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College of Optical Sciences

4.0 Basic Interferometry and Optical Testing

4.0 Basic Interferometry and Optical Testing

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4.1 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

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

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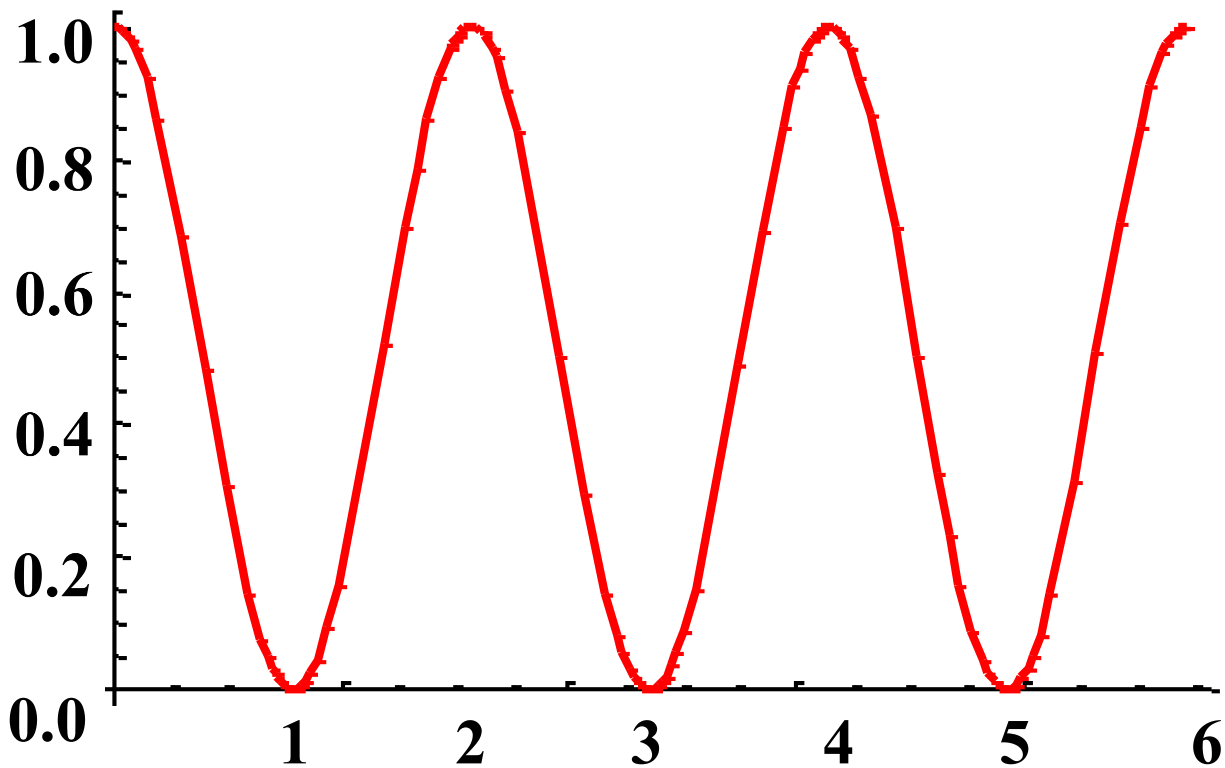
Sinusoidal Interference Fringes



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

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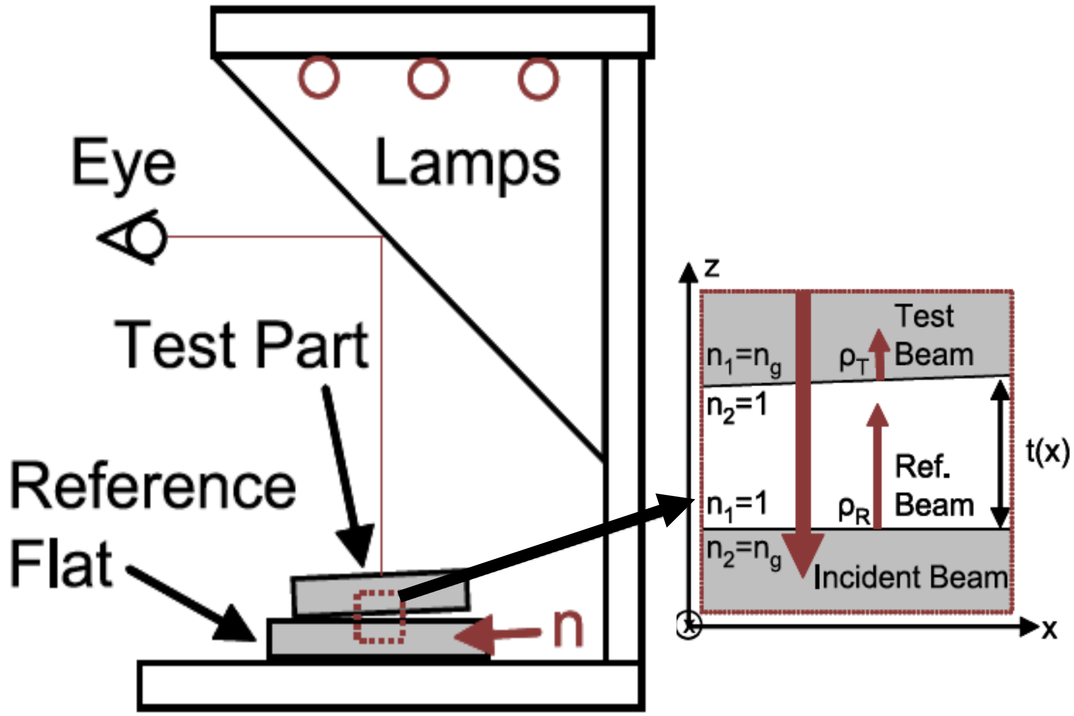
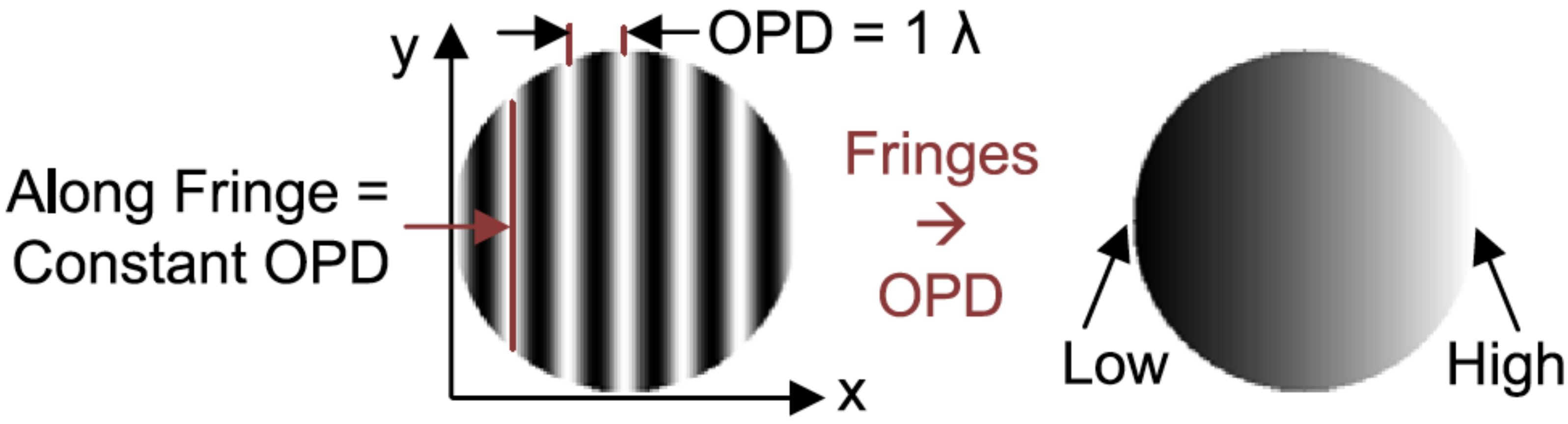
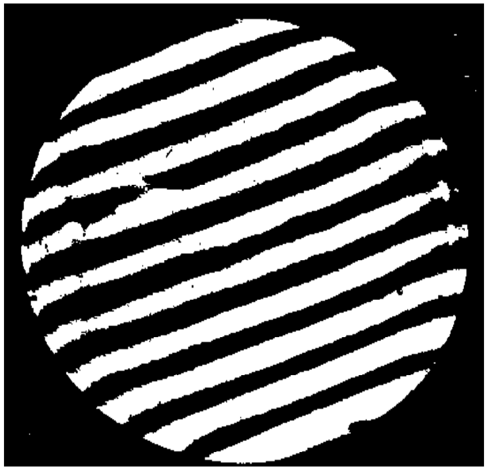
4.2 Pioneer Fizeau Interferometer

1862

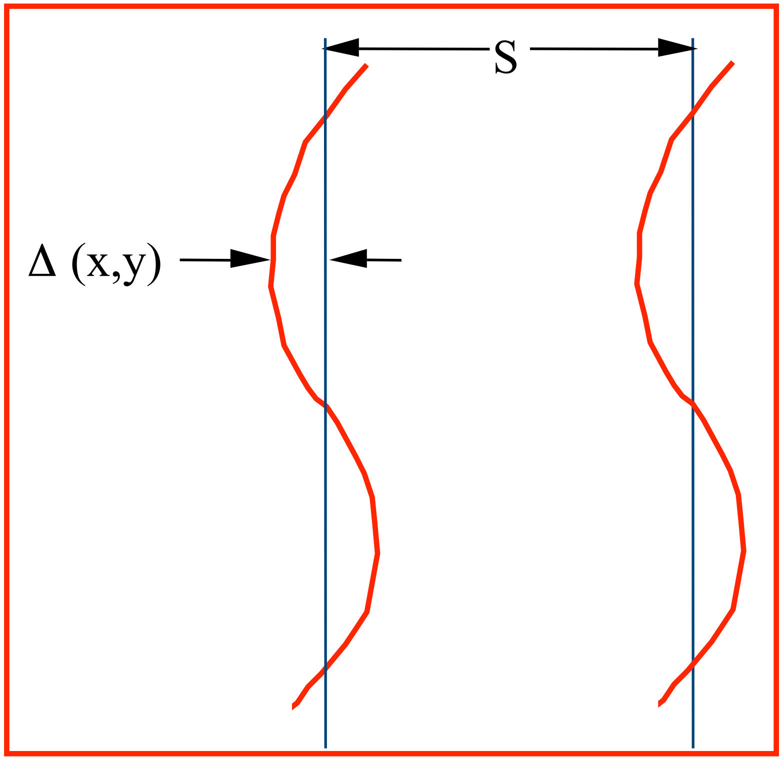


Typical Interferogram Obtained using Fizeau Interferometer



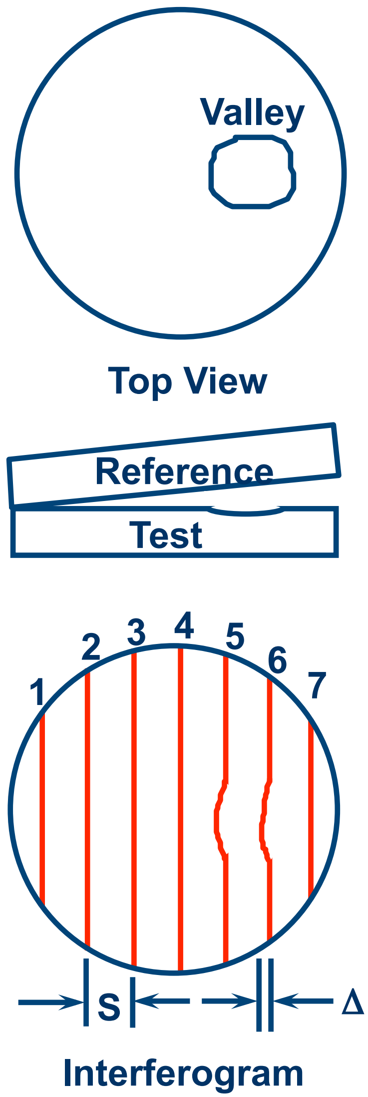


Relationship between Surface Height Error and Fringe Deviation



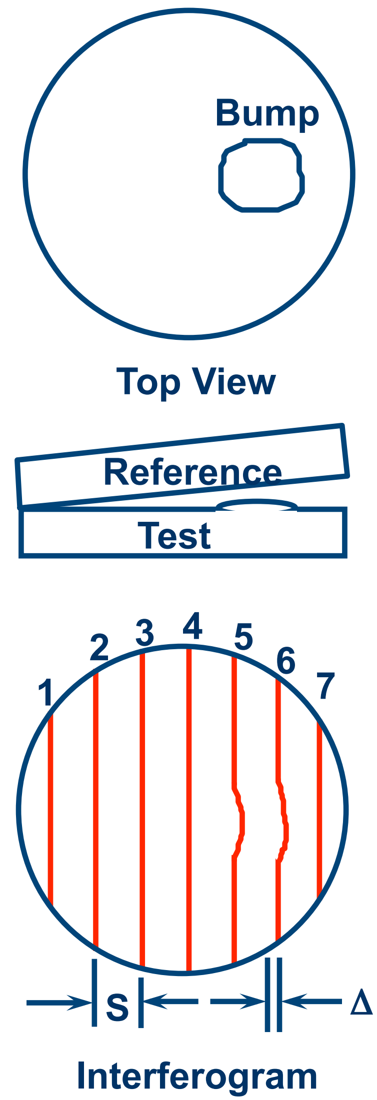
$$\text{Surface height error} = \left(\frac{\lambda}{2}\right)\left(\frac{\Delta}{S}\right)$$

