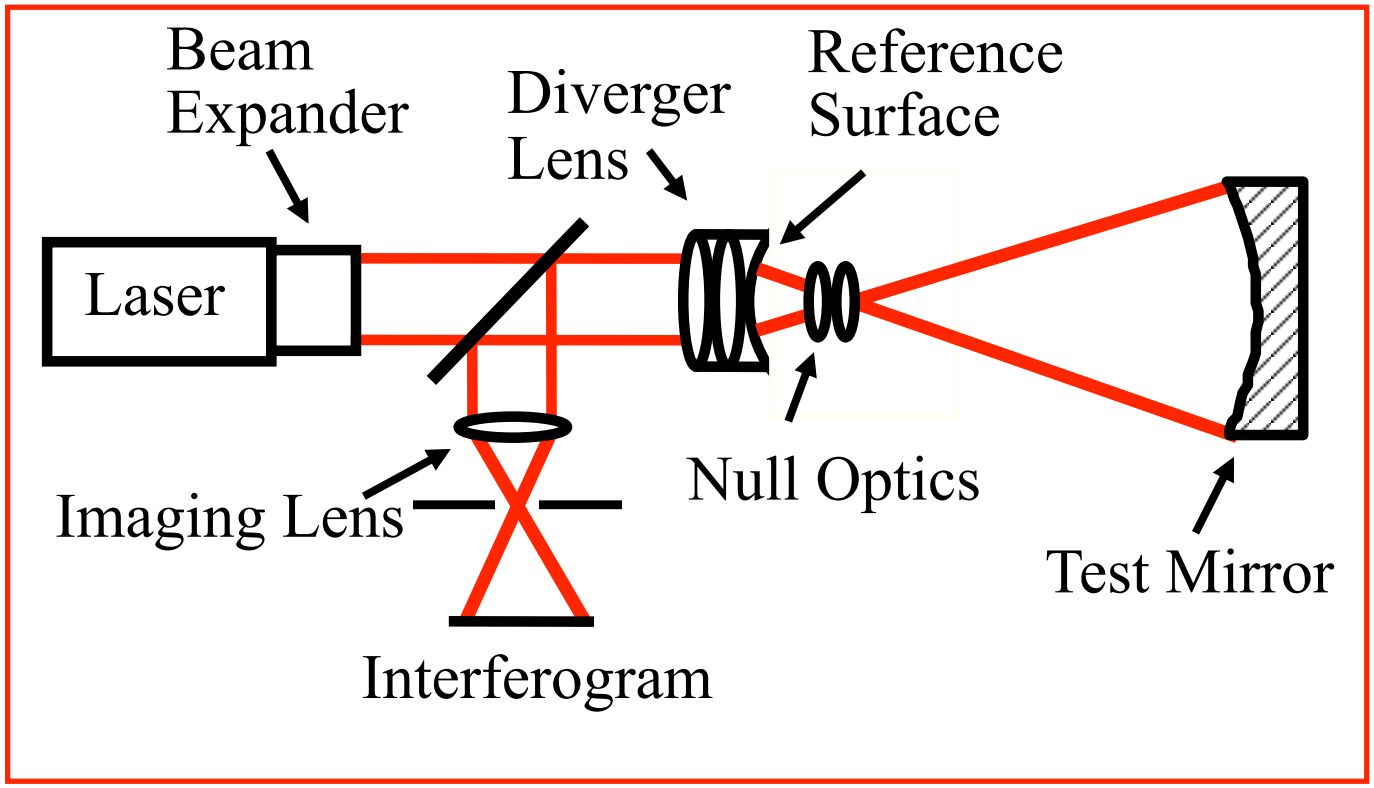
Wavefront Departure and Slope versus Radius



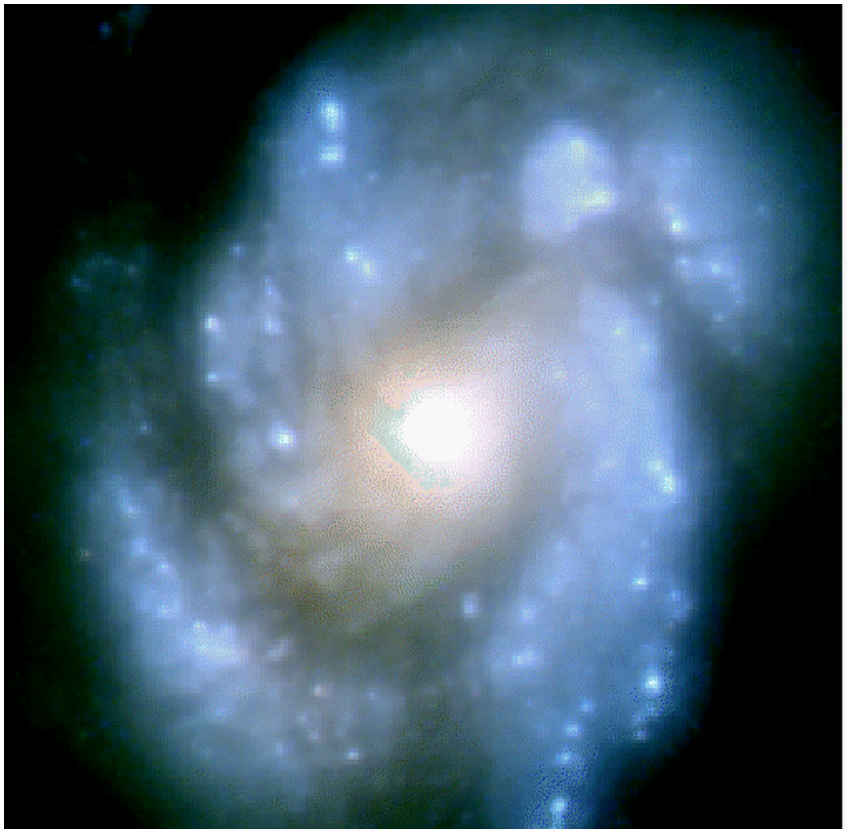
Aspheric Testing Techniques

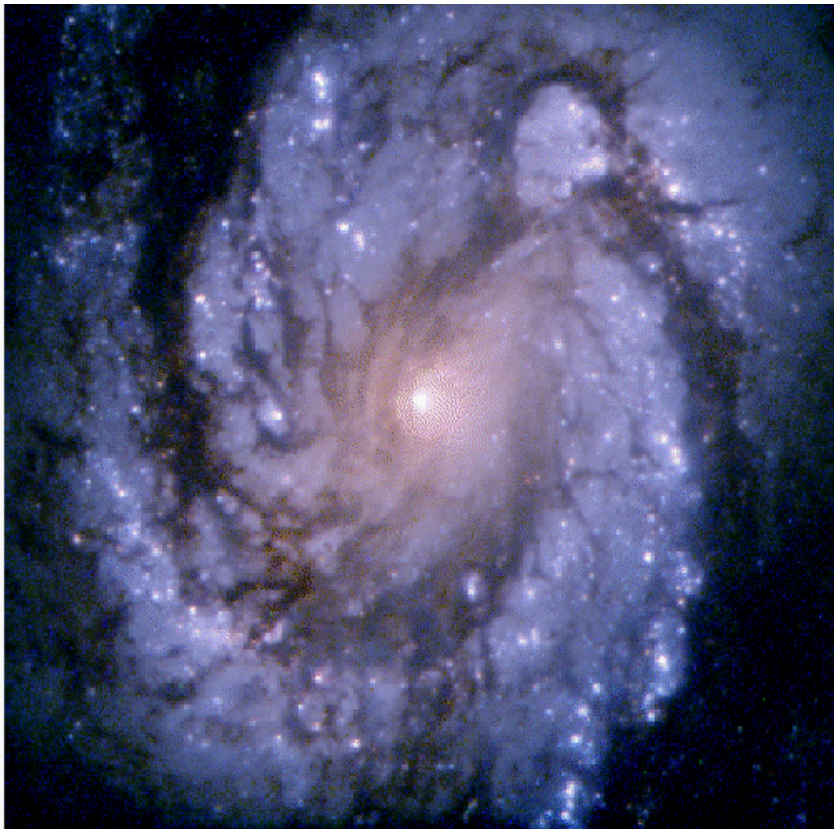
- **Null Tests - Perfect optics give straight equally spaced fringes**
  - Conventional null optics
  - Computer generated holograms
- **Non-null Tests - Even perfect optics do not give straight equally spaced fringes**
  - Deflectometry (SCOTS)
  - Shack-Hartmann
  - Lateral shear interferometry
  -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

Conventional Null Optics

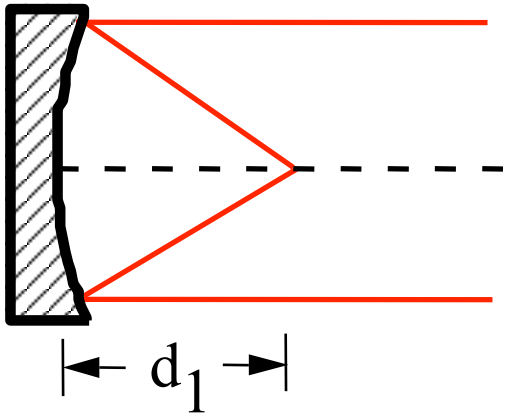


Hubble Pictures
(Before and After the Fix)

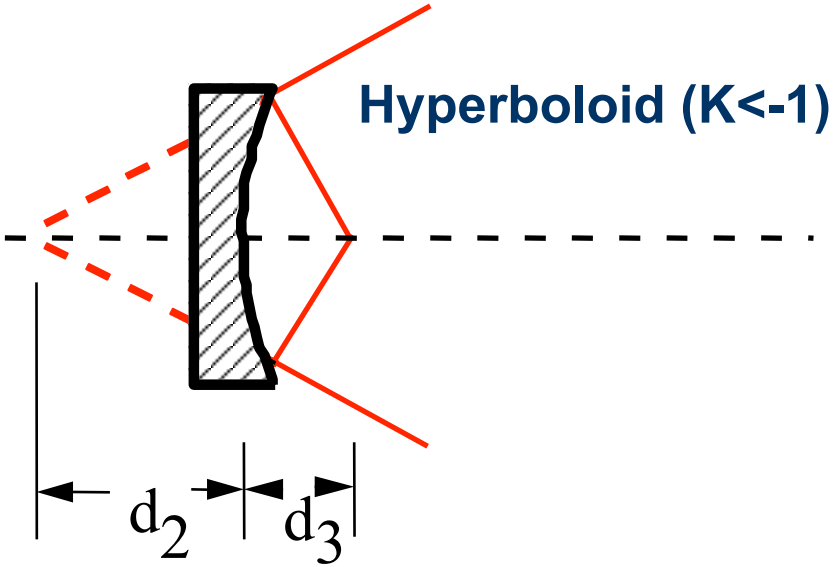




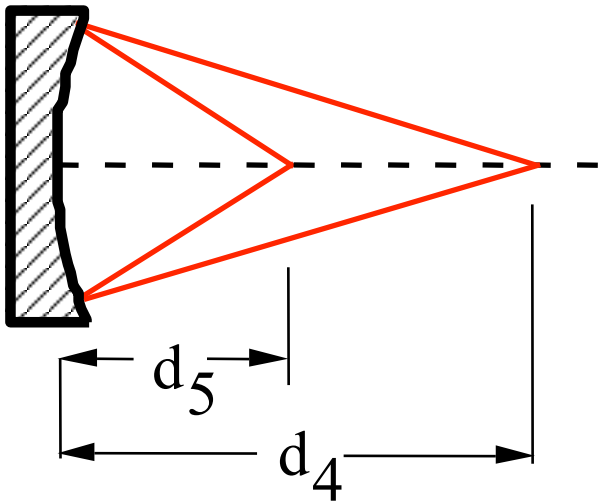
Null Tests for Conics



Parabola (K=-1)



Hyperboloid (K<-1)



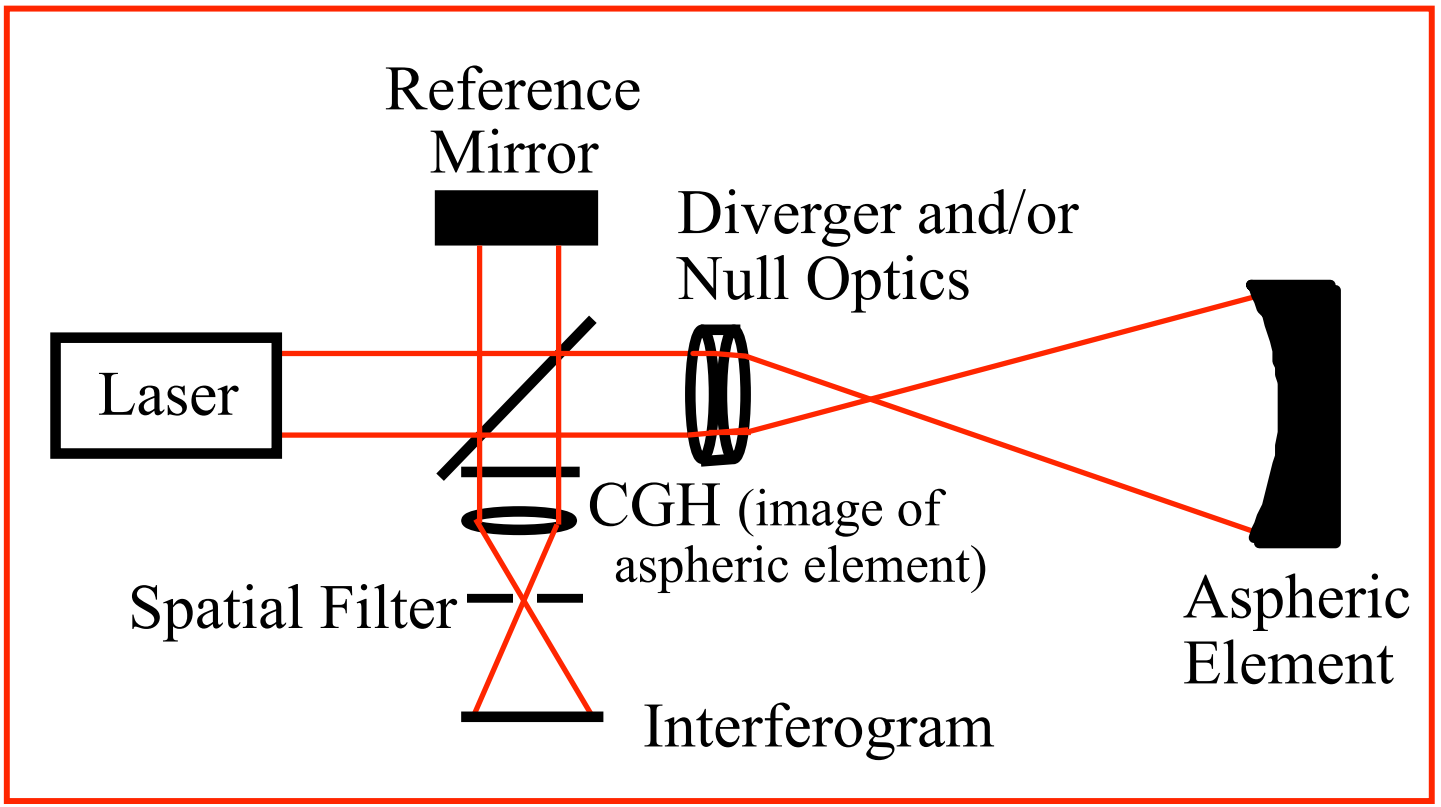
Ellipsoid (-1< K<0)

$$d_1 = r/2$$

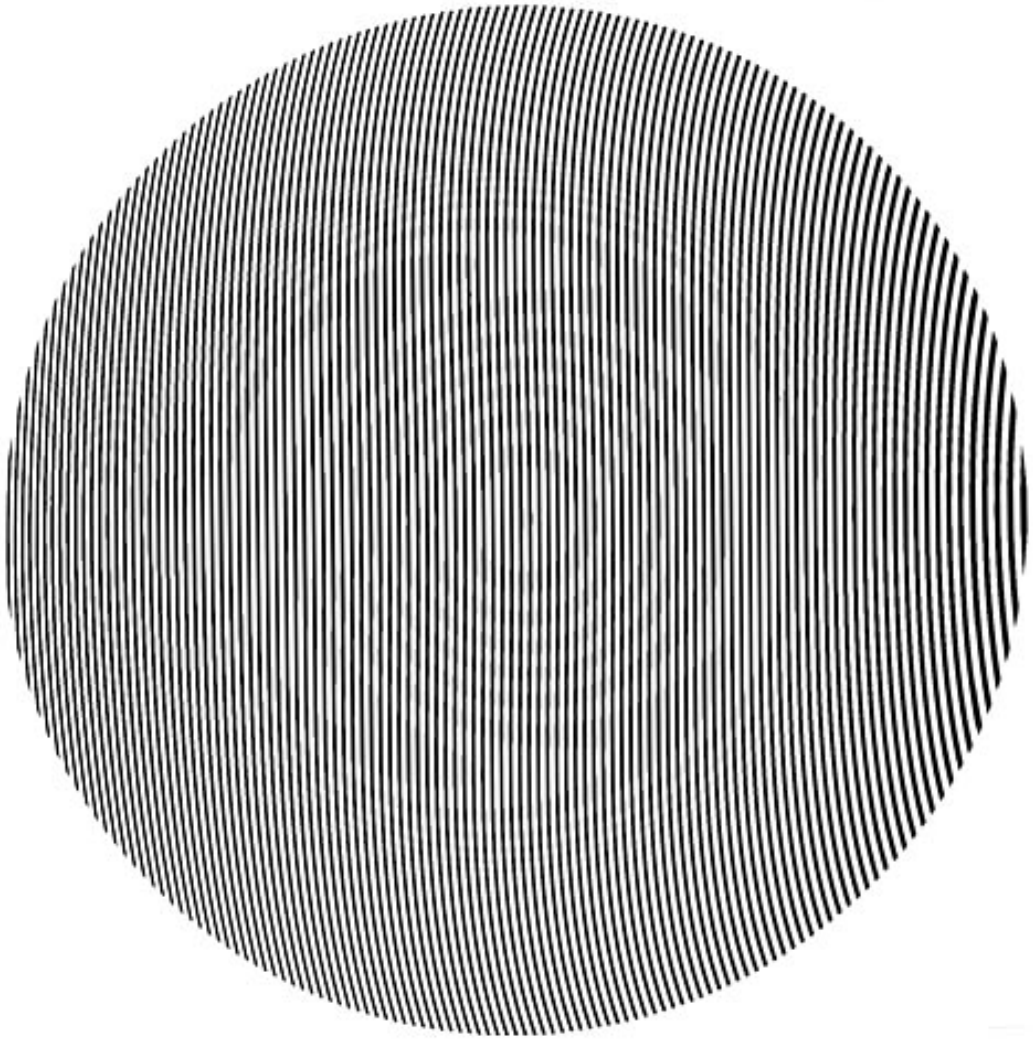
$$d_2, d_3 = \frac{r}{K+1}\left(\sqrt{-K} \pm 1\right)$$

