Light Waves as Standard of Length

Light Waves

- Wave Model of Light
- Introduction to Interference
- Interferometry Applied to Flatness Testing
- Additional Interferometry Applications
- Interferometers.

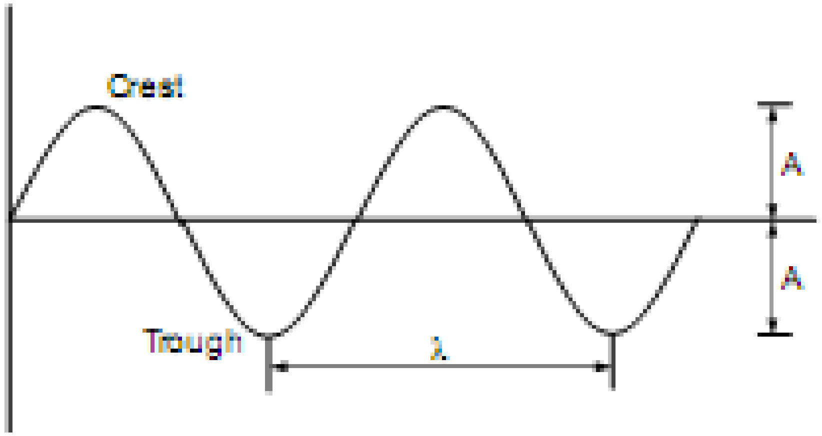
History

Christiaan Huygens

(1629-1695)

- First major proponent of the wave theory of light
- Considered light as a wave motion propagated in ether

Light Wave



A = Amplitude
A^2 = Intensity
λ = Wave Length
$V = \lambda/T$ = Velocity of Transmission
$n=1/T$ = Frequency

Light Waves as Standards-Benefits

- High Degree of Accuracy

– Used by the International Committee of Weights and Measures

– Meter is defined as: 1,650,763.73λ

– λ = Wavelength of the orange-red isotope of Krypton 86 (605.78 nm)

– Subdivision to 1 part per million

- Virtually Independent of Ambient Conditions

– Temperature

– Pressure

- Reproducible

– No need for a physical standard artifact.

Light Sources

Krypton 86 (605.78 nm)

- Excitation takes place at very low temperatures (~68°K)
- Used as International Standard of Length

Mercury 198 (546.1 nm)

- Less expensive
- Green light easily separated with filters
- Drawback – radiates a mixture of wavelengths

Cadmium (644.85 nm)

- (Almost) symmetrical red spectral line
- Official secondary standard of length

White light (~500 nm).

Light Sources

- Gas Lasers

– Helium – Neon (632.8 nm)

– CO2 – (10600 nm)

- Gas Lasers - advantages

– Produce highly monochromatic light

– Highly intense (1000 times more intense than others)

– Created by exciting a mixture of neon and helium in a special discharge tube

- Gas Lasers - disadvantages

– High cost

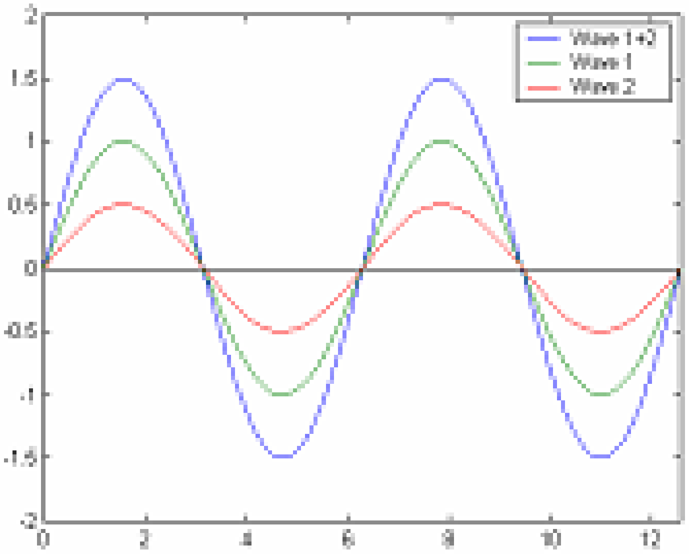
– Wavelength affected by temperature and vibration

– Special optics required to spread the ray.

Interference- Basics

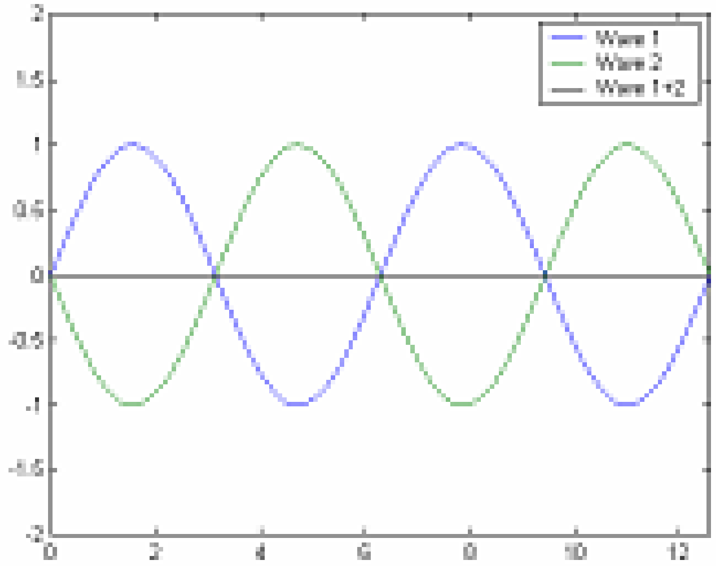
Consider Two Monochromatic Rays

When the two waves are in phase, they add:



