Optical Metrology and NDT
ME-5304, C'2025

https://users.wpi.edu/~cfurlong/me-593n.html

M and W: 1:00-1:50 pm, HL-031

Instructor: Cosme Furlong

Office: HL-152, **Laboratory:** HL-040
Email: cfurlong@wpi.edu
Tel. (508) 831-5126, **Fax.** (508) 831-5680

NEST - NanoEngineering, Science, and Technology
CHSLT - Center for Holographic Studies and Laser micro-mechaTronics
Mechanical Engineering Department
Worcester Polytechnic Institute

January 15, 2025

ME-593 / ME-5304

Laser metrology and Nondestructive Testing (NDT)

Term C'2025

Lectures: M and W, 1:00-2:50 pm
HL-031

Instructor: Cosme Furlong
Office: HL-151
Telephone: (508) 831-5126
E-mail: cfurlong@wpi.edu

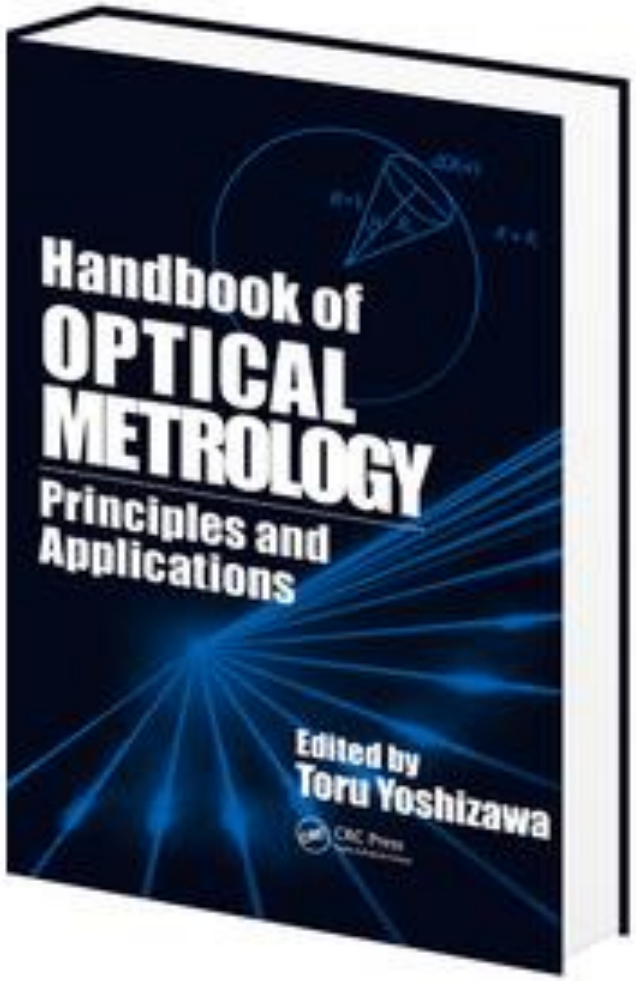
COURSE DESCRIPTION

In this course, modern laser metrology techniques are discussed and their practical applications to solve problems, with emphasis on nondestructive testing (NDT), are illustrated with laboratory demonstrations. Topics covered include wave and Fourier optics, classic and holographic interferometry, speckle techniques, solid-state lasers, fiber optics, CCD cameras, computer vision, camera calibration methods, and image processing and data reduction algorithms as required in quantitative fringe analysis. Detail examples of nondestructive testing and coherent optical metrology in solid mechanics, vibrations, heat transfer, electromagnetics, and reverse engineering are given.

Students are required to work on projects depending on their background and interests.