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

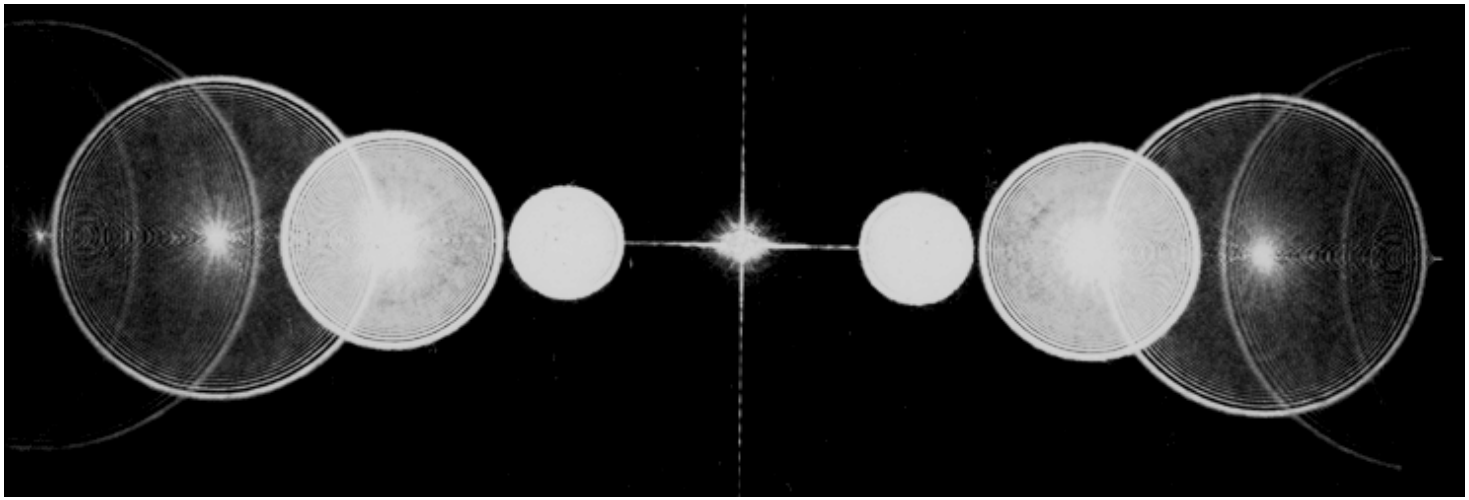
CGH Interferometer



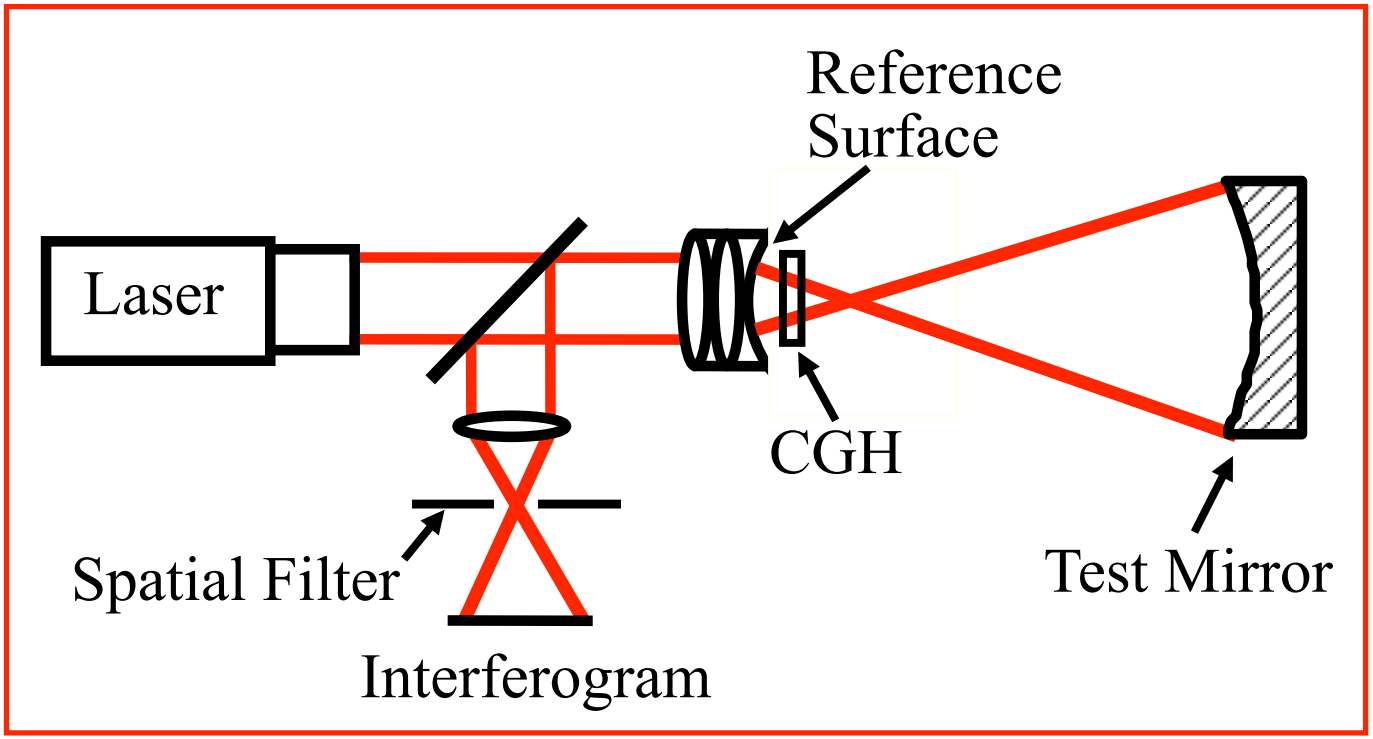
Computer Generated Hologram



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:

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

$\varepsilon(x,y)$ = 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

Calibration of Plotter Errors

- Put either orthogonal straight line gratings or circular zone plates on CGH along with grating used to produce the aspheric wavefront

- Straight line gratings produce plane waves which can be interfered with reference plane wave to determine plotter errors
- Circular zone plates produce spherical wave which can be interfered with reference spherical wave to determine plotter errors

Solving Substrate Distortion Problems

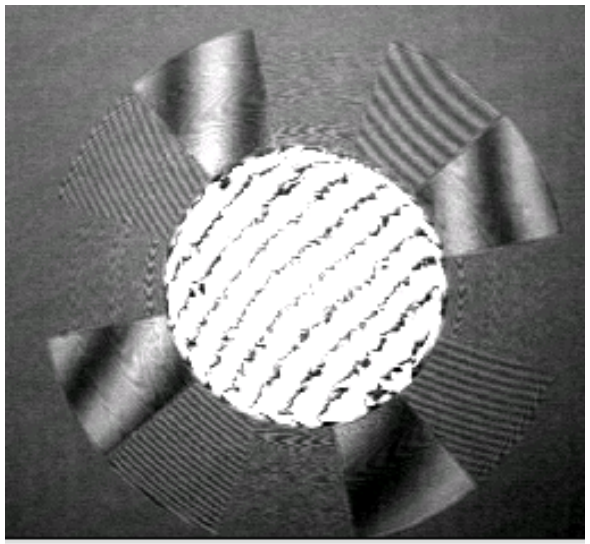
- Use direct laser writing onto custom substrates
- Use amplitude holograms, measure and back out substrate
- Use an optical test setup where reference and test beams go through substrate

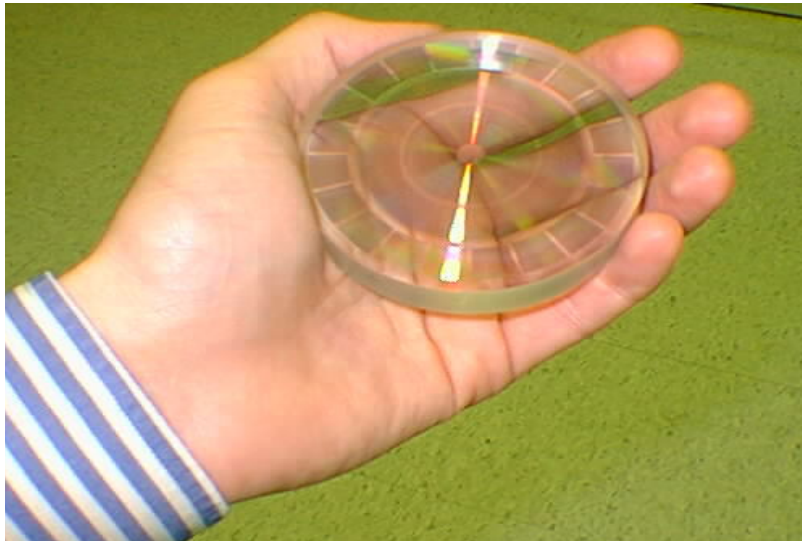
Alignment Errors

- 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

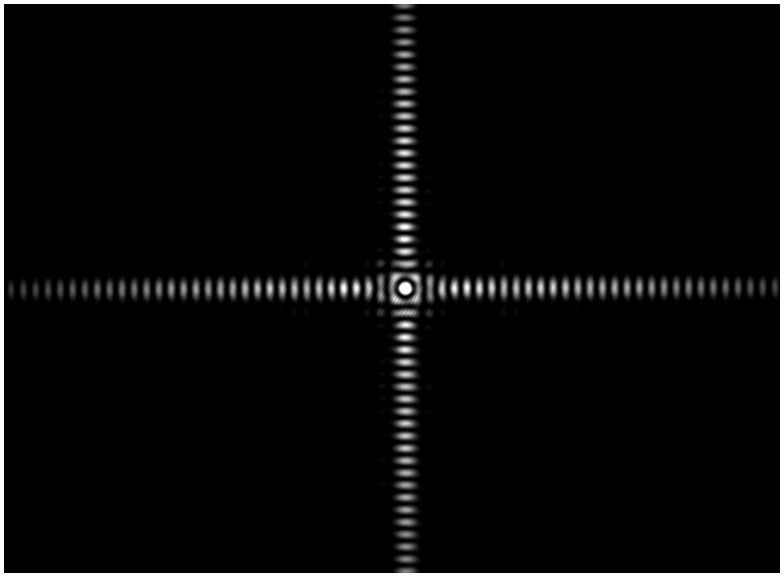
- Commonly CGH's have patterns that are used for aligning the CGH to the incident wavefront.





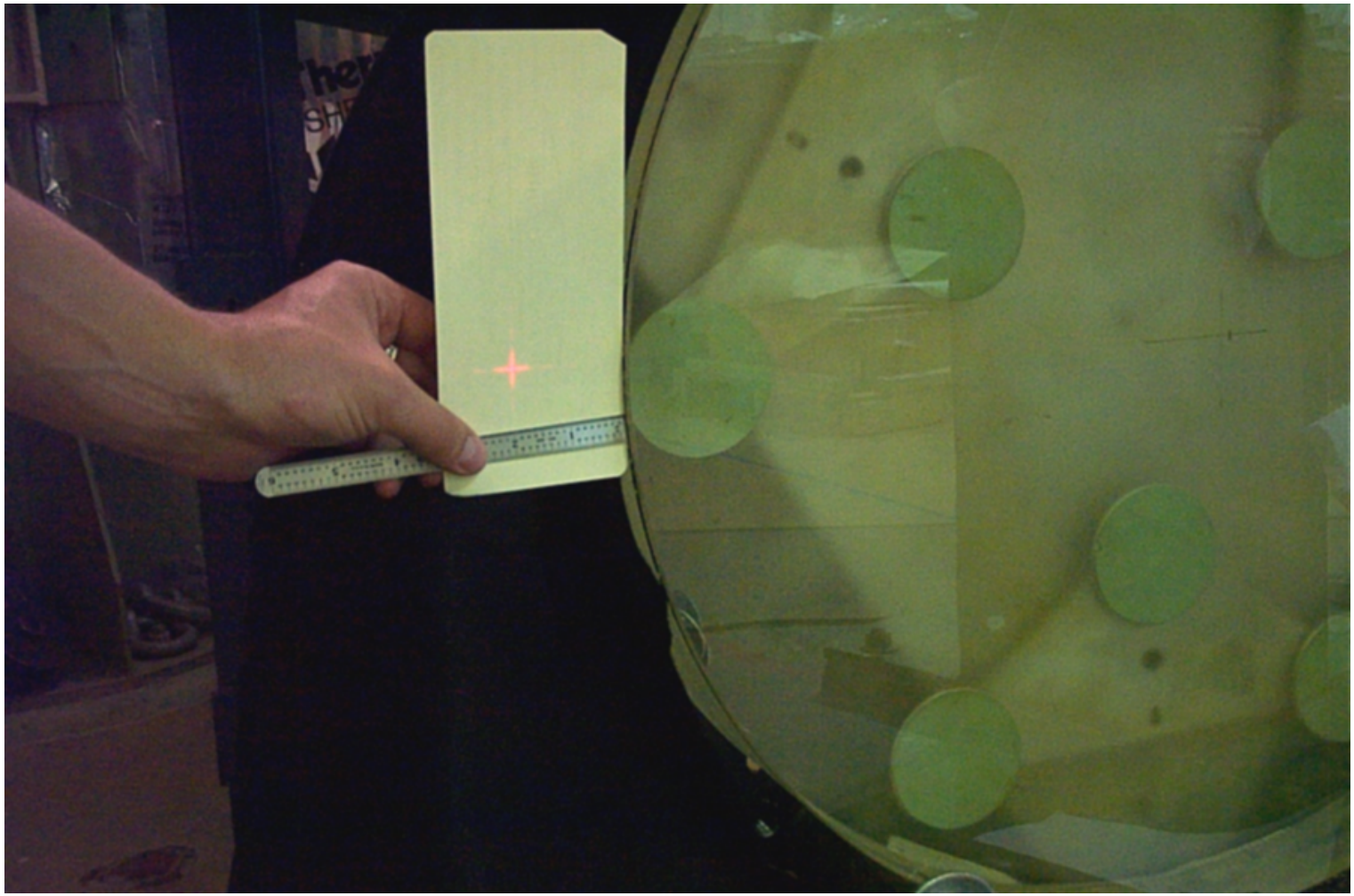
Using multiple patterns outside the clear aperture, many degrees of freedom can be constrained using the CGH reference.

Projection of Fiducial Marks

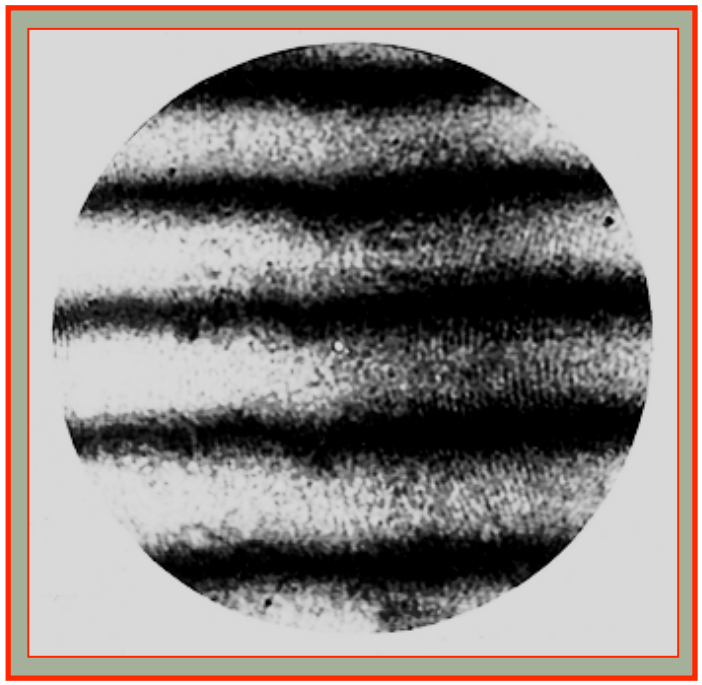


- The positions of the crosshairs can be controlled to micron accuracy
- The patterns are well defined and can be found using a CCD
- Measured pattern at 15 meters from CGH. Central lobe is only 100 μm FWHM

CGH Alignment for Testing Off-Axis Parabola



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

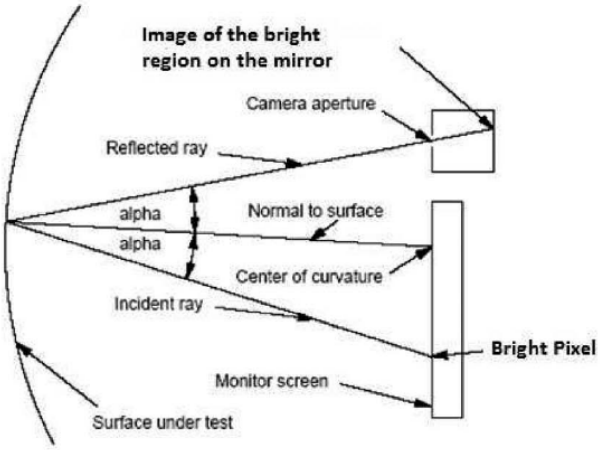


Deflectometry (SCOTS Test)

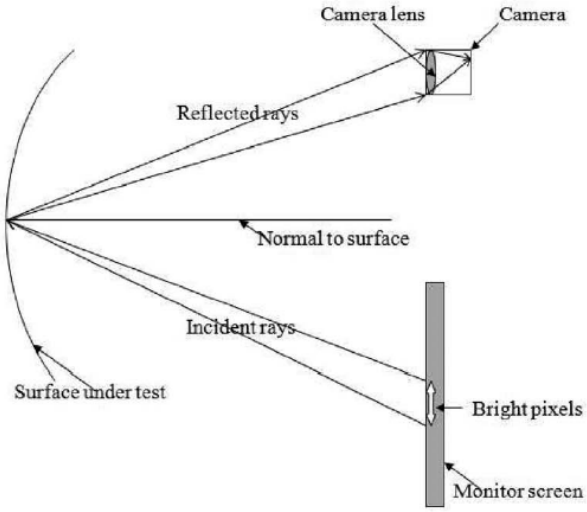
- Hartmann test in reverse
- Measures slope
- Accuracies in the range of 100 – 200 nrad (rms) have been achieved

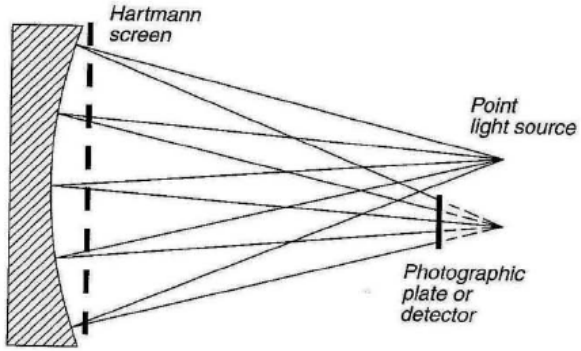
- Ref: Su, Parks, Wang, Angel, and Burge, "Software configurable optical test system: a computerized reverse Hartmann test", Appl. Opt, 49(23), 4404-4412, (2010).
- Ref: Su, Wang, Burge, Kaznatcheev, and Idir, "Non-null full field X-ray mirror metrology using SCOTS: a reflection deflectometry approach", 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.