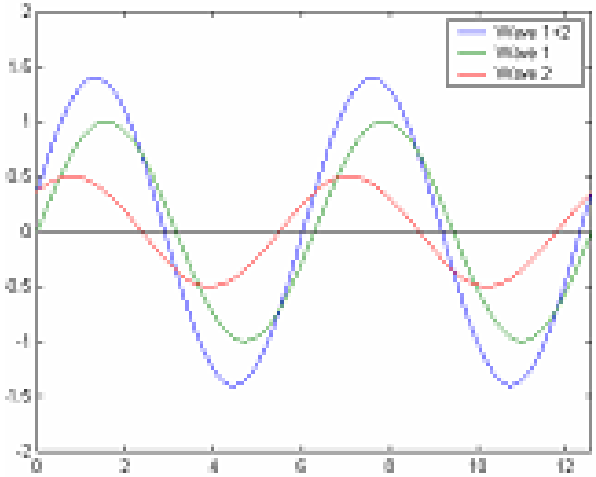
Interference- Basics

When they are 180° out of phase, they cancel.



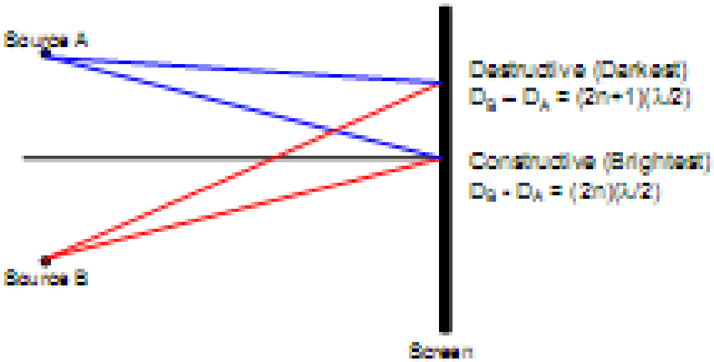
Interference-Basics

- The resultant wave will equal the sum of the amplitudes(R = A1 + A2)



Fringes

- Consider rays from two point sources, A & B



- The difference in the path lengths creates light and dark bands
  - Difference of odd number of half wavelengths: destructive
  - Difference of even number of half wavelengths: constructive

Fringe Formation

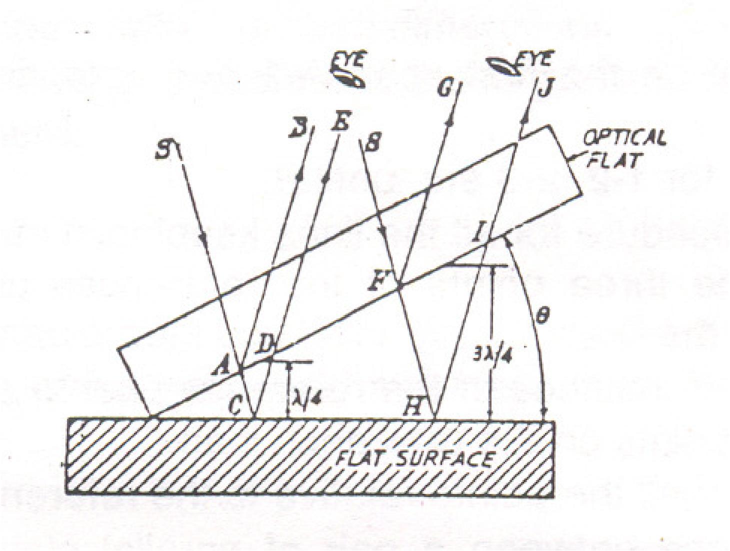
- In order for light interference to occur, the following conditions are necessary:
  - Light from a single source must be divided into two component rays
  - Before being re-combined at the receiver, the components must travel paths whose lengths differ by an odd number of wavelengths
  - Note, this is a relative measure

Using Interference for Flatness Testing

- Optical Flat
  - A circular piece of stress free glass or fused quartz
  - Has two planes that are flat and parallel
  - Surfaces are finished to an optical degree of flatness
- Properties of the Optical Flat
  - Vary in size from 25 mm to 300 mm diameter
  - Minimum expansion due to heat
  - Thickness (up to 50 mm) insures freedom from distortion.

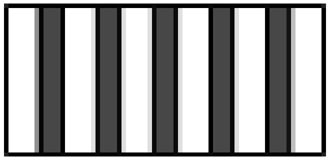
Optical Flat

- Interference in an optical flat



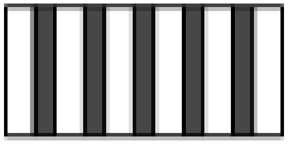
Using Interference for Flatness Testing

- Place an Optical Flat on the surface
  - Will lie at a small angle to the surface due to air cushion
- Illuminate with monochromatic light
- Will observe fringes like those shown below
  - Dark fringes occur for (1/2 + n)λ, n = 1,2,3,…
  - Light fringes occur for nλ, n = 1,2,3,…



Using Interference for Flatness Testing

- As the angle is increased, the fringes are brought closer together
- As the angle is decreased, the fringes spacing increases
- Each adjacent fringe represents a change in elevation of λ/2
- Total change in elevation = λ/2*n



Errors

- The line of sight should be perpendicular to the reference surface of the optical flat.
- Fringe spacing will be distorted
  - A viewing error of 30° results in an error of 15%
  - A viewing error of 45° results in an error of 40%

Convex / Concave Surfaces

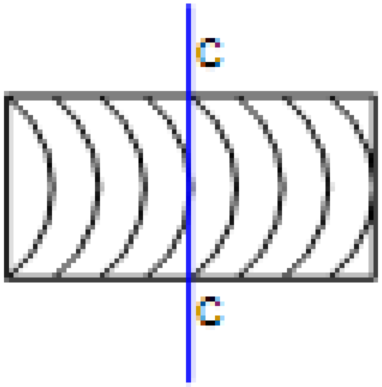
- A convex or concave surface will result in concentric fringes, as shown below
- To determine which, apply pressure to optical flat

Practice for Using Optical Flats

- Handle optical flats carefully
- Handle optical flats minimally
- Ensure optical flat and work surface are clean by using a lint free soft cloth
- Never wring an optical flat to a surface
  - do not push hard on an optical flat
- Never wring two optical flats together.

