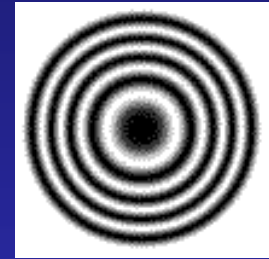
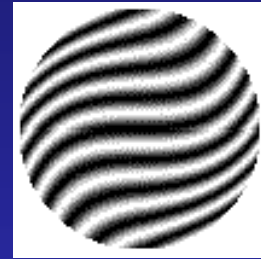
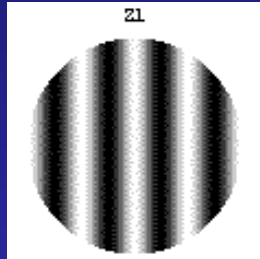
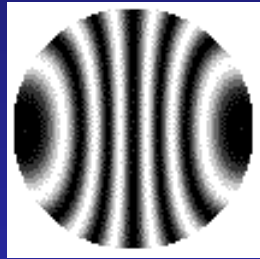
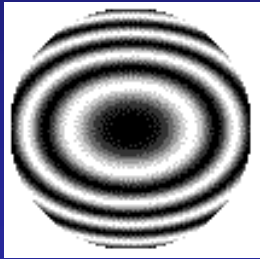


# Advanced Interferometric Surface Measurement in the Technology Frontier

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# **Old Optics + New(Computers + Software + Electronics) = Fantastic Measurement Capabilities**

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**Improved computers, electronics, and software have helped make possible enormous improvements in the measurement of surface shape and surface roughness.**

# Outline

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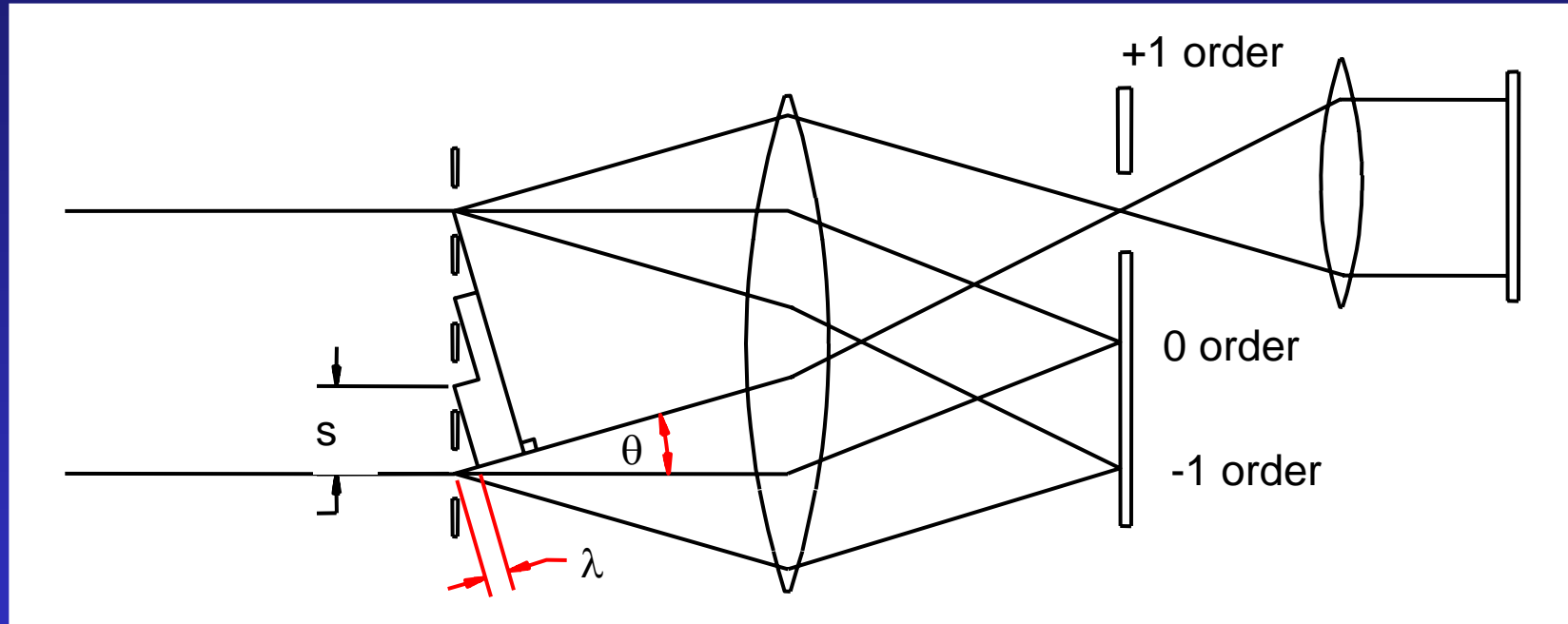
- **Computer Generated Holograms (CGH)**
- **Phase-Shifting Interferometry**
- **Performing Interferometric Measurements  
More Accurate than the Reference Surface**
- **Vibration Insensitive Interferometers**

# Problem #1: Testing Aspheric Surfaces

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- **Aspheric surfaces are of much interest because they can provide**
  - Improved performance
  - Reduced number of optical components
  - Reduced weight
  - Lower cost
- **A major stumbling block in using aspheric surfaces is being able to test the aspheric surfaces – need aspheric reference wavefront**

# Solution: Use Diffraction to Provide Reference Wavefront (CGH)

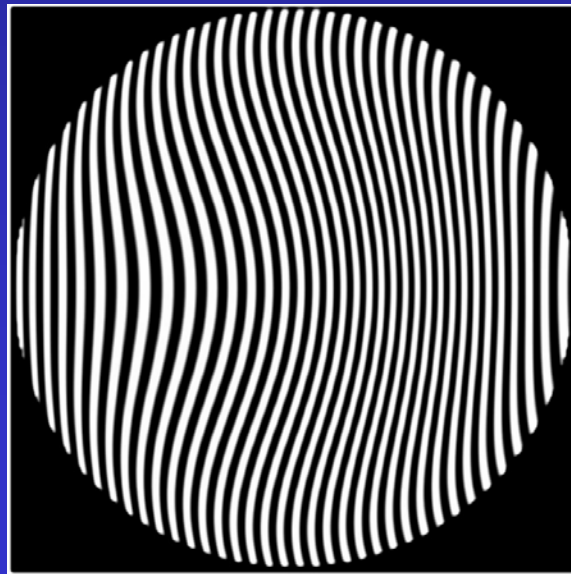


Diffraction from CGH alters wavefront,  
changes slope by  $\text{Sin}[\theta] = m\lambda/s$   
changes wavefront phase by adding  $m\lambda$  per line  
( $m = \text{order of diffraction} = 0, \pm 1, \pm 2, \dots$ )  
zero order is same as if there was no pattern