Fizeau Fringes



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

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



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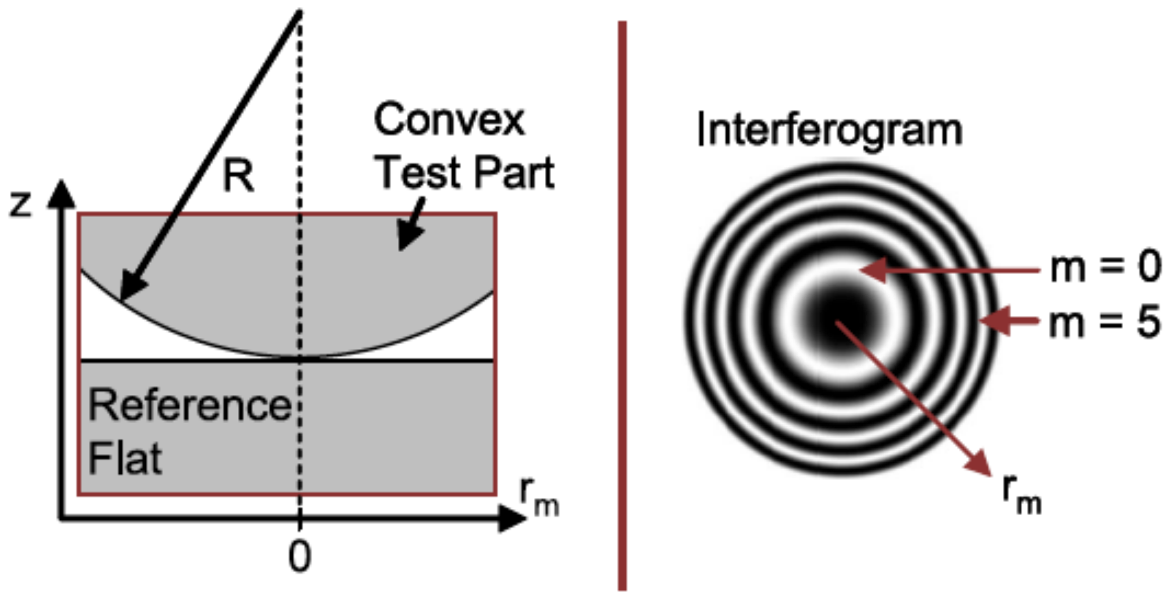
Newton’s Rings



$$R = \frac{r_m^2}{\lambda\left(m + \frac{1}{2}\right)}$$

$$R^2 = (R - z)^2 + r_m^2 = R^2 - 2zR + z^2 + r_m^2$$

$$z \sim \frac{r_m^2}{2R} = \left(m + \frac{1}{2}\right)\frac{\lambda}{2}$$

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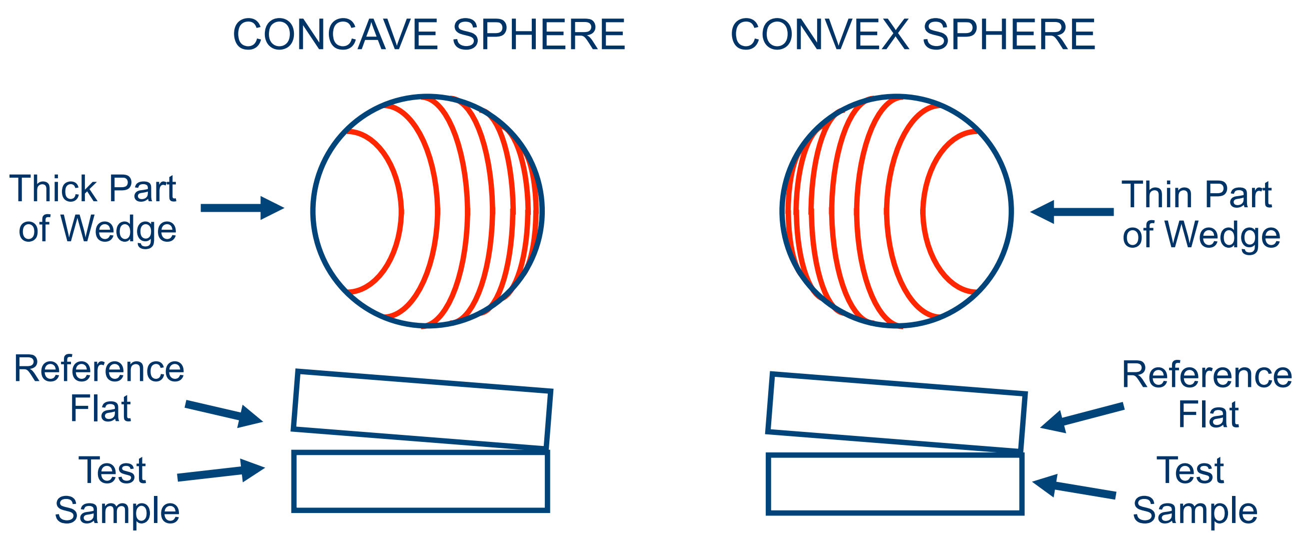
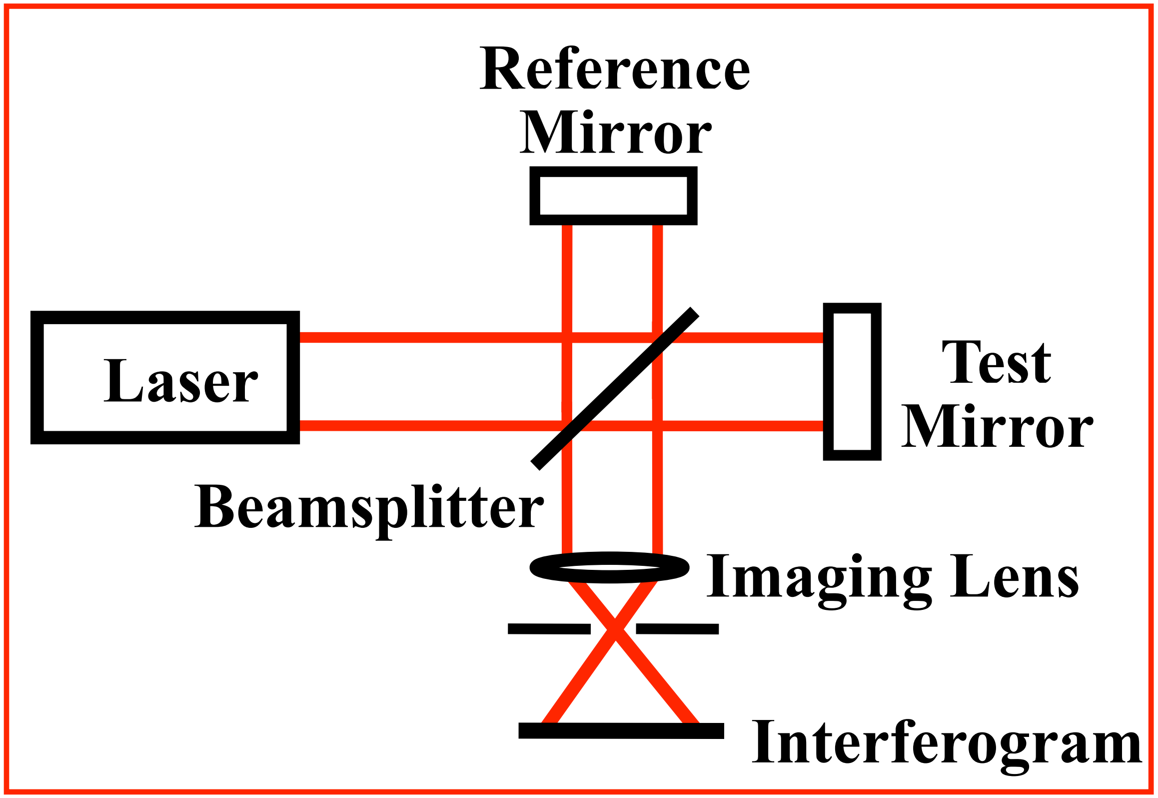
Fizeau Fringes for Concave and Convex Surfaces



4.3 Twyman-Green Interferometer (Flat Surfaces)

1918

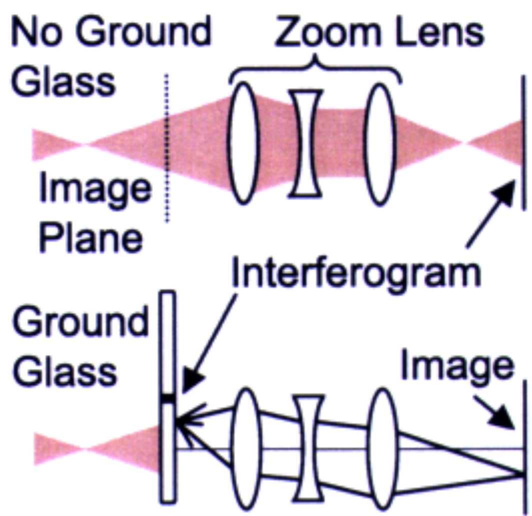


Use of Rotating Ground Glass to Limit Spatial Coherence of Source

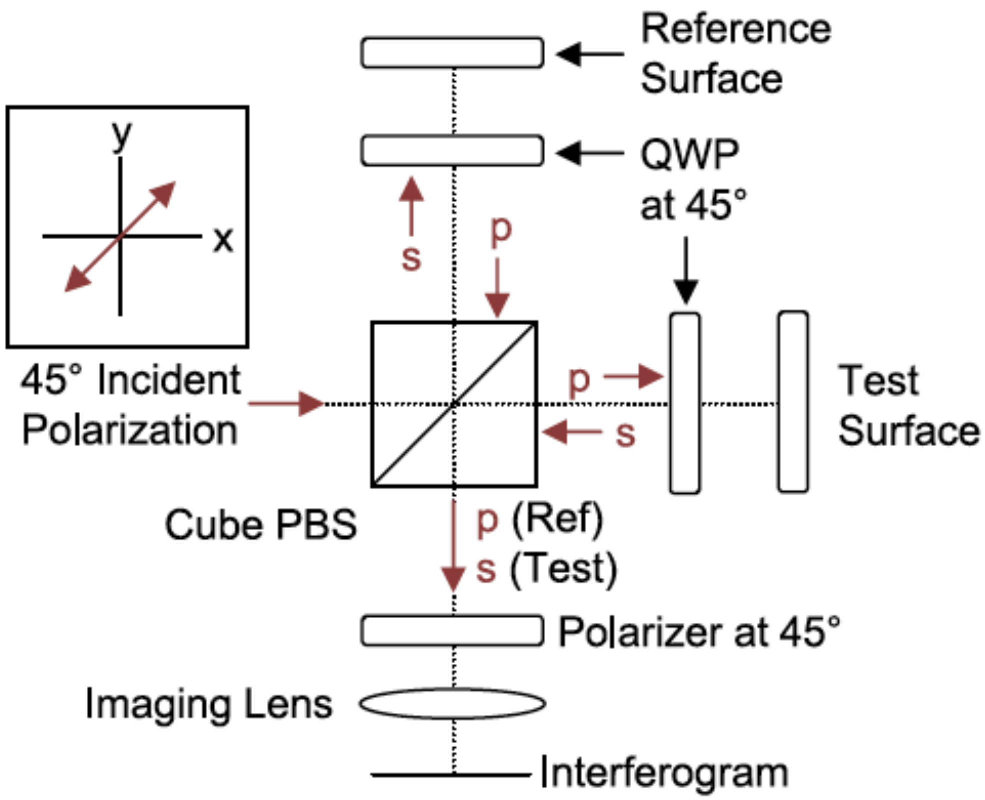
Using a **ground glass diffuser** in an interferometer is useful for destroying spatial coherence. Ground glass is often used to limit the spatial coherence of the source. Coherence is a requirement to obtain interference fringes, but spurious fringes due to stray reflections are a dominant noise source. A laser is focused onto a rotating ground glass diffuser to decrease the spatial coherence and render stray reflections incoherent with the test and reference beams. A stationary diffuser creates a stationary speckle pattern, so the ground glass must be rotated so the speckle pattern changes much faster than the camera integration cycle. Each scatter site on the ground glass has a random phase. Integrated over time, the phase distribution at each location becomes uniform.