Convex / Concave Surfaces

- In the following figure, the edge is half a wavelength higher/lower than the centerline

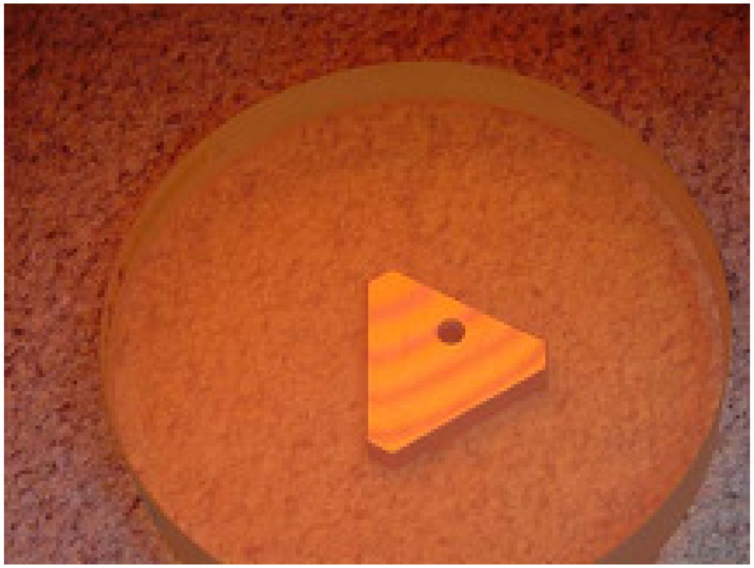


Drawbacks of Using Optical Flats

- Difficult to control the lay of the flat
  - difficult to orient the fringes to their best advantage
- Fringe patter not viewed from directly above can cause distortion and generate errors.

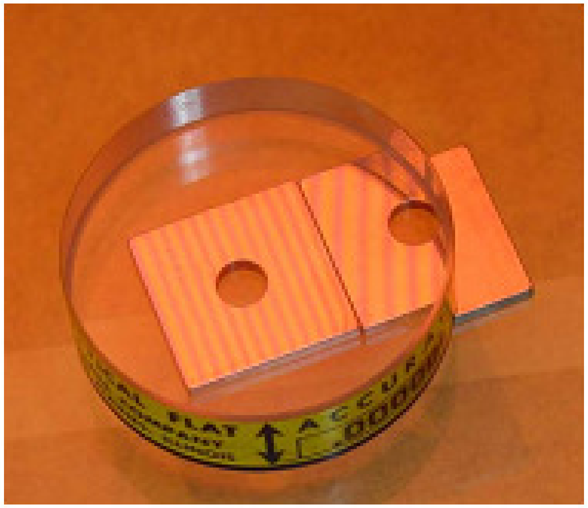
Optical Flat with Fringes

8 inch Zerodur, $\lambda/10$



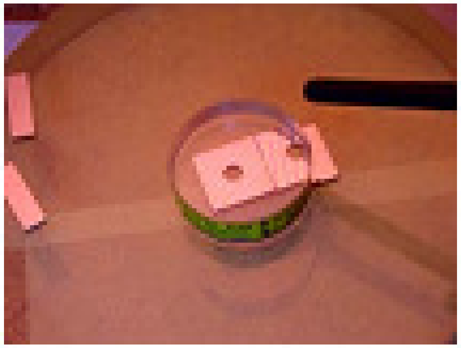
Two Flats

Difference in heights is 0.0001 (±2μin WRT calibration)