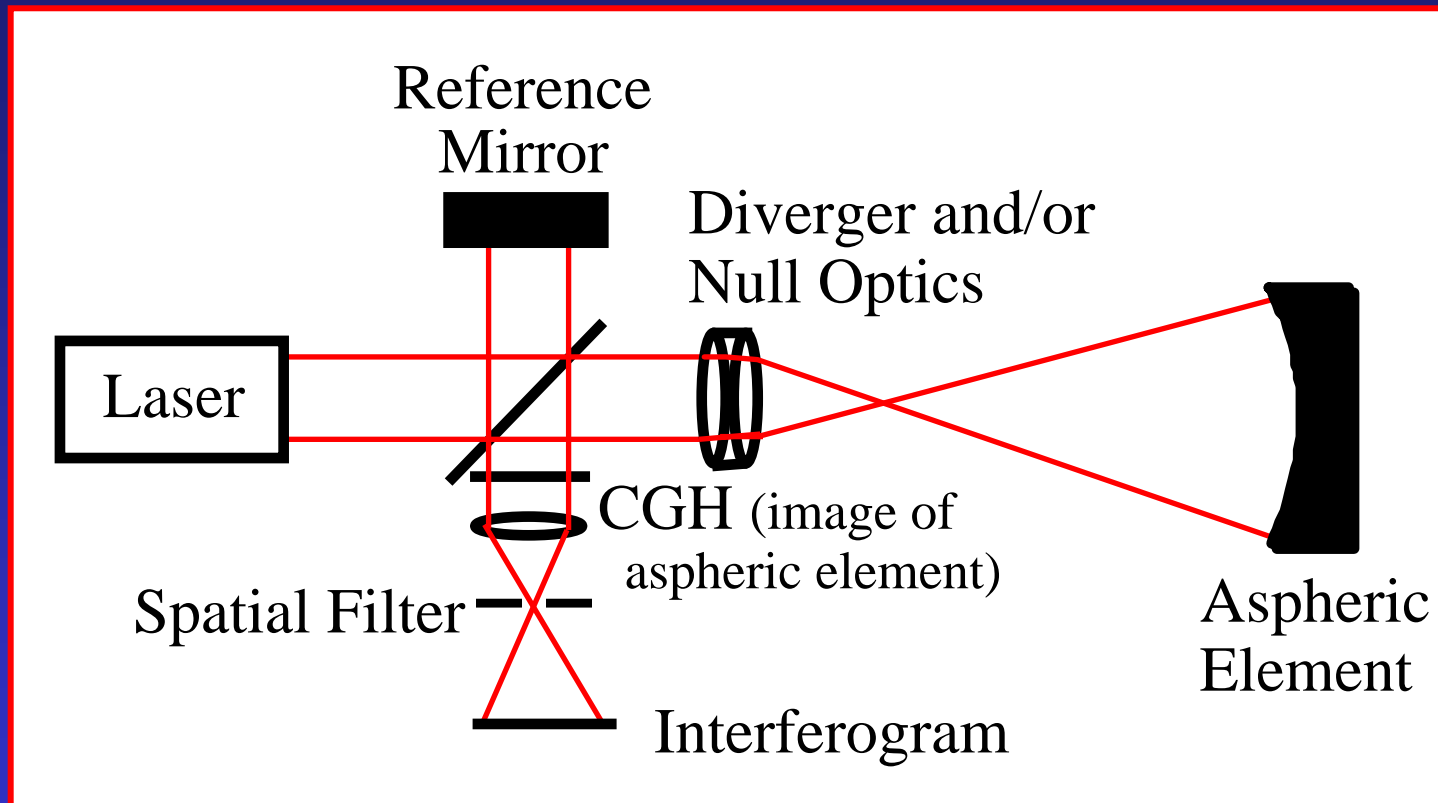
# What is the Computer Generated Hologram?

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- A CGH looks like a binary representation of an interferogram
  - Chrome pattern on glass (density hologram)
  - Pattern etched into glass (phase hologram)



