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College of Optical Sciences

7.0 Testing Flat Surface Optical Components

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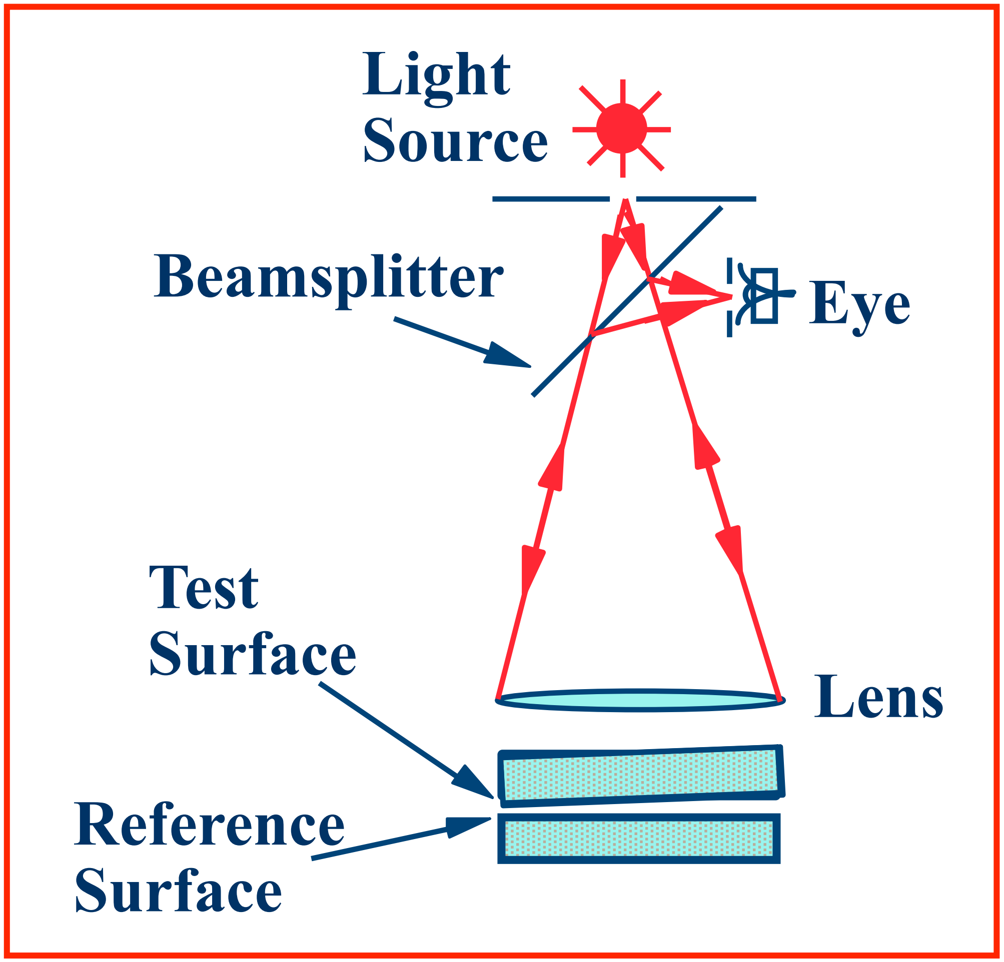
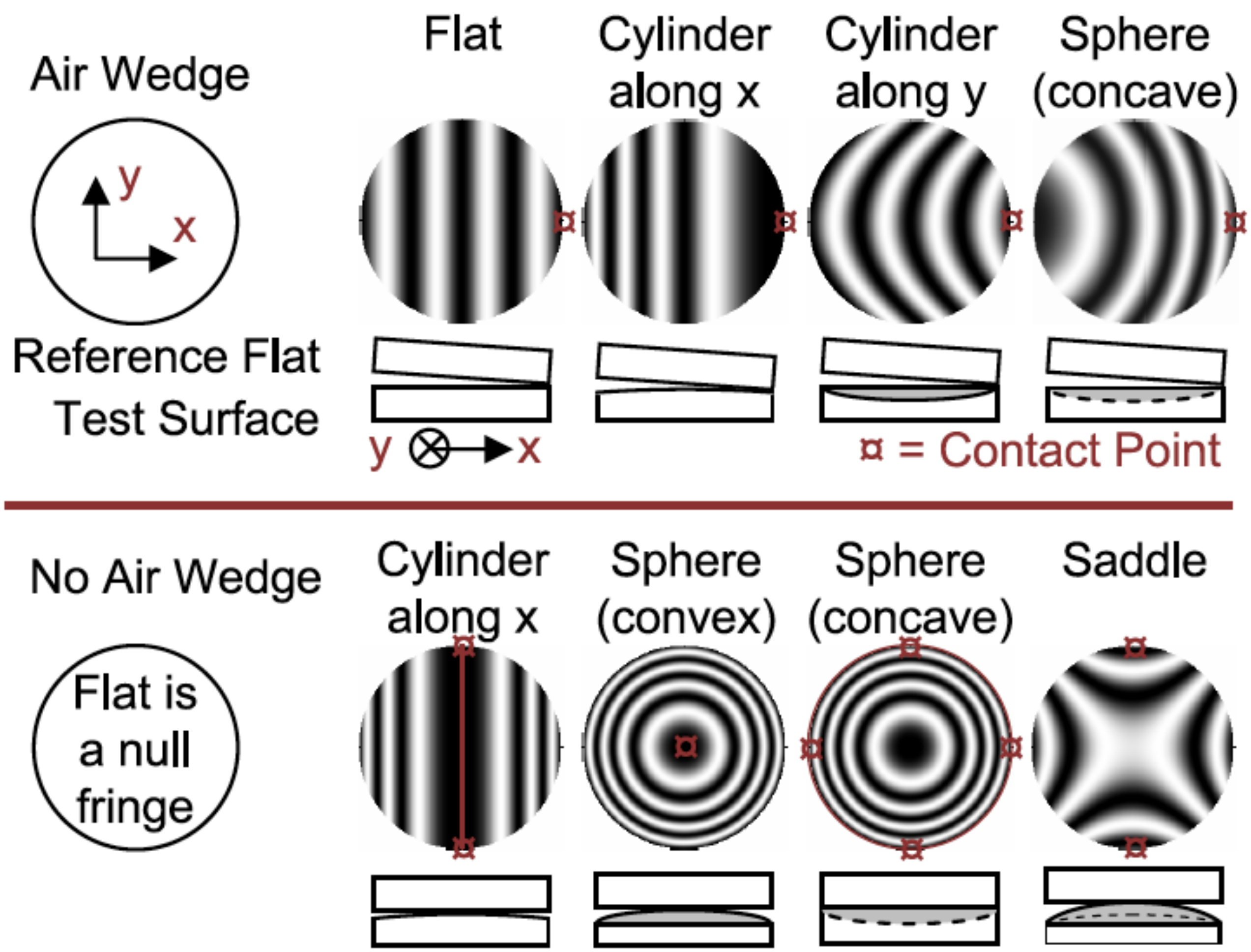
7.1 Mirrors

An interferometer is generally used to measure surface flatness. The best interferometer for a particular measurement depends upon the equipment available and the size of the sample being tested. The simplest interferometer for many surface flatness measurements is the Fizeau interferometer.

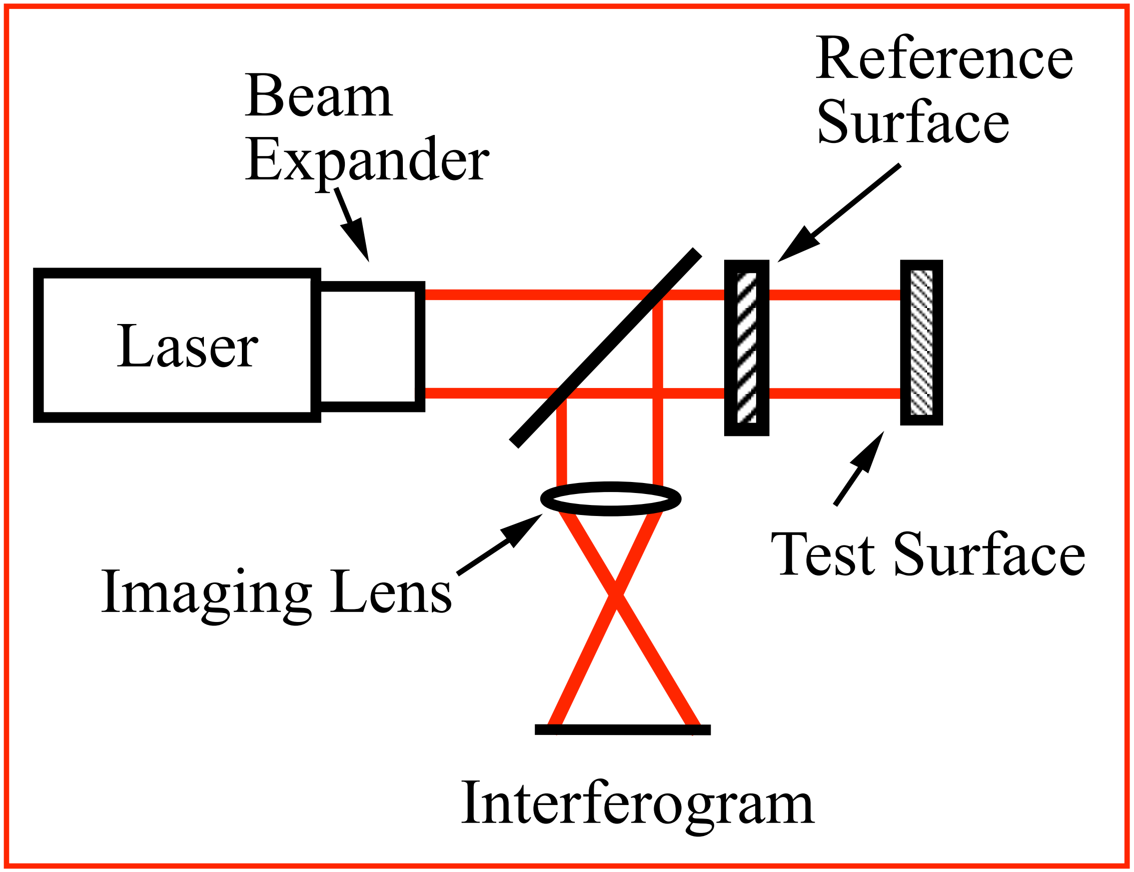
7.1.1 Fizeau Interferometer - 1862



Some Interferograms



Fizeau Interferometer-Laser Source (Flat Surfaces)



Comments on Fizeau Interferometer

- If two surfaces match for various rotations and translations
  - The two surfaces need not be flat
  - The two surfaces could be spherical, where one is convex and the second is concave
- To be sure the surfaces are indeed flat
  - Three surfaces are required, where the interference between any two gives straight equi-spaced fringes
  - This will be discussed in more detail when we discuss absolute testing in Chapter 10