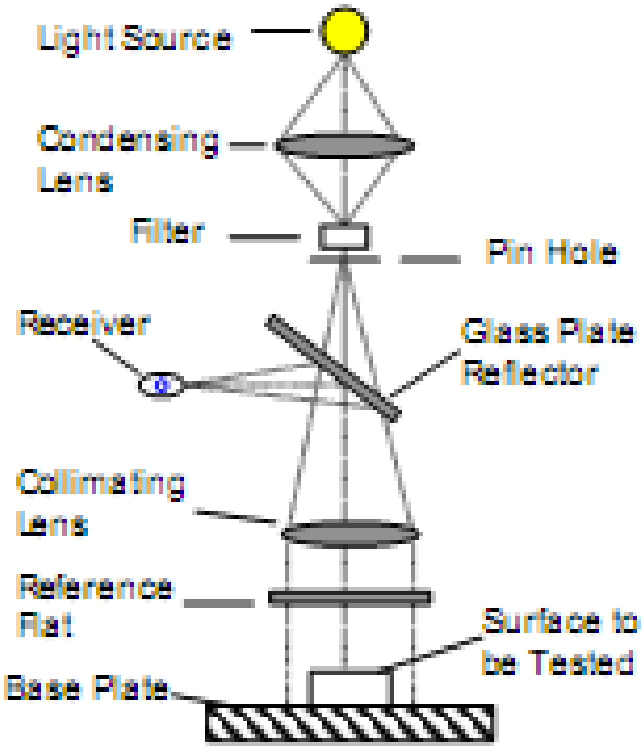
Flat's in Operation

Pushing on a Flat

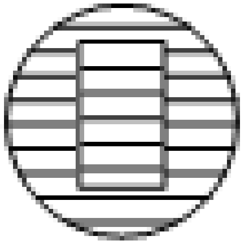


Pivot Points

Interferometers for Flatness Testing

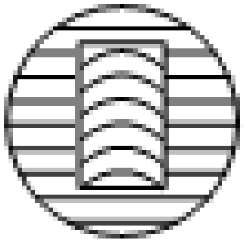


Interferometers for Flatness Testing

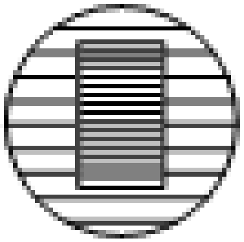


Surface flat & parallel

Surface flat but not
parallel from left to right



Surface convex or concave



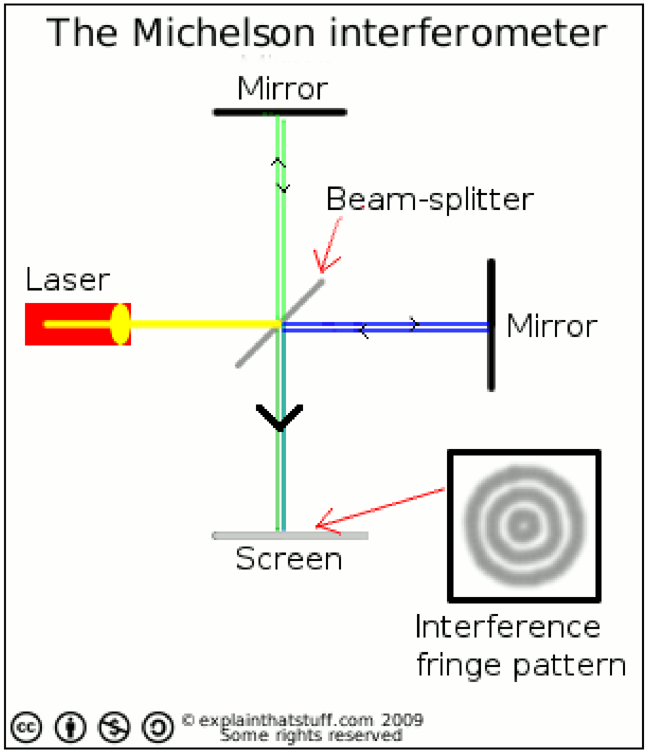
Surface flat but not
parallel from top to bottom

Interferometers

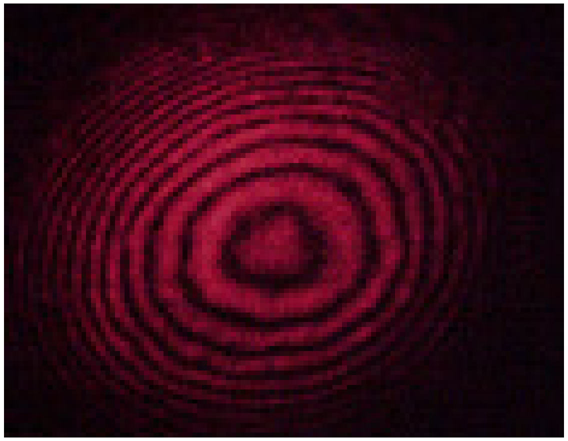
- Michelson Interferometer
- Wyko NT9100 3-D Surface Profiler
- Laser Interferometer

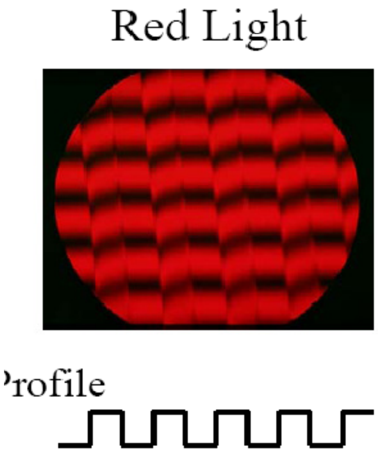
Michelson Interferometer

- Compares the path lengths of light traveling two different directions



Michelson Interferometer





- Used for examining minute details of surfaces
- Used by Michelson to disprove the theory of ether