Use of Rotating Ground Glass in Imaging Optics

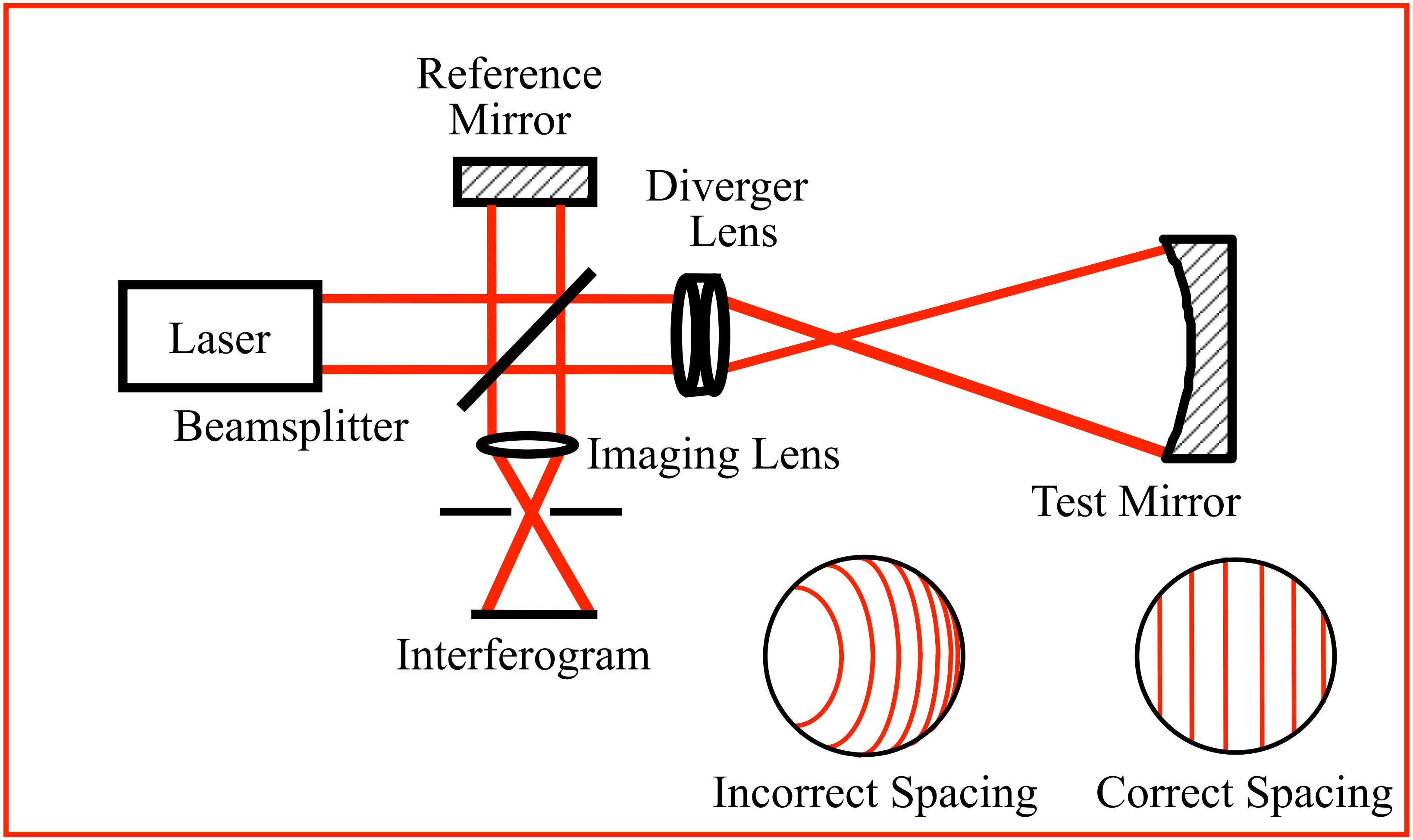
In order to increase the flexibility of commercial laser-based Fizeau interferometers, a zoom lens can be used to adjust for varying test part sizes. A multi-element zoom lens creates many stray reflections, which cause spurious fringes in the recorded interferogram. Imaging the interferogram onto ground glass before the zoom lens converts the two coherent waves into an incoherent irradiance signal that is imaged to the camera via the zoom lens. Any stray reflections within the zoom lens are incoherent; they add in irradiance and do not cause phase errors. Ground glass scatters light, causing a large amount of loss in the system. A second drawback is that the motor that rotates the ground glass inevitably introduces vibrations, another major noise source in interferometers.



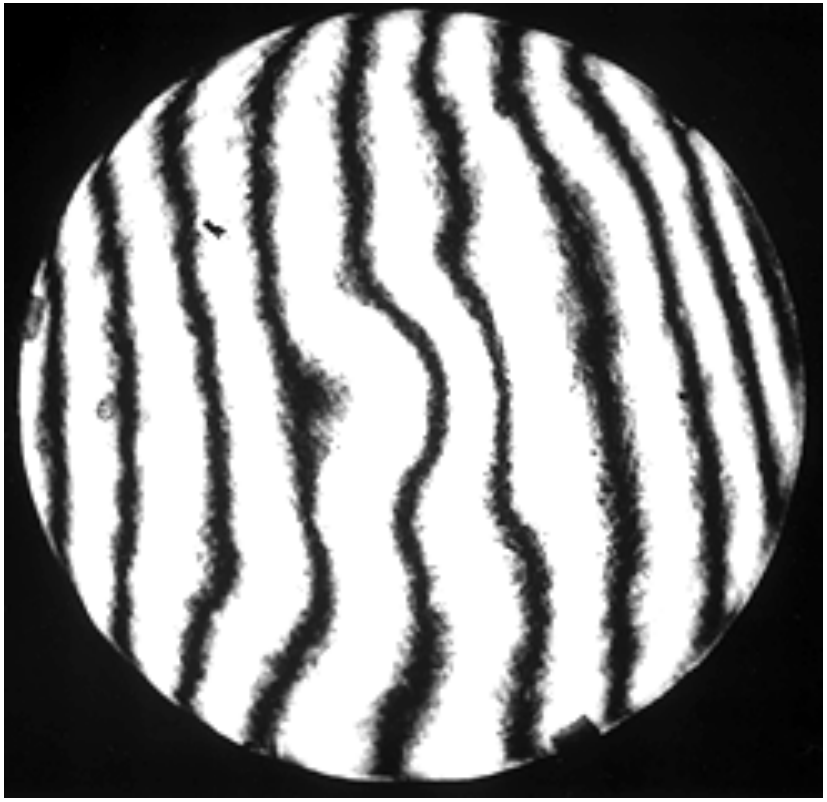
Polarization Beam Splitter (PBS) Twyman-Green Interferometer



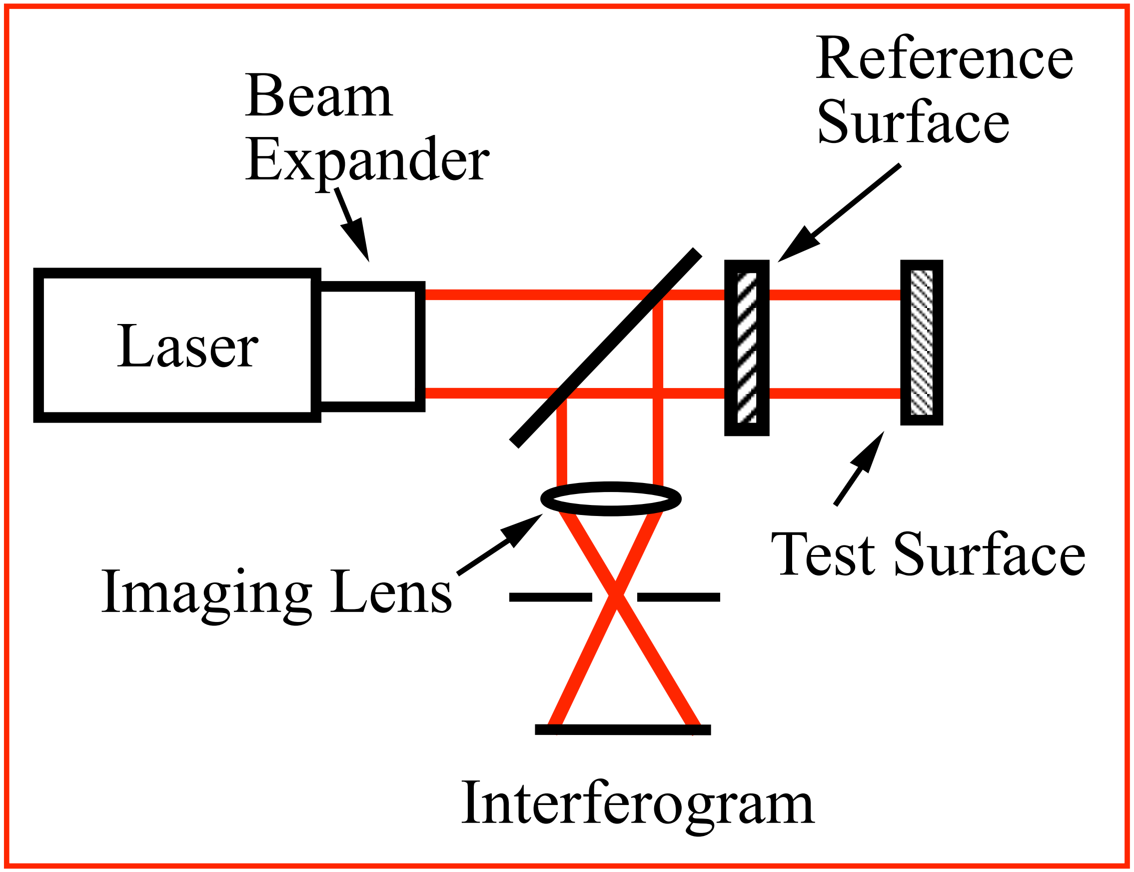
Twyman-Green Interferometer (Spherical Surfaces)