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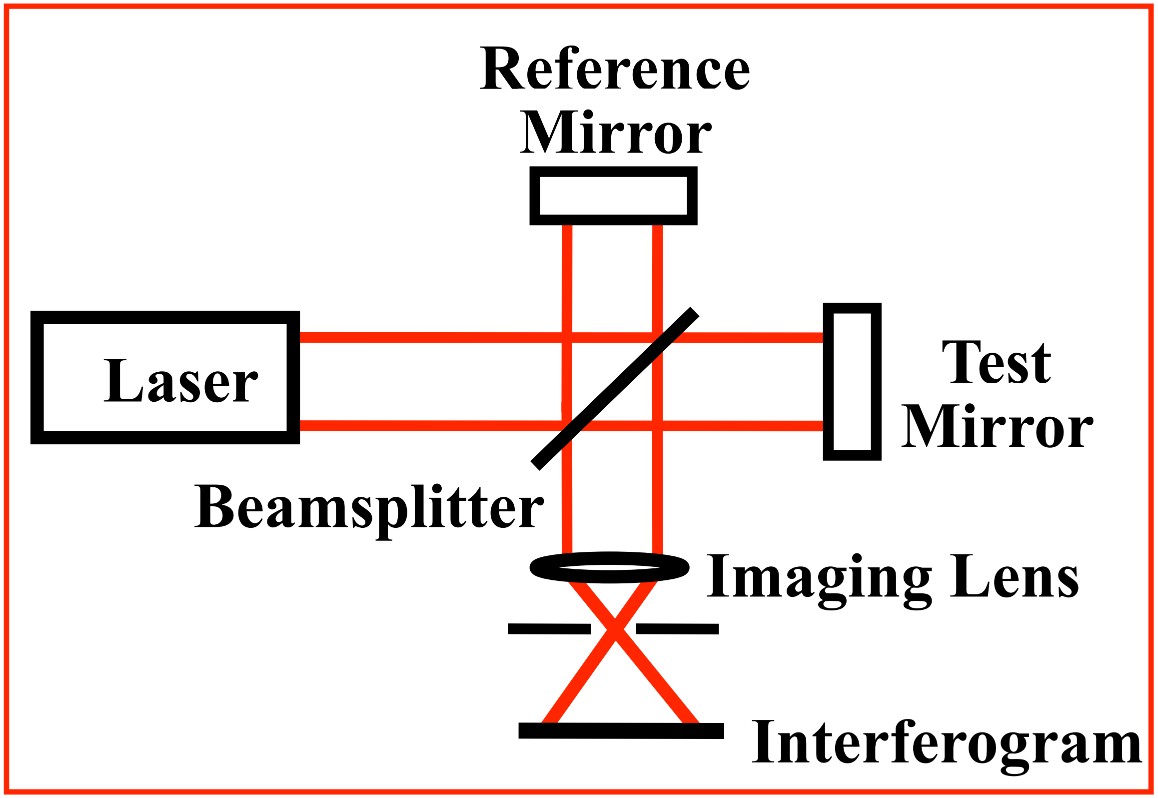
7.1.2 Twyman-Green Interferometer (Flat Surfaces)

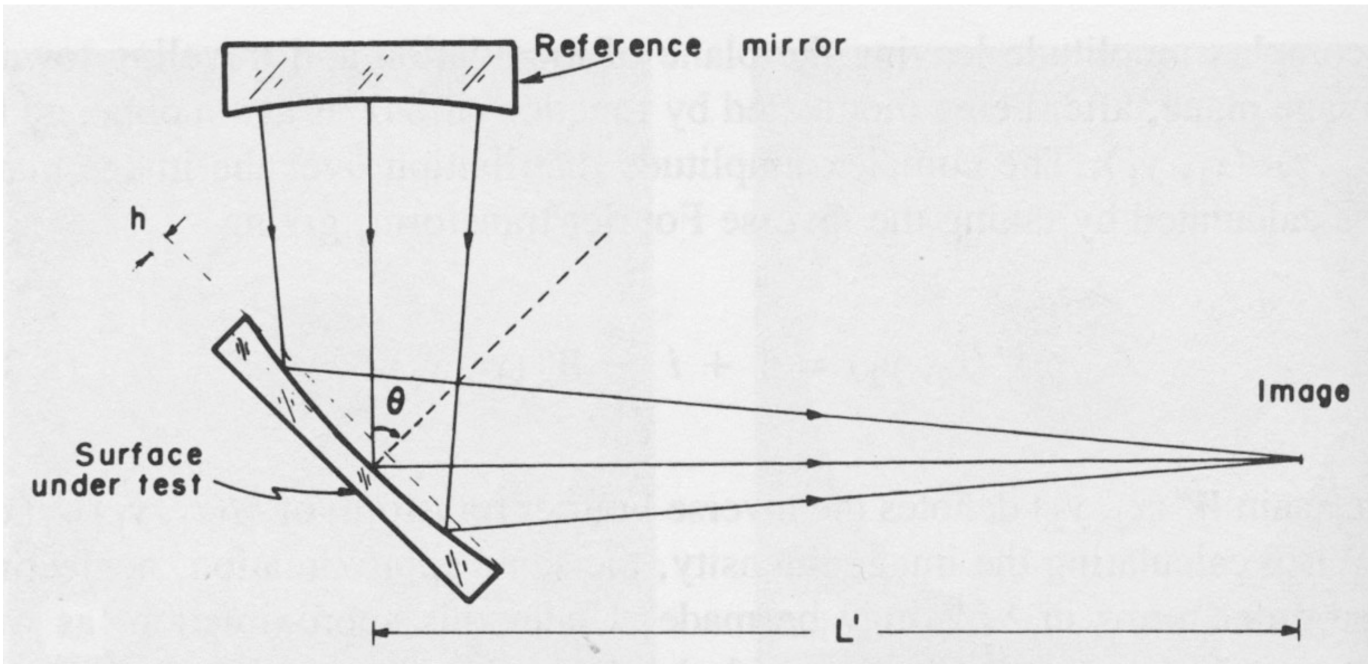
1918



Comparing Twyman-Green and Fizeau

- The Twyman-Green and Fizeau give the same interferograms for testing surface flatness
- Main advantage of the Twyman-Green is more versatility
- Main disadvantage of the Twyman-Green is that more high-quality optical components are required

7.1.3 Ritchey Common Test



Any small curvature of the surface under test appears as astigmatic aberration in the image of the illuminating point source.

Ref: Malacara – Optical Shop Testing

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Amount of Astigmatism is Very Sensitive to Curvature

- Example (See Malacara for details)
  - 1.5 m diameter flat
  - 60^{o} angle of incidence
  - 5 m between source and flat
  - 300 km radius of curvature
  - The sag is about 1.7 λ ~ 1 μm
  - Results in 250 microns between S and T foci

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Advantages and Disadvantages

- **Advantages**
  - – Flat not required
  - – Very sensitive to small curvature
- **Disadvantage**
  - – Difficult to measure small irregularities because OPD introduced by irregularity reduced by cosine of incident angle

Note: If null test is obtained the mirror may not be a flat, it might be a hyperbola. To check to make sure mirror is flat rotate the flat 90° and repeat the test.

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7.1.4 Naked Eye Test

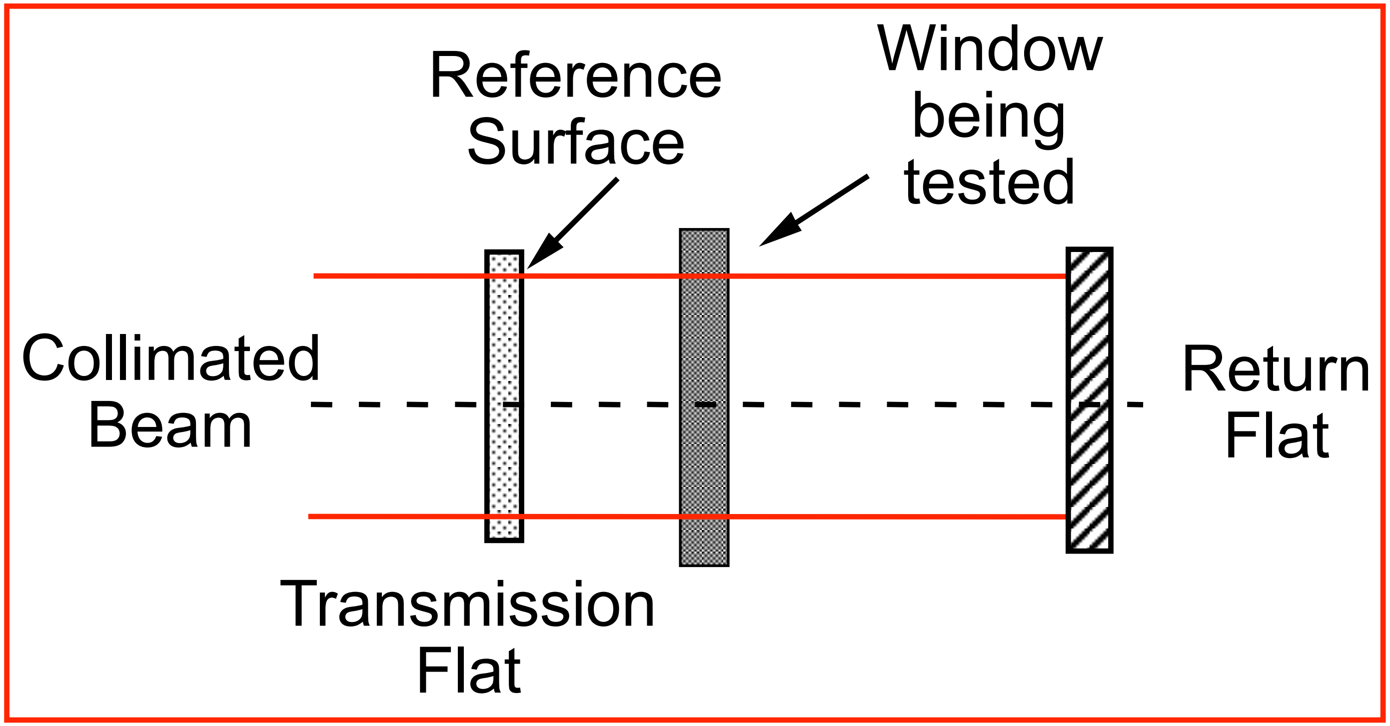
- If curvature then astigmatism and dots of either the vertical or horizontal line merge into a grey line.
- Estimated that a naked eye can detect a radius of curvature up to about ten thousand times the length of the surface used to reflect light into the eye.

Ref: Johnson, Optics and Optical Instruments

7.2 Windows

- The most common instrument for testing windows in transmission or measuring the surfaces is an interferometer.
- For the measurement of window parallelism both interferometers and autocollimators are used.

7.2.1 Interferometer Test of Windows in Transmission



δt = window thickness variations

OPD measured = 2 (n-1) δt

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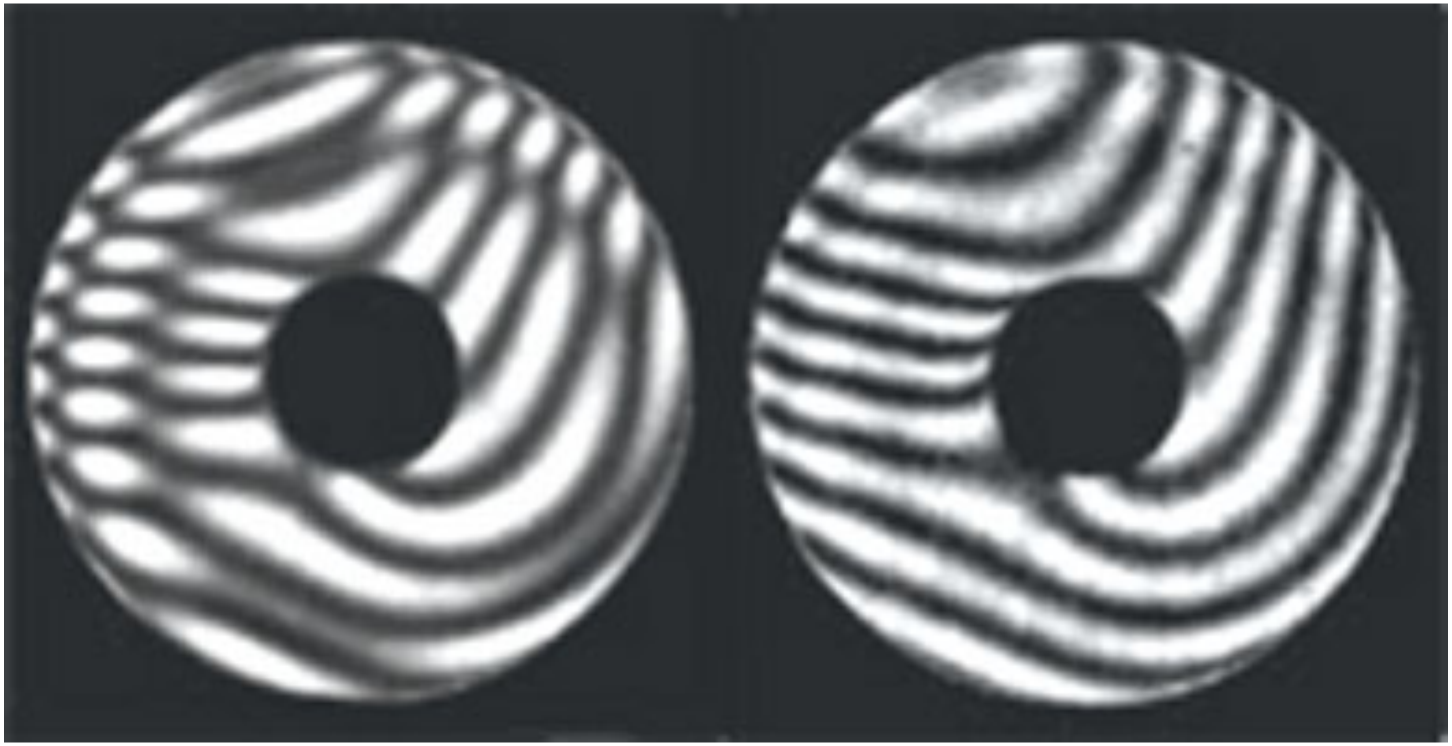
Problem Measuring Windows Having Small Wedge

- Spurious interference fringes are obtained if a long coherence length source (laser) is used to measure windows having a small wedge.
- Can use a short coherence source to reduce this coherence noise.
- Spurious interference fringes from other reflections in the test setup are also reduced.