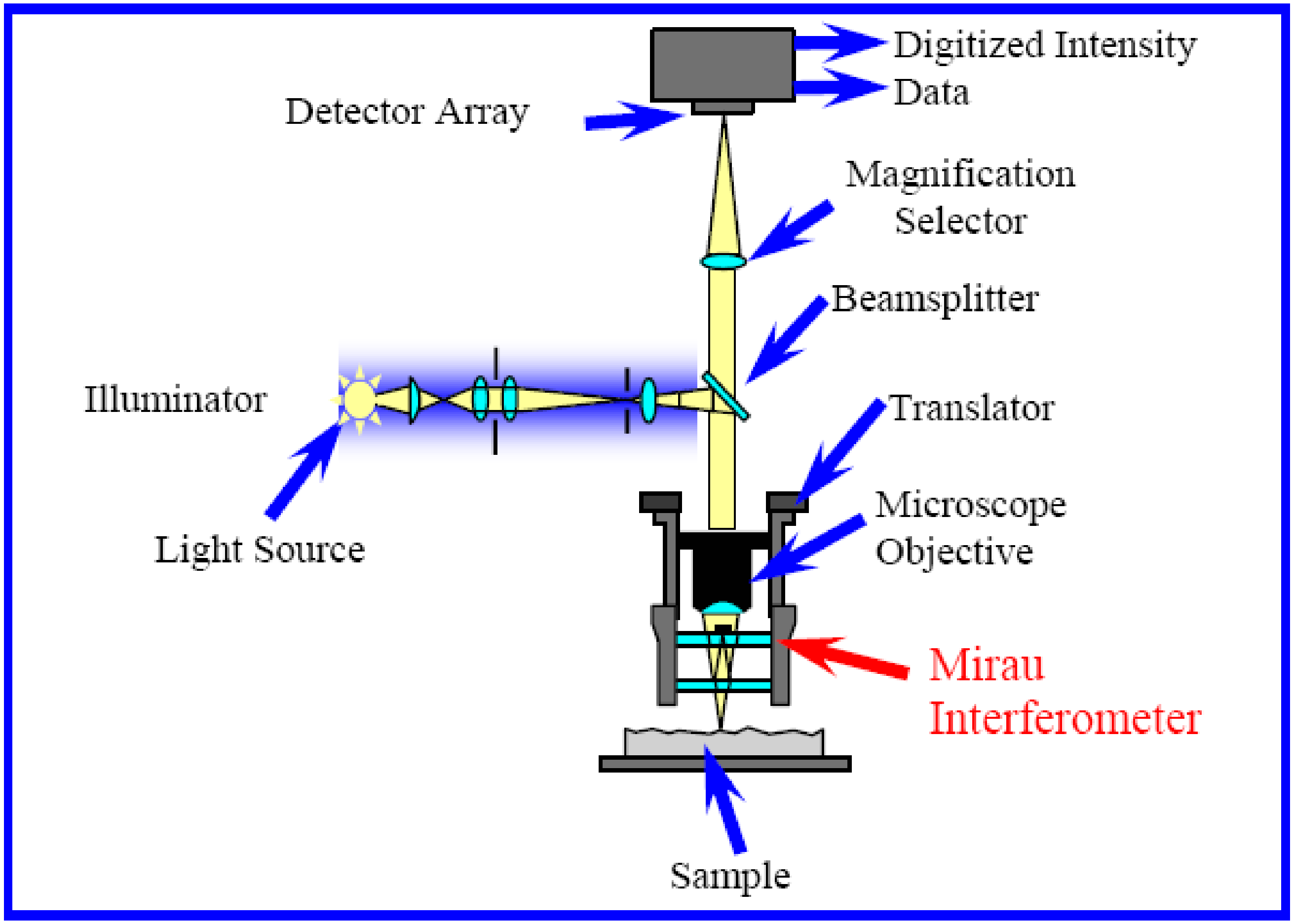
WYKO NT9100

Z- Resolution – 0.01 nm

Scan length – 10 mm

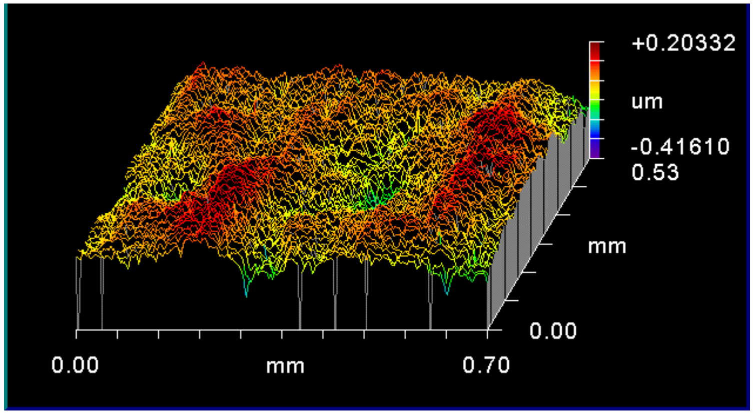
Lateral resolution – 1 μm

Interferometry-Basics

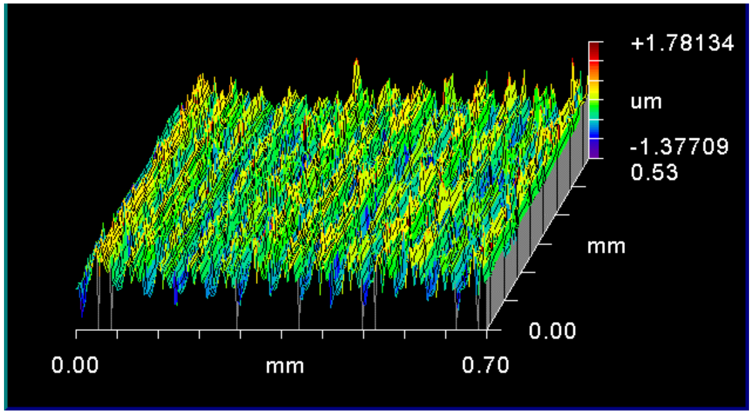


Plots from Whitelight Interferometer

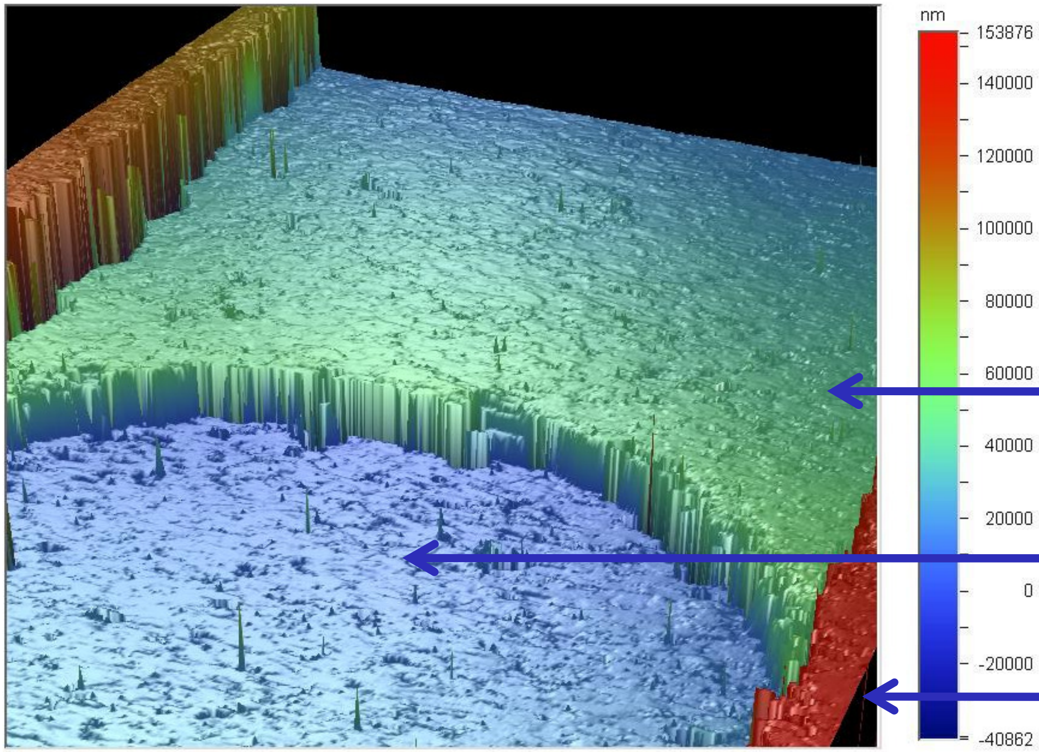
Periodic and/or random deviations of a real surface from the nominal surface (texture)