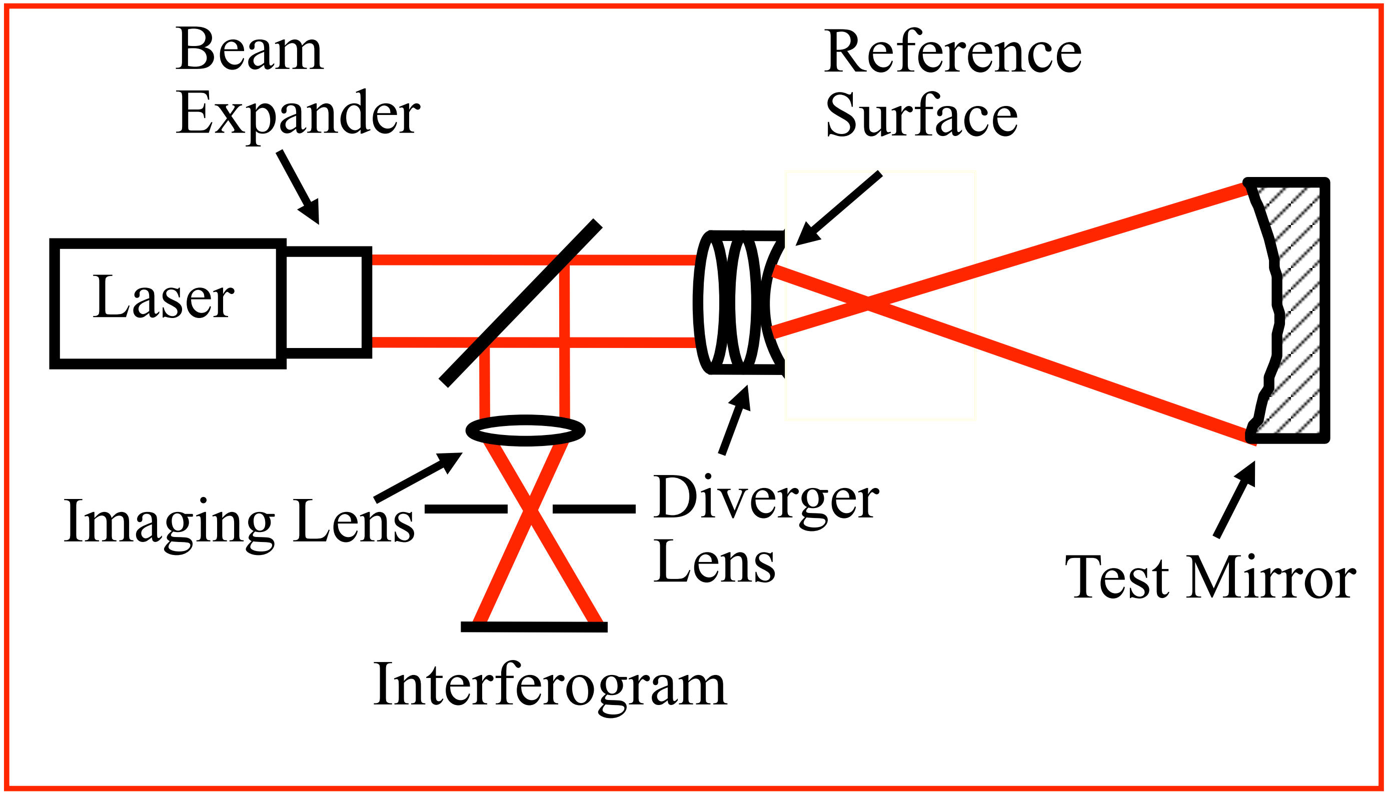
Typical Interferogram



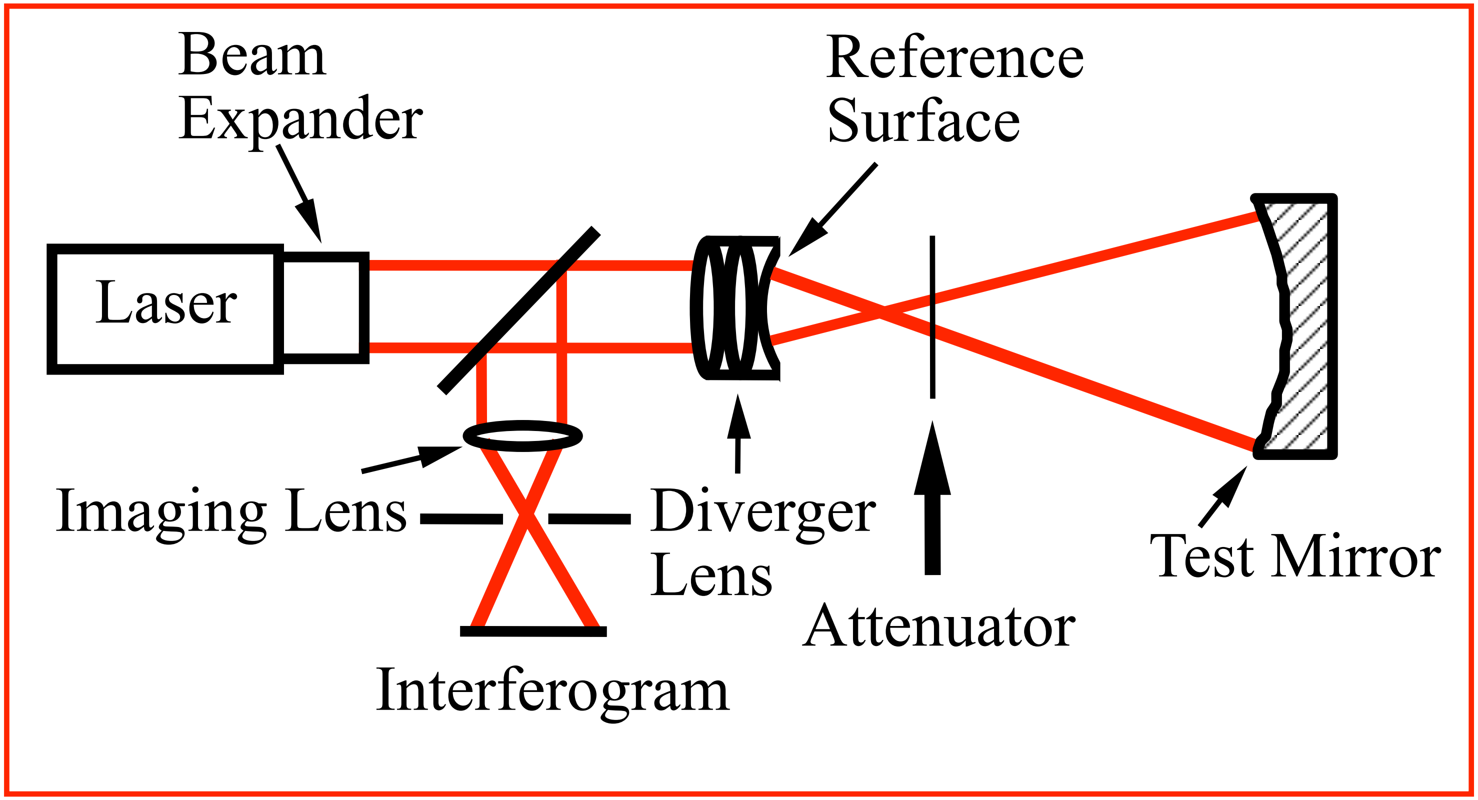
4.4 Fizeau Interferometer - Laser Source (Flat Surfaces)



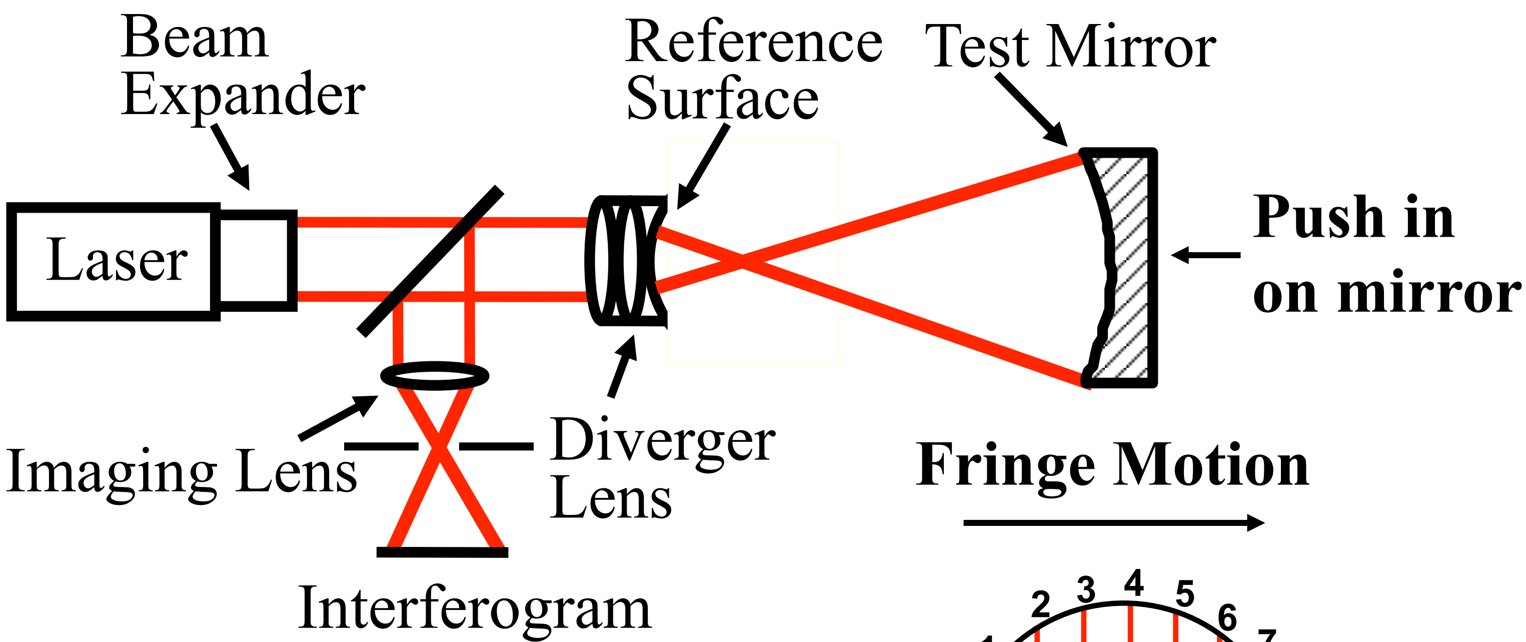
Fizeau Interferometer - Laser Source (Spherical Surfaces)

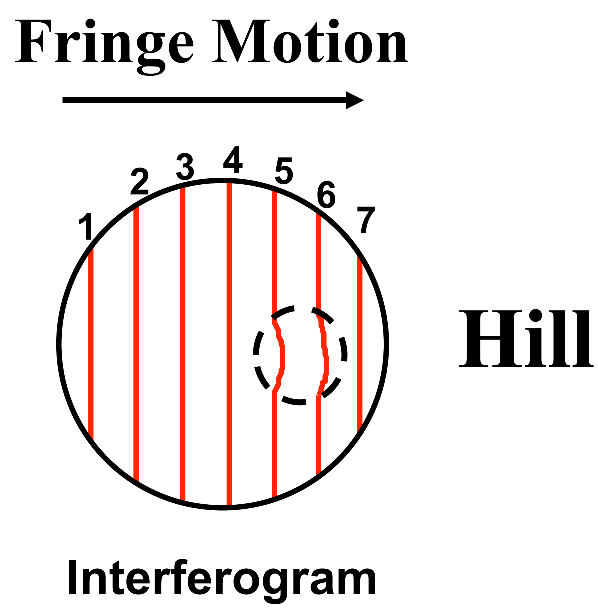


Testing High Reflectivity Surfaces

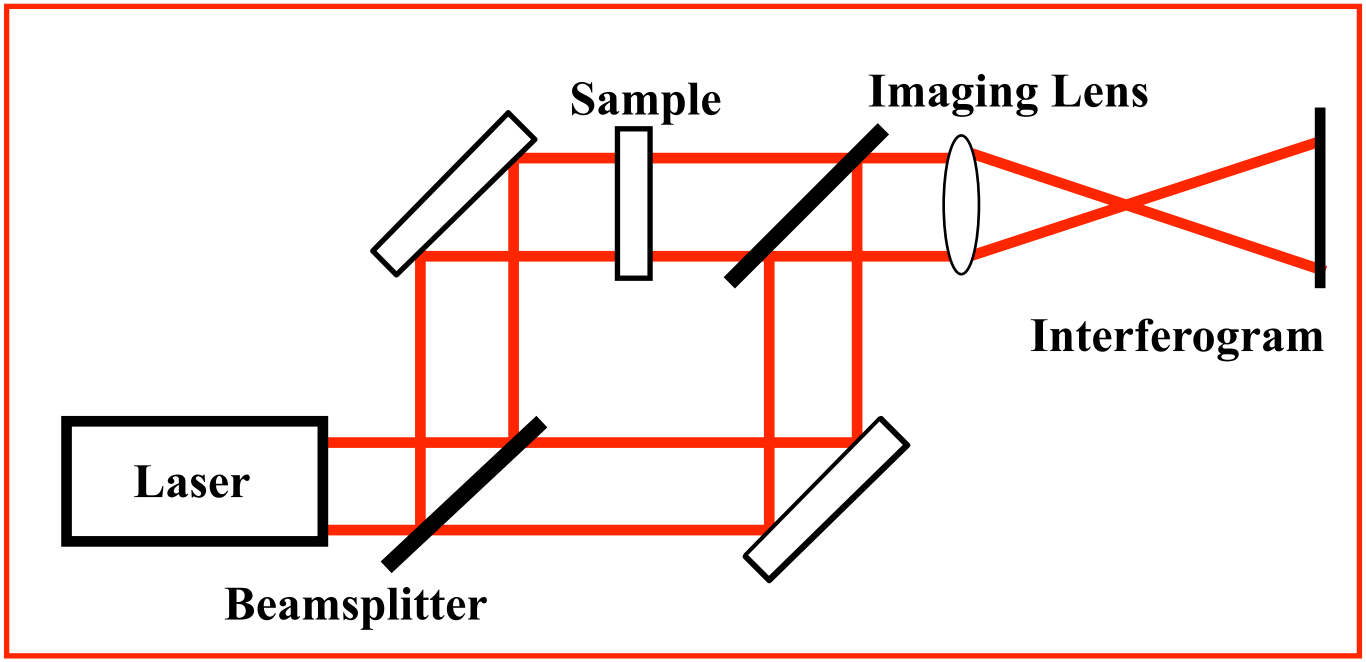


Hill or Valley?