Use Short Coherence Source to Reduce Coherent Noise

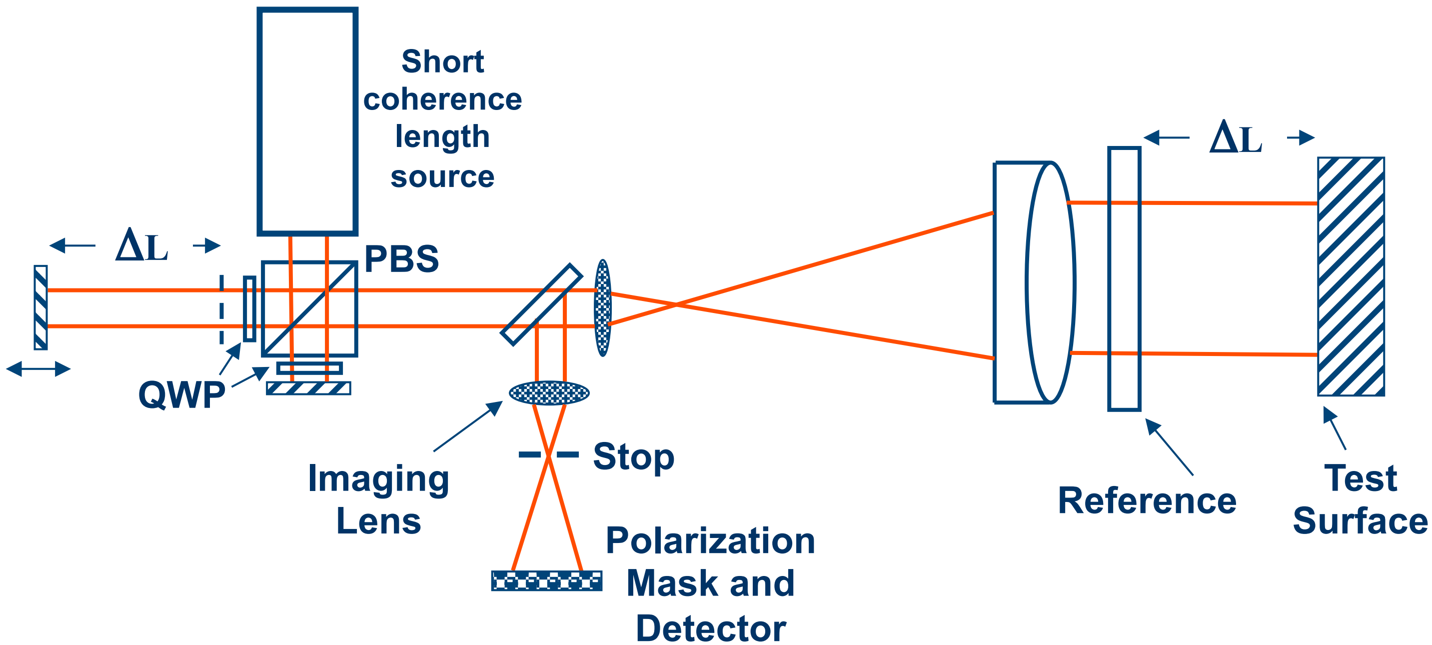
Interference Fringes Obtain Testing a Thin Glass Plate



a) Long coherence length source

b) Short coherence length source

Simultaneous Phase-Shifting Fizeau – Short Coherence Length Source

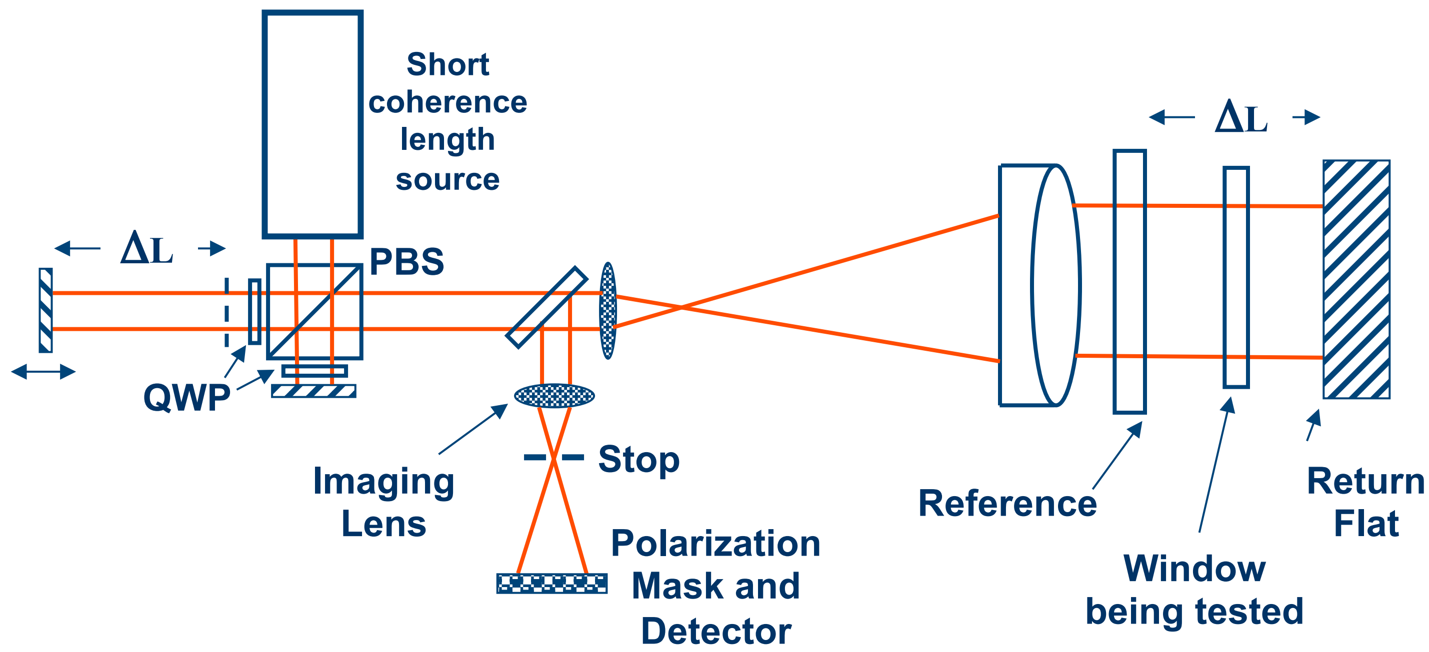


Interference pattern resulting from long path length source beam reflected off reference and short path length source beam reflected off test surface.

Test and reference beams have orthogonal polarization.

Fewer spurious fringes.

Testing Glass Sample – Short Coherence Length Source



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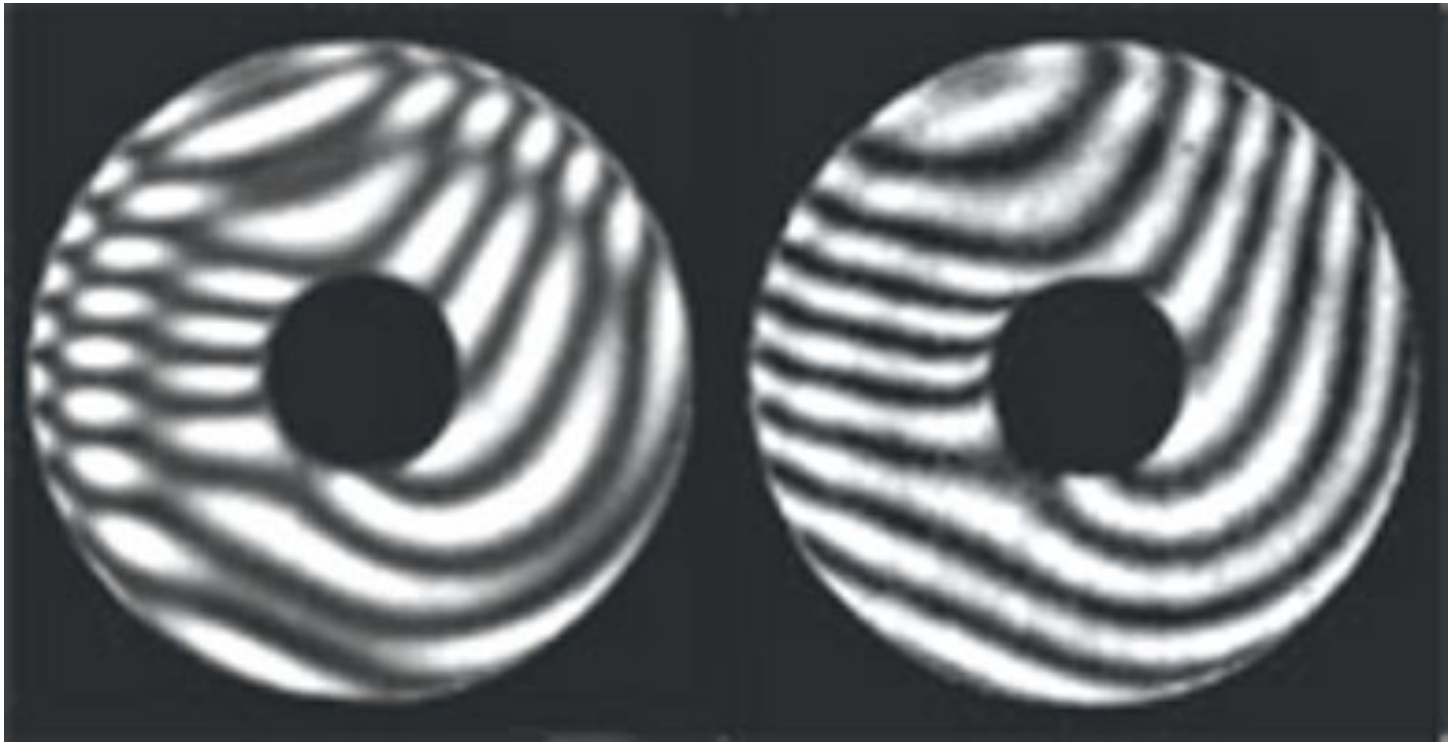
Interference Fringes Obtain Testing a Thin Glass Plate



a) Long coherence length source

b) Short coherence length source

Measuring Window Wedge

- Same approach can be used to measure window surface parallelism (wedge).
- First adjust the interferometer so a single interference fringe covers the interference field. Place the window in the interferometer and if an appropriate amount of wedge is present interference fringes will be observed.
- The OPD introduced for window of diameter D, refractive index n, and wedge, α, is given by

$$OPD = 2(n-1)\alpha D$$

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Window Wedge – Fringe Spacing