Isotropic Surface: random



Turned Surface: Periodic



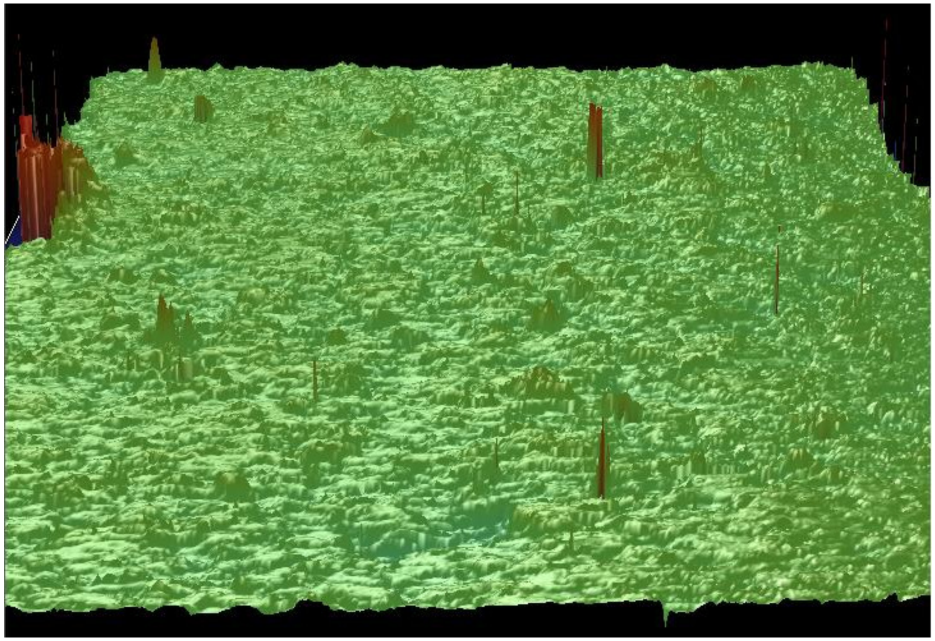
3D groove height (other fresh groove)

Reference surface

Machined surface

Top surface

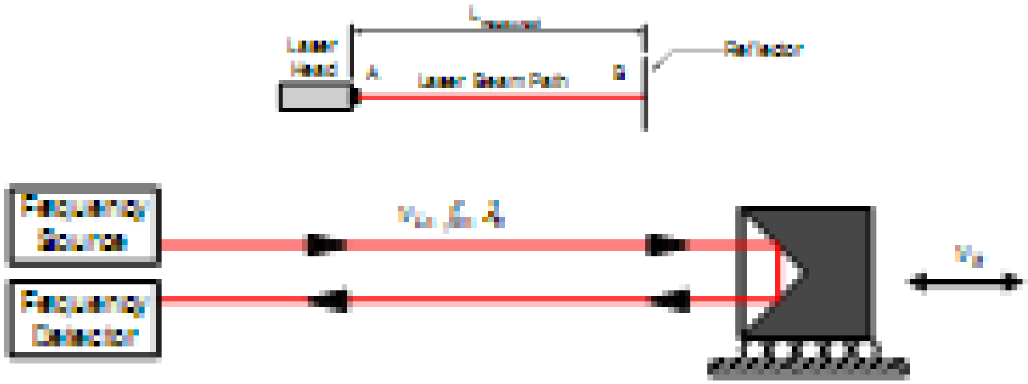
Surface morphology of groove bottom surface



Laser Interferometer

- Counts the number of wavelengths that the laser traverses between the two points to determine distances
  - Measures only relative displacements
- Can be used to measure:
  - Linear Displacement
  - Angular Displacement
  - Straightness
  - Squareness
  - Parallelism