SCOTS and Hartmann Test



Geometry of SCOTS Test

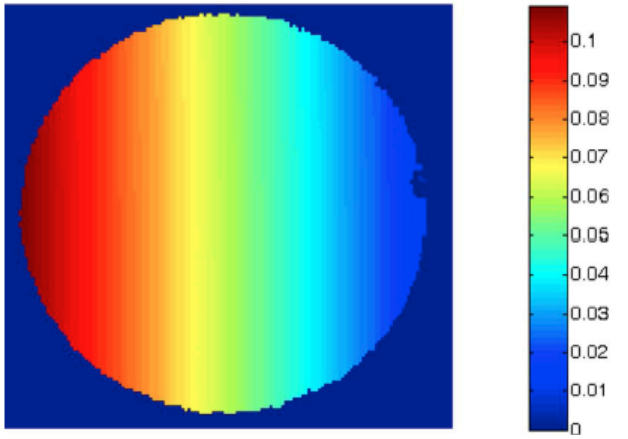




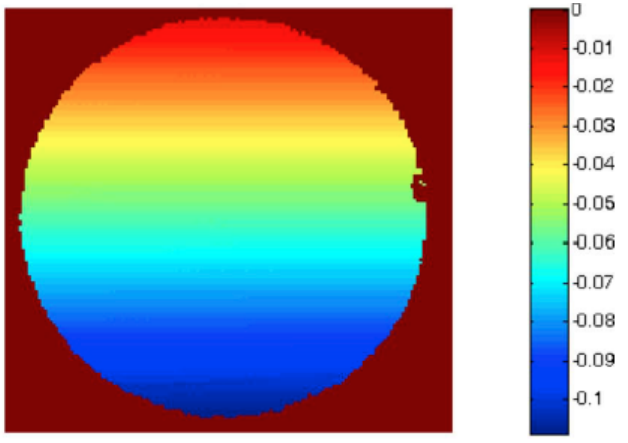
HartmannTest

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

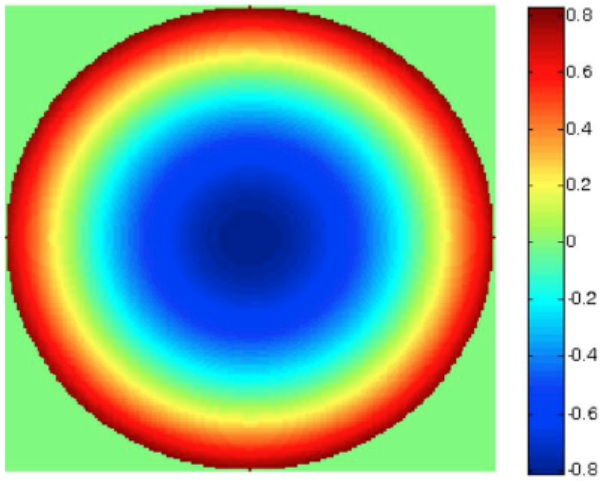


X-slope

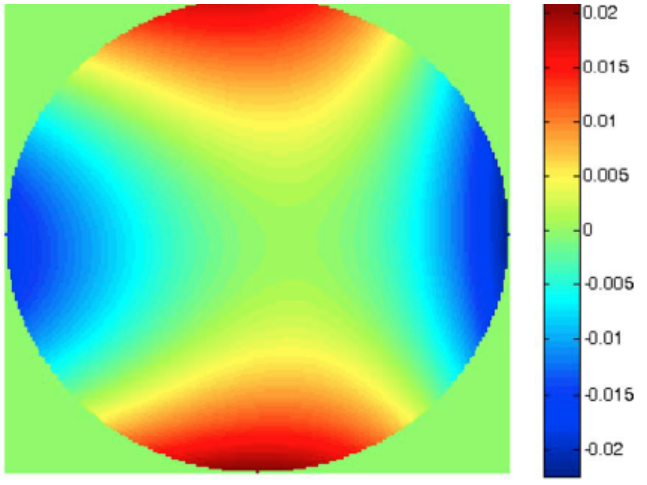


Y-slope

Radians



Surface



Surface Departure

mm

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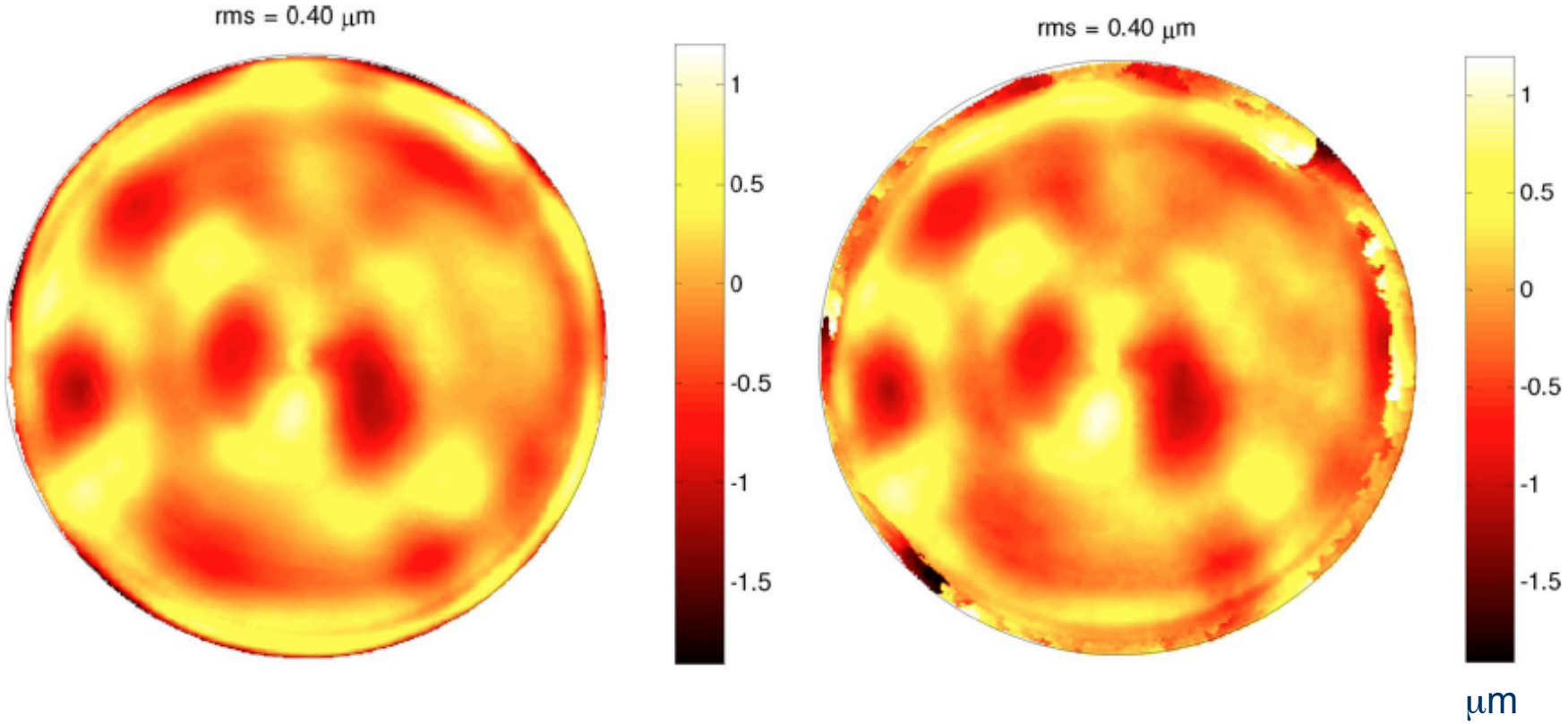
8.4 m Giant Magellan Telescope



SCOTS

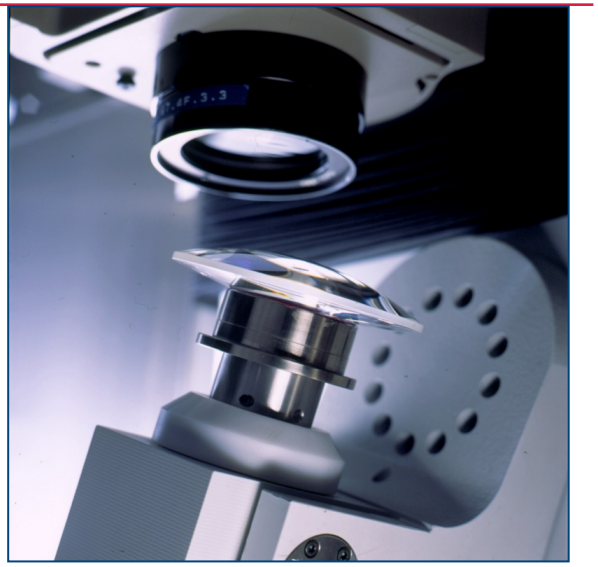
Interferometry

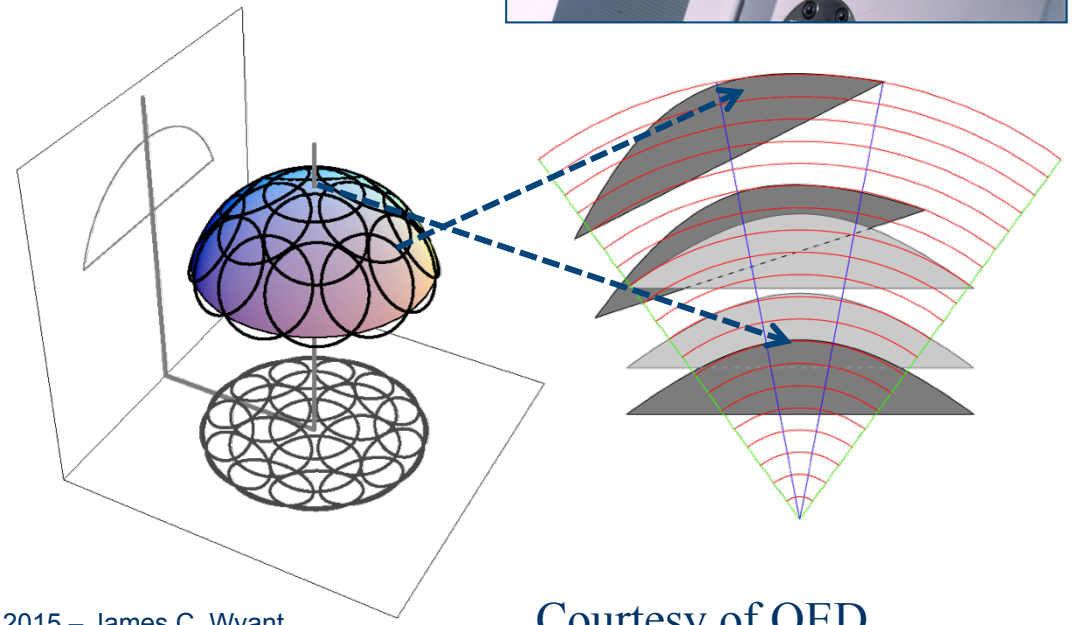
Stitching Interferograms

- 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

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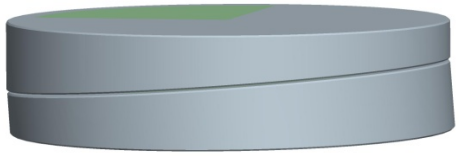
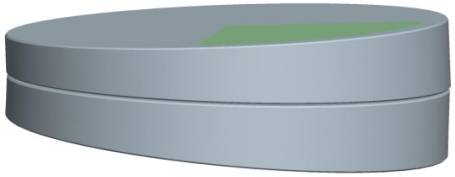
Extending the SSI to ASI®

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



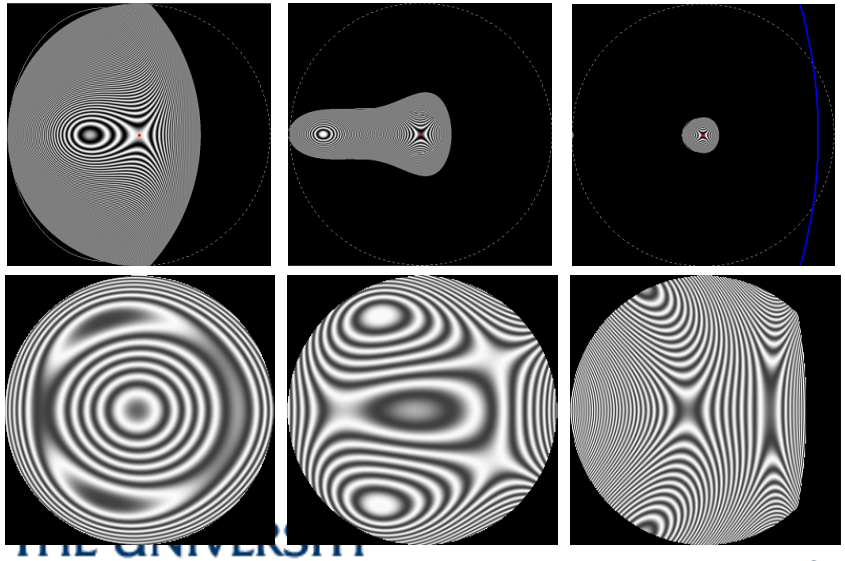
Plane-parallel

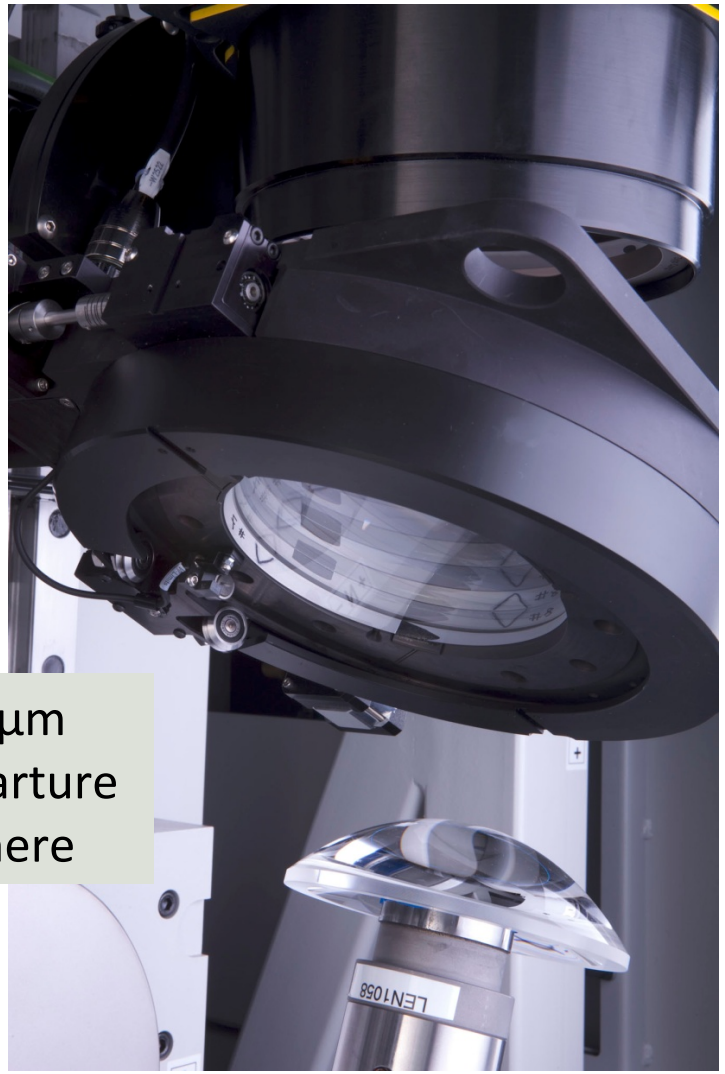


Maximum wedge

SSI

ASI (VON)