- The fringe spacing, S, is given by

$$S = \frac{\lambda}{2(n-1)\alpha}$$

- Same result for testing in Mach-Zehnder except no 2 in the denominator.
- Another approach is to look at fringes formed by the interference of the wavefronts reflected off the two surfaces of the sample. The fringe spacing is given by

$$S = \frac{\lambda}{2n\alpha}$$

Fringe Spacing as Function of Wedge Angle

Fringe spacing as a function of wedge angle α for $n = 1.5$ and $\lambda = 633$ nm				
α (sec)	S (mm)	1/S (1/mm)	S (mm)	1/S (1/mm)
	Double Pass Transmission		Reflection	
1	126.6	0.008	42.20	0.024
5	25.32	0.039	8.44	0.118
10	12.66	0.079	4.22	0.237
30	4.22	0.237	1.41	0.711
60	2.11	0.474	0.70	1.422

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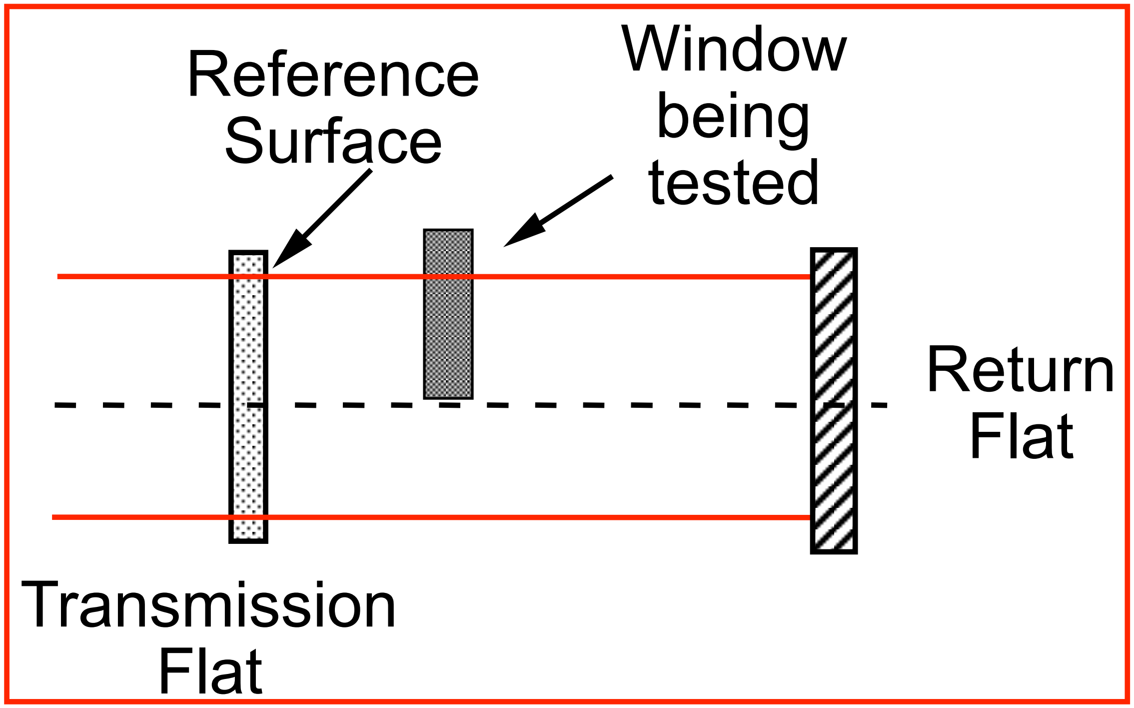
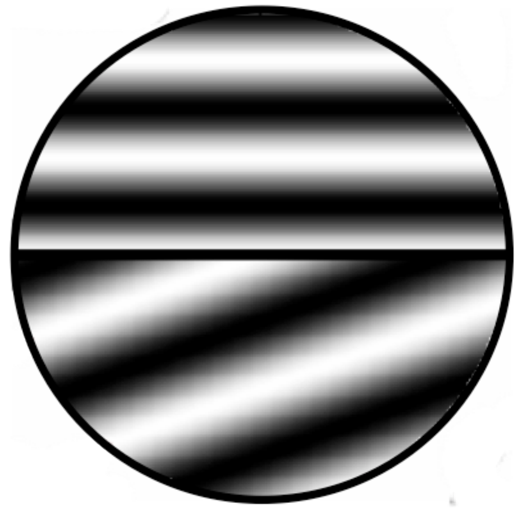
Measuring Window Wedge
A Better Approach



Tilt difference between two interferograms gives window wedge.

Calculating Window Wedge

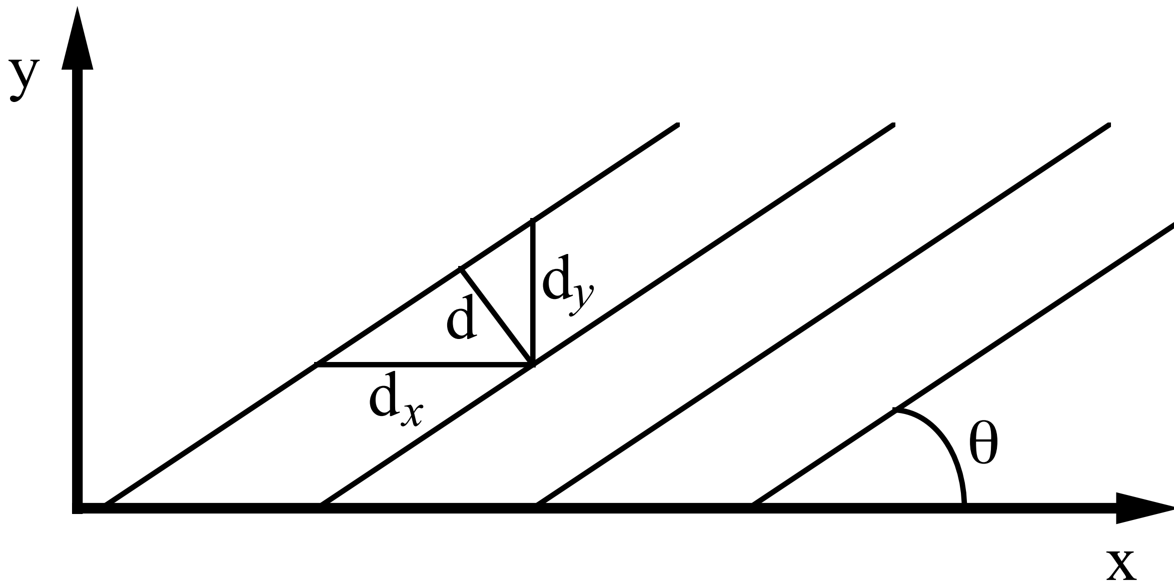
Tilt difference between two interferograms gives window wedge.



α = window wedge

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

Calculation of Tilt

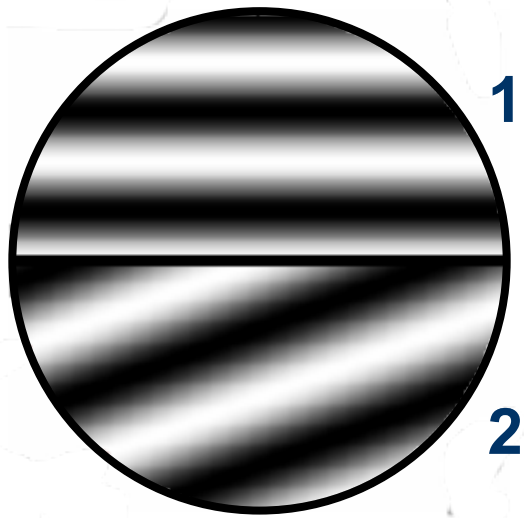


d = fringe spacing $\quad d_x = d / \sin\theta \quad d_y = d / \cos\theta$

$$\boxed{\beta = \text{Tilt} = \frac{\lambda}{d}}$$

$$\boxed{\beta_x = \frac{\lambda}{d_x} \qquad \beta_y = \frac{\lambda}{d_y}}$$

Calculation of Tilt Difference



1 Tilt β_{x1}, β_{y1}

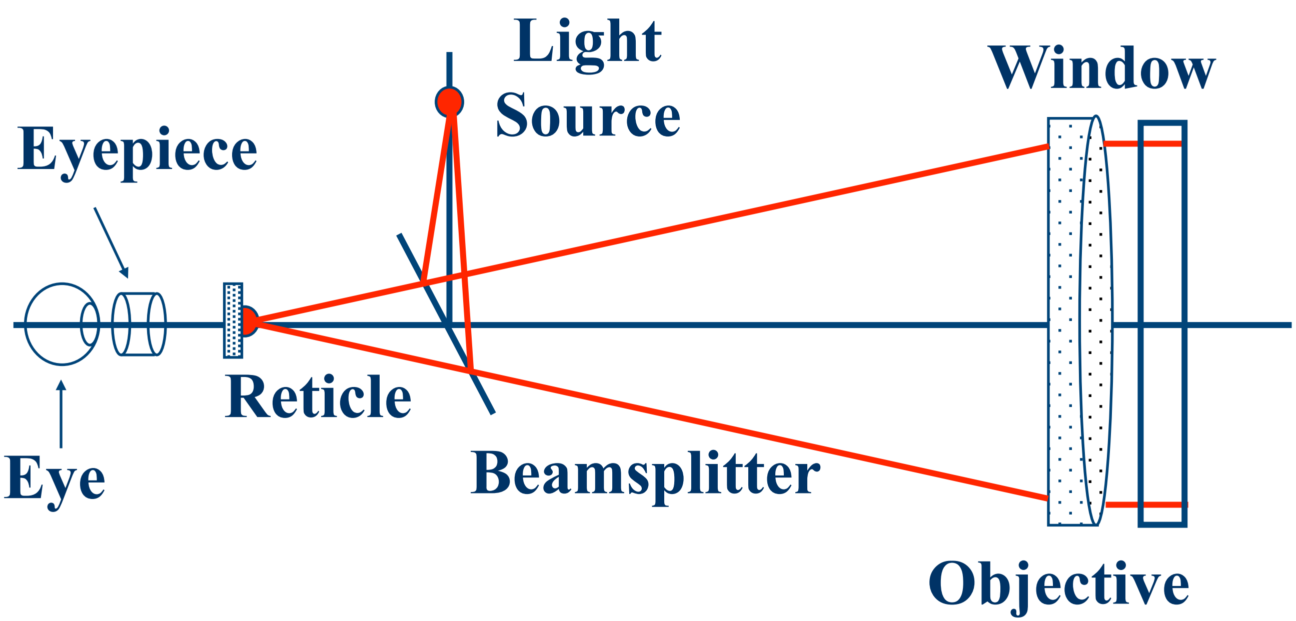
2 Tilt β_{x2}, β_{y2}

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

7.2.2 Use Autocollimator to Measure Wedge

- In autocollimator a reticle is projected to infinity and a mirror in the path of the beam reflects back the image of the reticle to the focal plane of autocollimator. Position of image depends upon relative inclination of mirror and autocollimator. If relative inclination varies by angle θ, the image moves through angle 2θ.
- Accuracy is 1 sec of arc or better.
- To measure parallelism use autocollimator to observe reflections off two surfaces of sample and measure the angular distance between two reflections. If α is wedge angle, angular distance is $2n\alpha$. Generally autocollimator already accounts for the factor of 2.