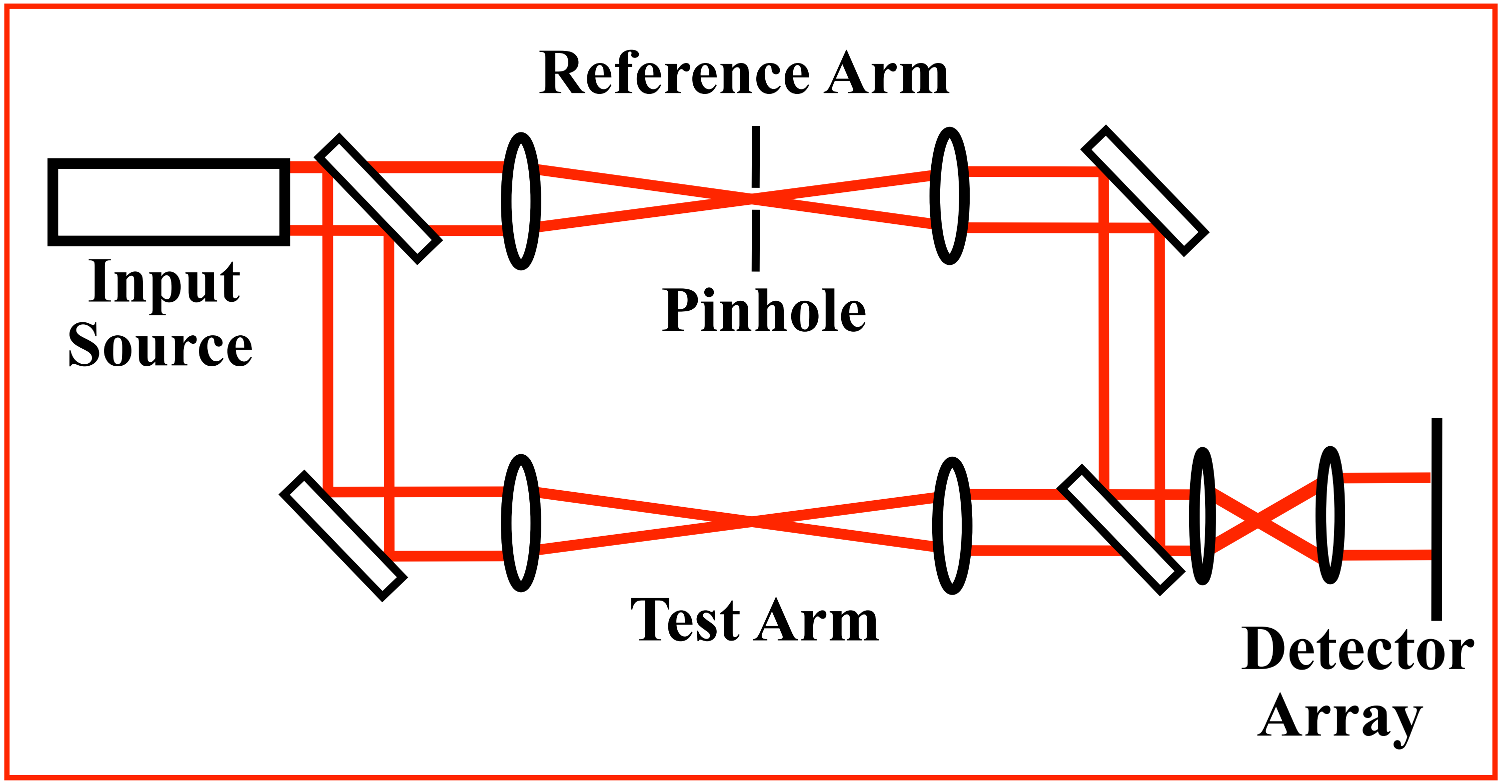


4.5 Mach-Zehnder Interferometer

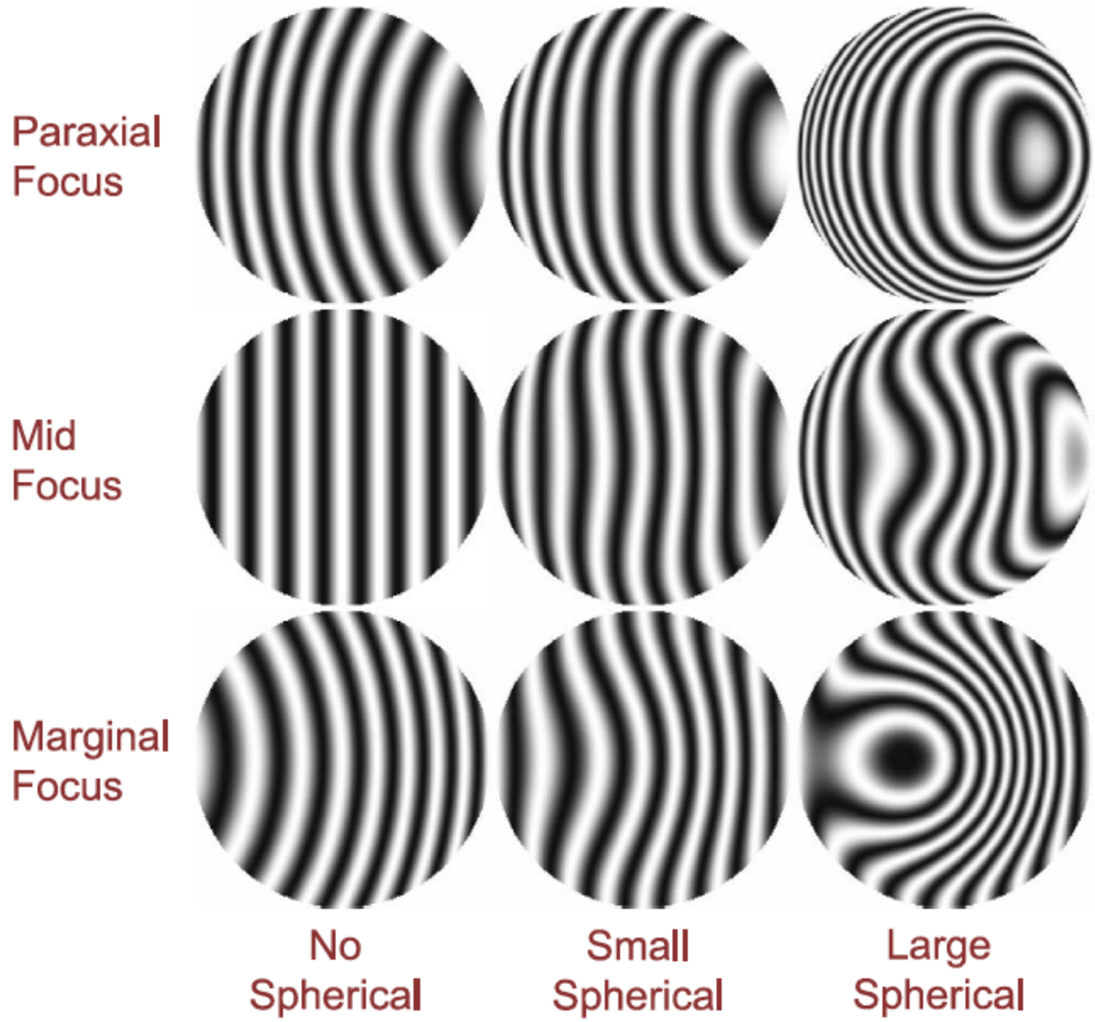


Testing samples in transmission

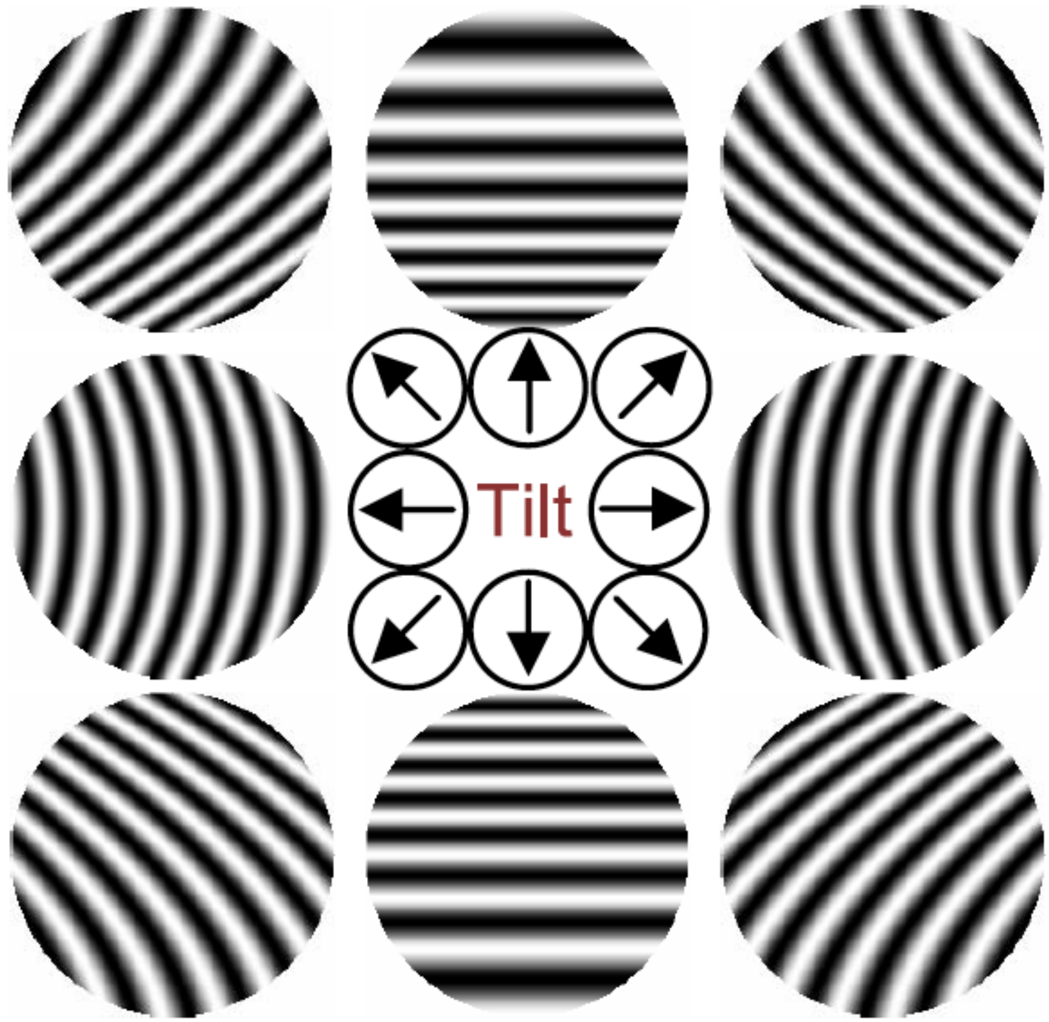
Laser Beam Wavefront Measurement



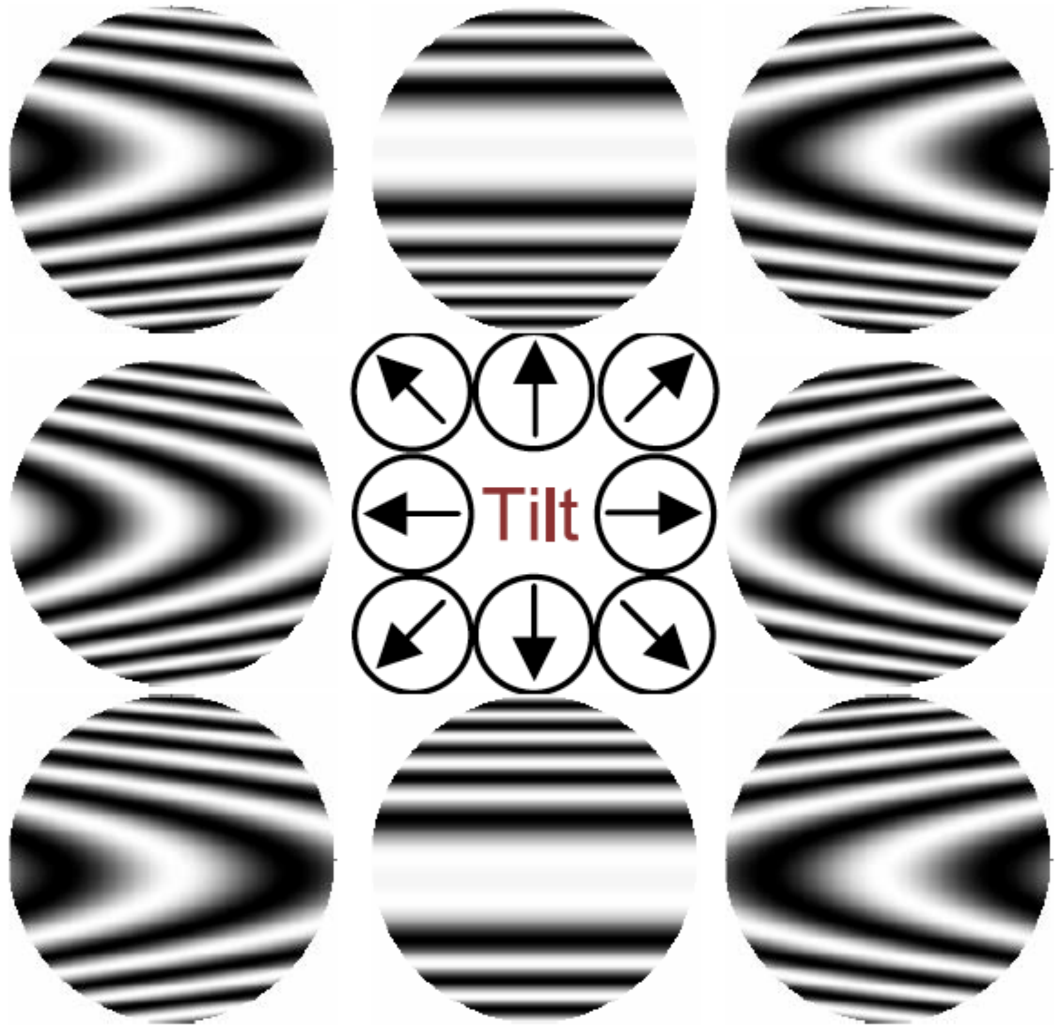
4.6 Interferograms, Interferograms Spherical Aberration



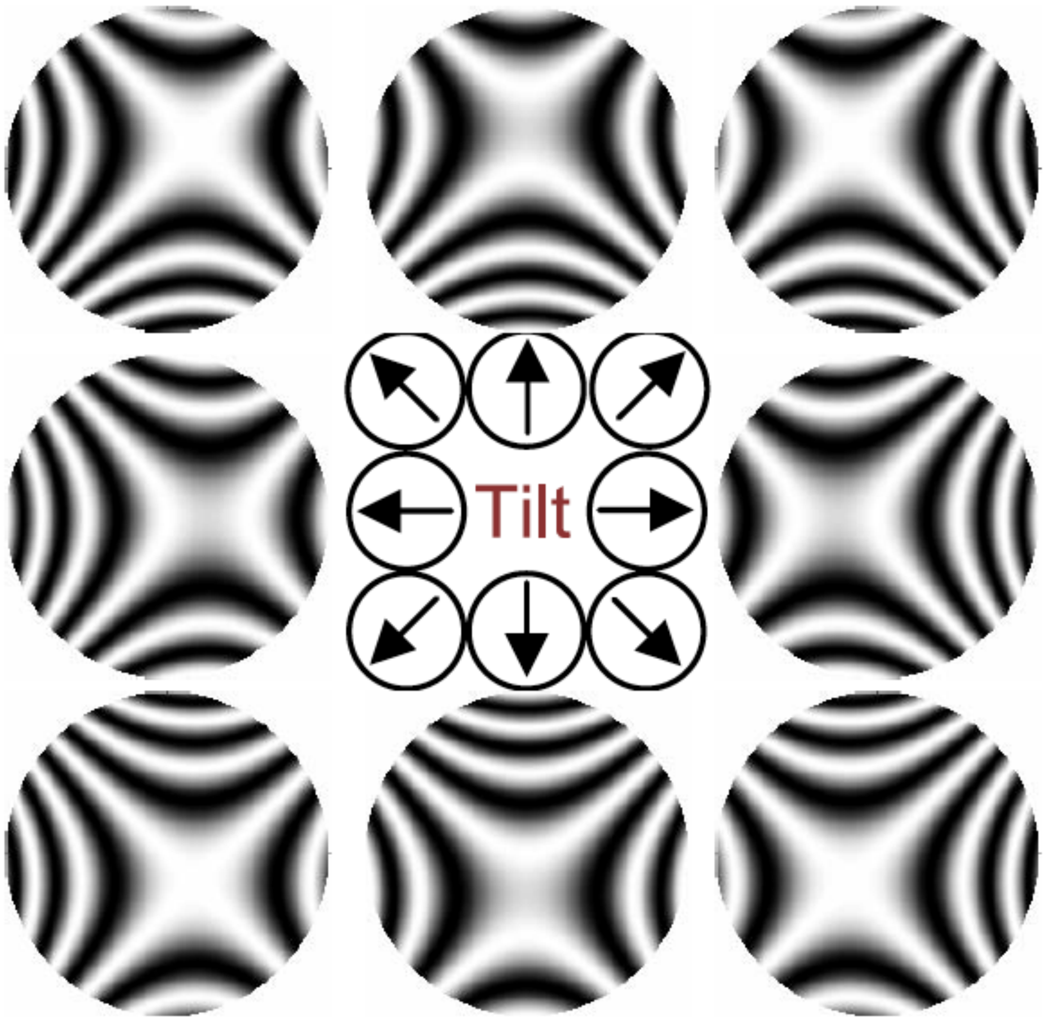
Interferograms
Small Astigmatism, Sagittal Focus