# CGH Interferometer

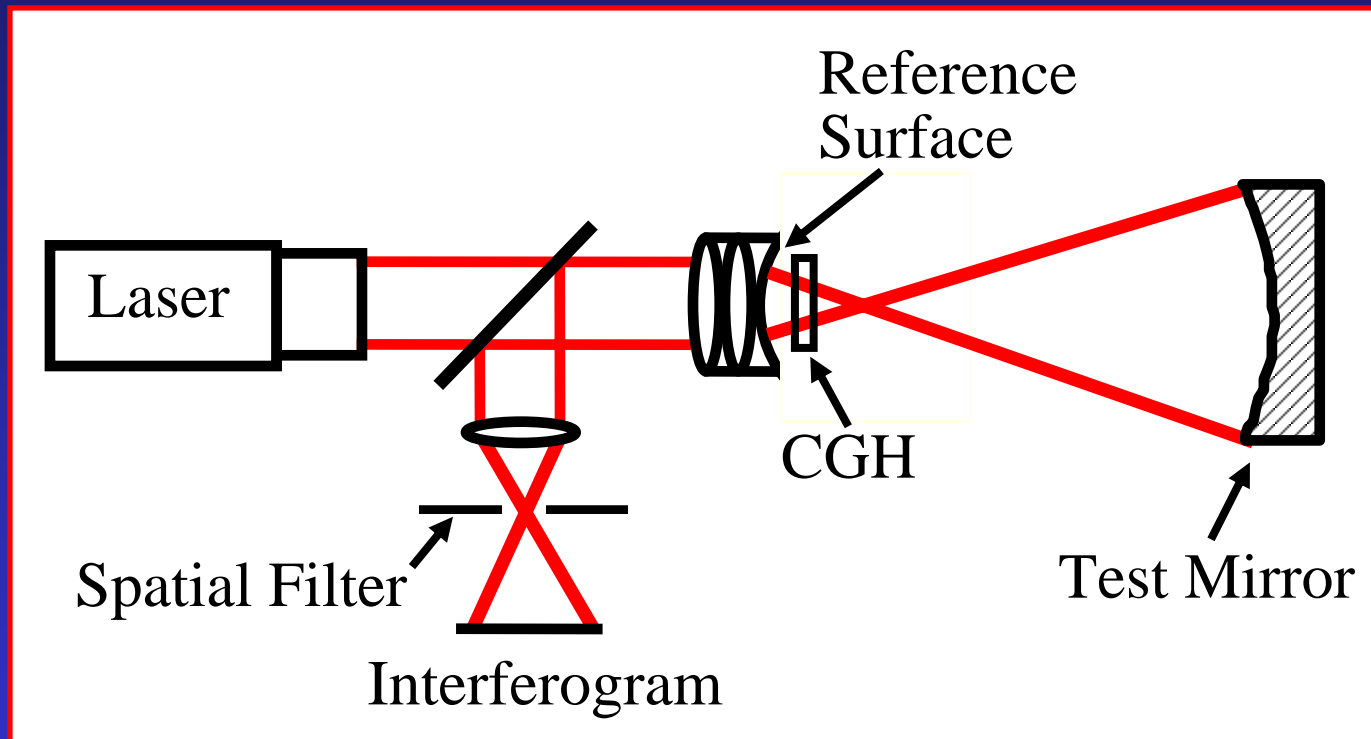


Must know diverger lens so it can be ray traced.

Need to get inside the interferometer.

Errors in CGH substrate thickness cancel out.

# 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

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

**Calibration can remove errors**

# Plotters

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- **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

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- 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

# Alignment Errors

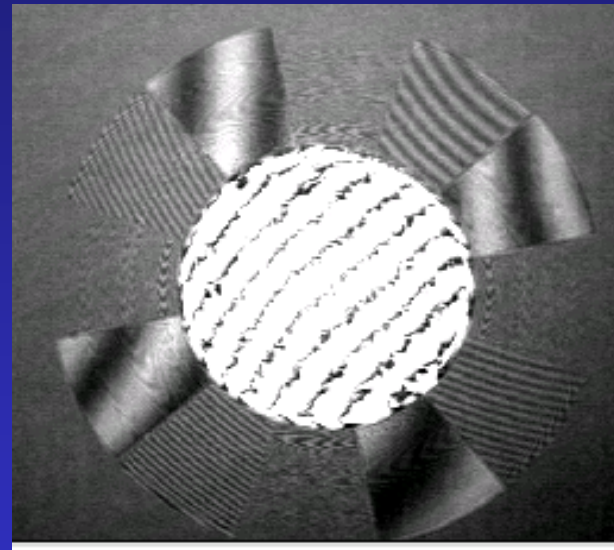
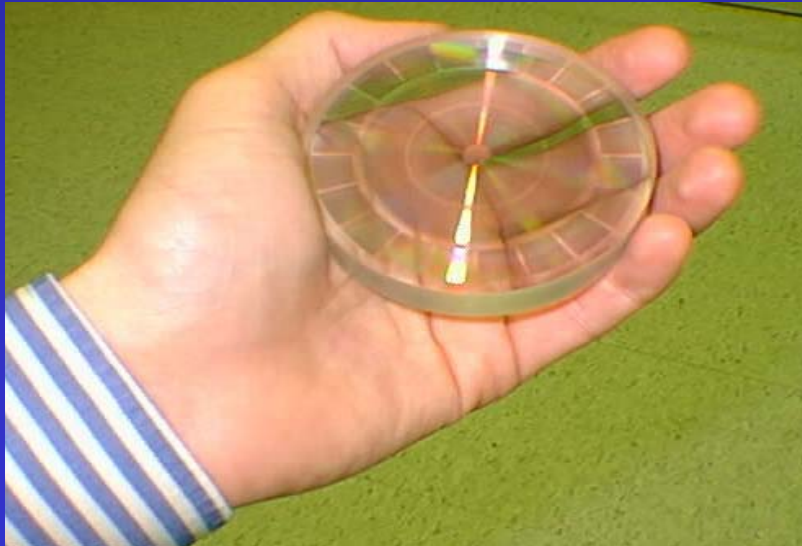
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- **Lateral misalignment gives errors proportional to slope of wavefront**
- **Errors due to longitudinal misalignment less sensitive if hologram placed in collimated light**
- **Alignment marks (crosshairs) often placed on CGH to aid in alignment**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

# Use of CGH for Alignment

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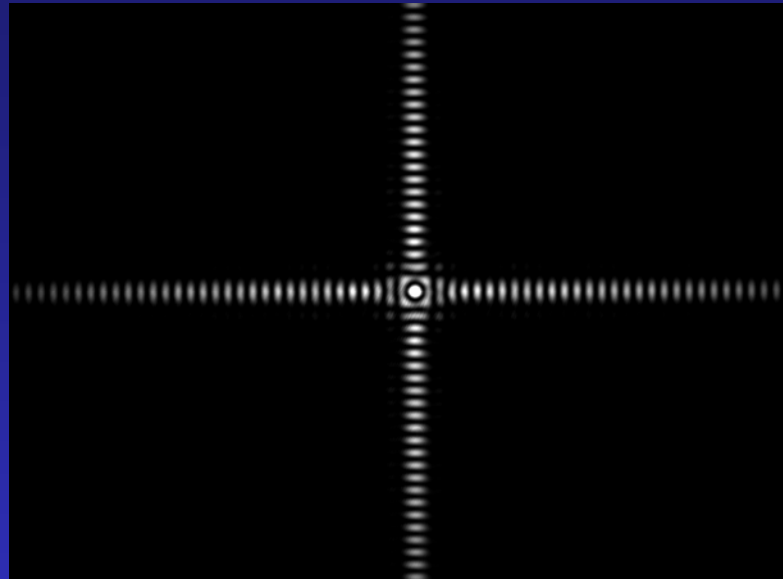
- Commonly CGH's have patterns that are used for aligning the CGH to the incident wavefront.