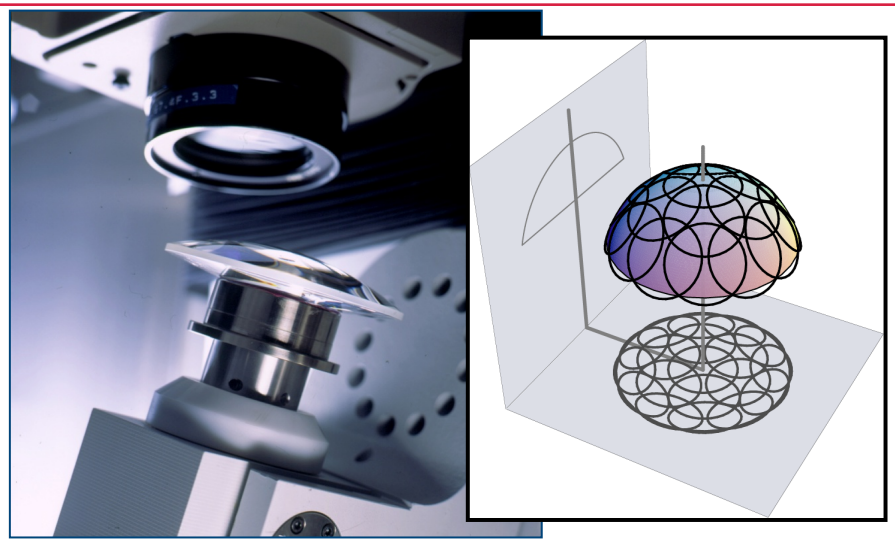


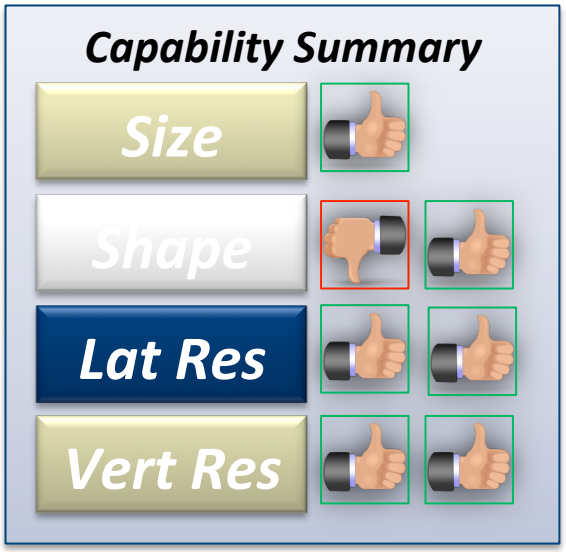
650 µm departure asphere

Courtesy of QED

SSI/ASI: *Summary*

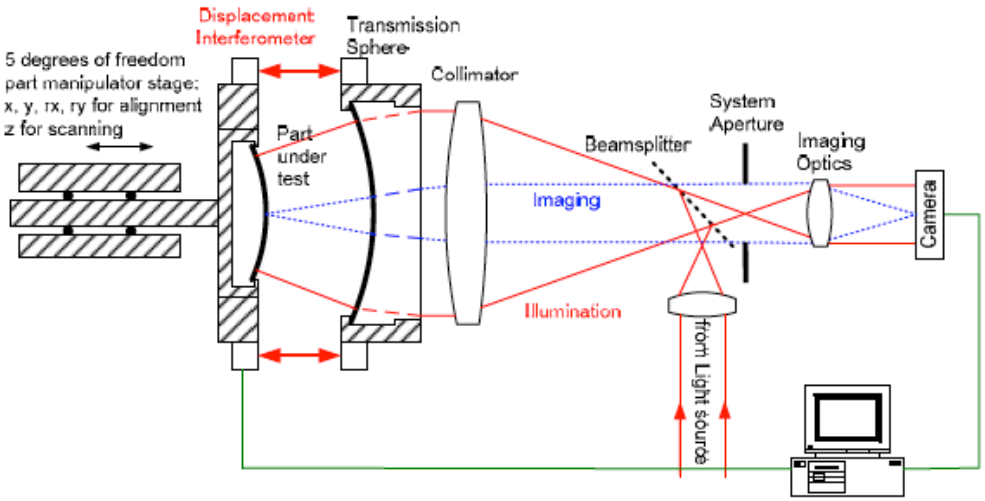
- What is it good for?
  - Flexible – no dedicated nulls
  - High departure
  - Large NA or CA
  - High vertical resolution
  - High lateral resolution
  - Compensation of systematic errors
- What are its key limitations?
  - Inflection points
  - High slope deviations
  - 3rd order spherical uncertainty

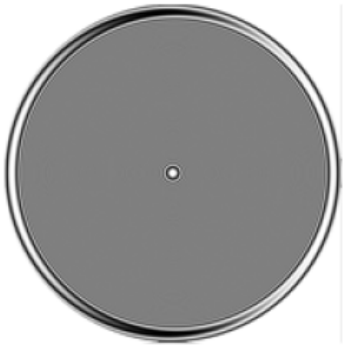




Courtesy of QED

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.

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)

Basic Limitations of Aspheric Testing

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

This is the most serious problem

Part 4 - Measurement of Surface Microstructure

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

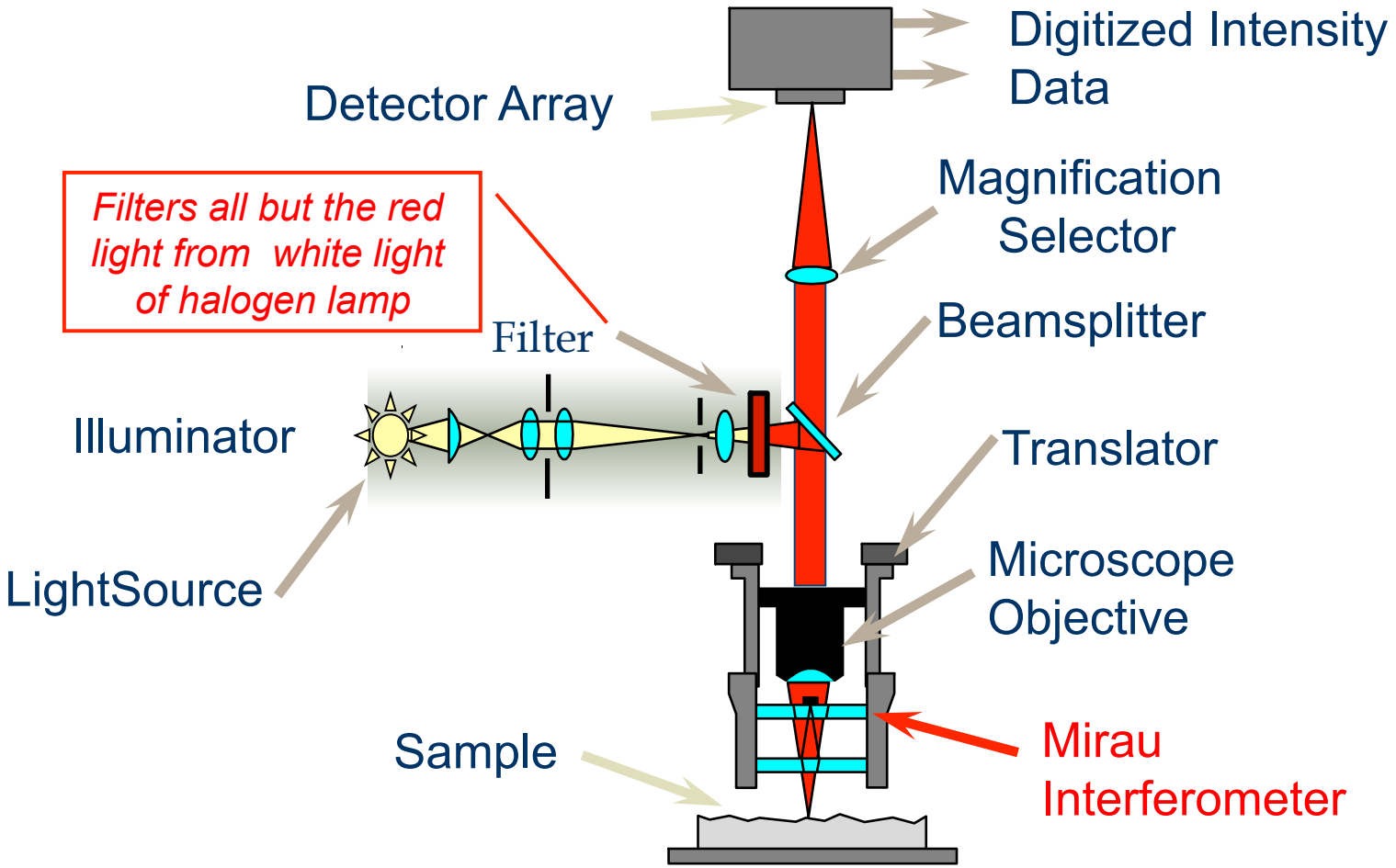
Non-Contact Optical Profilers for Measurement of Surface Microstructure

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

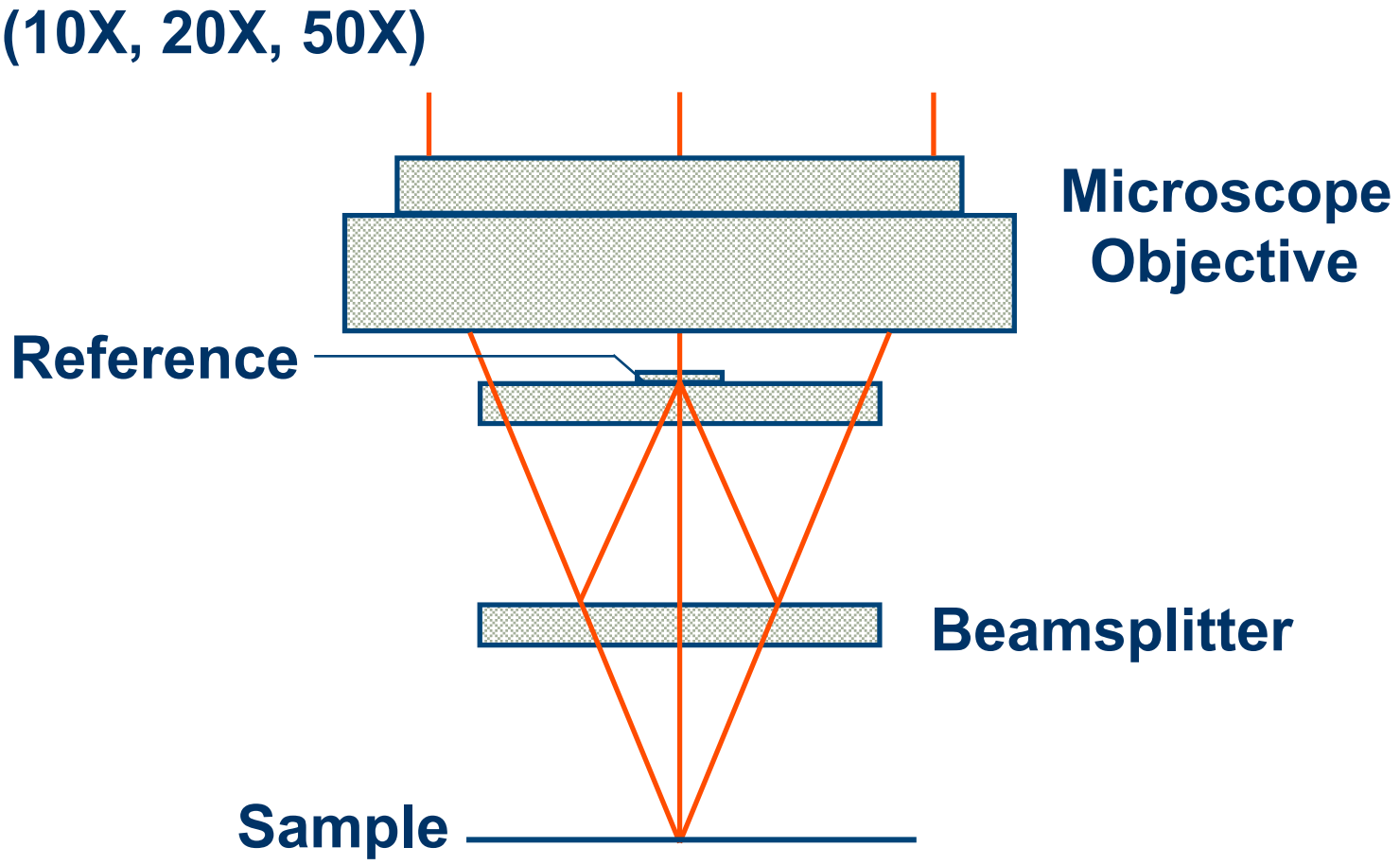
Advantages of White Light over Laser Light