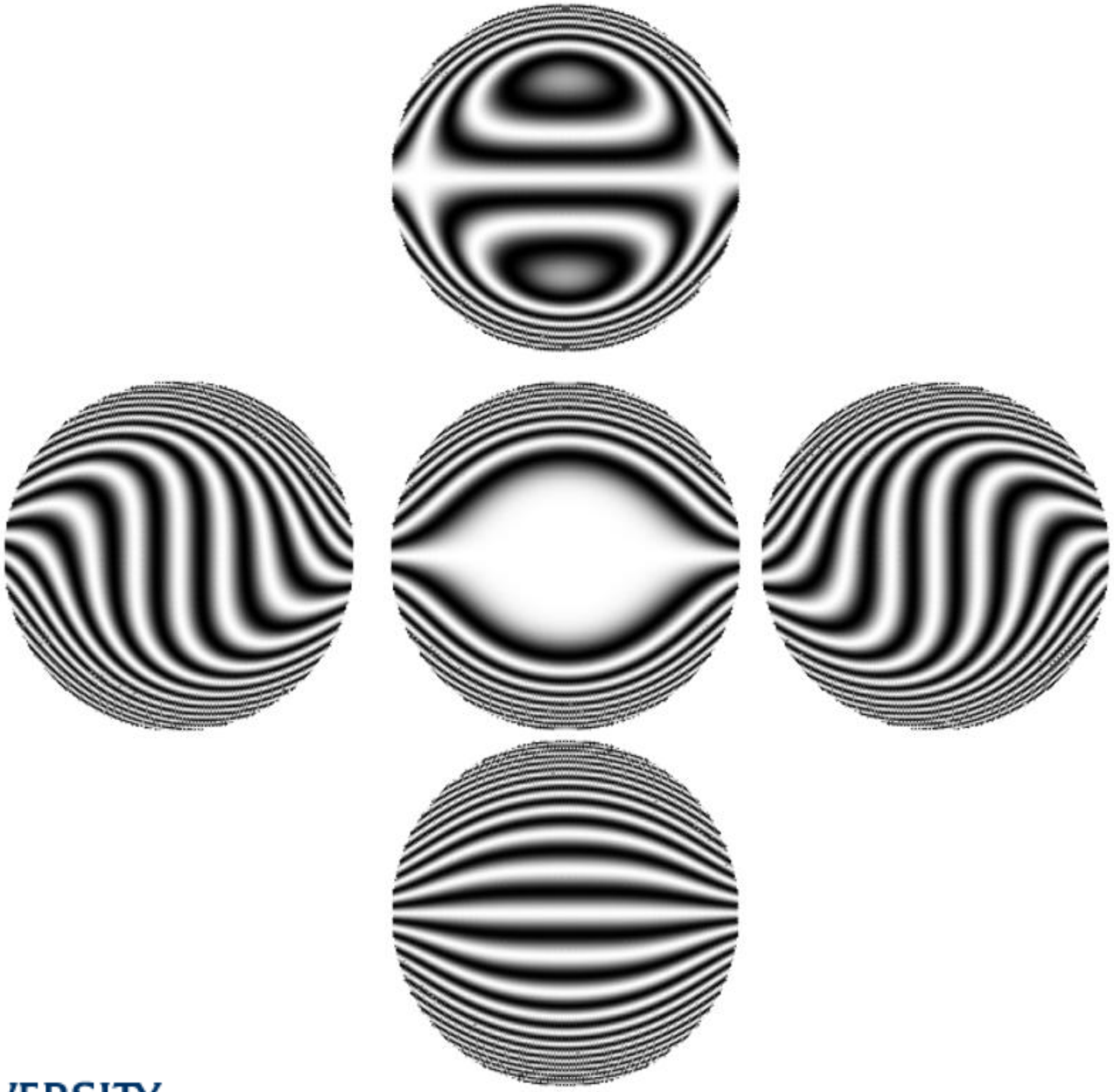
Interferograms
Large Astigmatism, Sagittal Focus



Interferograms
Large Astigmatism, Medial Focus



Interferograms
Large Coma, Varying Tilt



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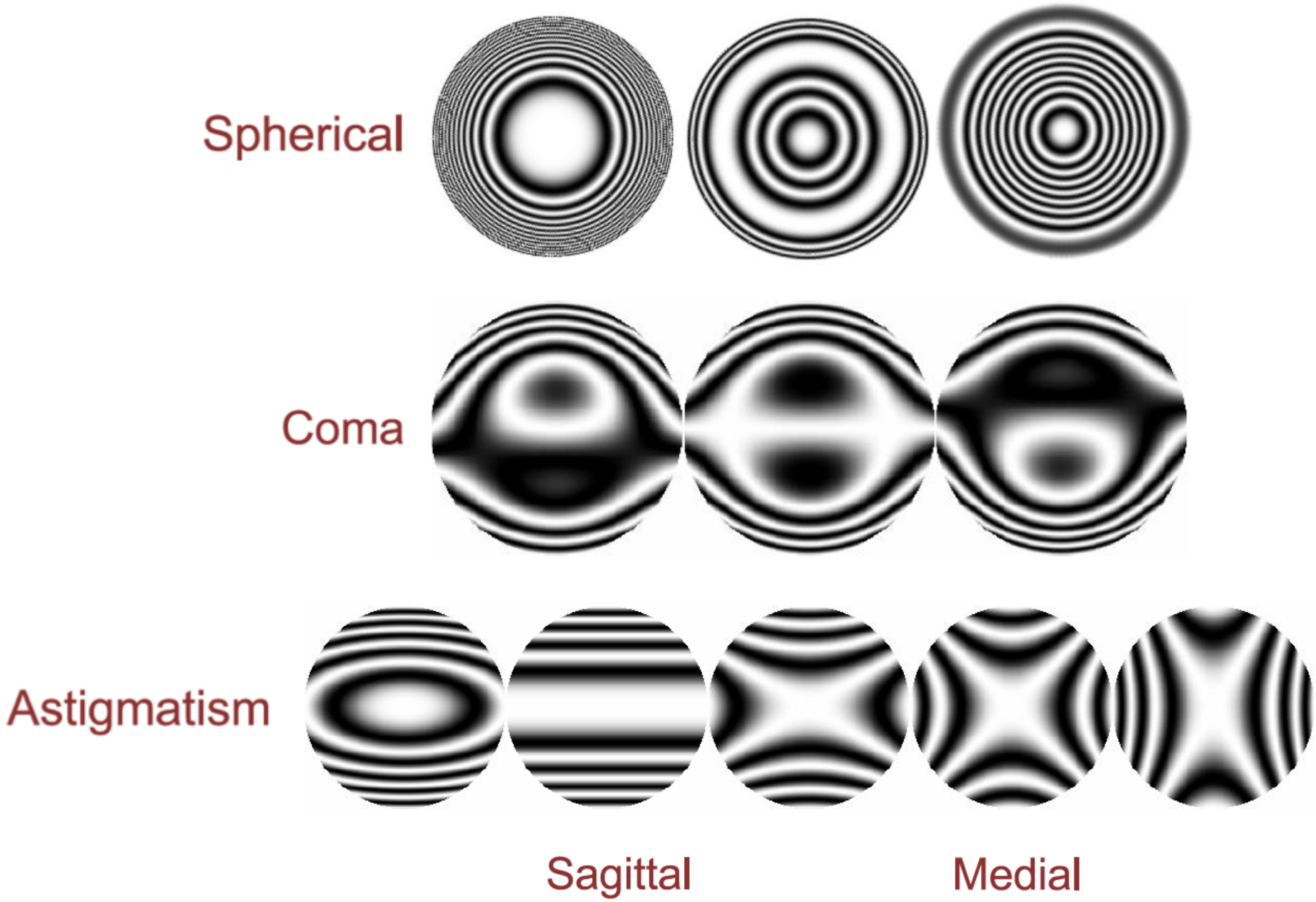
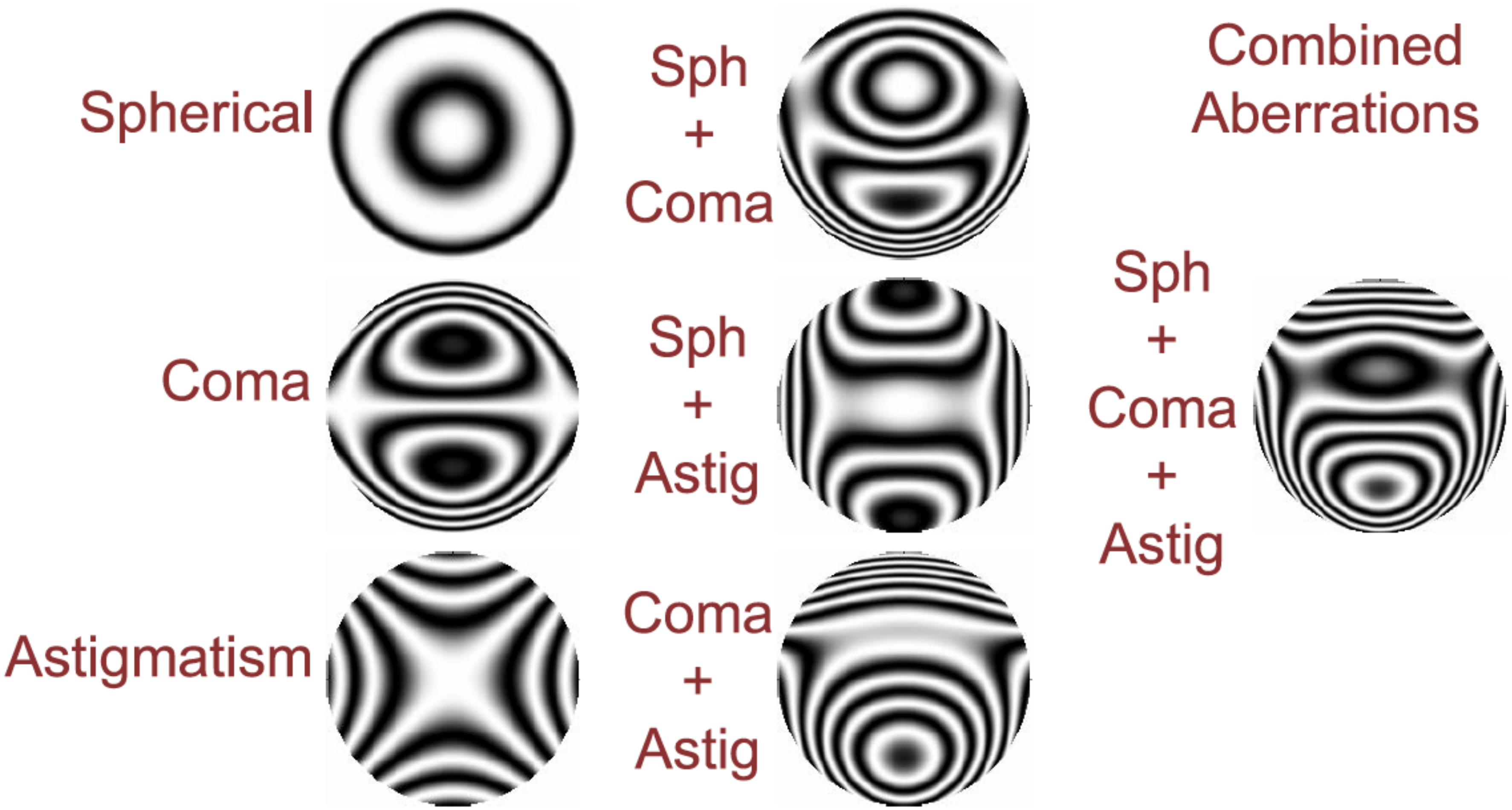
Interferograms
Changing Focus

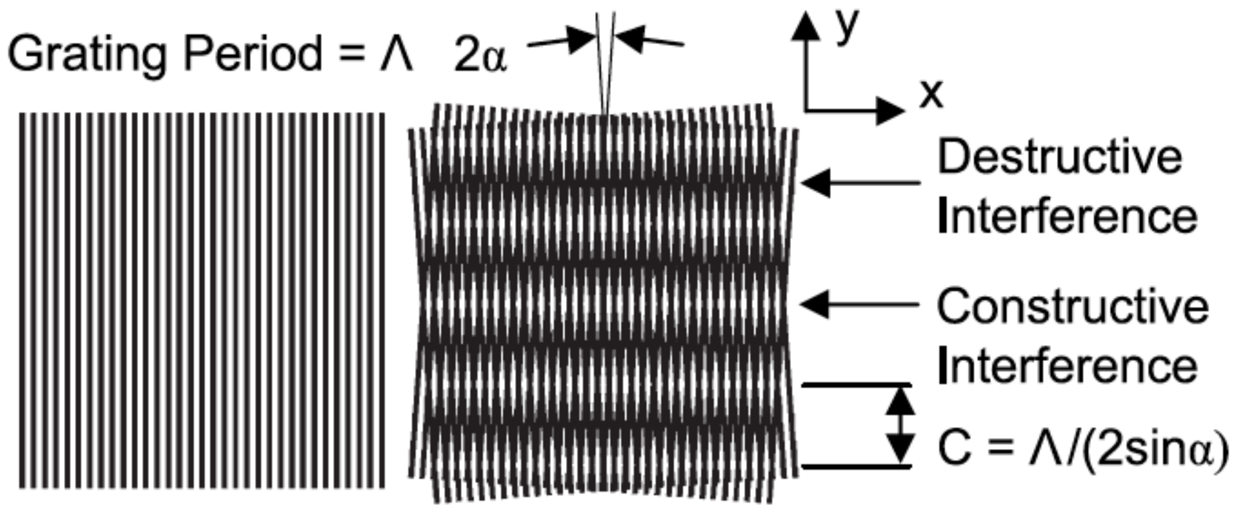


Interferograms
Combined Aberrations



4.7 Interferograms and Moiré Patterns

- In optics moiré refers to a beat pattern produced between two gratings of approximately equal spacing.
- Moiré is a useful technique for aiding in the understanding of interferometry.