Autocollimator



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7.3 Prism Testing

7.3.1 Interferometer
7.3.2 Goniometer
7.3.3 Autocollimator
7.3.4 Naked Eye Tests

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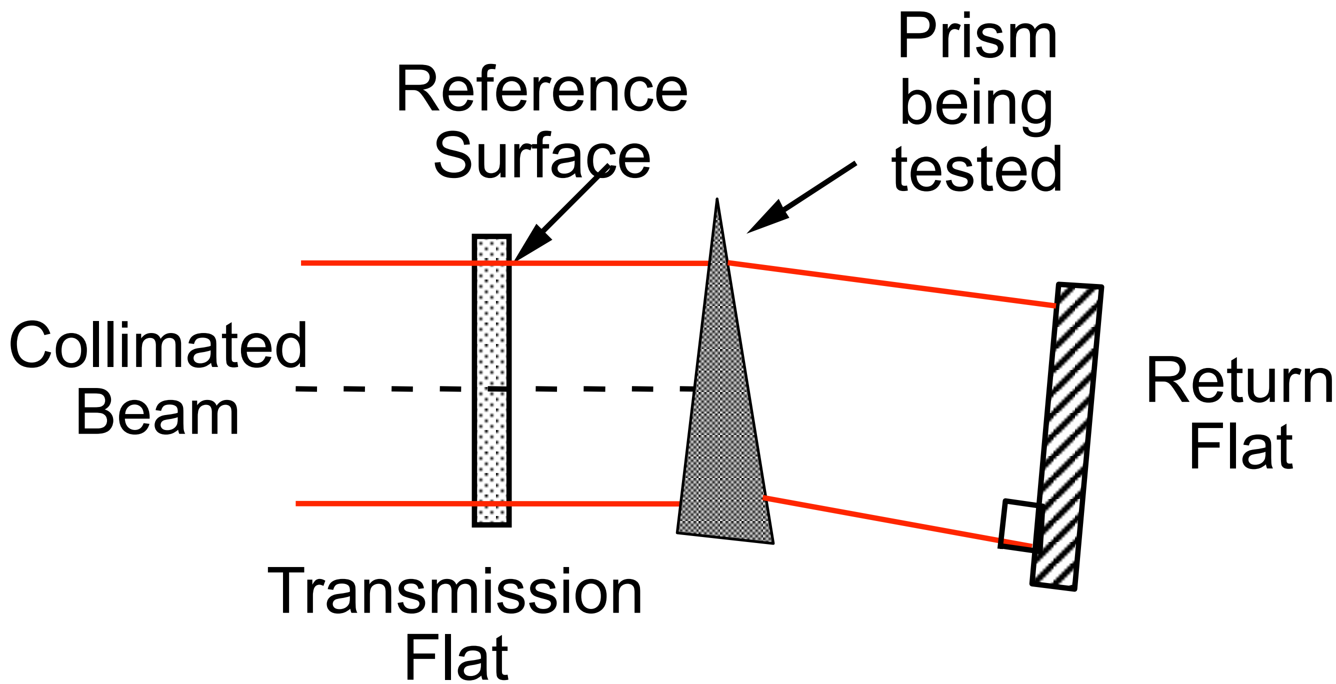
7.3.1 Interferometer Test of Prisms

Test Parameters

1. Surface accuracy of each face
2. Accuracy of angles
3. Material homogeneity
4. Transmitted wavefront accuracy

Testing Prisms in Transmission



δt = error in prism thickness

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

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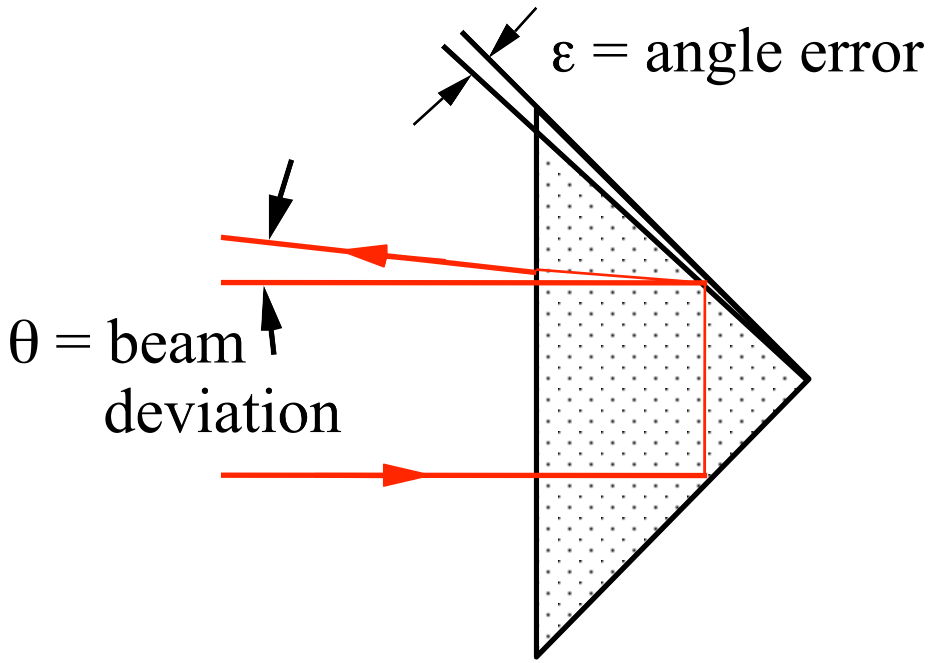
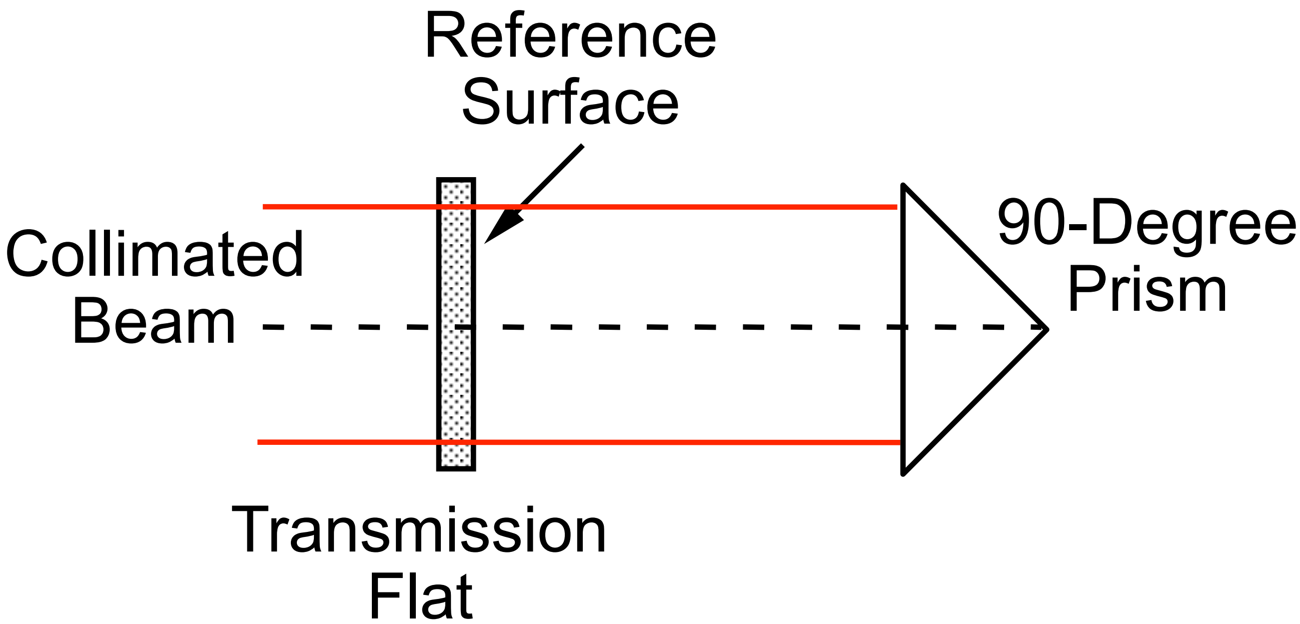
Angle Accuracy of 90-Degree Prisms



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

Testing 90-Degree Prisms (Single Pass)

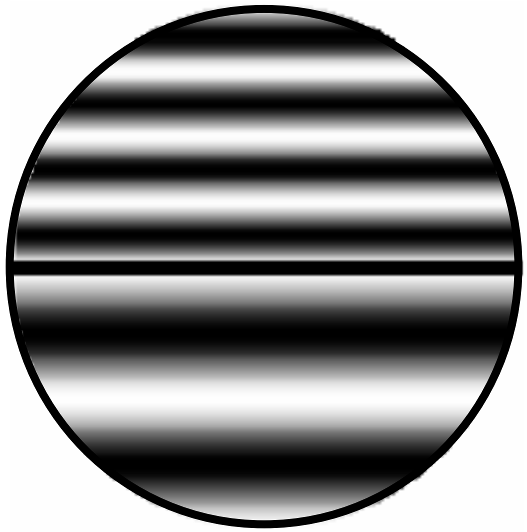


Tilt difference between two interferograms gives error in 90-degree angle.

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

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

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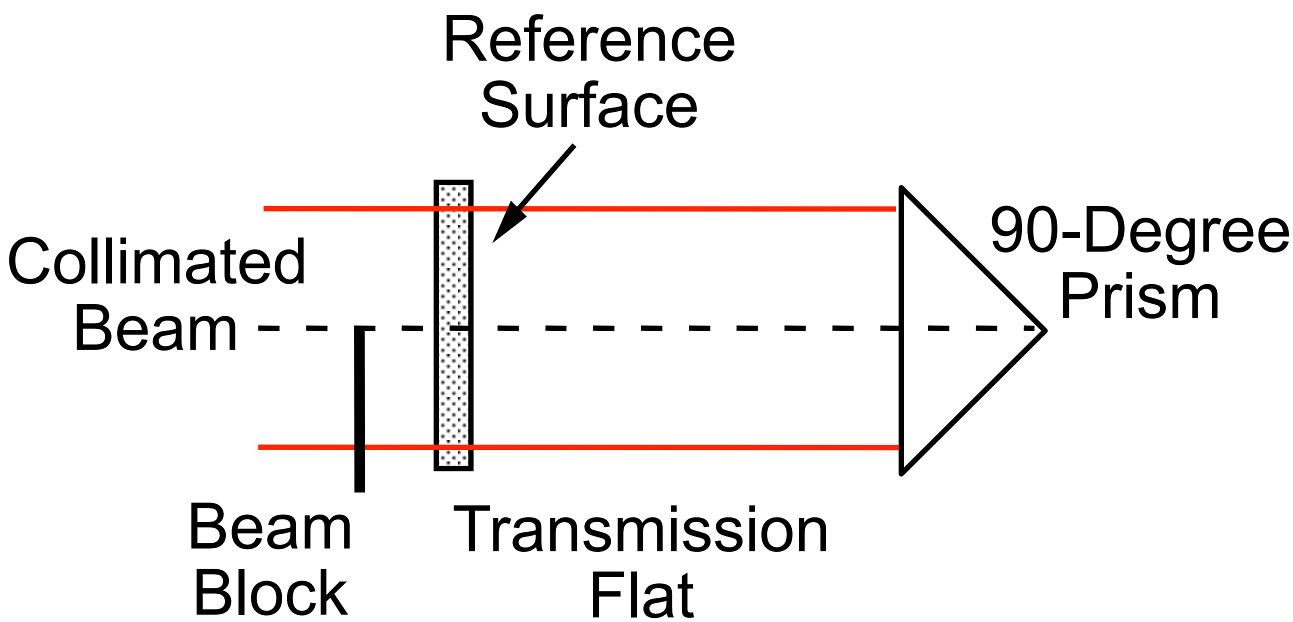
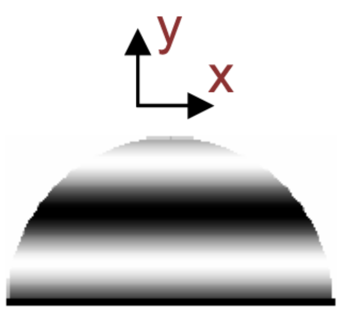
Testing 90-Degree Prisms (Double Pass)