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

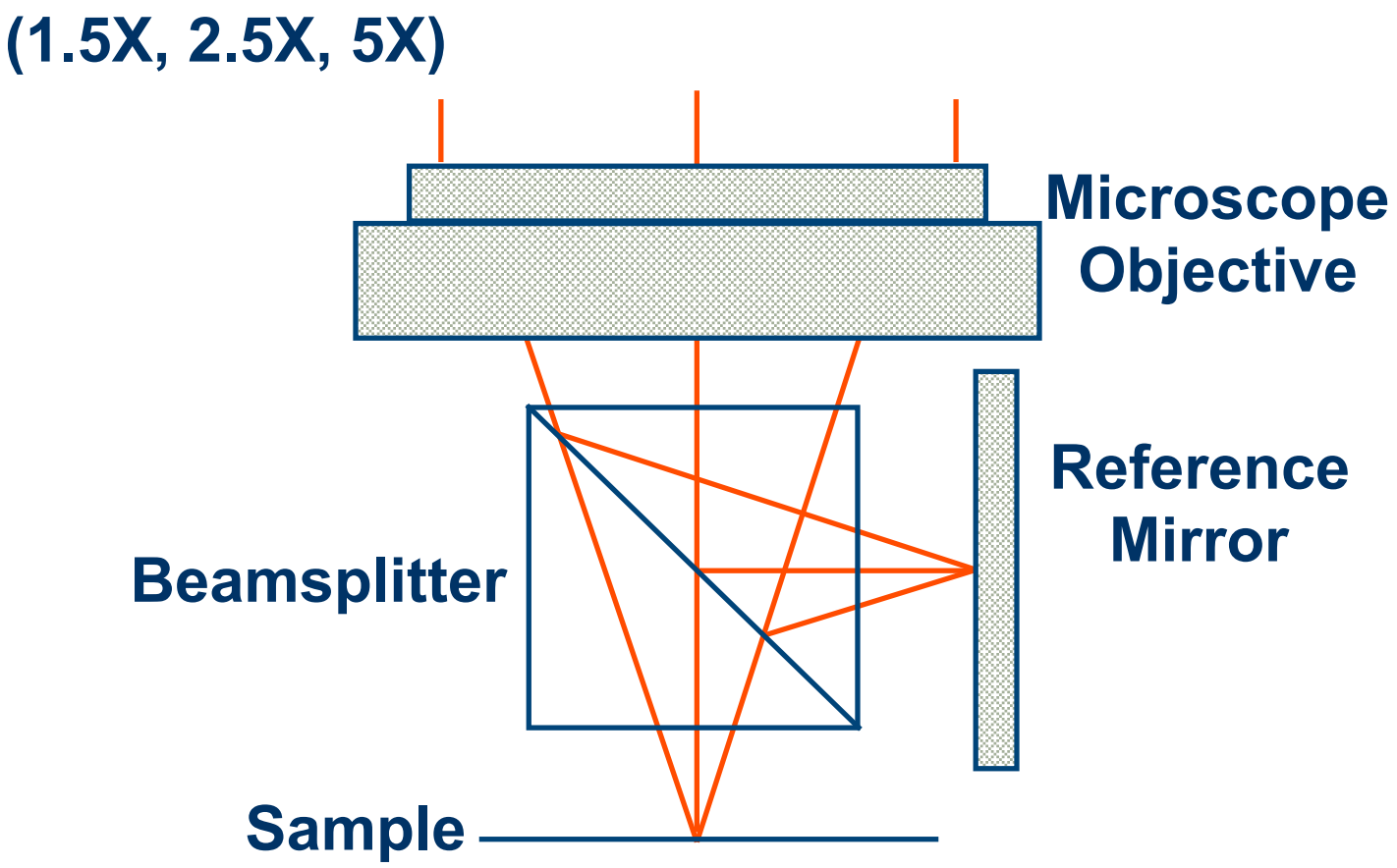
Interference Microscope Diagram



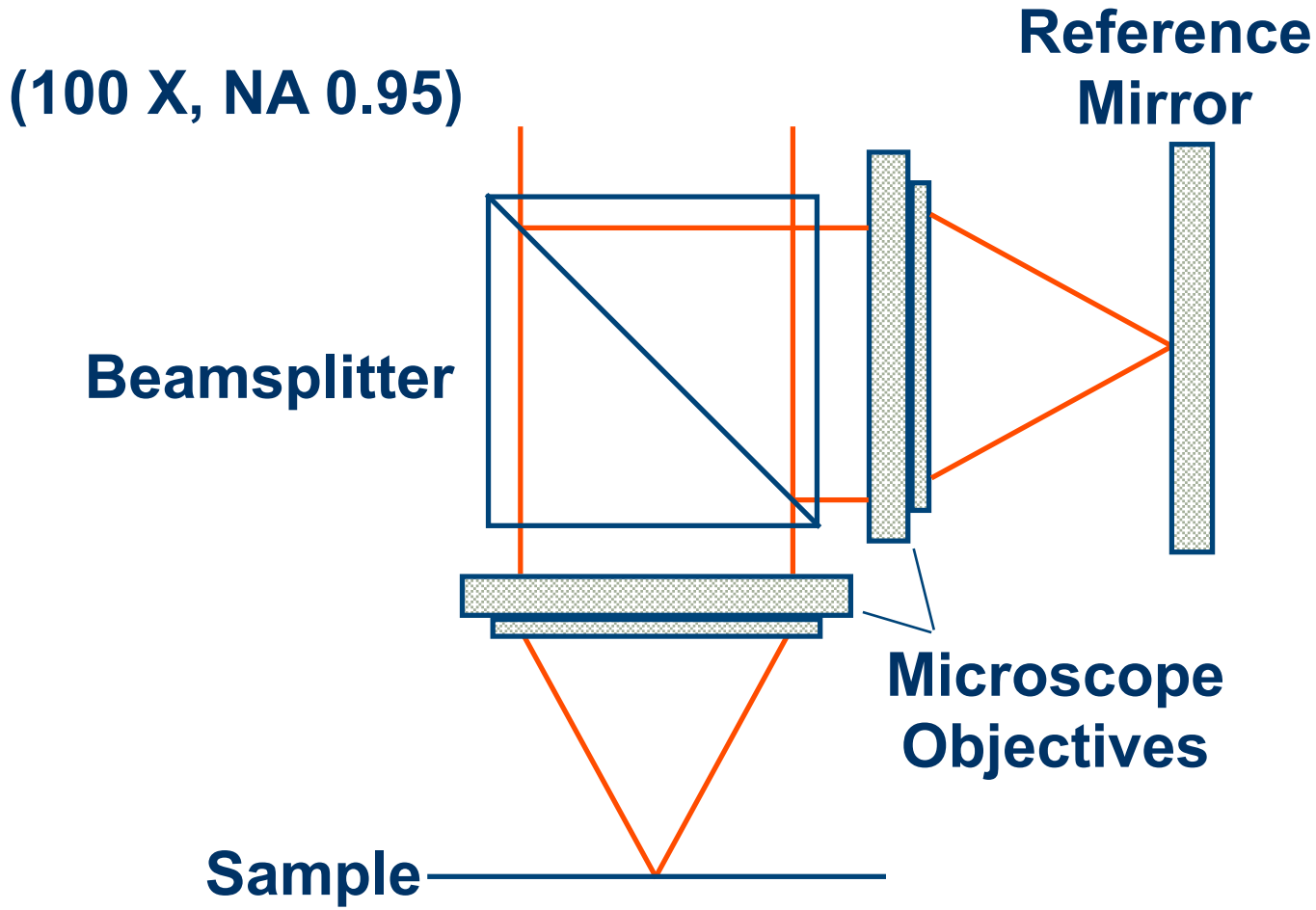
Mirau Interferometer



Michelson Interferometer



Linnik Interferometer

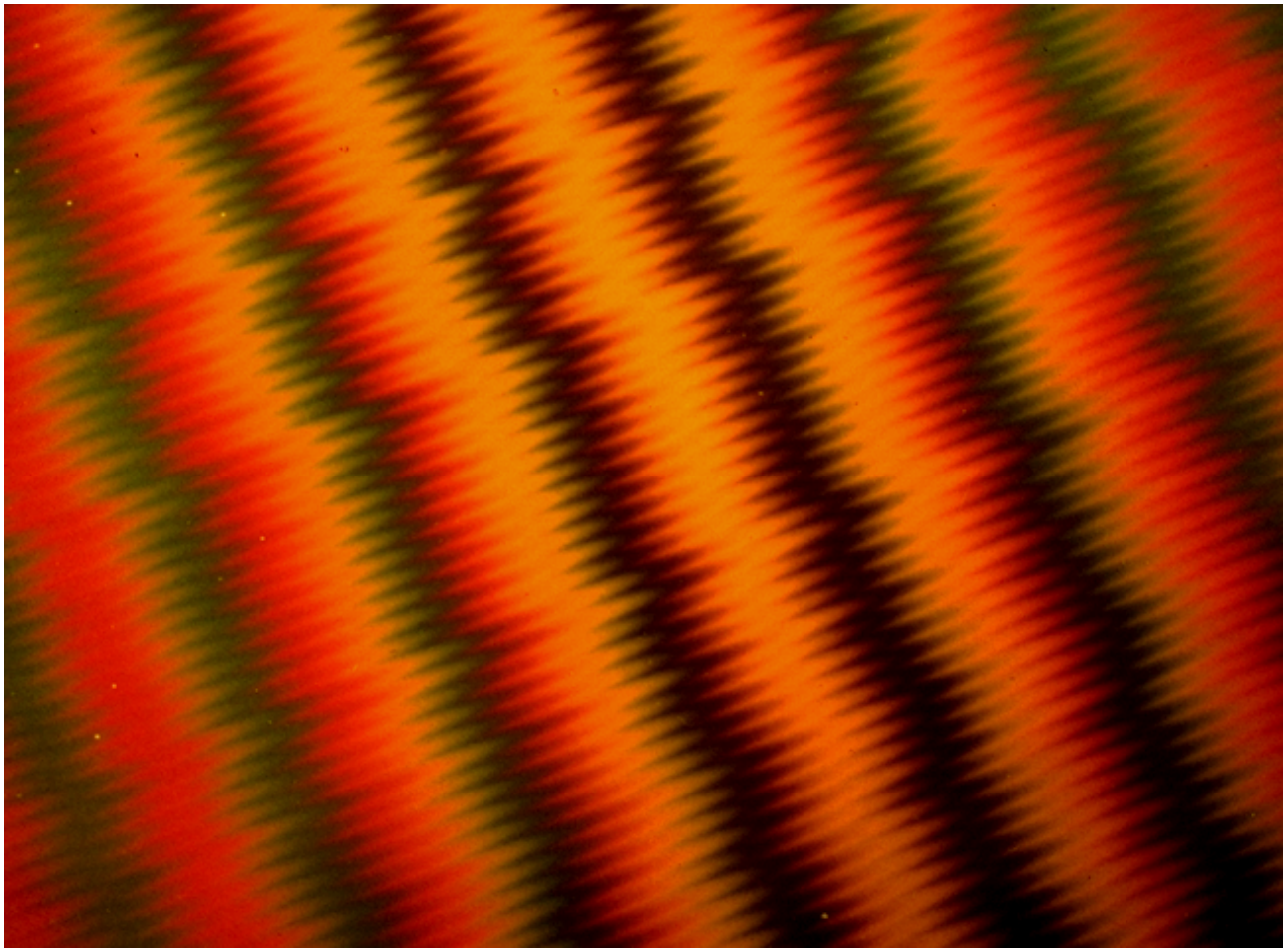


Interference Objectives

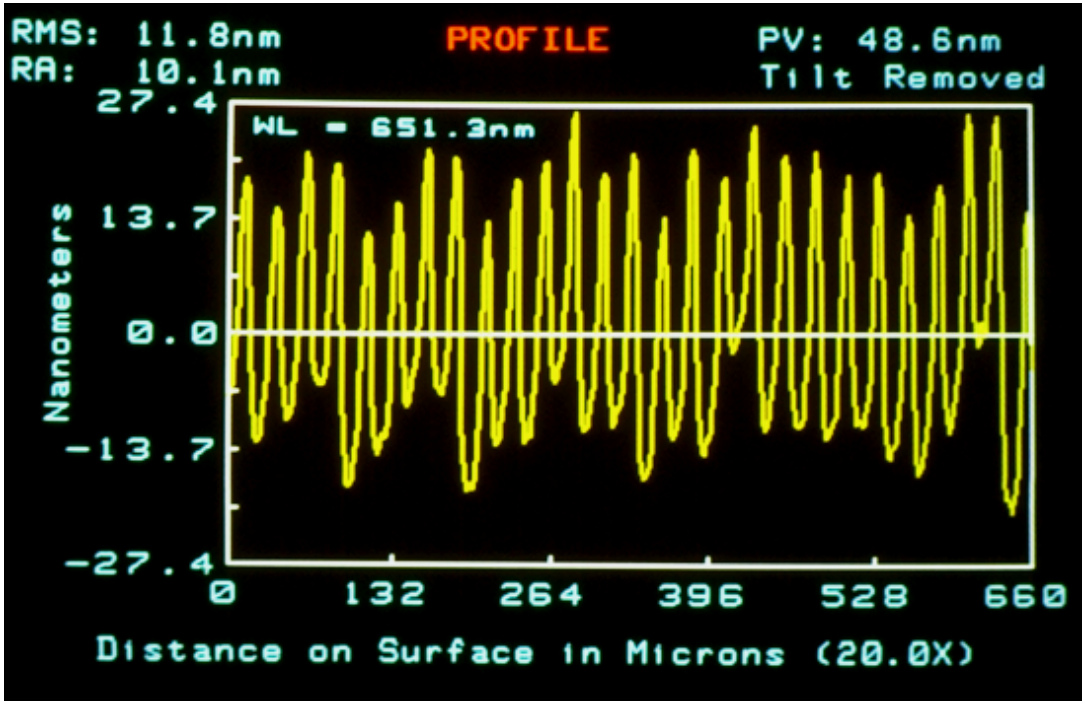
- **Mirau**
  - Medium magnification
  - Central obscuration
  - Limited numerical aperture
- **Michelson**
  - Low magnification, large field-of-view
  - Beamsplitter limits working distance
  - No central obscuration
- **Linnik**
  - Large numerical aperture, large magnification
  - Beamsplitter does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

Optical Profiler

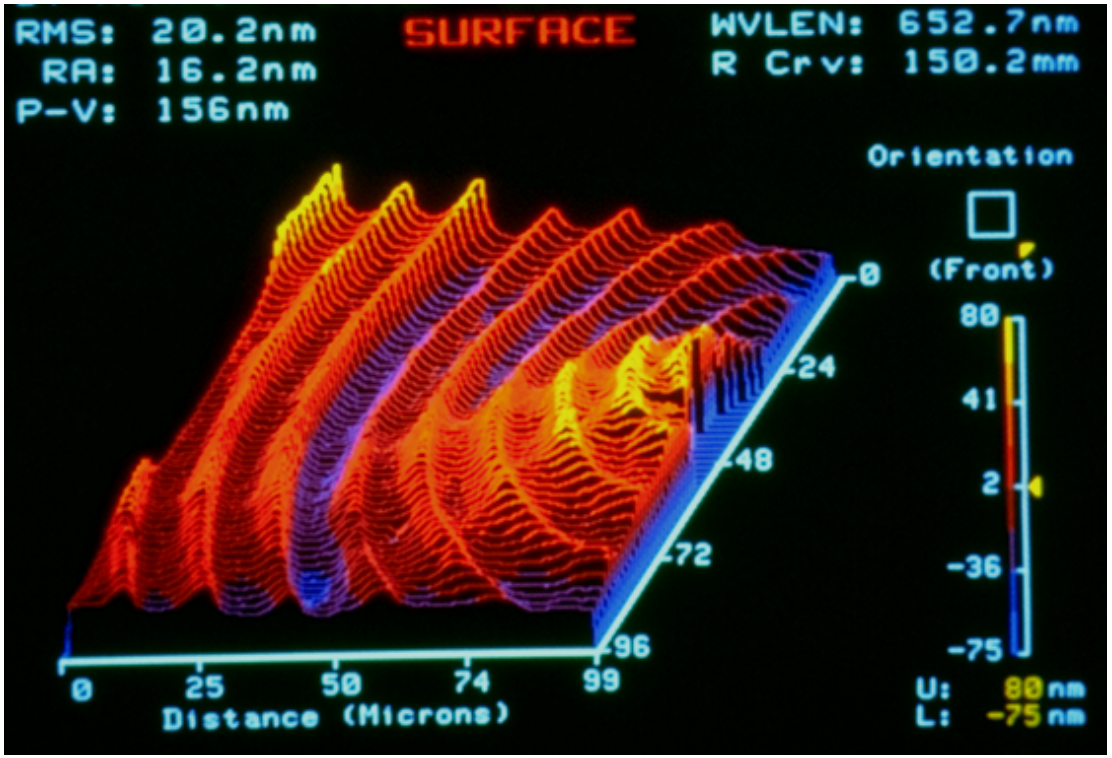
White Light Interferogram



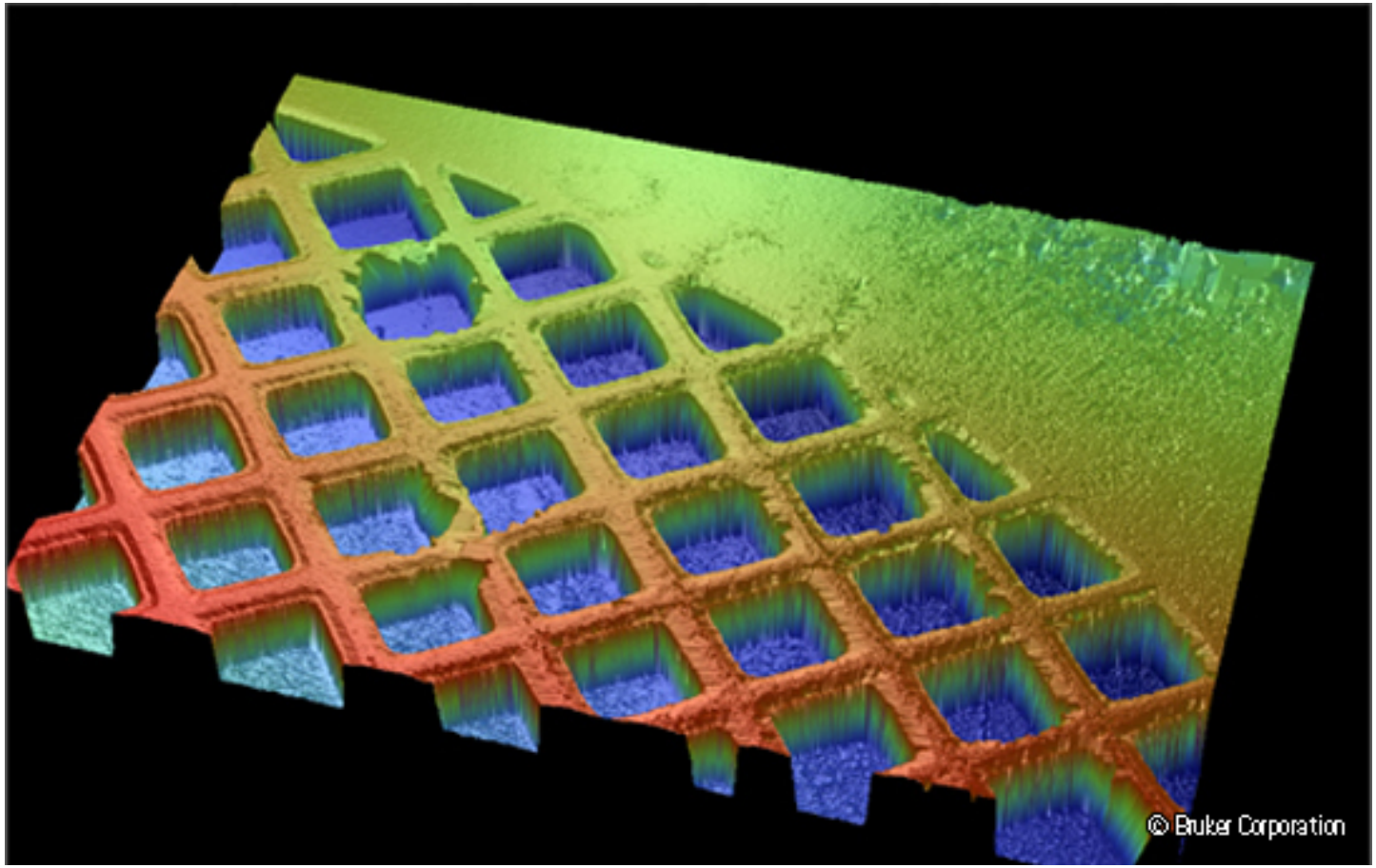
Profile of Diamond Turned Mirror



Diamond Turned Mirror

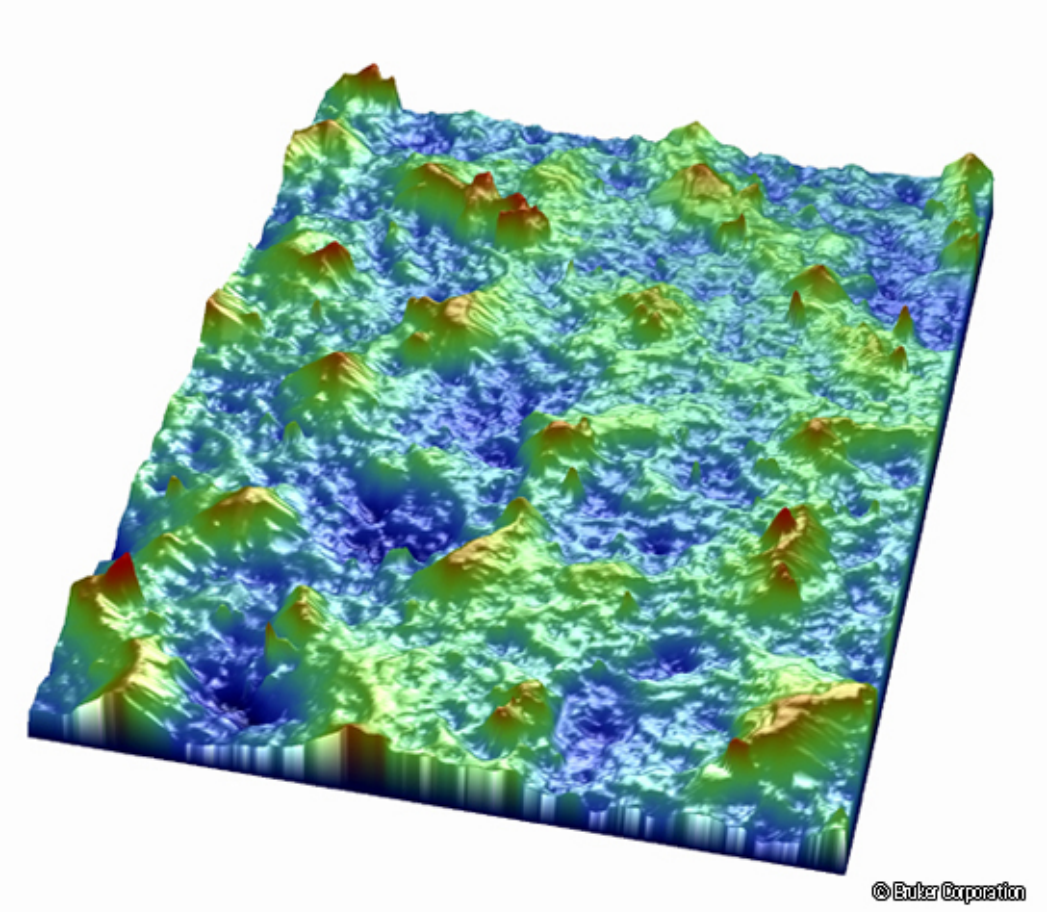


Grating



Ref: Bruker

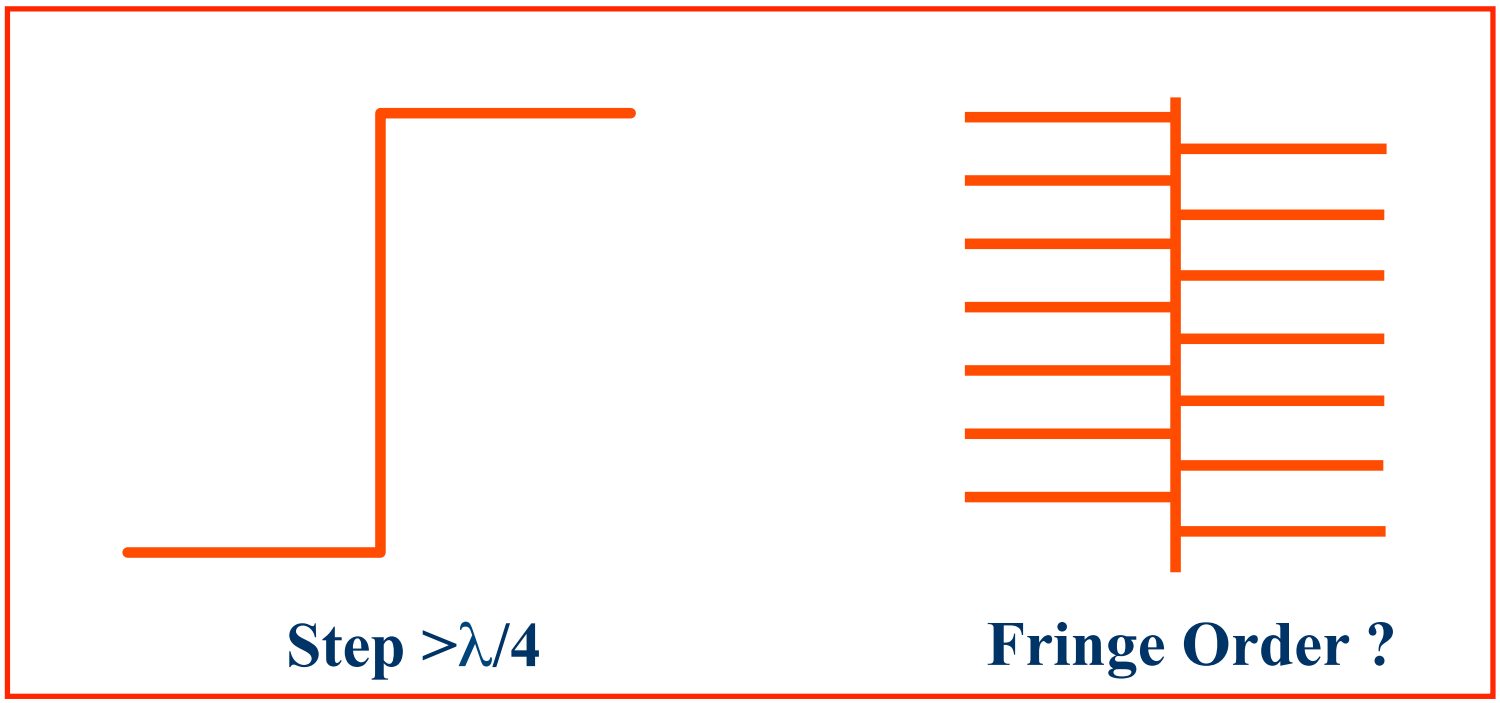
Diamond Film



Ref: Bruker

How High is the Step?