Using multiple patterns outside the clear aperture, many degrees of freedom can be constrained using the CGH reference. 13

# Projection of Fiducial Marks

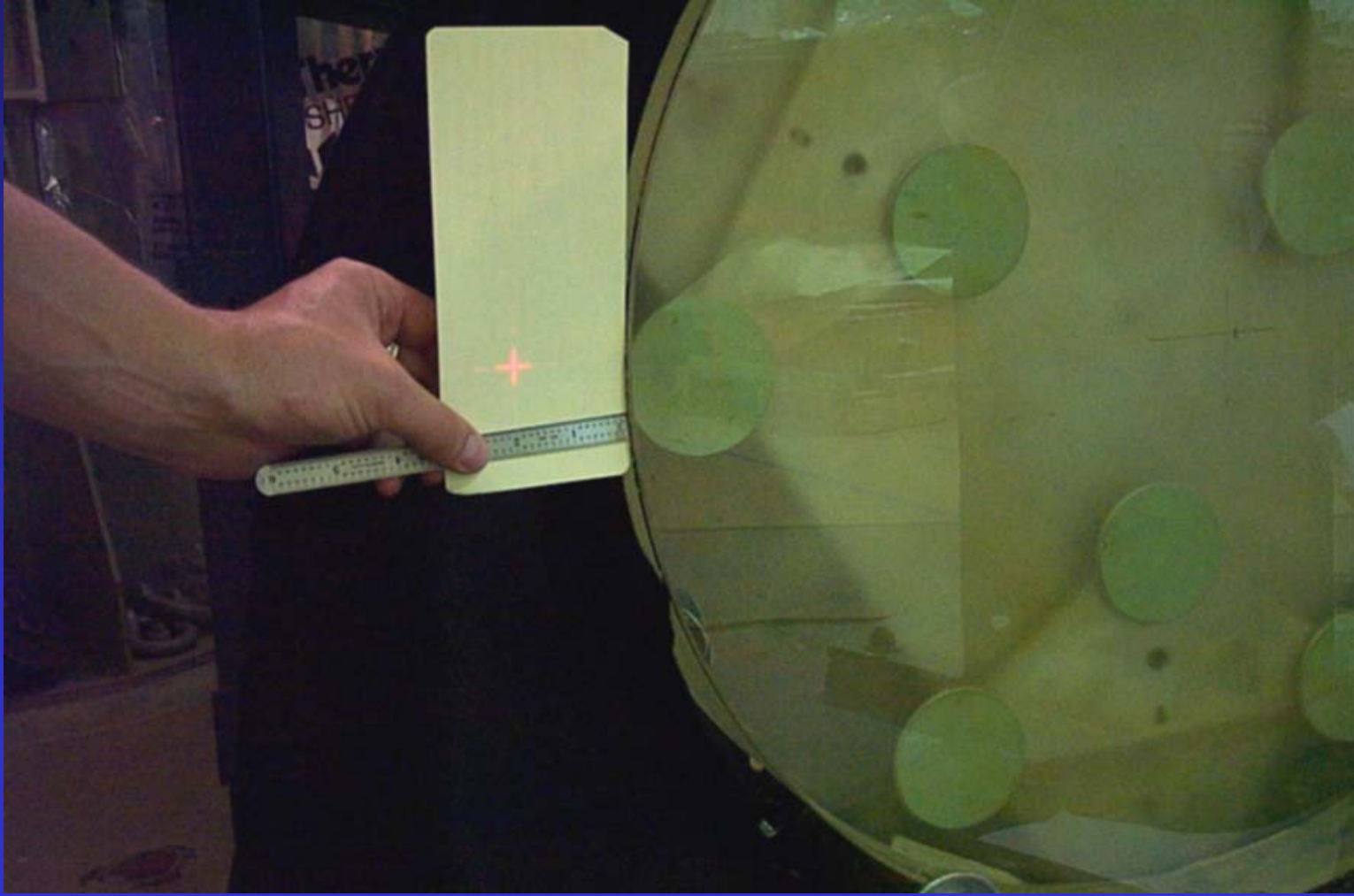
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- The positions of the crosshairs can be controlled to micron accuracy
- The patterns are well defined and can be found using a CCD
- Measured pattern at 15 meters from CGH. Central lobe is only 100  $\mu\text{m}$  FWHM

# CGH Alignment for Testing Off-Axis Parabola

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# Development of 1.8-m CGH

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# CGH Summary

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- **CGHs are now widely used in the testing of aspheric optics and their use will probably increase as their capabilities are more widely known**
- **Wide variety of surface shapes can be measured**
- **Alignment and calibration holograms can be put on CGH in addition to the hologram for the testing of the aspheric optic**

# **Problem #2: Getting Interferogram Data into the Computer**

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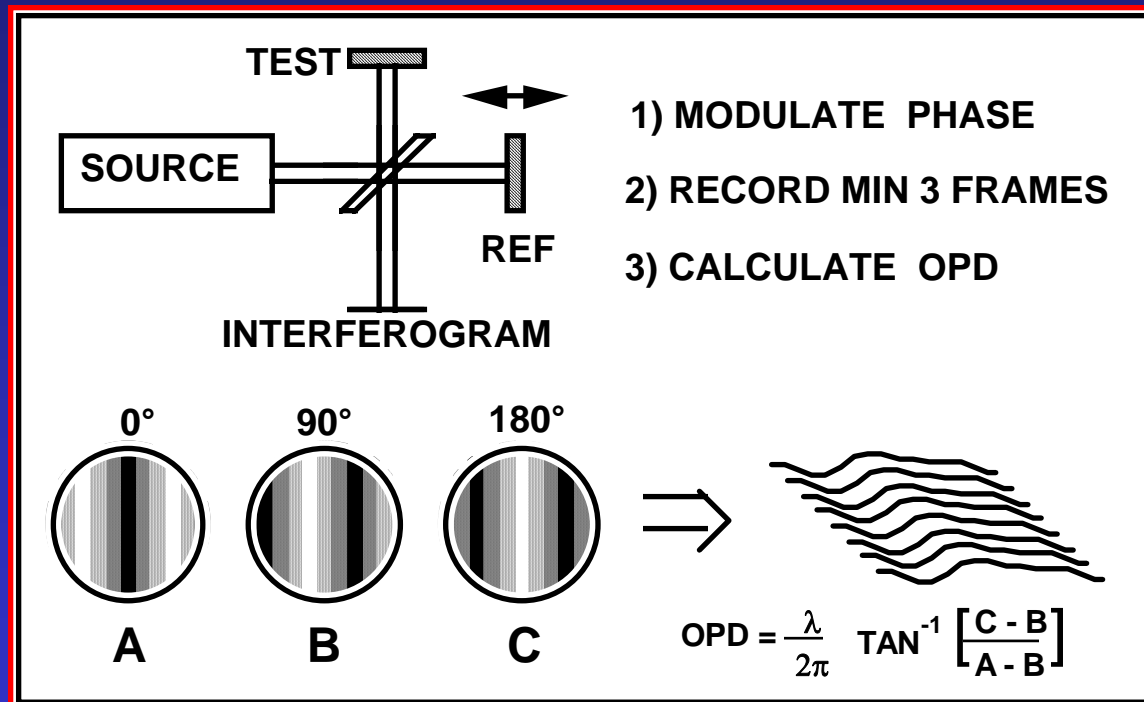
- **If we can get the interferogram data into the computer we can analyze the data to determine**
  - **What is wrong with the surface being measured**
  - **How to correct the surface**
  - **How well will the system perform if surface not corrected**