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

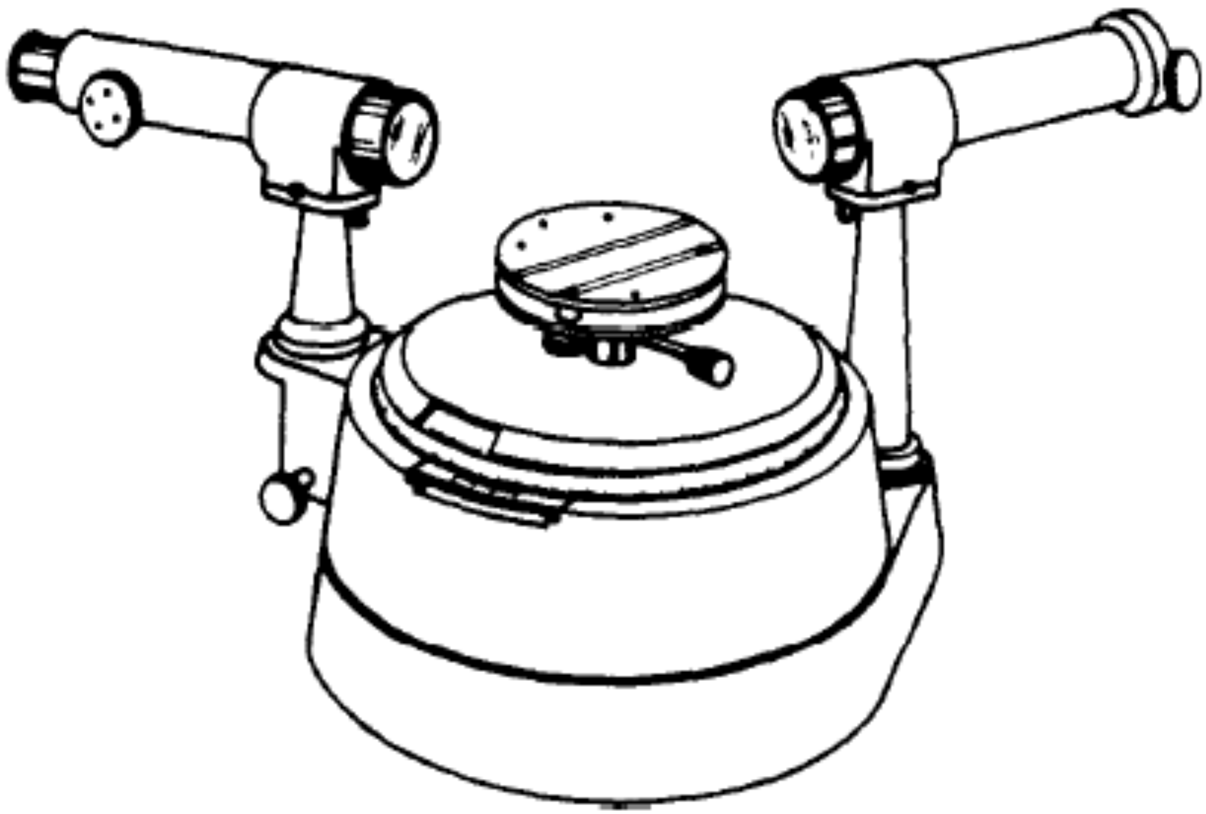
ε = prism angle error

Errors in collimated beam cancel.

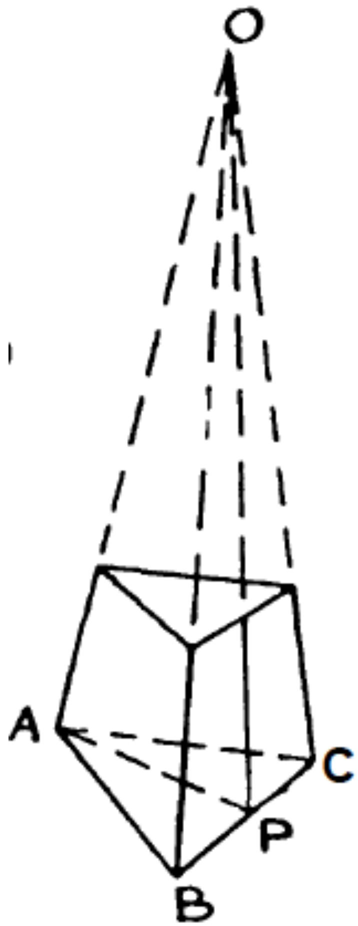
7.3.2 Goniometer

- The most general instrument for measuring prism angles is the goniometer. A goniometer consists of a collimator, telescope, and a sample table, all arranged so they rotate about a common axis. The angular positions of collimator and telescope are accurately measured.
- The goniometer is usually used in the autocollimating mode to measure the geometrical angles between the various faces of the prism under test.

Drawing of Goniometer



Pyramidal Error of Prisms



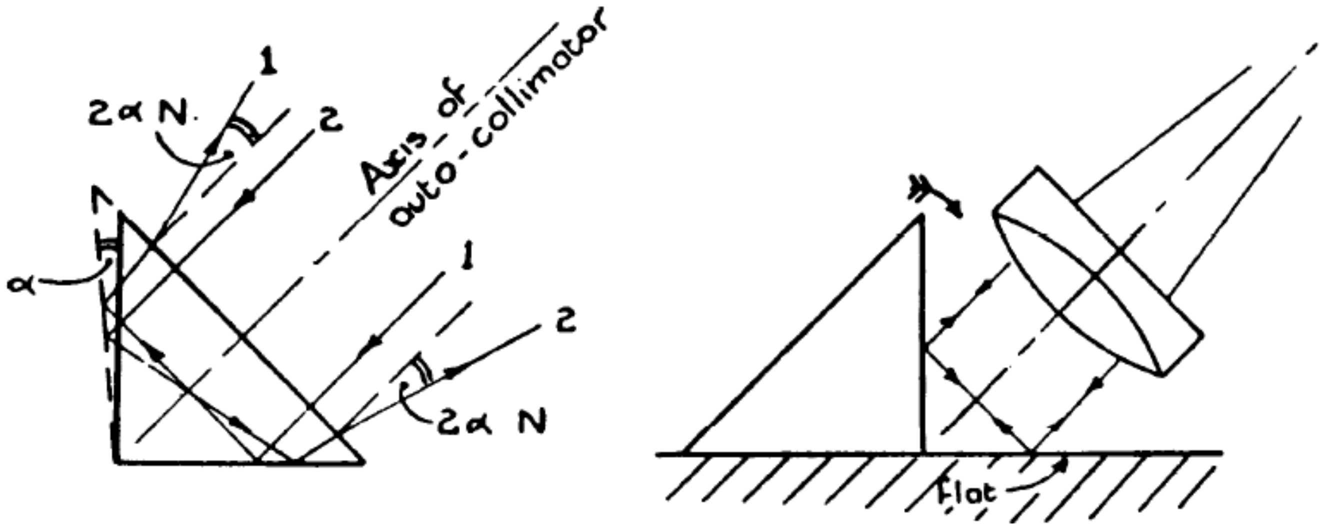
Let plane ABC be perpendicular to OA and let AP be drawn perpendicular to BC, meeting it at P. Angle AOP is measure of the pyramidal error.

Using Goniometer to Measure Pyramidal Error

- Adjust so telescope axis is perpendicular to faces AB and then AC. Edge AO is now perpendicular to optical axis of the telescope.
- If now the telescope is directed towards the face BC the displacement of the back-reflected horizontal line image is equal to twice the angle AOP.

7.3.3 Autocollimator

Measuring 90° angle of 90° prism



To determine sign of error put prism on optical flat. Get same error as before, except for n factor. Tilt the prism and if two images come together the exterior angle must be > 90°, and if continue to separate the exterior angle must be < 90°.

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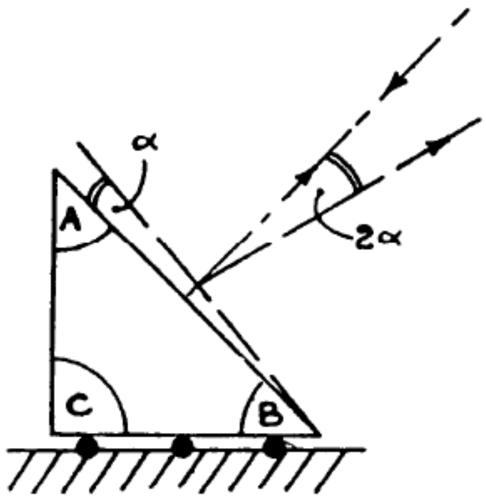
Autocollimator
Measuring 45^o Angle of 90^o Prism



Put Vaseline on surfaces other than hypotenuse.
Put side AC on balls and adjust telescope so axis is perpendicular to hypotenuse. Now put side BC on balls as shown.

The reading, 2α, is twice the difference in angle between A and B. By observing the direction in which the image has moved it is possible to determine which angle is larger. Since the value of the 90^o angle is known, the true value of the 45^o angles can be determined.

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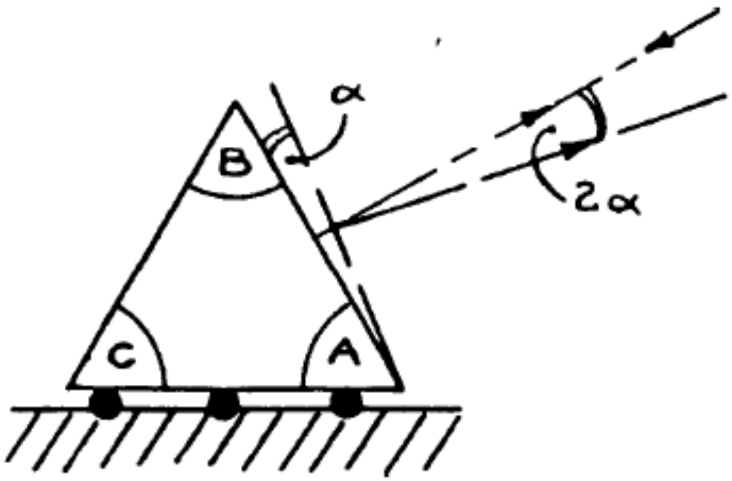
Autocollimator Measurement of 60° Prism



By taking turns having angles B and C in the same position as angle A in the drawing, the difference between A and C and A and B can be determined. Then

$$A + B + C = 180^o$$

$$2(A - C) = \alpha \qquad 2(A - B) = \beta \qquad \text{C}=(2A - \alpha)/2 \qquad \text{B}=(2A - \beta)/2$$

$$A + A + A - \alpha/2 - \beta/2 = 180^o$$

$$A = (180^o + \alpha/2 + \beta/2)/3$$

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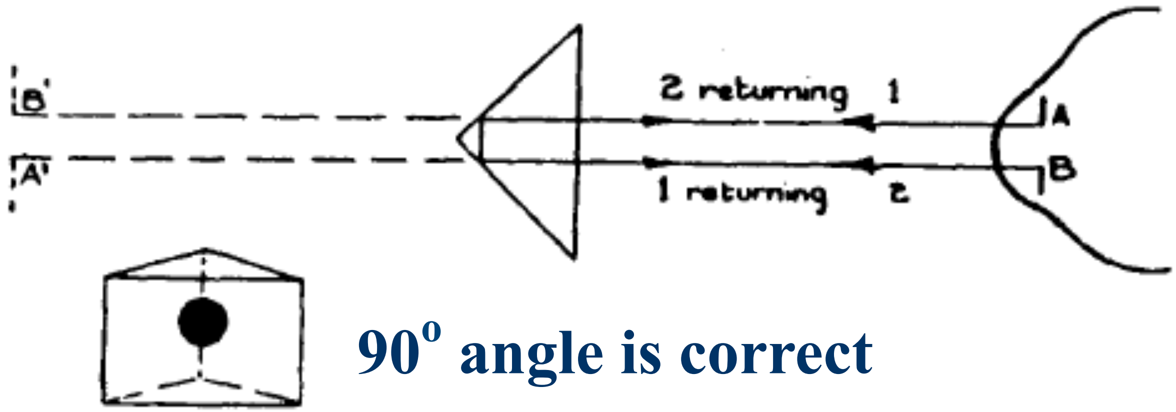
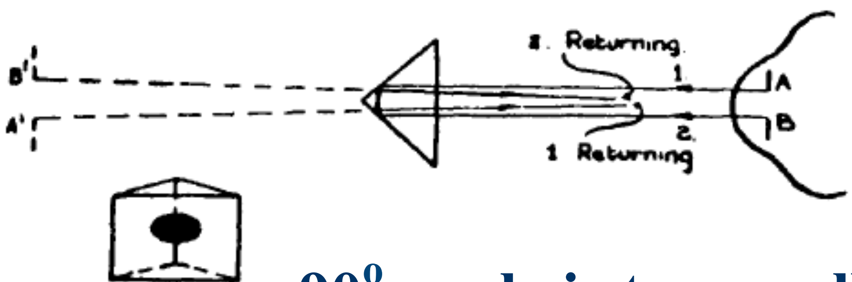
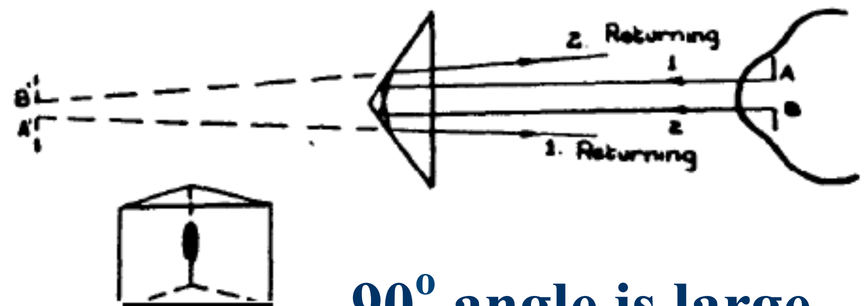
7.3.4 Naked Eye Tests - 90^o Prism



90^o angle is correct



90^o angle is too small



90^o angle is large

Look at the image of your iris. Angular error is 4nε. Accuracy is a few minutes of arc.