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

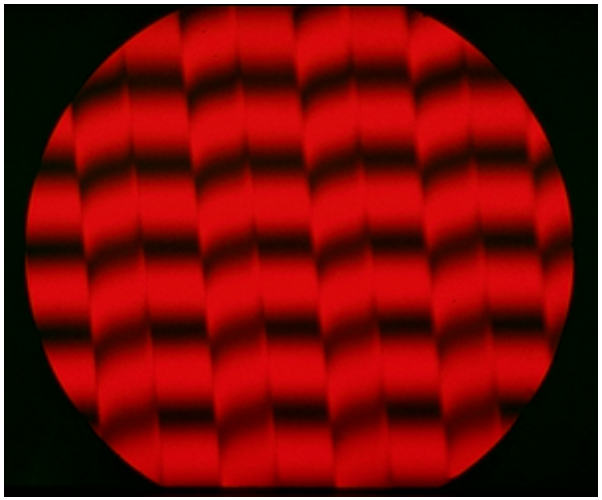


White Light Interferometry

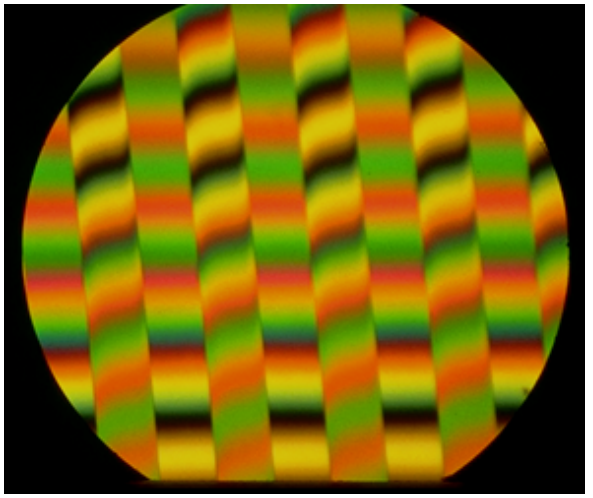
- Eliminates ambiguities in heights present with monochromatic interferometry
- Techniques old, but use of modern electronics and computers enhance capabilities and applications

Interferograms of Diffraction Grating

Quasi-Monochromatic Light



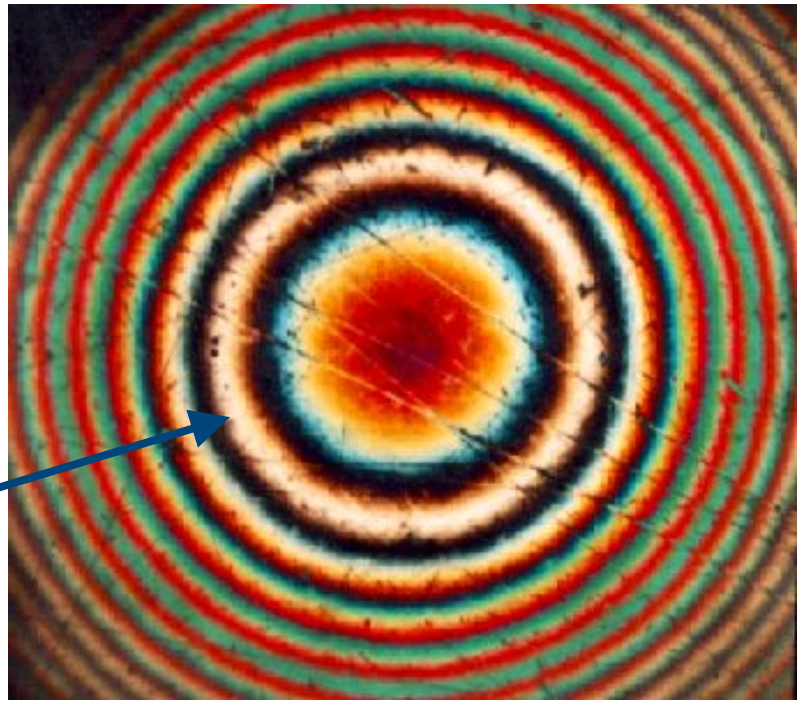
White Light



Profile

White Light Interference Fringes

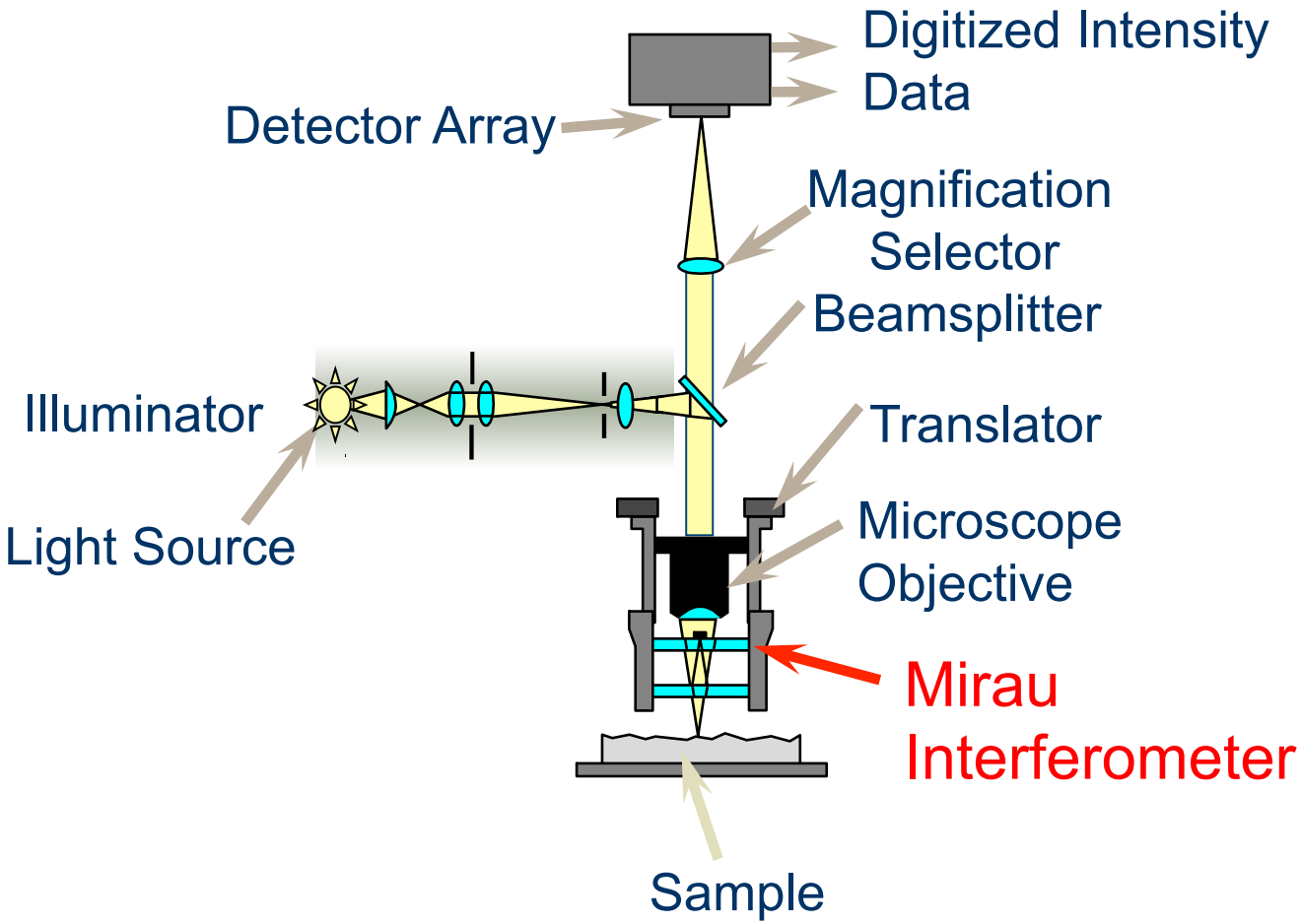
- Fringes form bands of contour of equal height on the surface with respect to the reference surface.
- Fringe contrast will be greatest at point of equal path length or "best focus."



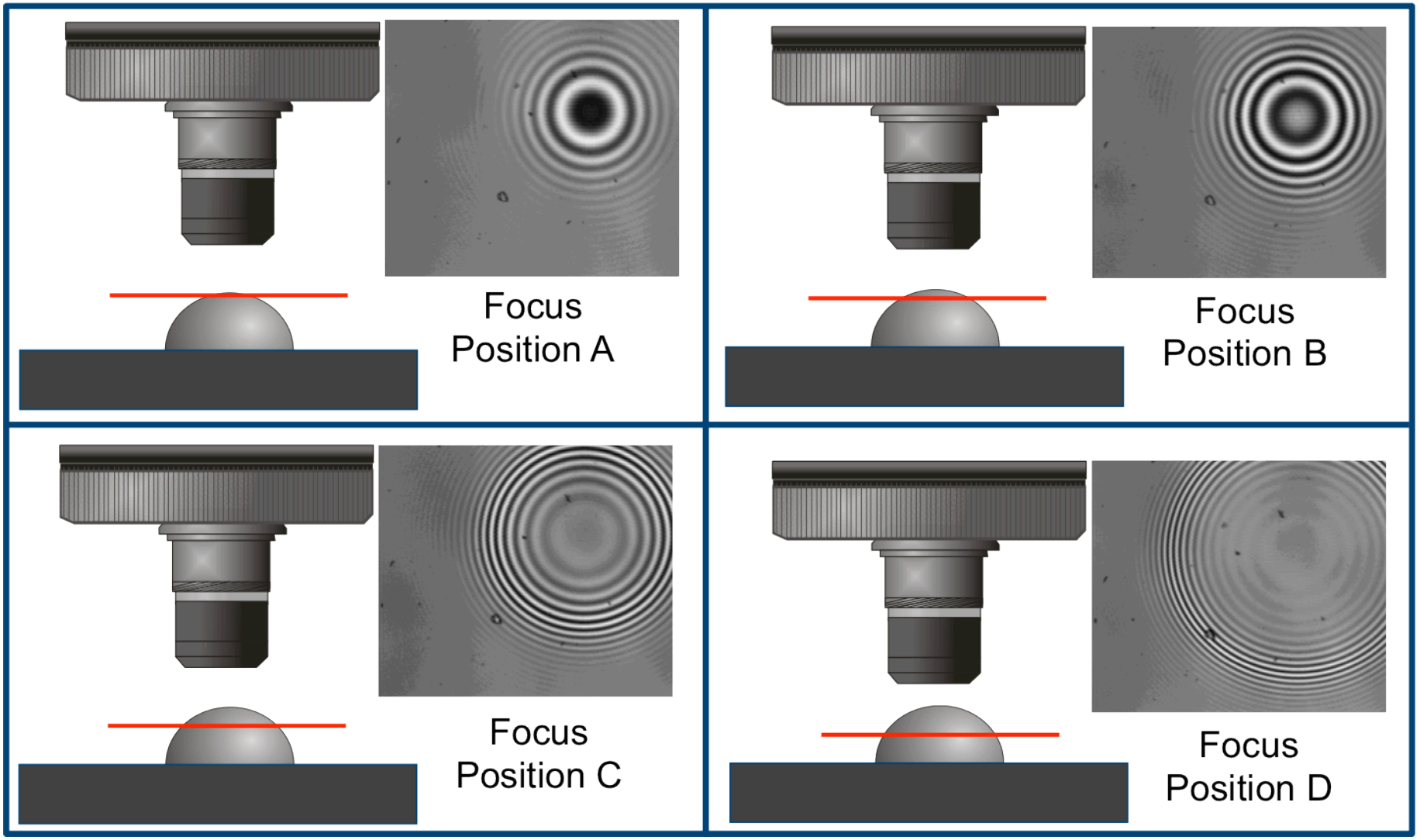
Principles of Vertical Scanning Interferometry

- 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.

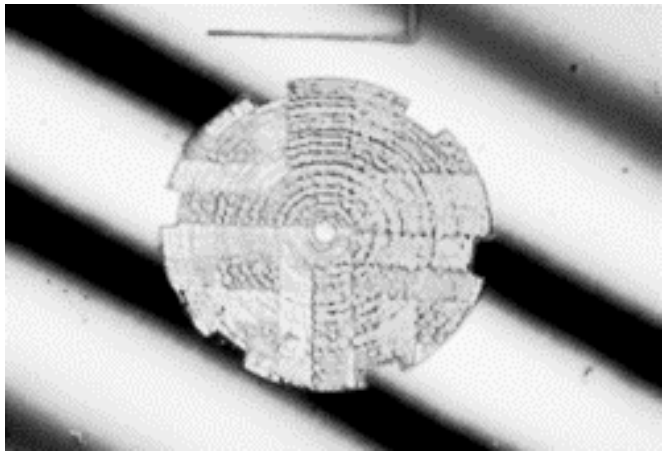
Interference Microscope Diagram



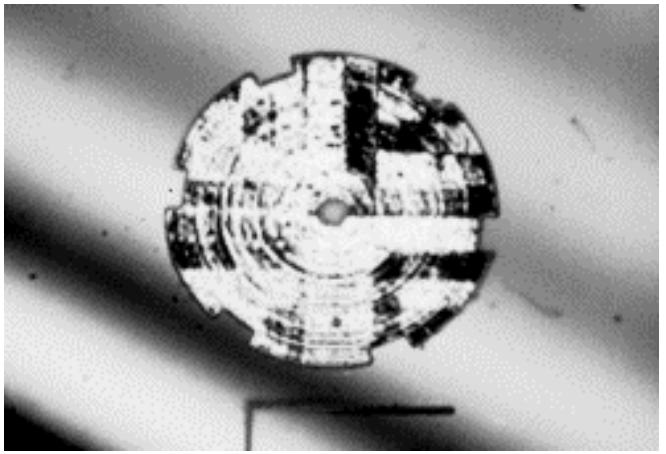
Vertical Scanning Interference Microscope



White Light Interferograms



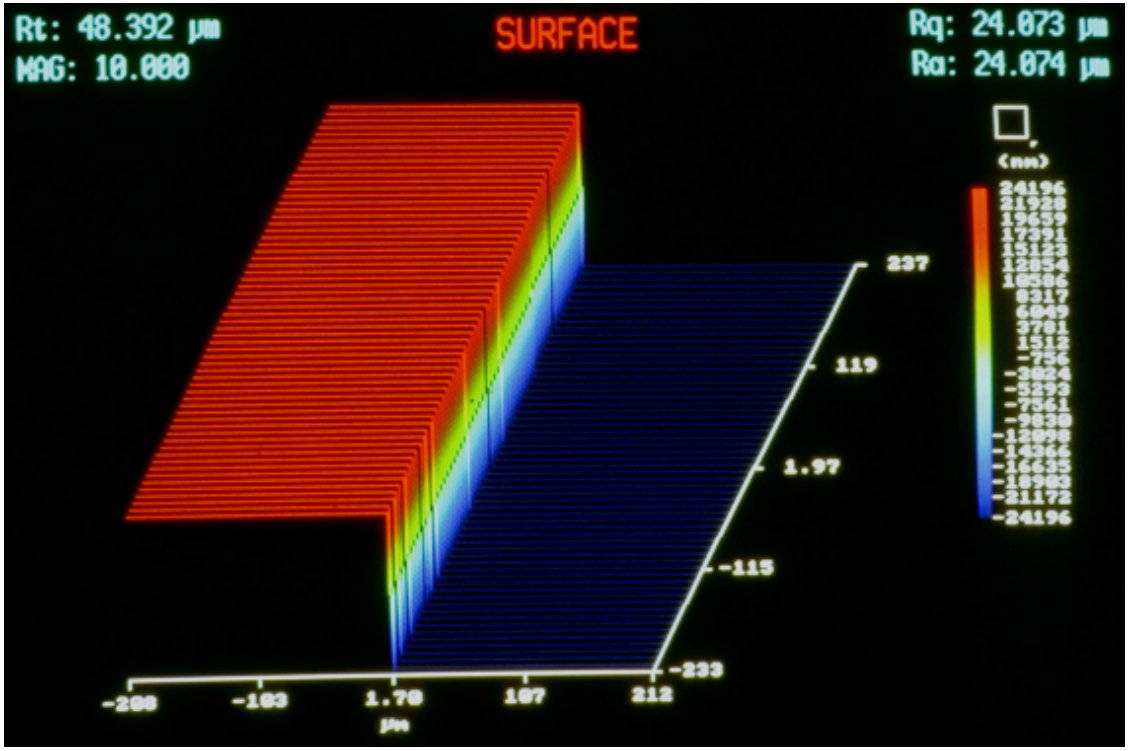
Focus Position A



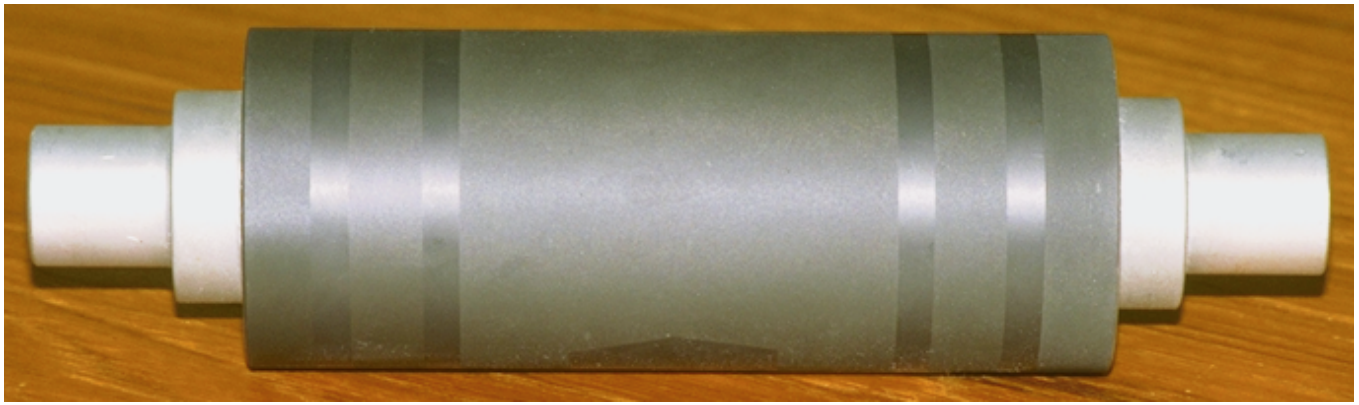
Focus Position B

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.