# **Solution: Use Phase-Shifting Interferometry (PSI)**

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- **PSI Provides**
  - **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 Interferometry



# Four Step Method

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

**phase shift** (pointing to  $\phi(t)$ )  
**measured object phase** (pointing to  $\phi(x,y)$ )

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

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

# Relationship between Phase and Height

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$$\phi(x, y) = \text{Tan}^{-1} \left[ \frac{I_4(x, y) - I_2(x, y)}{I_1(x, y) - I_3(x, y)} \right]$$

$$\text{Height Error}(x, y) = \frac{\lambda}{4\pi} \phi(x, y)$$

# Phase-Measurement Algorithms

**Three Measurements**       $\phi = \tan^{-1} \left[ \frac{I_3 - I_2}{I_1 - I_2} \right]$

**Four Measurements**       $\phi = \tan^{-1} \left[ \frac{I_4 - I_2}{I_1 - I_3} \right]$

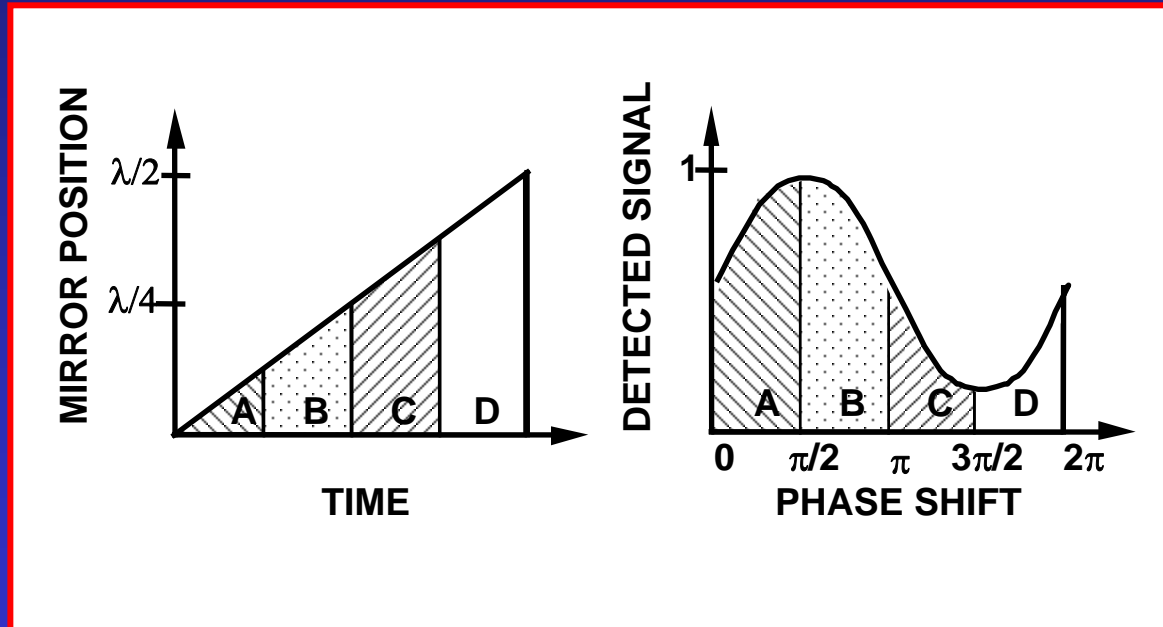
**Schwider-Hariharan  
Five Measurements**       $\phi = \tan^{-1} \left[ \frac{2(I_2 - I_4)}{2I_3 - I_5 - I_1} \right]$

**Carré Equation**

$$\phi = \tan^{-1} \left[ \frac{\sqrt{[3(I_2 - I_3) - (I_1 - I_4)][(I_2 - I_3) - (I_1 - I_4)]}}{(I_2 + I_3) - (I_1 + I_4)} \right]$$

# Integrated-Bucket (Phase Shifting)

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# Conclusions: Phase-Shifting Interferometry

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- **Most optical testing interferometers use phase-shifting techniques because**
  - **Phase-shifting is a high accuracy rapid way of getting the interferogram information into the computer**
  - **Inherent noise in the data taking process is so low that in a good environment Angstrom or sub-Angstrom surface height measurements can be performed**

# **Problem #3: Measurements More Accurate than Reference Surface**

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**We want to perform surface measurements more accurate than our reference surface.**

# **Solution: Use Multiple Measurements and Phase-Shifting Interferometry (PSI)**

---

- **Several techniques for performing measurements of flat surfaces, spherical surfaces, or surface roughness more accurate than the reference surface.**
- **All techniques require making multiple measurements while rotating or translating the surface under test and performing arithmetic calculations on the measured data.**
- **Techniques have been available for many years, it is only due to the high precision of PSI that the techniques have become extremely useful for improving the ability to produce high quality optical surfaces.**