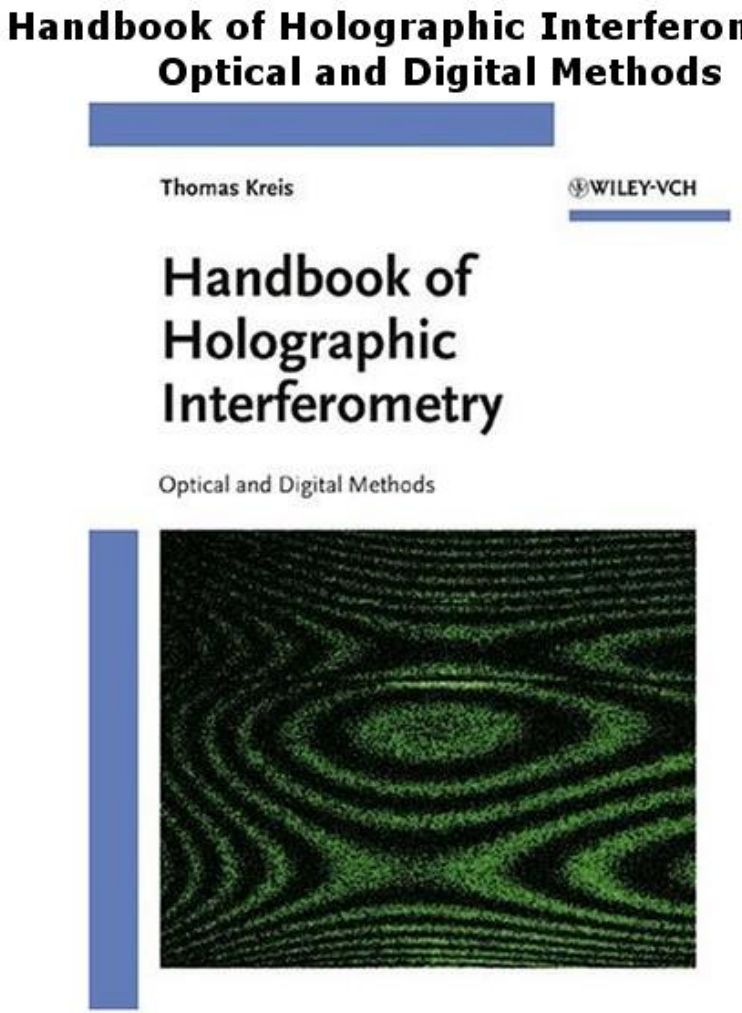
Recommended background: mechanics, materials, physics, knowledge of a high-level computer programming language.

Textbook: available to students soon



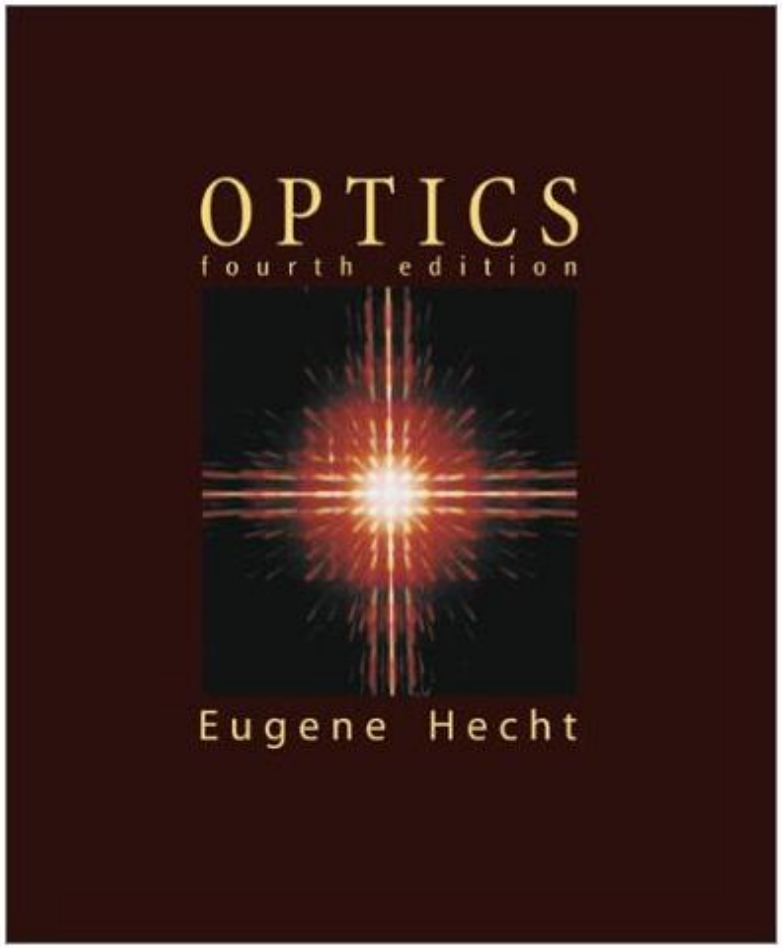
Hardcover: 744 pages
Publisher: CRC Press; 1 edition (February 25, 2009)
Language: English
ISBN-10: 0849337607
ISBN-13: 978-0849337604

Recommended Textbook



Hardcover: 554 pages
Publisher: Wiley-VCH; 1 edition (January 31, 2005)
Language: English
ISBN-10: 3527405461
ISBN-13: 978-3527405466

Recommended Textbook: optics background



Hardcover: 680 pages
Publisher: Addison Wesley; 4 edition (August 12, 2001)
Language: English
ISBN-10: 0805385665
ISBN-13: 978-0805385663