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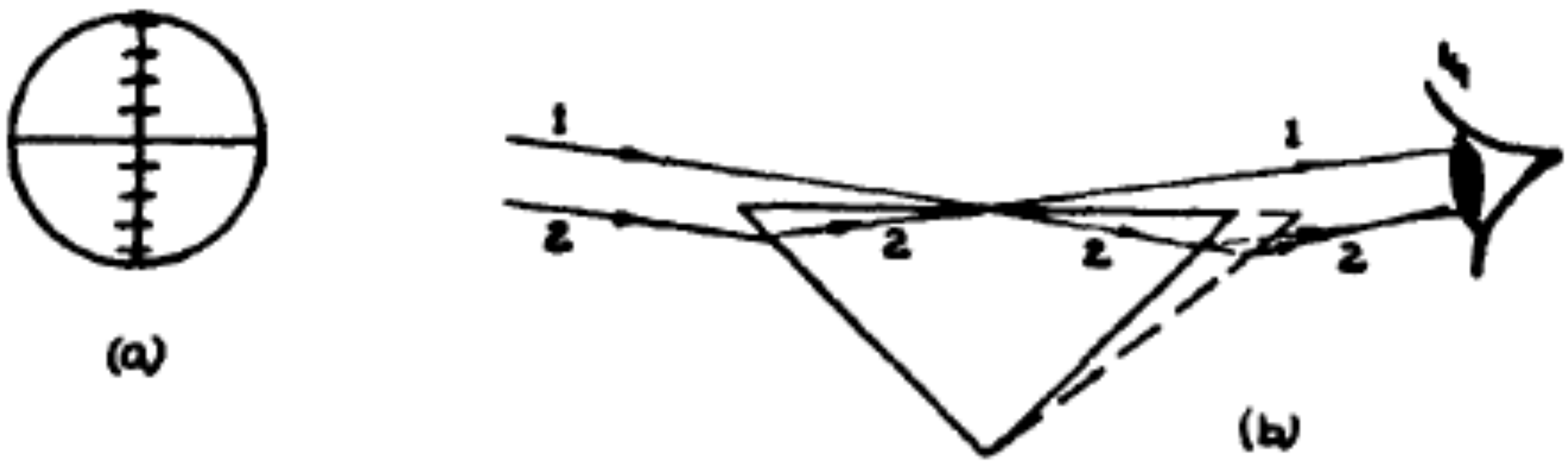
Naked Eye Test - 45^{o} Angles



(a) (b)

View a distance screen. If the angles are both 45^{o}, no vertical displacement will occur between light reflected directly from hypotenuse of the prism and the light that passes through the prism. Horizontal displacement gives pyramidal error. Can detect errors larger than a few minutes of arc.

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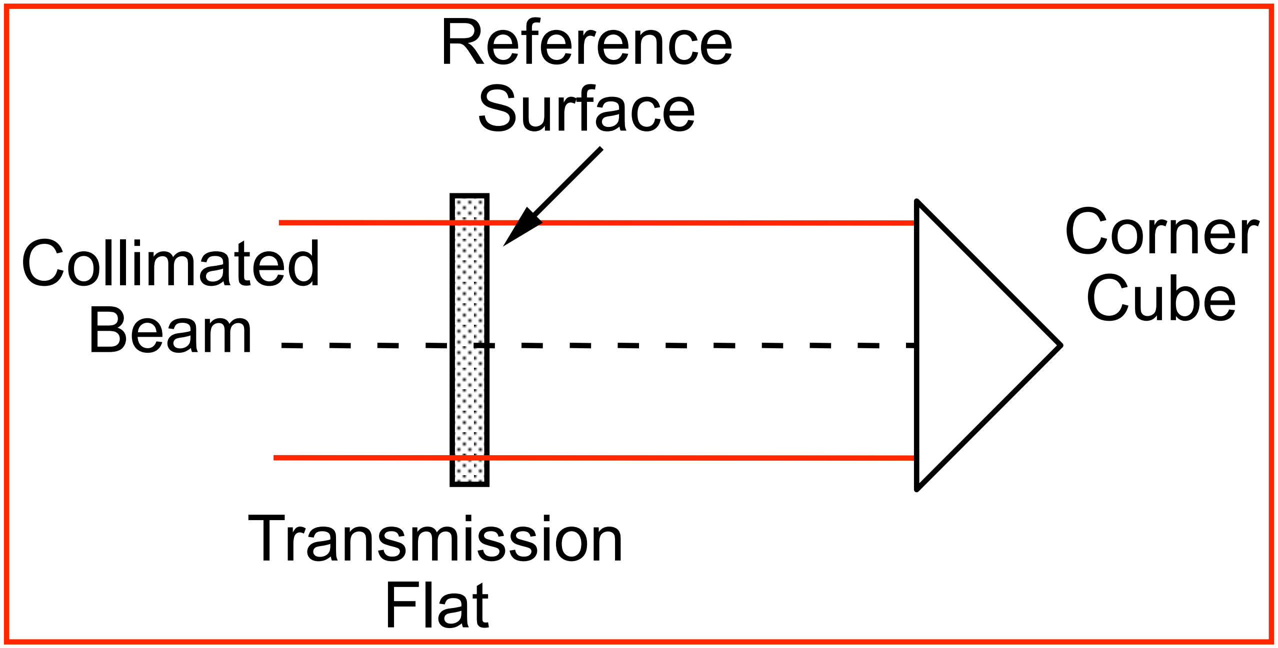
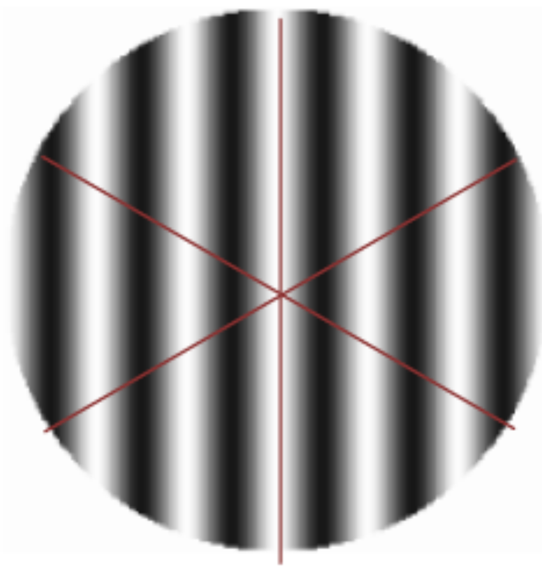
7.4 Testing Corner Cubes (Single Pass)



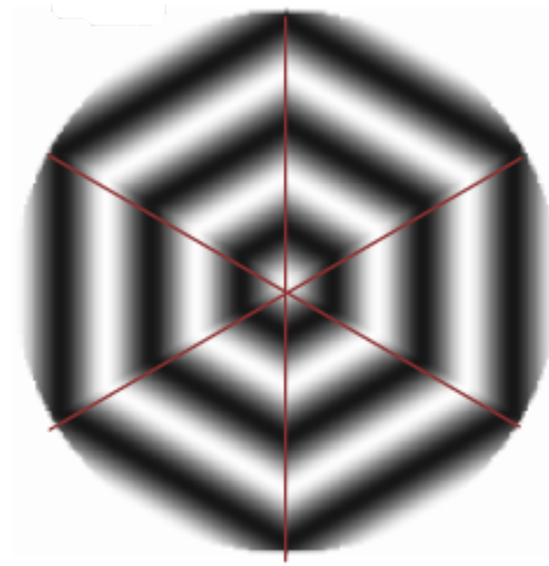
Errors in collimated beam do not cancel.

Analyzing Corner Cube Interferograms (Single Pass)

Perfect



Angle Errors



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)

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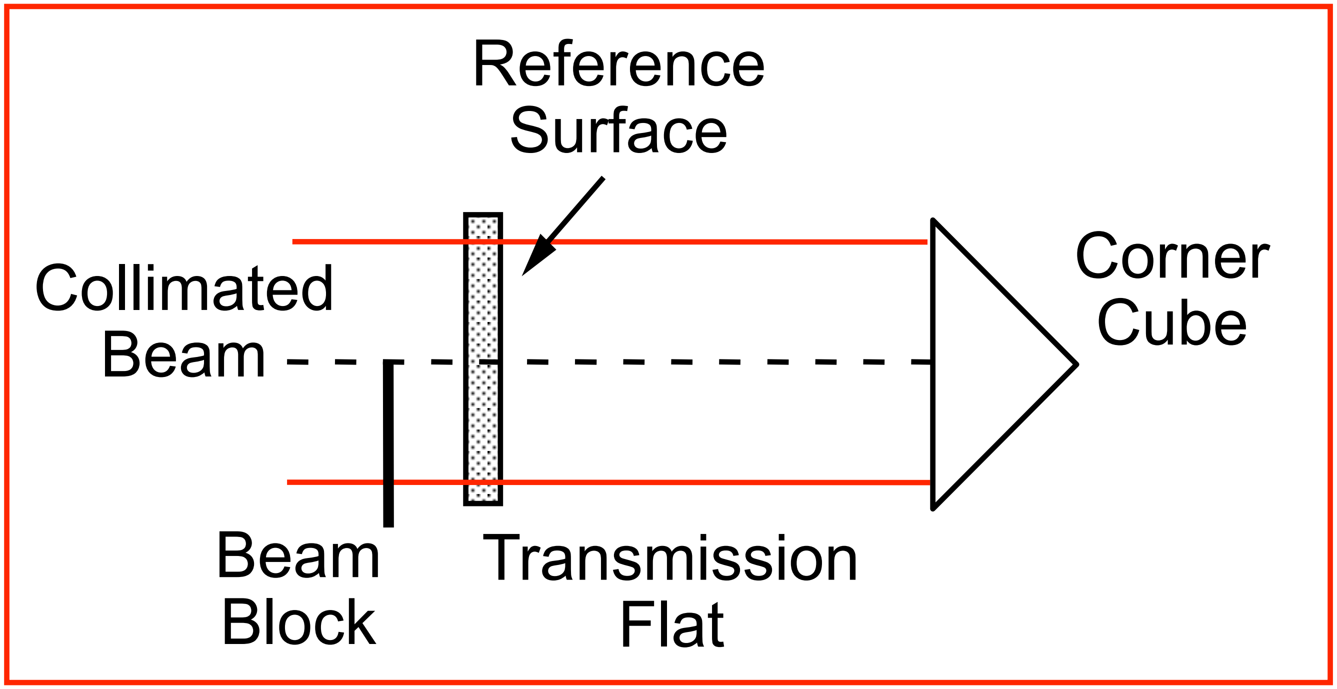
Ref: Thomas and Wyant, JOSA, p. 467, 1977.