# Absolute Surface Roughness Measurement Assumptions

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

$$RMS_{meas} = \sqrt{RMS_{test}^2 + RMS_{ref}^2}$$

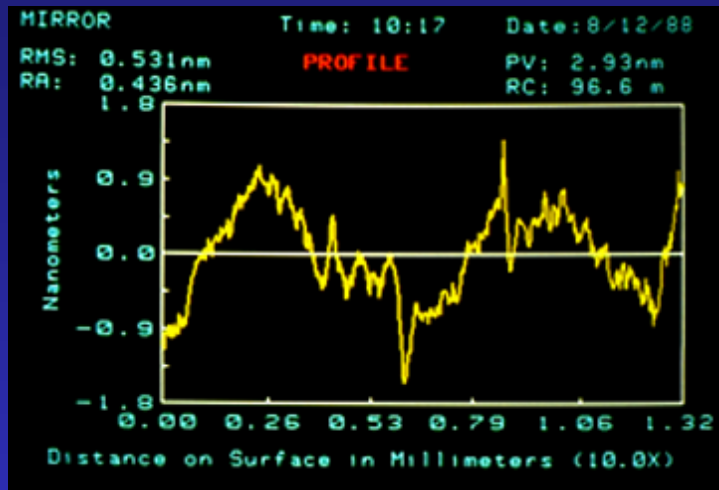
# Generate Reference

---

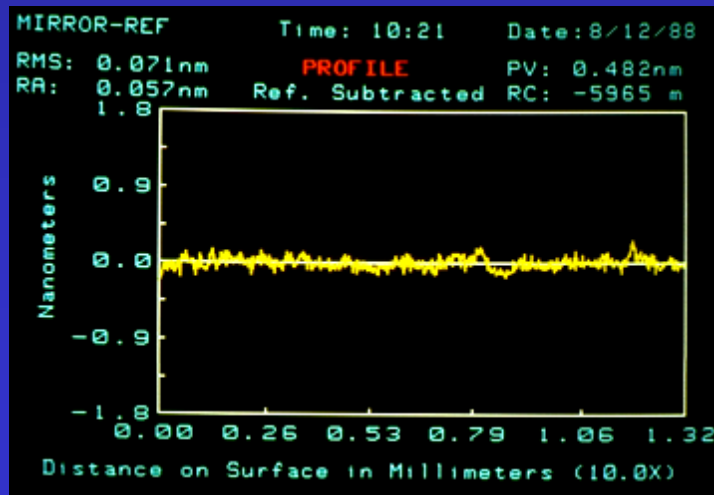
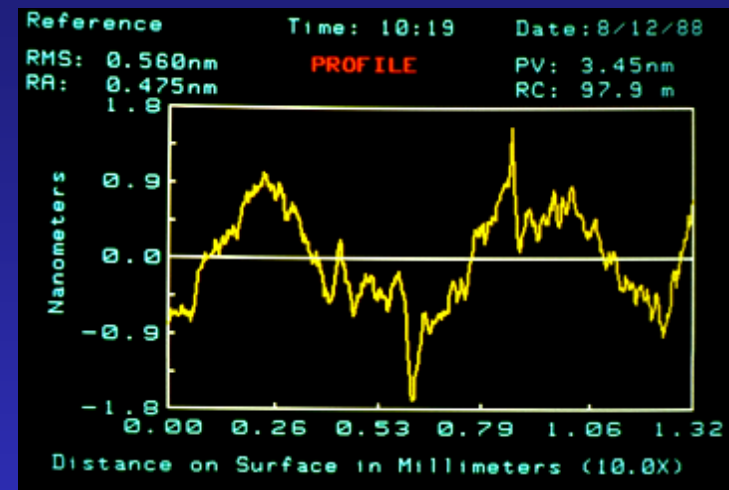
- **Average many measurements**
- **Move random surface  $>$  correlation length between measurements**
- **Effects of random surface reduce as square root of number of measurements**
- **Subtract averaged measurement (reference surface) from one of the measurements**

# Generate Reference and Subtract

Surface + Reference



Reference



Surface  
(0.071 nm)

# **Conclusion: Measurement of surface more accurate than reference surface**

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- **All techniques require making multiple measurements**
- **Techniques have been available for many years, but it is only due to the high precision of PSI that the techniques have become extremely useful for improving the ability to produce high quality optical surfaces.**

# **Problem #4: Measurement Accuracy Limited by Environment**

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**The measurement accuracy of PSI is  
generally limited by the environment**

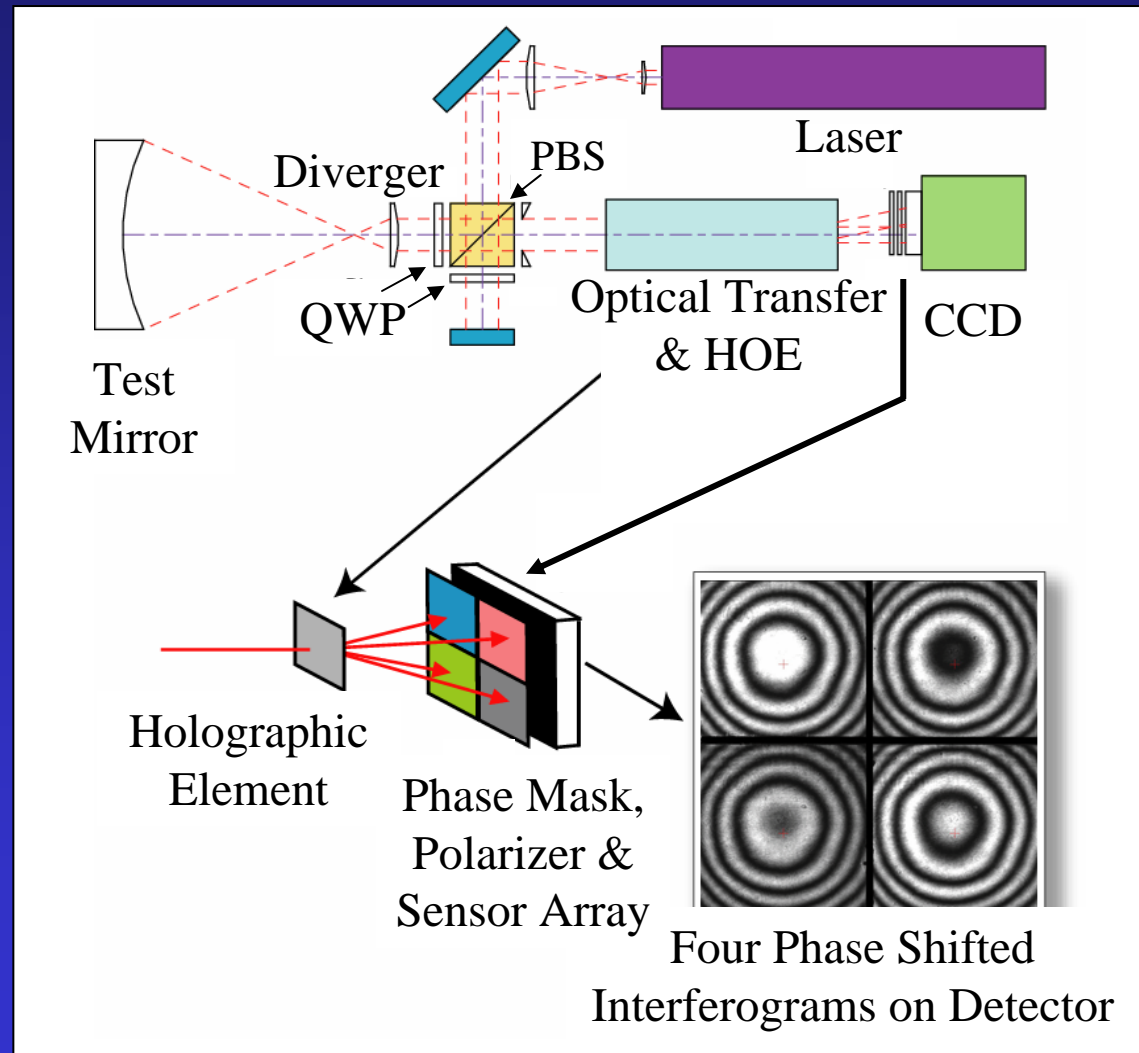
# **Solution: Vibration Insensitive Interferometers**