General information

Review course overview: see handout

Homework, due next Class:

- Reading assignment:

  Chapter 1 of Yoshizawa: Light Sources

- Homework assignment:

  See website of our course:

  https://users.wpi.edu/~cfurlong/me-593n.html

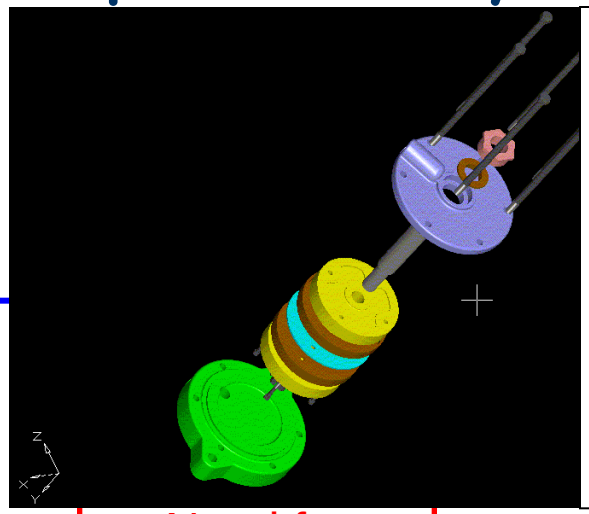
General information

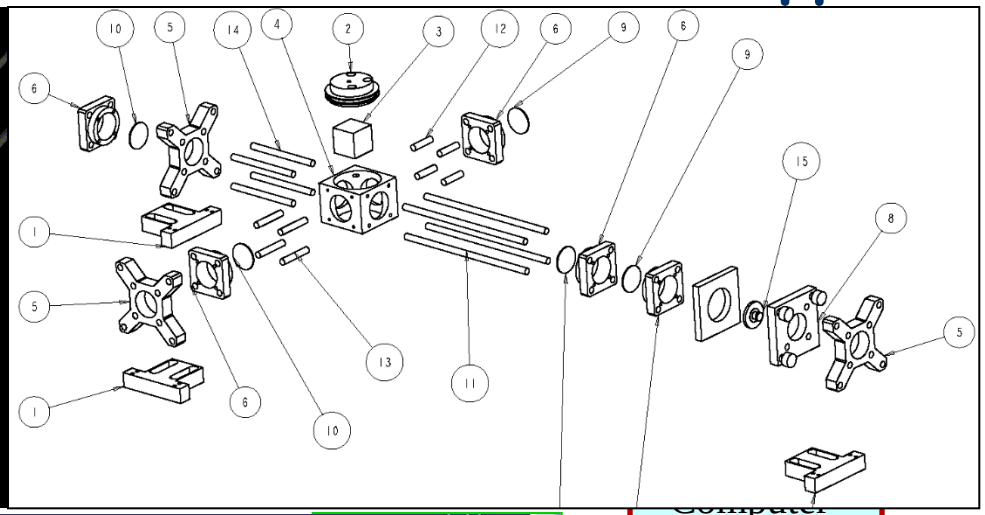
Office hours (to be set or by request):

In the meantime:

-> 2:00 to 5:00 pm Thursdays <-

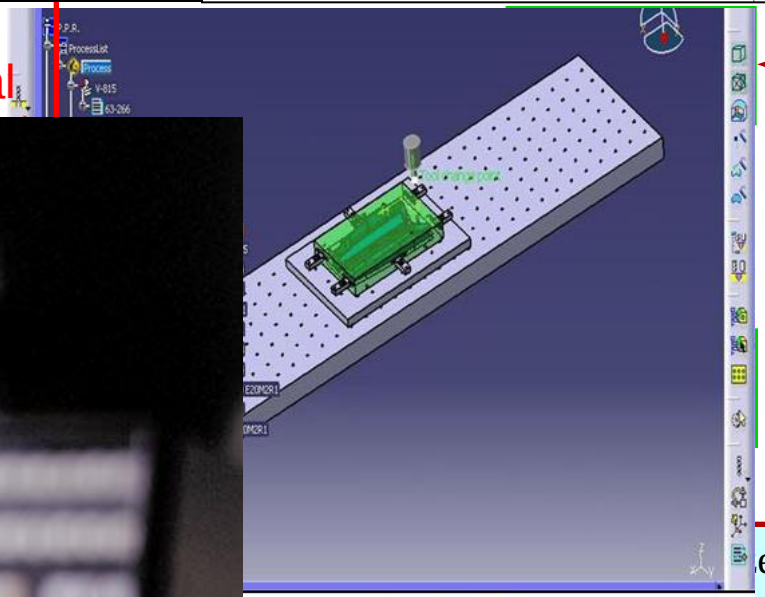
Motivation: production cycle with CAD/CAE/CAM support