Ref: Chapter 16 of Malacara's Optical Shop Testing book

Calculating Moiré Pattern for Arbitrary Gratings

Let the transmission function for two gratings $f_1(x,y)$ and $f_2(x,y)$ be given by

$$f_1(x,y) = a_1 + \sum_{n=1}^{\infty} b_{1n} Cos\left[n\phi_1(x,y)\right]$$

$$f_2(x,y) = a_2 + \sum_{m=1}^{\infty} b_{2m} Cos\left[m\phi_2(x,y)\right]$$

$\phi(x,y)$ is the function describing the basic shape of the lines. The b coefficients determine the profile of the lines.

When these two gratings are superimposed, the resulting intensity function is given by the product.

Two Gratings Superimposed

$$f_1(x,y)\,f_2(x,y) = a_1 a_2 + a_1 \sum_{m=1}^{\infty} b_{2m} Cos\left[m\phi_2(x,y)\right] + a_2 \sum_{n=1}^{\infty} b_{1n} Cos\left[n\phi_1(x,y)\right]$$

$$+ \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} b_{1n} b_{2m} Cos\left[n\phi_1(x,y)\right] Cos\left[m\phi_2(x,y)\right]$$

$$\text{Term \#4} = \frac{1}{2} b_{11} b_{21} Cos\left[\phi_1(x,y) - \phi_2(x,y)\right] + \frac{1}{2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} b_{1n} b_{2m} Cos\left[n\phi_1(x,y) - m\phi_2(x,y)\right]$$

n and m both $\neq$ 1

$$+ \frac{1}{2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} b_{1n} b_{2m} Cos\left[n\phi_1(x,y) + m\phi_2(x,y)\right]$$

The first term represents the difference between the fundamental pattern making up the two gratings.

Moiré for Two Straight Line Patterns

Two gratings of line spacing λ with an angle of 2α between them

$$\phi_1(x,y) = \frac{2\pi}{\lambda}\left(xCos[\alpha] + ySin[\alpha]\right)$$

$$\phi_2(x,y) = \frac{2\pi}{\lambda}\left(xCos[\alpha] - ySin[\alpha]\right)$$

$$\phi_1(x,y) - \phi_2(x,y) = M\,2\pi$$

the fringe centers are given by

$$M\lambda = 2ySin[\alpha]$$

Same result as for interfering two plane waves tilted at an angle of 2α with respect to each other.

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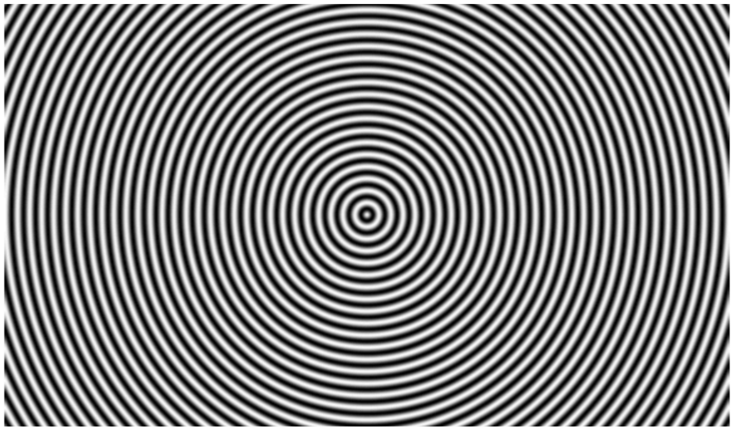
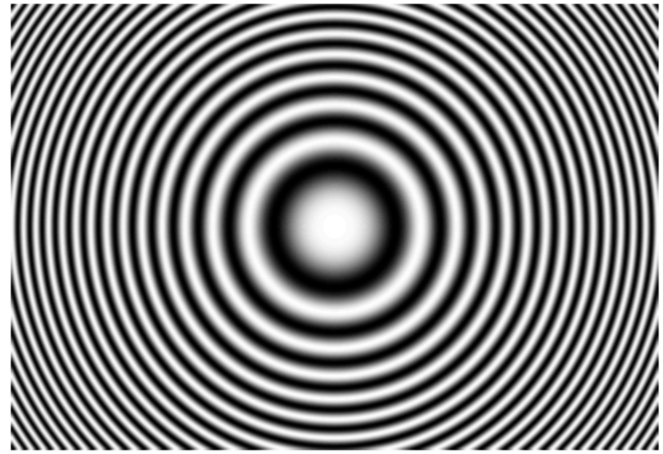
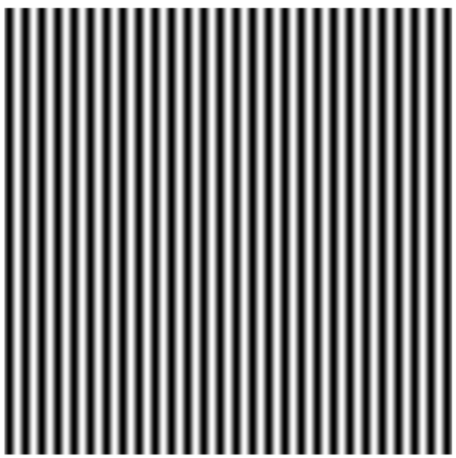
Interference of Two Spherical Waves



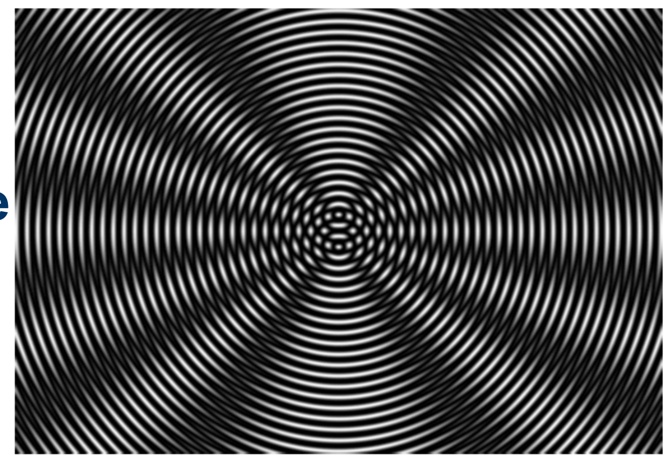
Spherical Wave



Plane A

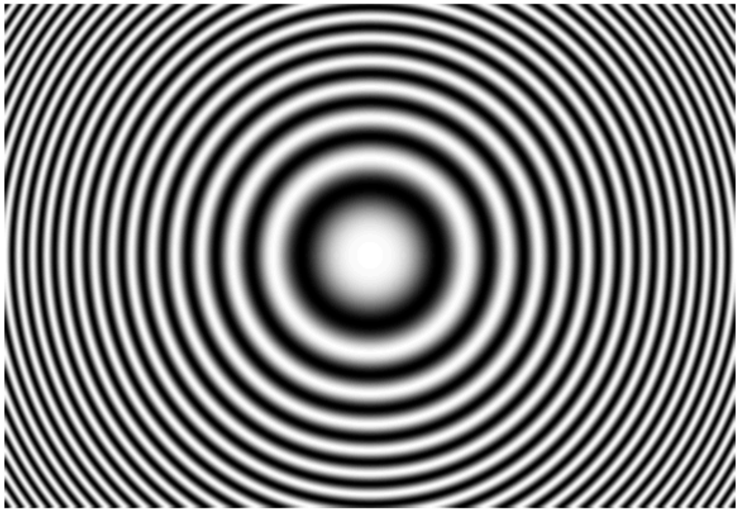


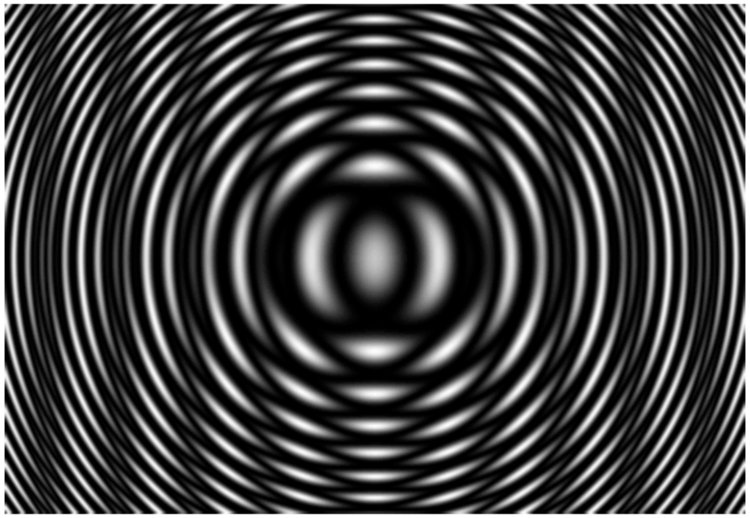
Plane B



Interference

Moiré of Two Zone Plates





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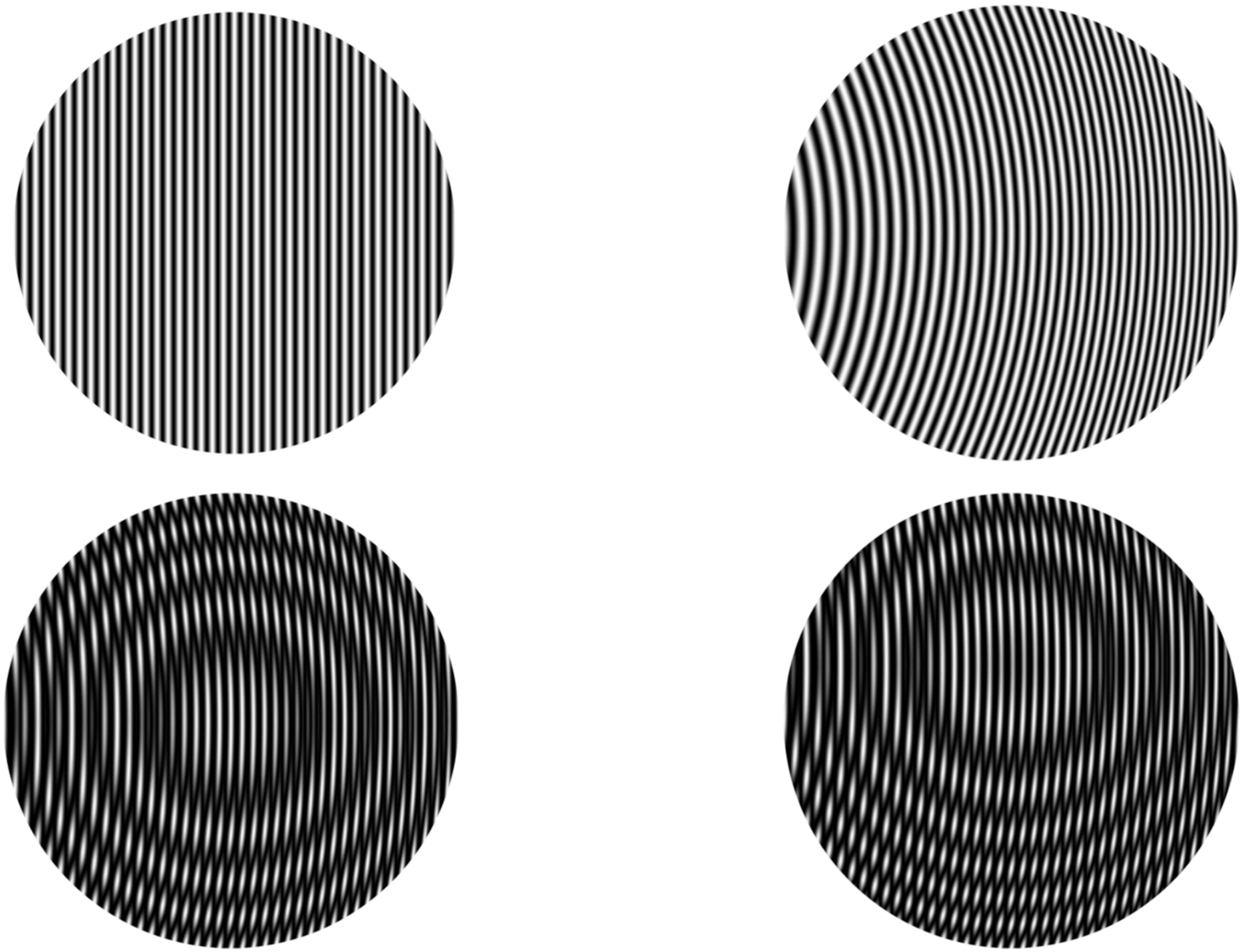
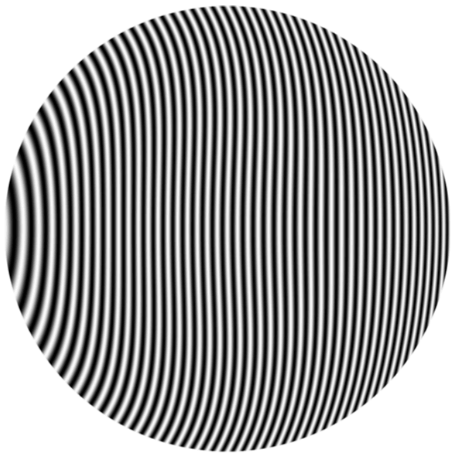
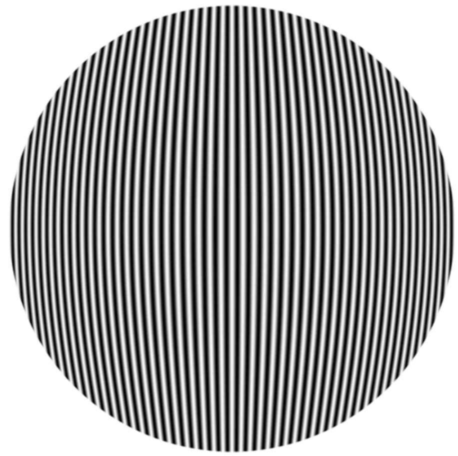
Moiré Between Two Interferograms
20 λ tilt, and 20 λ tilt + 4 λ defocus