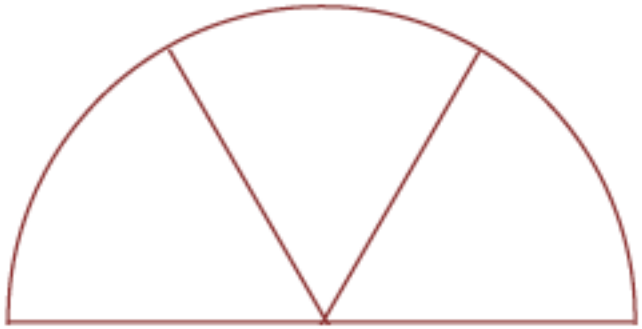
Testing Corner Cubes (Double Pass)



Errors in collimated beam cancel.

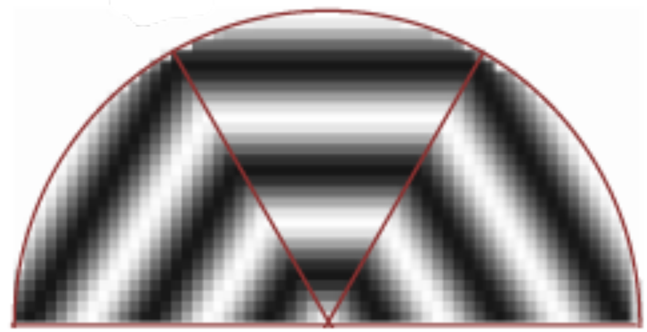
Analyzing Corner Cube Interferograms (Double Pass)

Perfect



One uniform fringe

Angle Errors



- 3 interferograms obtained.
- Tilt of each interferogram gives one angle error in corner cube.
- n is refractive index of corner cube.

$$\text{Error} = \text{Tilt}/(3.266\ n)$$

7.5 Diffraction Gratings

Measuring the straightness and spacing variations of a diffraction grating

For reflection gratings use Twyman-Green or Fizeau and for transmission gratings use Mach-Zehnder.

For a perfect straight line grating

$$\frac{x}{\Delta x} = m, \quad \Delta x = \text{line spacing}, \; m = \text{ integer}$$

If there are errors in the lines then

$$\frac{x}{\Delta x} + \frac{\delta[x, y]}{\Delta x} = m, \quad \text{where } \delta[x, y] = \text{ error in line position}$$

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Compare Grating with Interferogram or Hologram

$e^{-ikxSin[\theta]}$ represents amplitude of tilted plane wave

$e^{ik\Delta W[x,y]}$ represents wavefront having aberration $\Delta W[x,y]$

Irradiance of interference pattern given by

$$\mathrm{I}=\mathrm{I}_o(1+Cos[kxSin[\theta]+k\Delta W[x,y]])$$

For bright fringe

$$\frac{xSin[\theta]}{\lambda}+\frac{\Delta W[x,y]}{\lambda}=m$$

Therefore, for grating the aberration in the first order in units of waves is $\frac{\delta[x,y]}{\Delta x}$. N^{th} order will have N times as much aberration.

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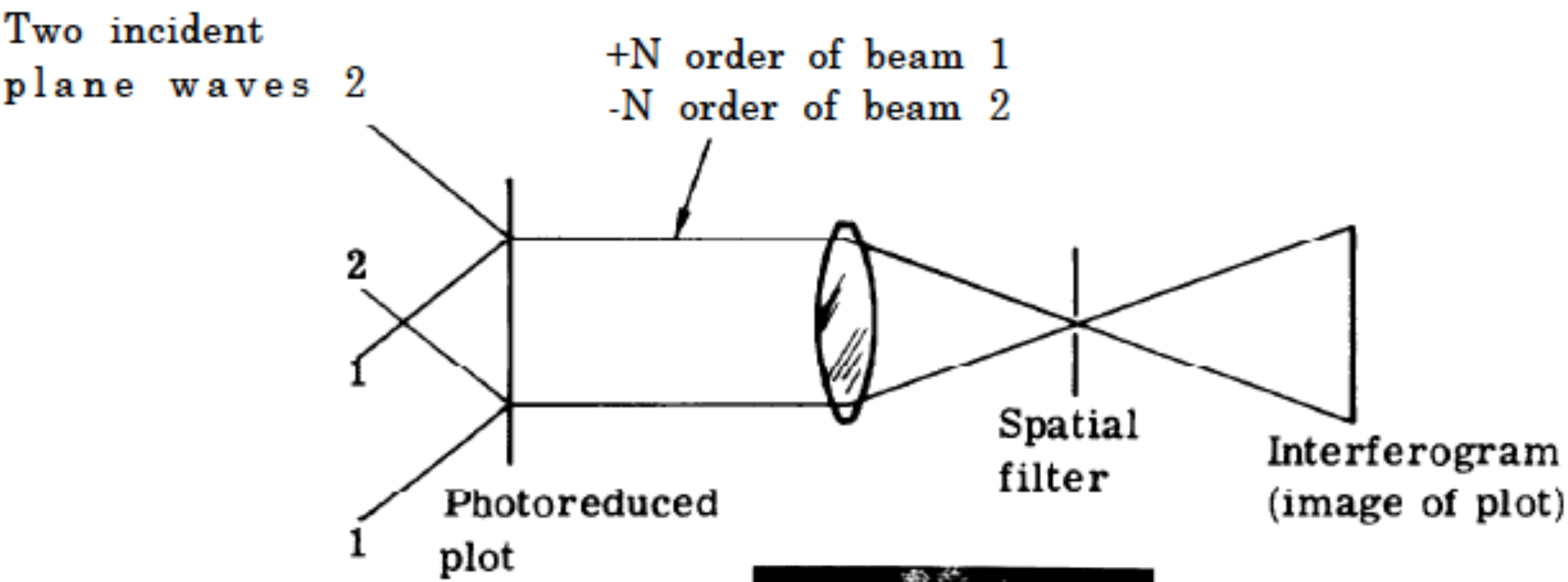
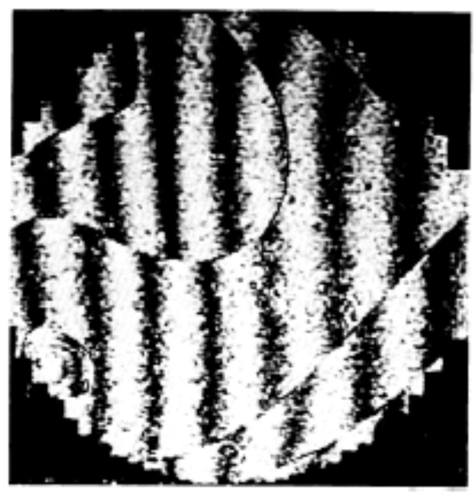
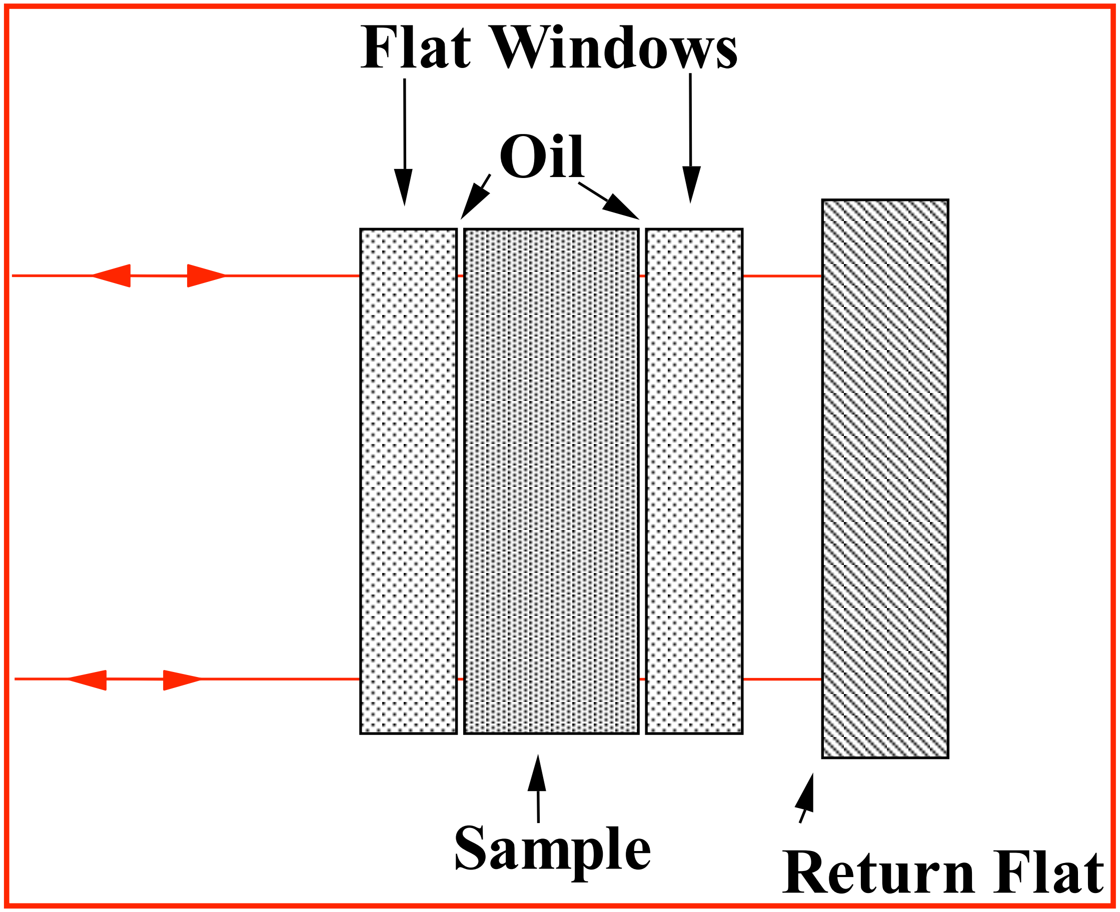
Experimental Setup for Measuring Line Straightness



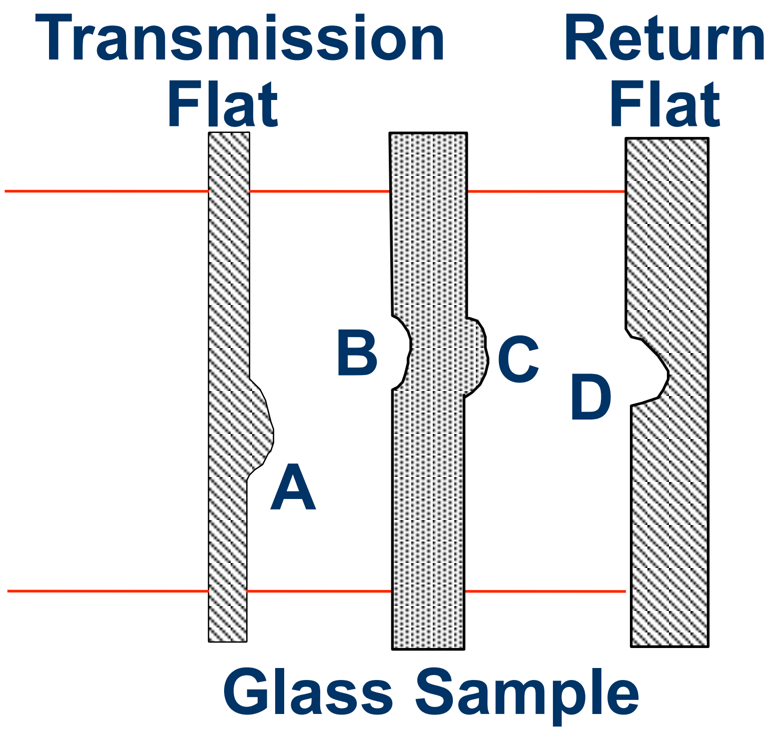


Error in straight lines (200μm per fringe).

7.6 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.

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

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

$$= (n-n_o)T$$

THE UNIVERSITY OF ARIZONA.

Index Inhomogeneity Test Results

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