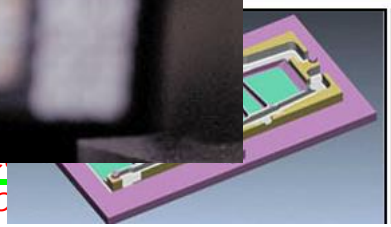
Original need

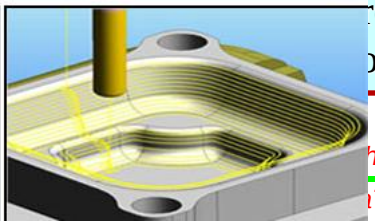
Need for experimental



Computer aided process planning

ed scheduling, requirements, oor control





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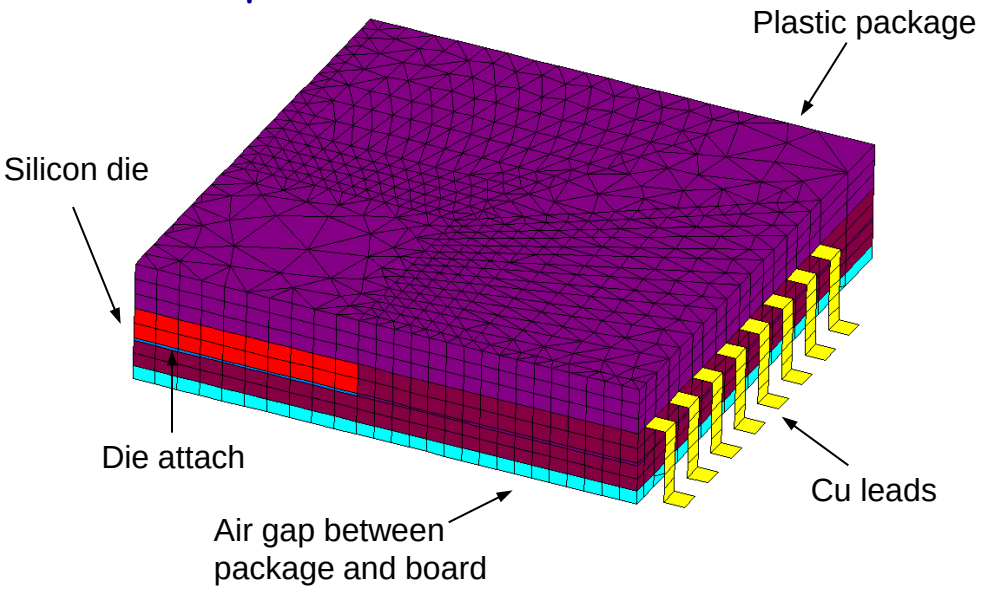
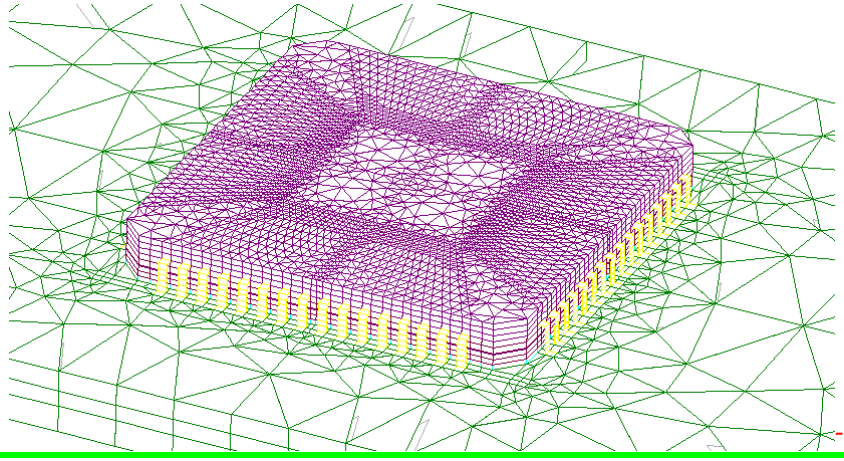
Multiphysics FE modeling: need for experimental validations