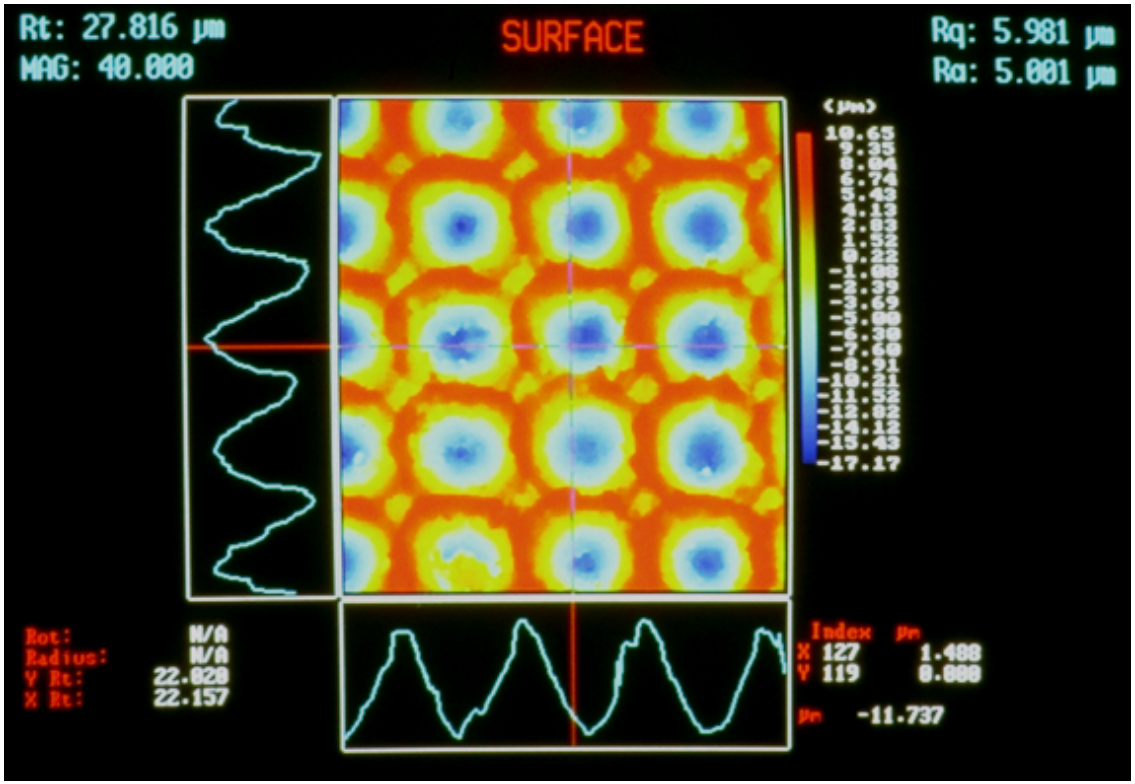
Step Measurement



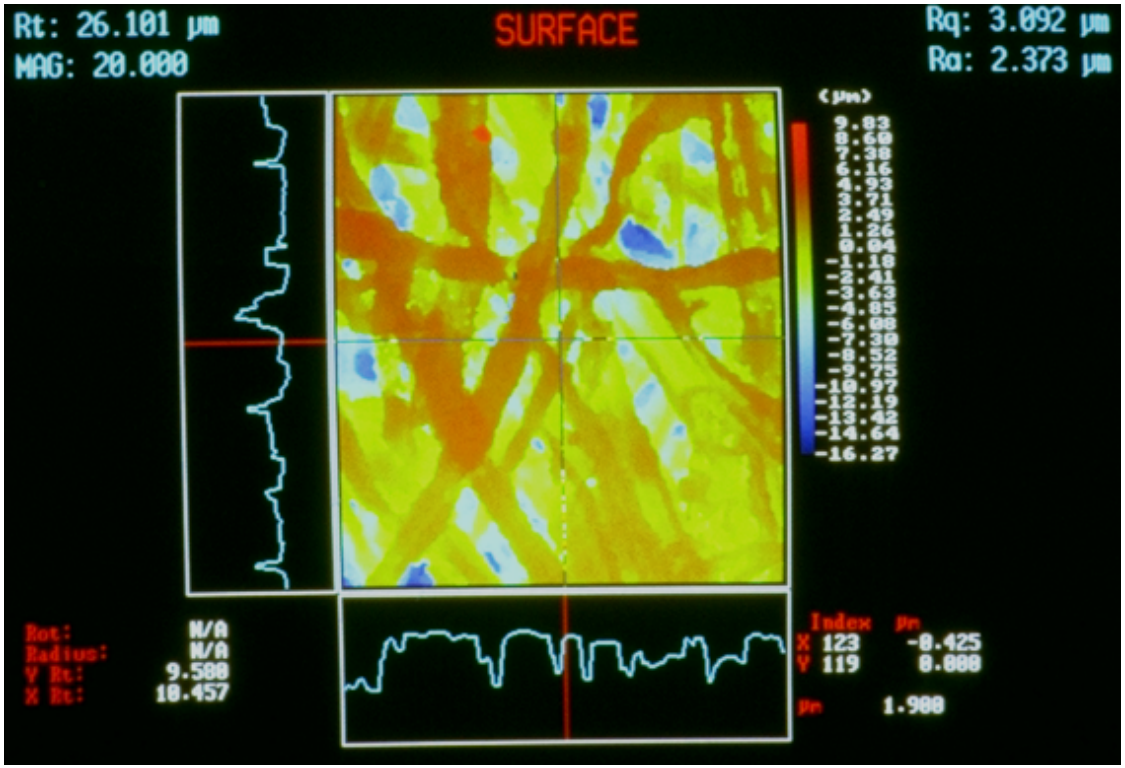
Print Roller



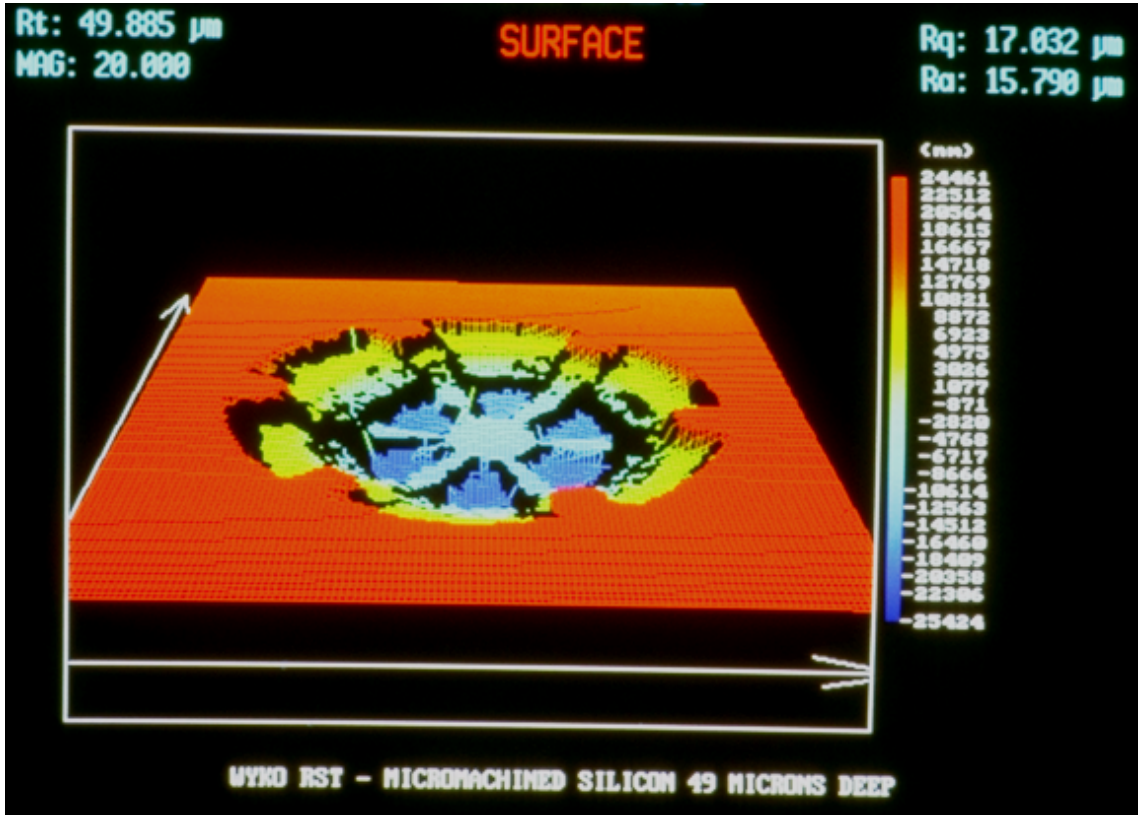
Print Roller Measurement



Paper Measurement



Micromachined Silicon Measurement

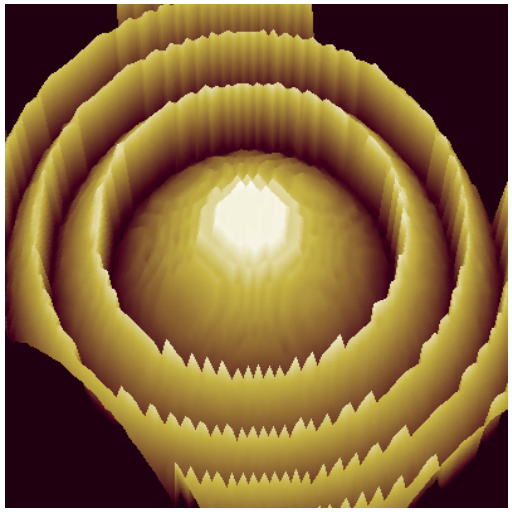


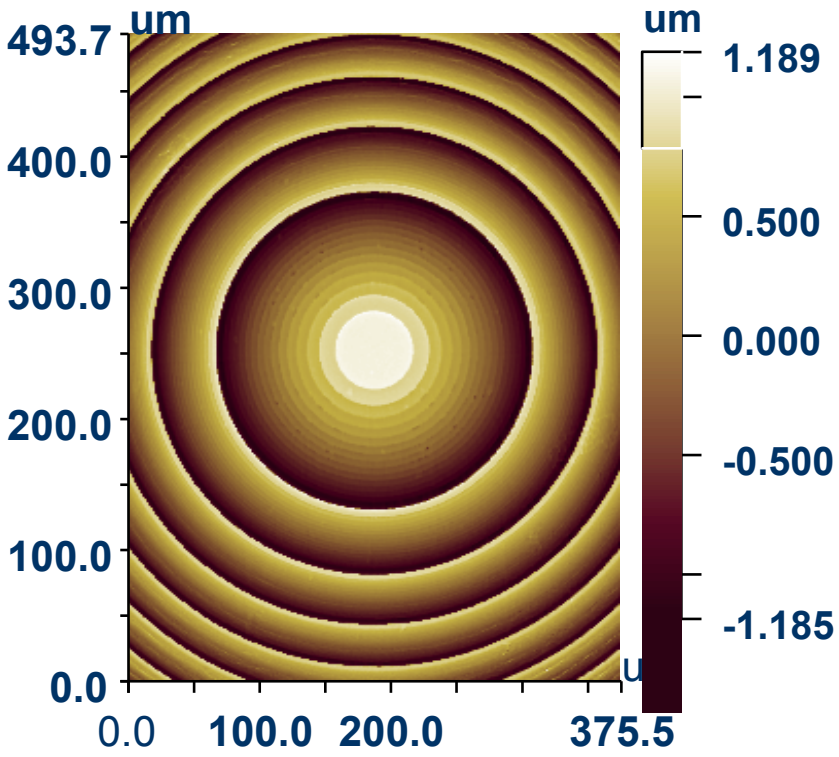
Binary Optic Lens

Surface Stats:

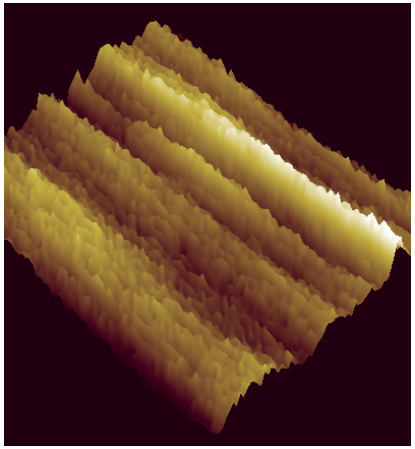
RMS: 561.30 nm

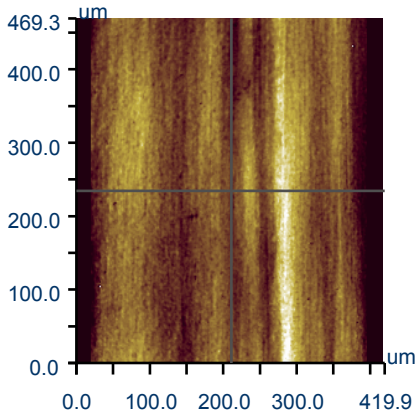
PV: 2.37 um



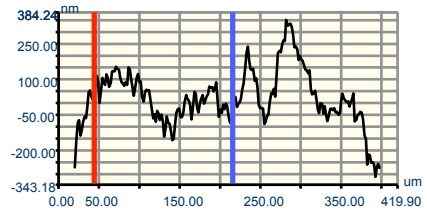


Heart Valve

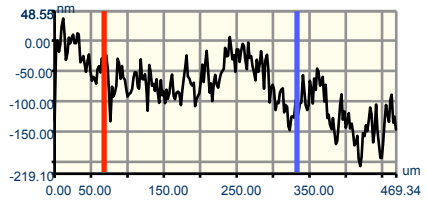




X-Profile



Y-Profile



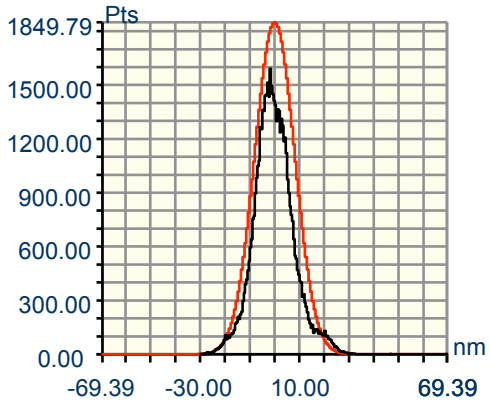
Data Statistics

Rt: 1.419 um

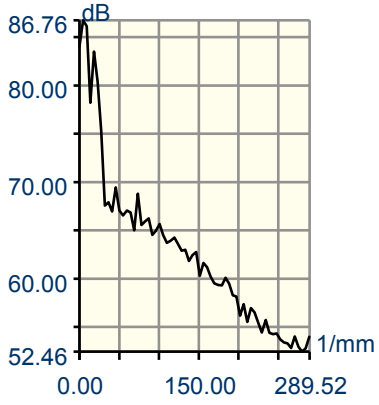
Ra: 87.391 nm

Rq: 113.942 nm

Histogram



Avg X PSD



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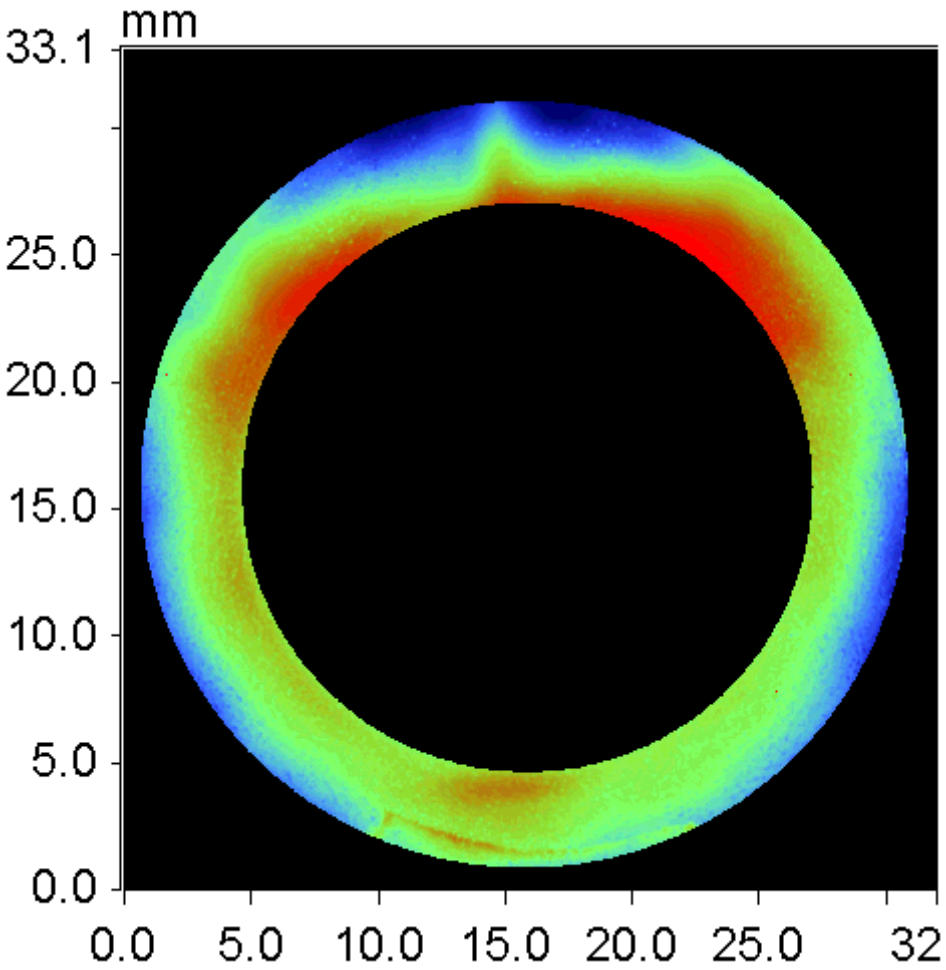
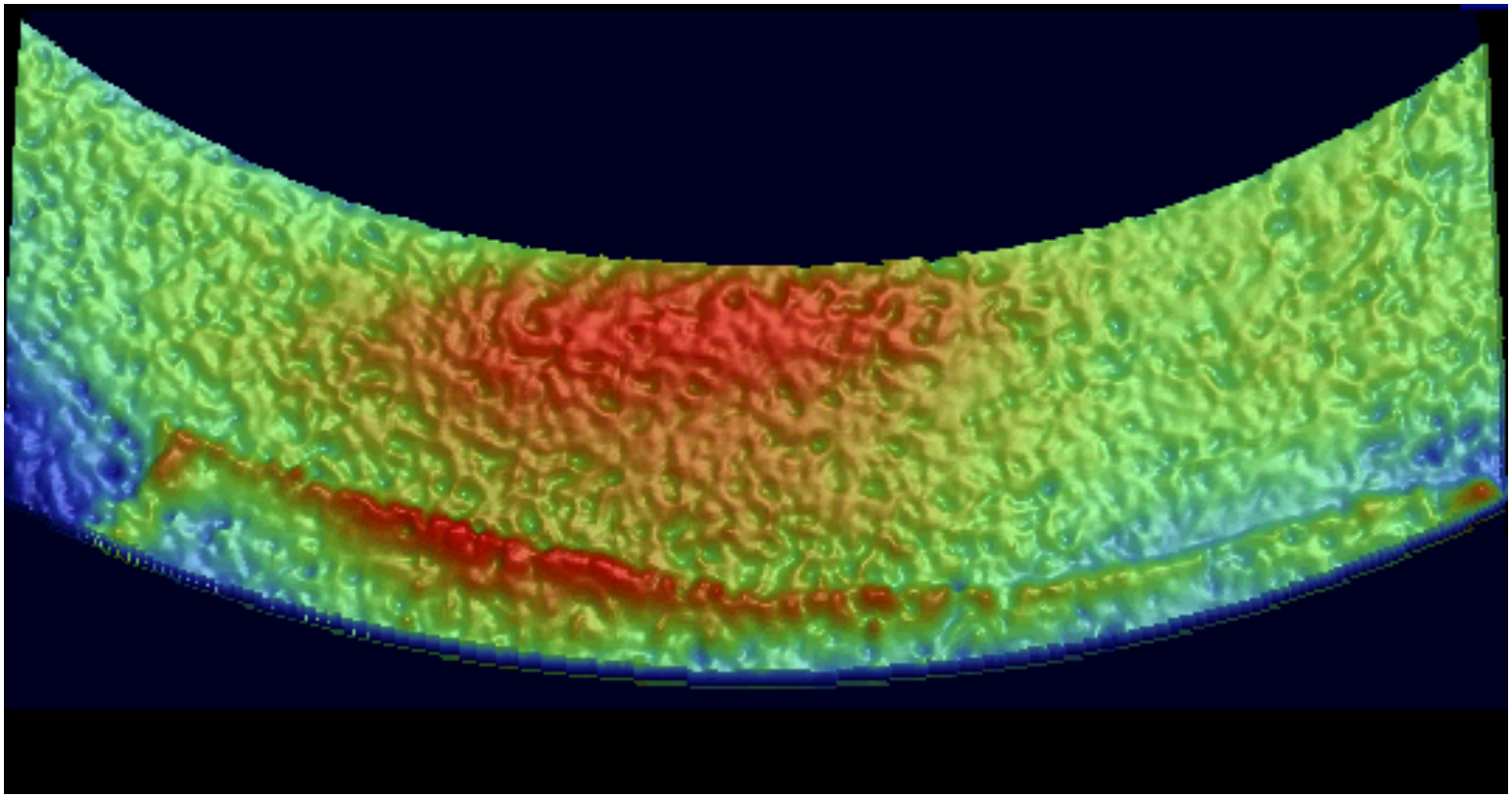
Stitched Measurement - Fuel Cap



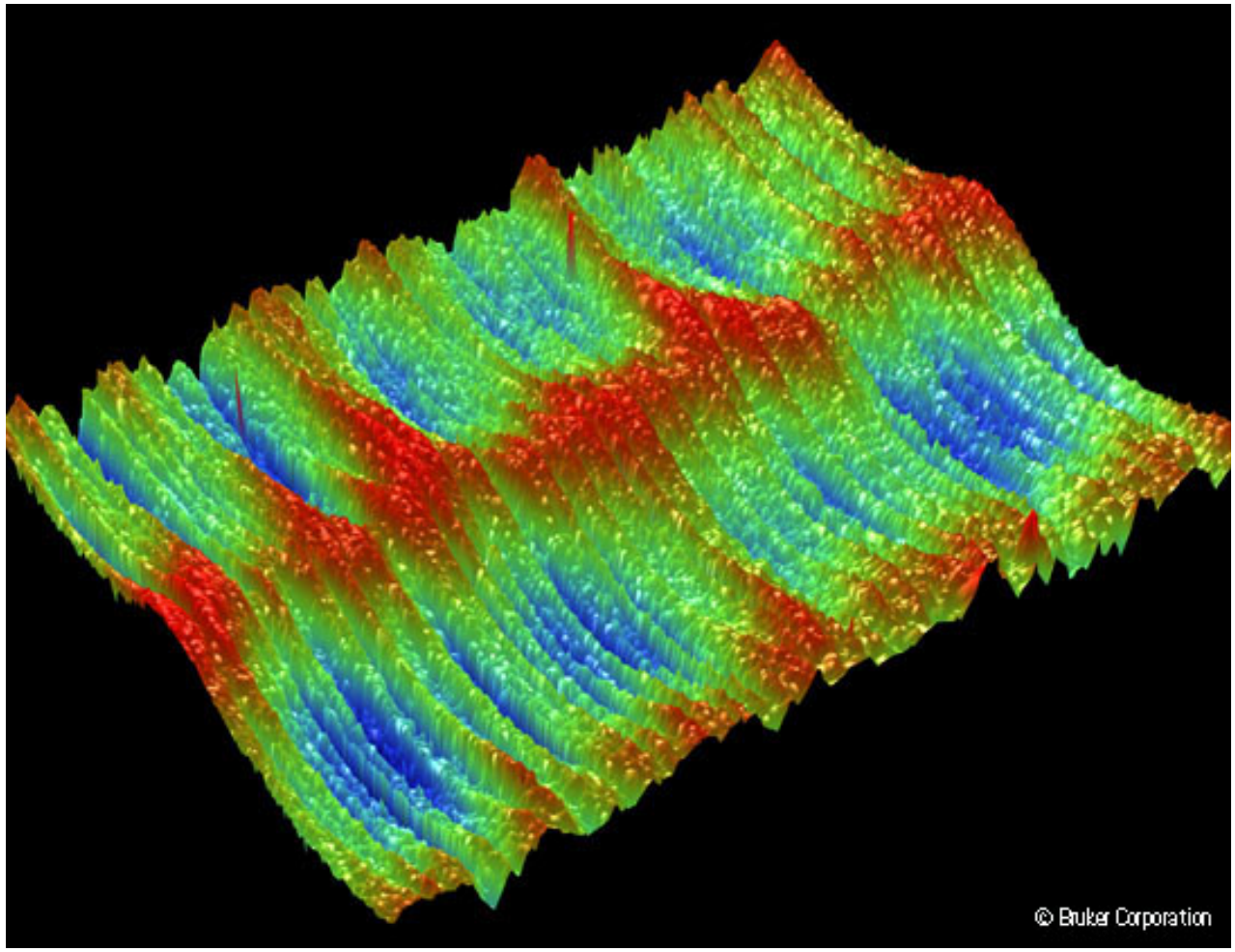
VSI
mode

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

Sub-Region of Stitched - Fuel Cap



Chatter on Camshaft



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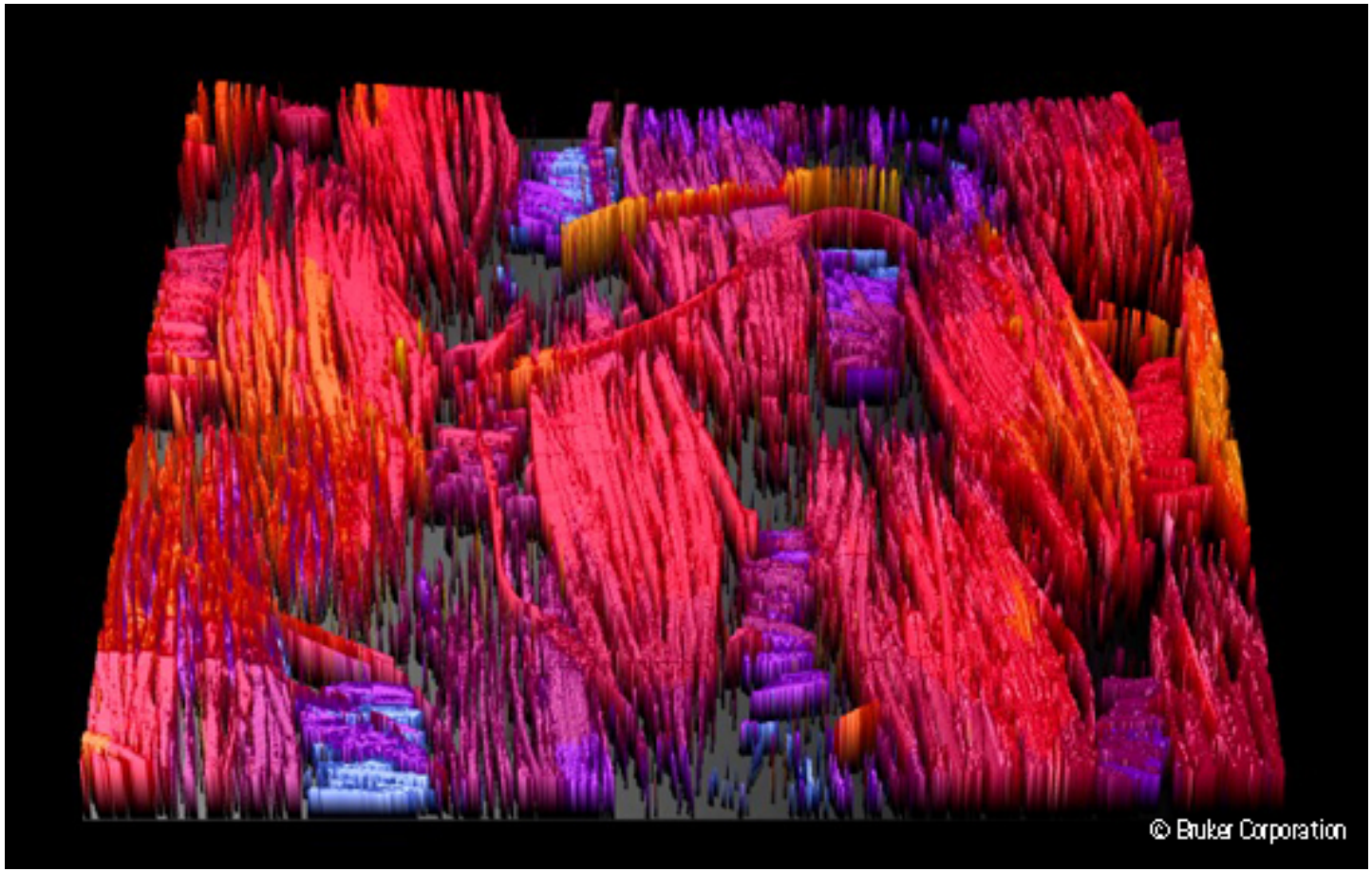
Ref: Bruker

Woven Cloth



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Ref: Bruker
2015 – James C. Wyant

Part 5 –Concluding Remarks

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

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.

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

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SPIE
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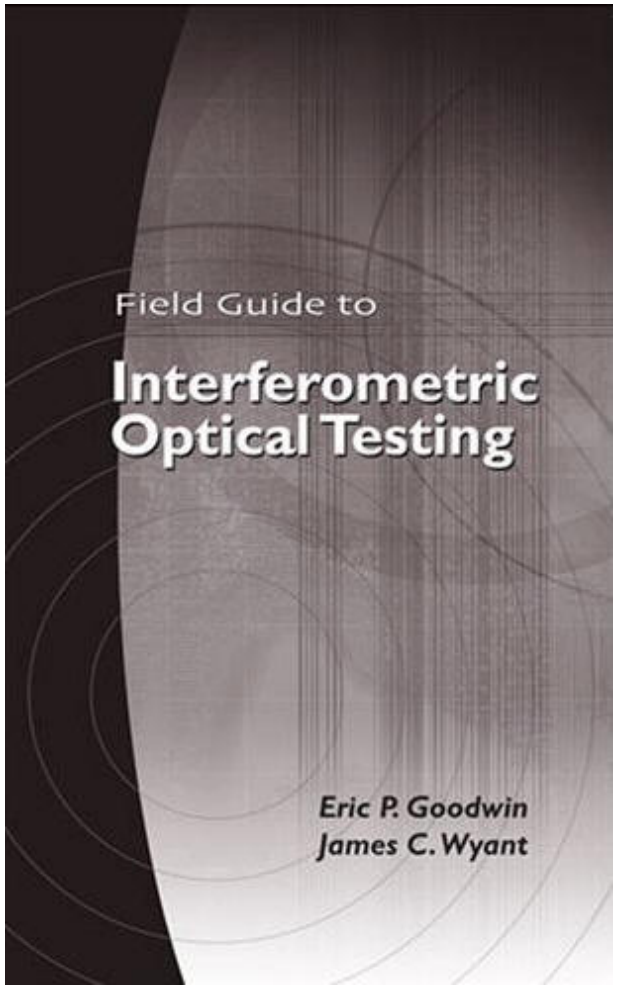
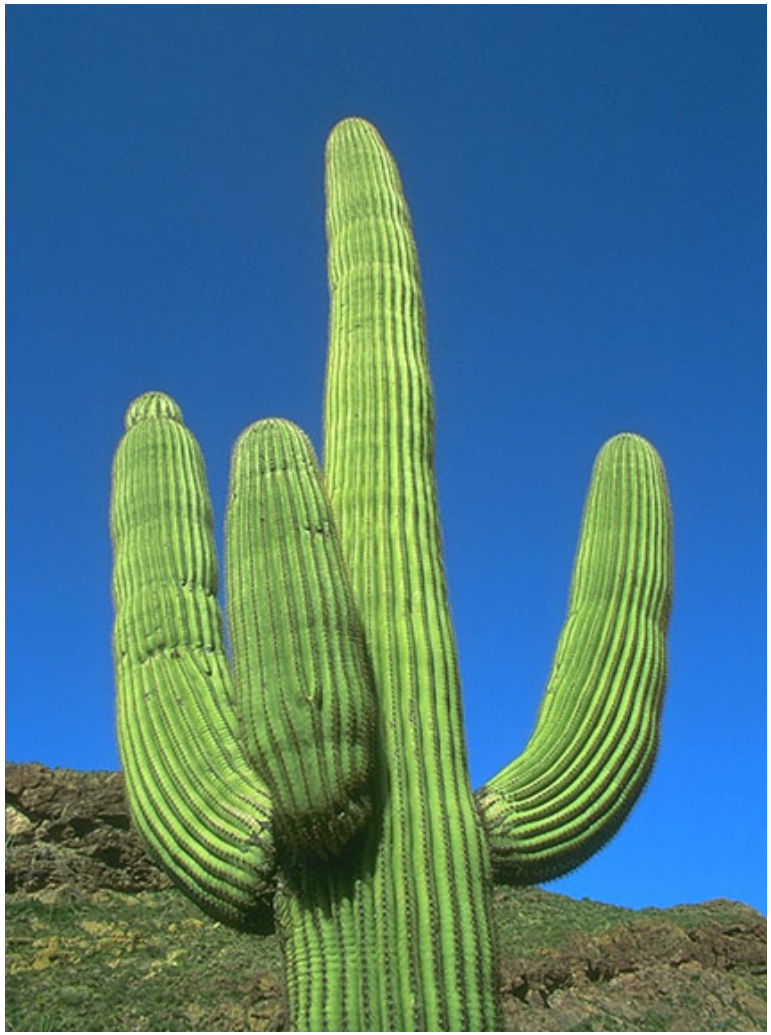
Thank you for taking the short course!