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- **Possible techniques**
  - **Carrier frequency interferometry (single interferogram)**
  - **Closed-loop feedback vibration compensated interferometry**
  - **Single-shot phase-shifting interferometry can be used to reduce the effect of the environment**

# Single shot vibration insensitive interferometer

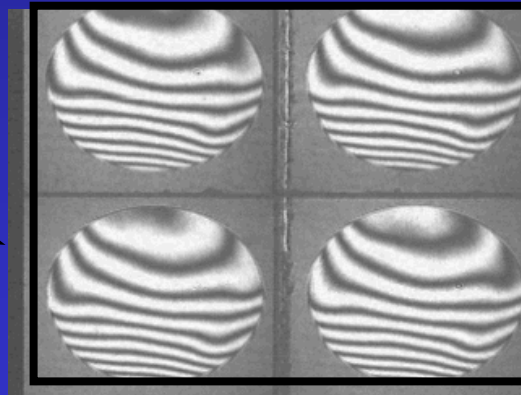
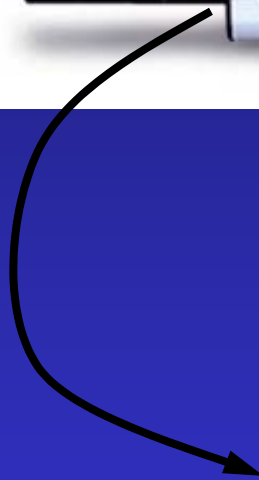
- Two beams have orthogonal polarization
- 4 Images formed
  - Holographic element
- Single Camera
- Polarization used to produce 90-deg phase shifts
- CGH can be placed between diverger and test mirror or in output beams