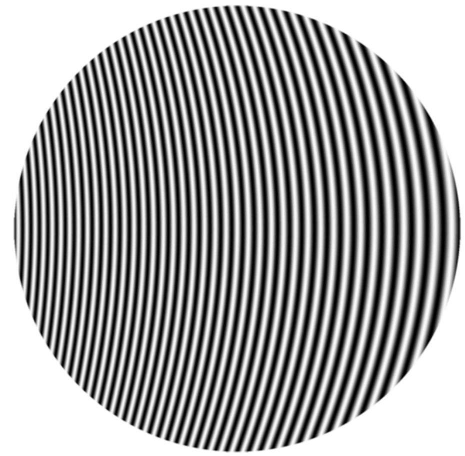
Moiré Patterns Showing Third-Order Aberrations



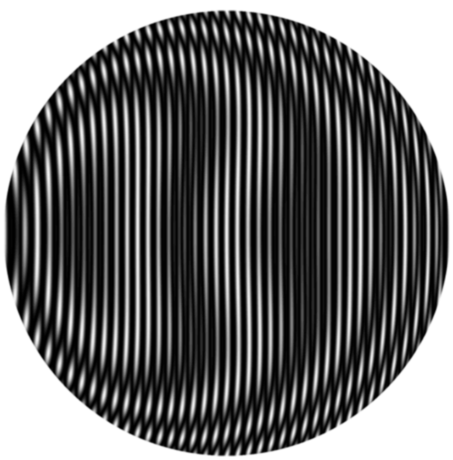
22λ tilt, 4λ sph, -2 defocus

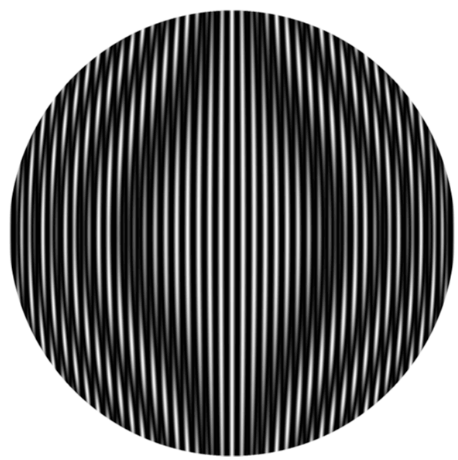


20λ tilt, 5λ coma



20λ tilt, 7λ ast, -3.5 defocus

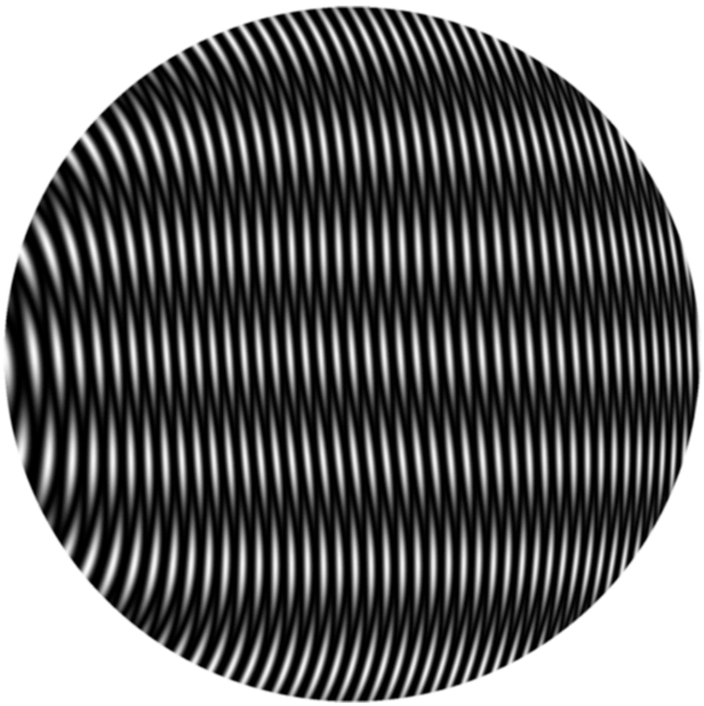




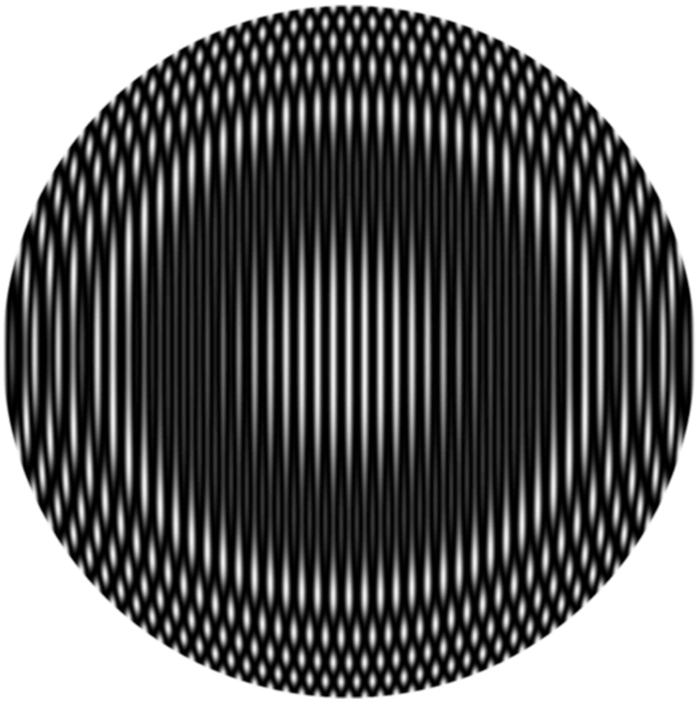
Moiré of above with 20λ tilt

Note: Tilt pattern on previous slide

Moiré Pattern by Superimposing Two Identical Interferograms



Same orientation with slight rotation



One pattern is flipped

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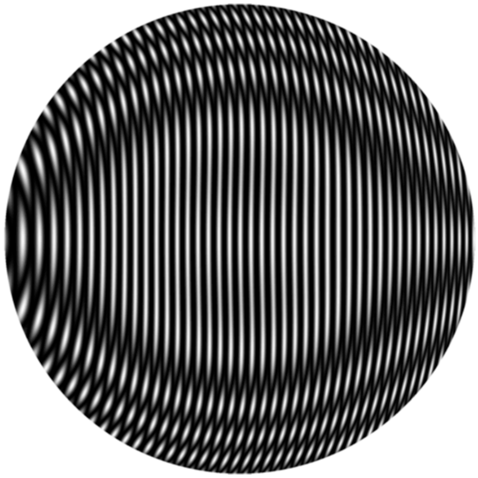
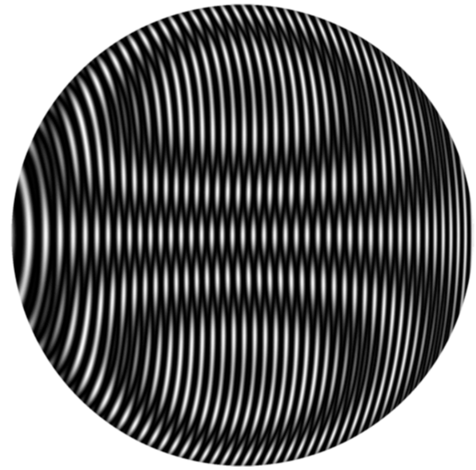
Moiré Pattern Formed Using Two Identical Interferograms with Shear

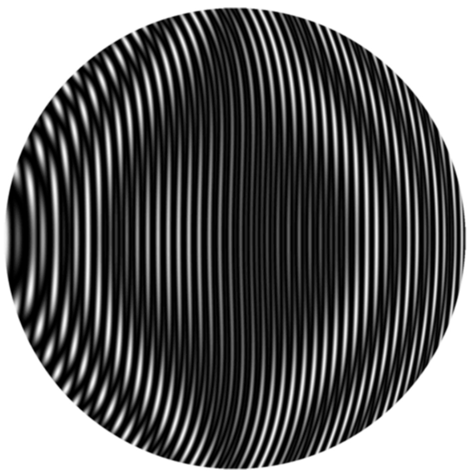
Vertical Shear





Vertical Shear plus Rotation

Horizontal Shear



Horizontal Shear plus Rotation

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Original Pattern: 22λ tilt, 4λ spherical, -2 defocus

Comments on Moiré Patterns

- Moiré patterns are produced by multiplying two patterns.
- A moiré pattern is not obtained if two intensity functions are added because the difference term shown in the derivation of moiré patterns is not present.
- The only way to get a moiré pattern by adding two intensity functions is to use a nonlinear detector that produces terms proportional to the product of the two intensity functions. For example

$$\text{Nonlinear Response} = a(I_1 + I_2) + b(I_1 + I_2)^2 + \cdots$$

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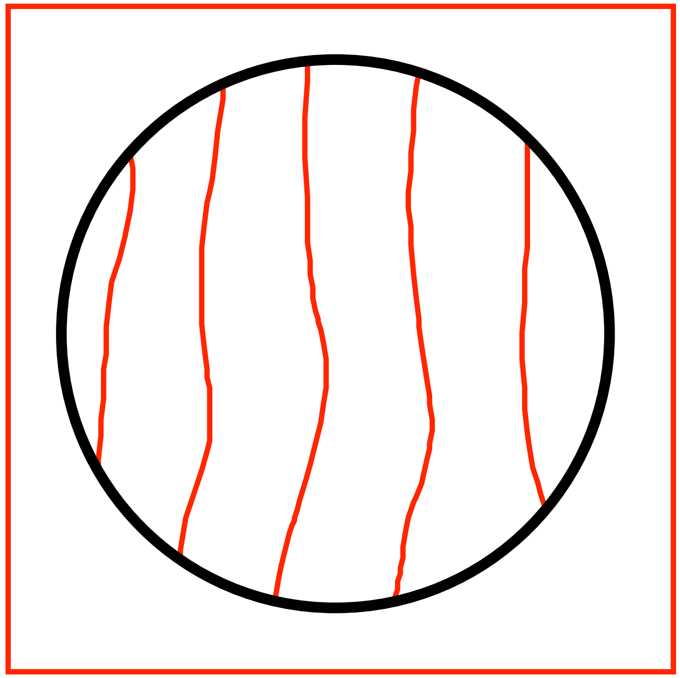
4.8 Classical Techniques for Getting Data into the Computer

- Elementary analysis of interferograms
- Computer analysis of interferograms

Typical Interferogram

Surface Error =
(λ/2) (Δ/S)



Classical Analysis

Measure positions of fringe centers.

Deviations from straightness and equal spacing gives aberration.

Elementary Interferogram Analysis

- Estimate peak to valley (P-V) by looking at interferogram.
- Dangerous to only estimate P-V because one bad point can make optics look worse than it actually is.
- Better to use computer analysis to determine additional parameters such as root-mean-square (RMS).

Computer Analysis of Interferograms

Largest Problem

Getting interferogram data into computer

Solutions

- Graphics Tablet
- Scanner
- CCD Camera
- Phase-Shifting Interferometry

Digitization

Automatic Interferogram Scanner

One solution

Video system and computer automatically finds locations of two sides of interference fringe where intensity reaches a given value.

Fringe center is average of two edge locations.

Computer Analysis Categories

- Determination of what is wrong with optics being tested and what can be done to make the optics better.
- Determination of performance of optics if no improvement is made.

Minimum Capabilities of Interferogram Analysis Software

- RMS and P-V
- Removal of desired aberrations
- Average of many data sets
- 2-D and 3-D contour maps
- Slope maps
- Spot diagrams and encircled energy
- Diffraction calculations - PSF and MTF
- Analysis of synthetic wavefronts