Laser Interferometer



v_L: WaveVelocity

v_R : Reflector Velocity

f_0 : Wave frequency

λ 0: Wavelength

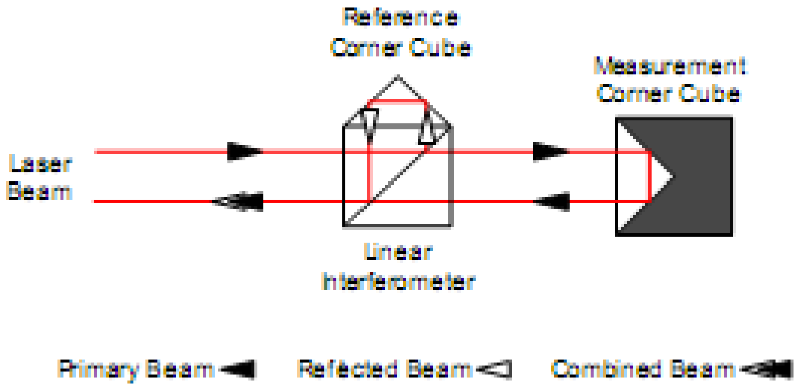
$\Delta\varphi$: Position Shift

Δx : Position shift

$$\Delta x=\Delta\phi\lambda/4\pi$$

Laser Interferometer

- Typical laser path

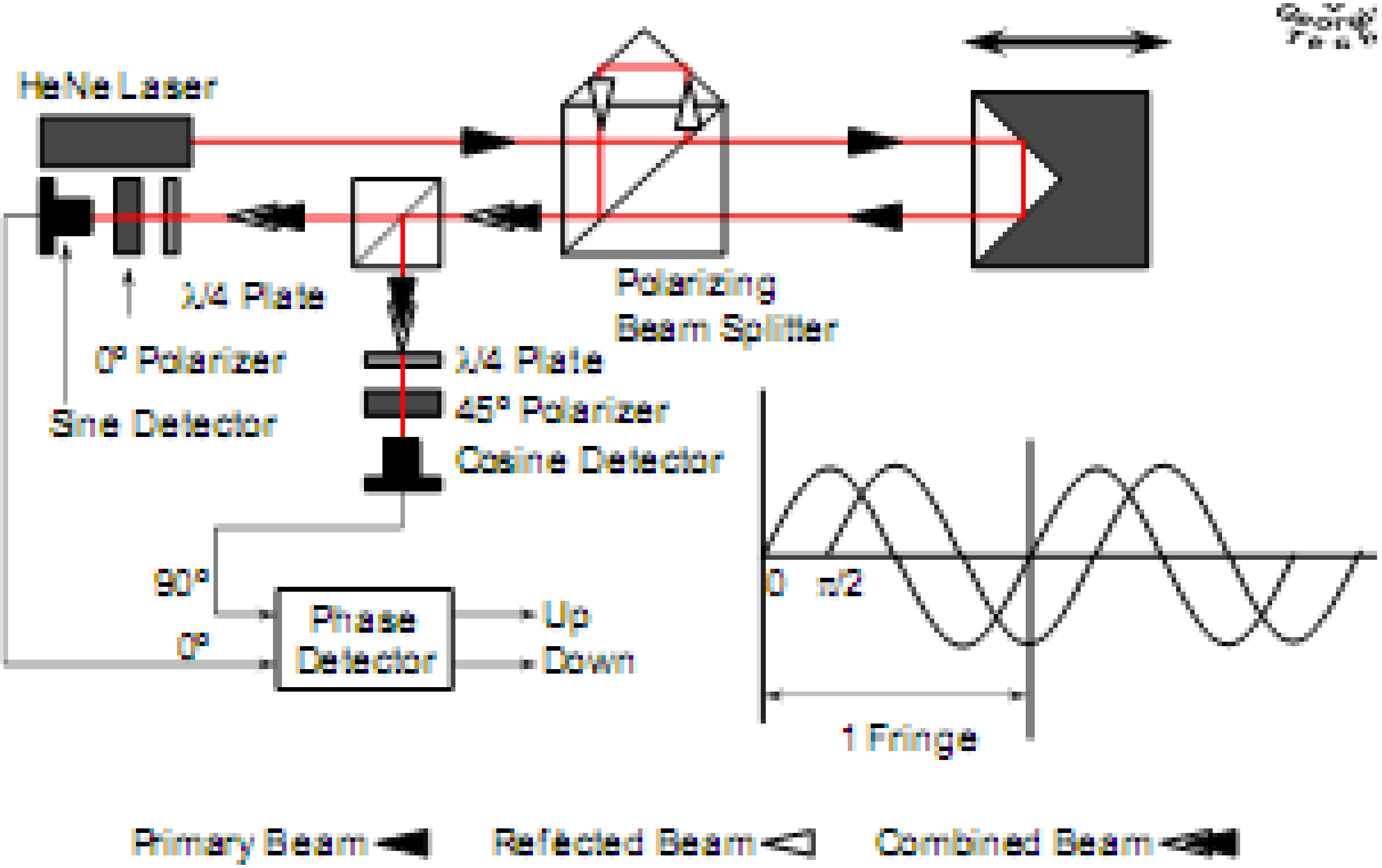


- The accuracy of the interferometer is determined by the laser wave length, which is known to better than 0.05 parts per million.

Improvements

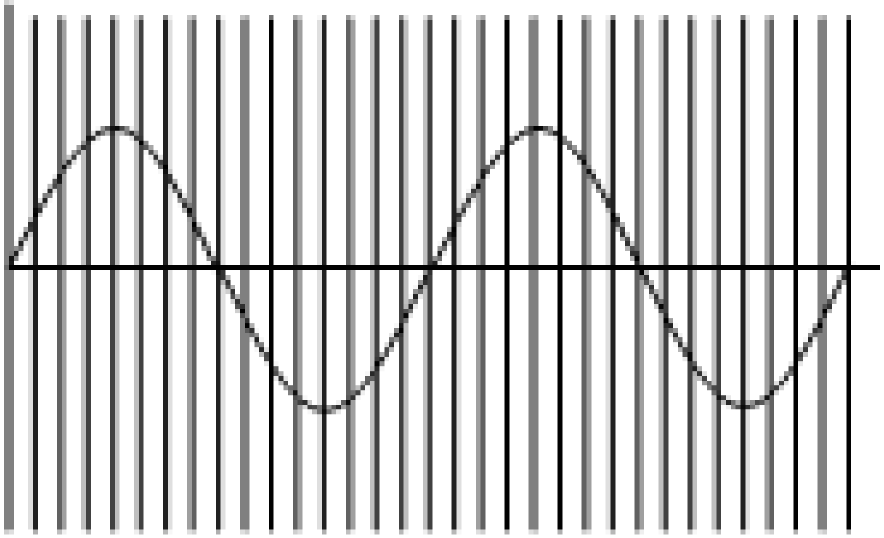
- Phase Detection
  - Michelson interferometer l/8 resolution, easily
  - Can take half the signal and retard it by 90 phase
  - Using a quarter wave plate
  - First detector and second detector generate sine and cosine components.