# Effects of vibration



*Relative motion  
between PhaseCam  
and test object*



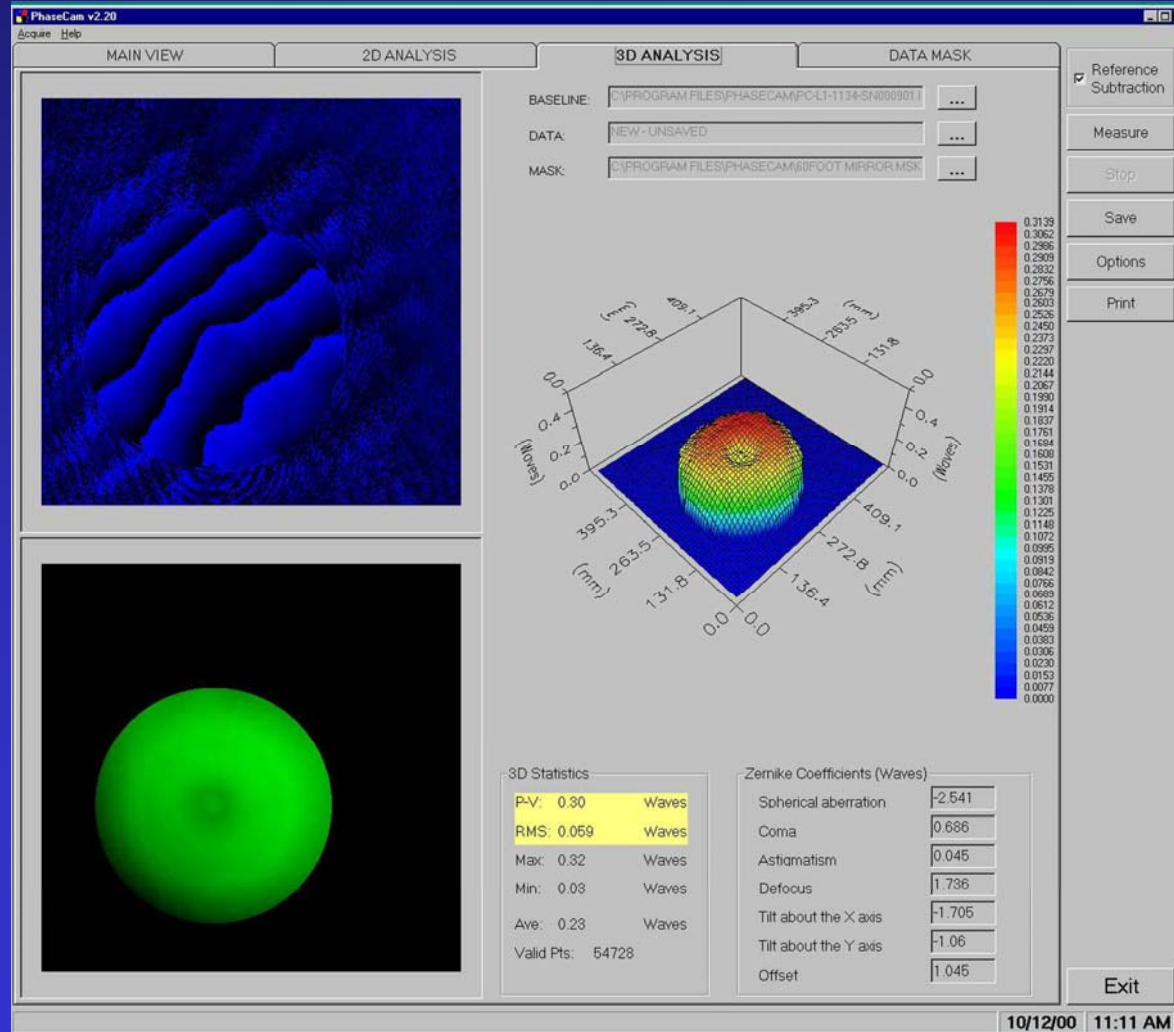
*Phase relationship is fixed*

# Testing a 0.5 meter diameter, 20 meter ROC mirror

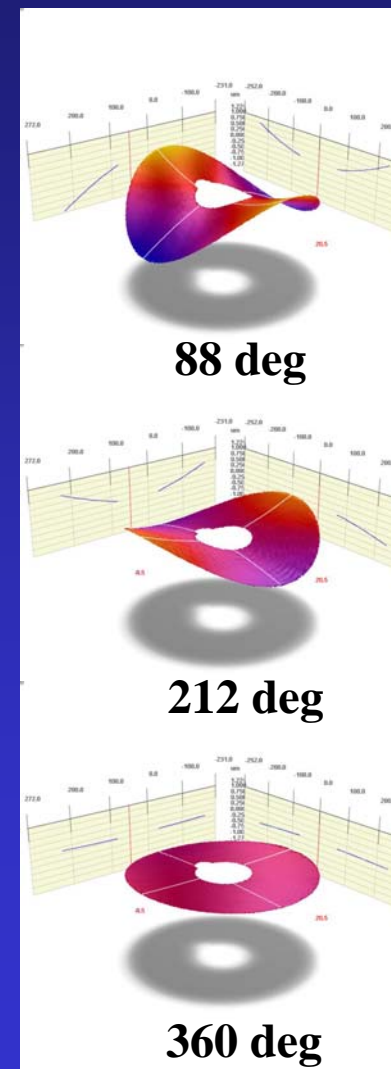
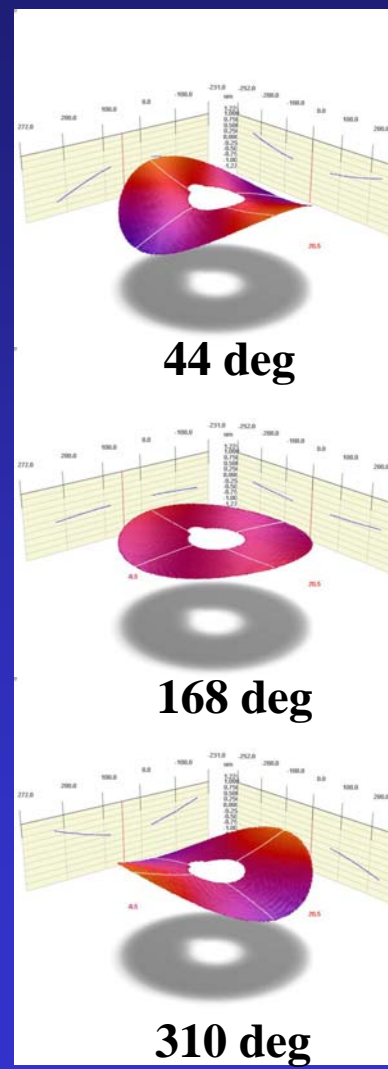
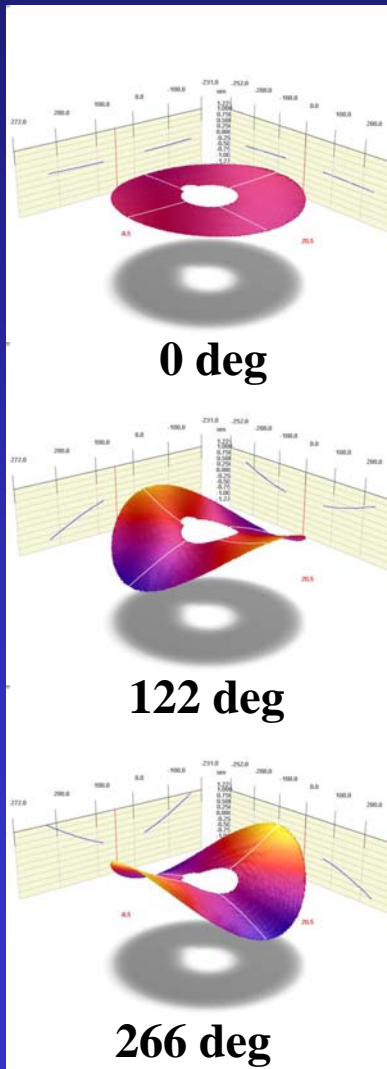
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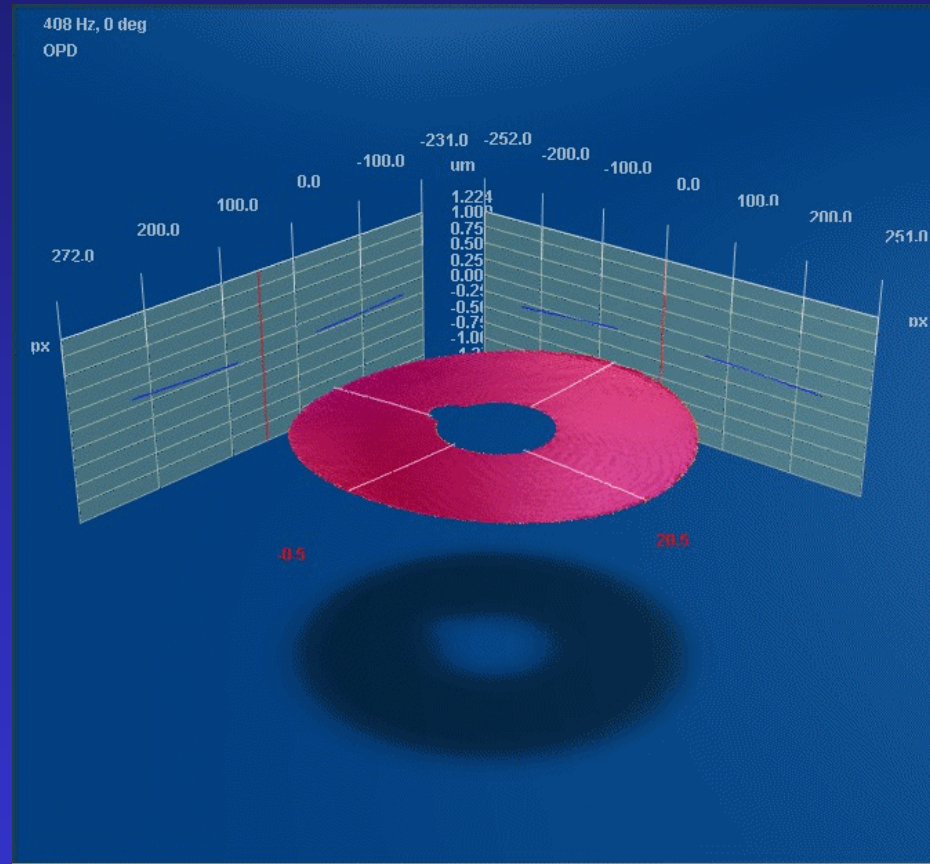
# 0.5 m diameter mirror, 20 m ROC 5 nm rms repeatability (in air)



# Phase Sweep at 408 Hz



# Modal Movie - Disk Vibration



Al mirror, 408 Hz

# Conclusions – Single Shot Interferometer

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- **Vibration insensitive, quantitative interferometer**
- **Surface figure measurement (nm resolution)**
- **Snap shot of surface height**
- **Acquisition of “phase movies”**
- **Measurement accuracy no longer needs to be limited by the environment**

# Conclusions

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**Due to advances in electronics, computers, and software the applications of interferometry are limited only by one's imagination.**