Improvements



Subdividing –Expanding Resolution

- Sine and cosine detector output follow a predictable sinusoidal curve
- Common resolution interpolators 16X to 256X



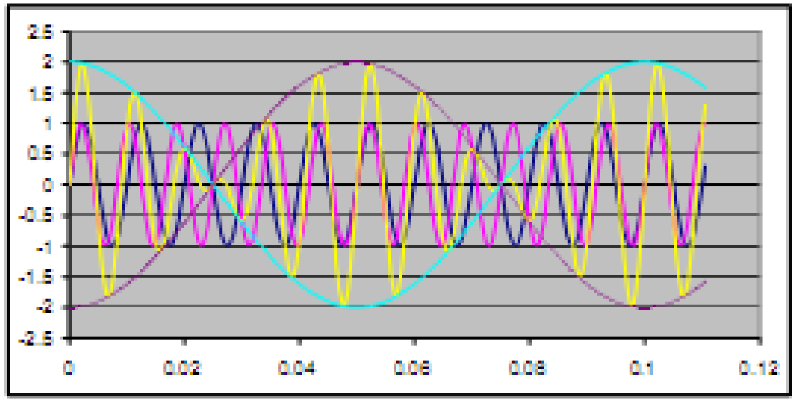
Improvements-Hetrodyne lasers

- As target moves faster, fringes occur faster and Doppler effects become significant
- Using a dual frequency laser with a slight variation in frequencies (20 MHz) one can generate a beat frequency.

$$Y_1 = A\cos\left(2\pi f_1 t\right) \qquad Y_2 = A\cos\left(2\pi f_2 t\right)$$

$$Y_1 + Y_2 = A\cos\left(\frac{2\pi\left(f_2 - f_1\right)t}{2}\right)\cos\left(\frac{2\pi\left(f_1 + f_2\right)t}{2}\right.$$

$$f_{waveform} = \frac{f_1 + f_2}{2} \qquad f_{amplitude} = \frac{f_2 - f_1}{2}$$

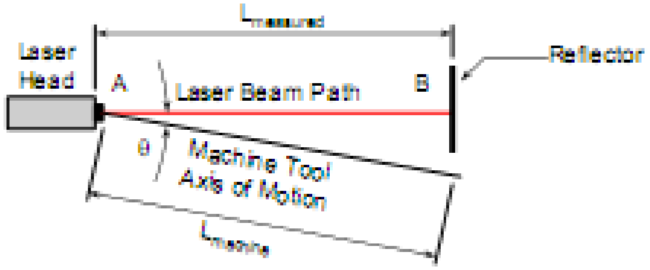


Laser Interferometry - Cosine Error

- Definition
  - the measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the gate of displacement being measured
  - cosine errors are present when comparing any 2 displacement measuring systems
- Assuming perfect laser (or artifact) and machine
  - a laser angular misalignment causes the laser to always display a smaller or shorter value that the machine's display
  - an angular misalignment of an artifact of length standard causes the machine's display to always be longer than the artifact's length

Laser Interferometry - Cosine Error

- Misalignment of the laser beam path to the axis of motion of the machine tool with results in an error between the measured distance and the actual distance traveled



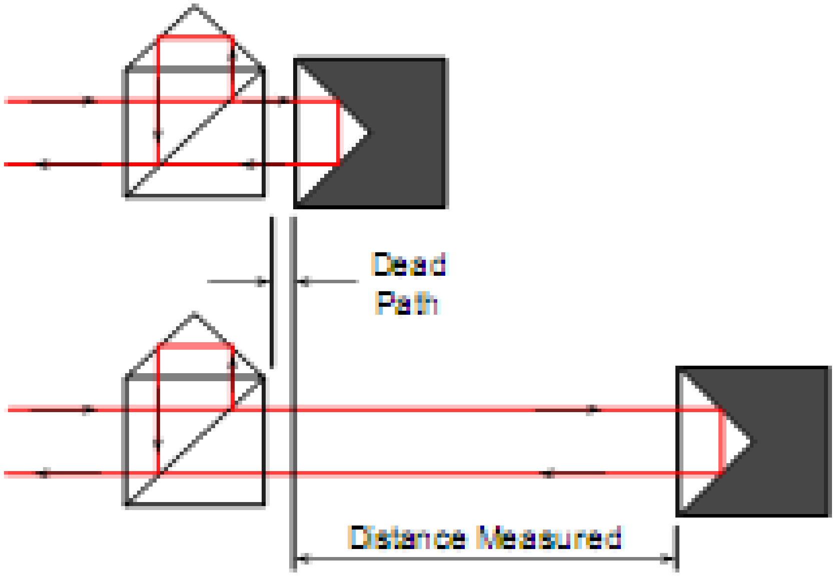
$$L_{measured} < L_{machine}$$
$$L_{measured} = L_{machine} \cos(\theta)$$

Environmental Conditions

- In making linear measurements, it is necessary to compensate for:
  - the change in wave length of the laser light doe to the ambient conditions o the air (VOL)
  - The change in length of the machine’s scales due to thermal expansion or contraction

Laser Dead Path

- The compensation for velocity-of-light (VOL) error is applied only to the portion of the path where displacement is measured



Summary

- Interferometery
- Laser Interferometer
- White Light Interferometer
- Errors