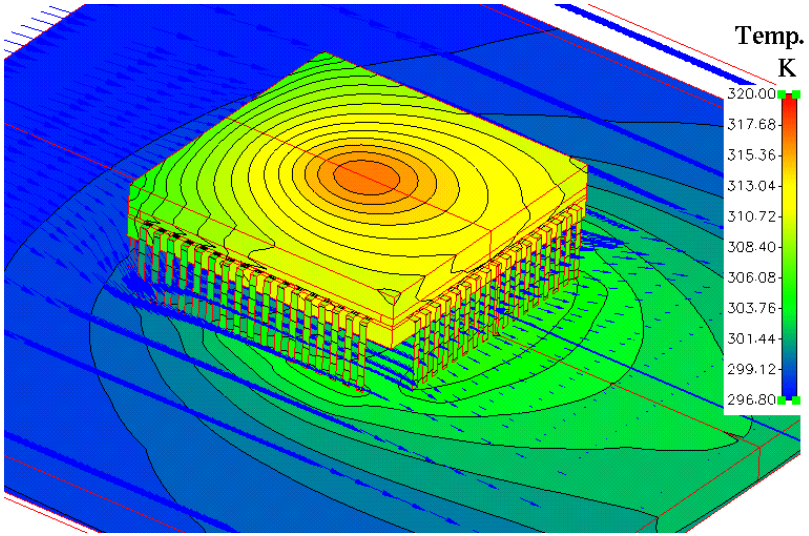
e.g., multi-physics modeling of the package of a computer chip

Computational domain





Computed temperature distribution

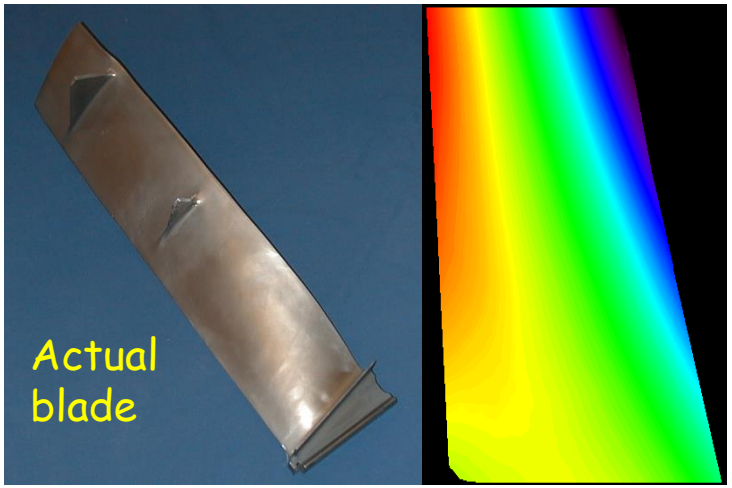


Fluid + heat + structural effects are modeled

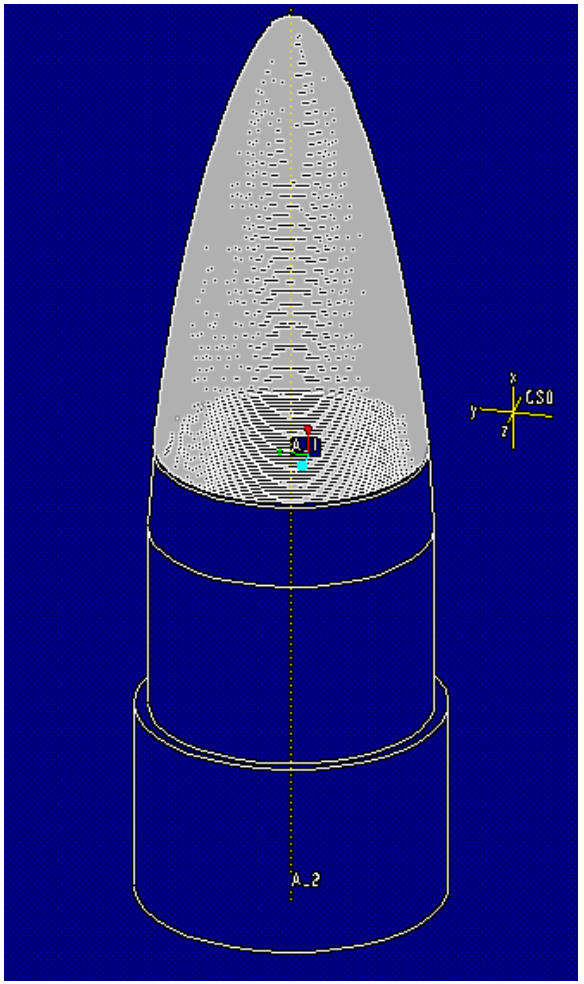
Measurement of shape and deformations at different scales

Computer-Aided Optical Metrology: full-field-of-view non-contact capabilities

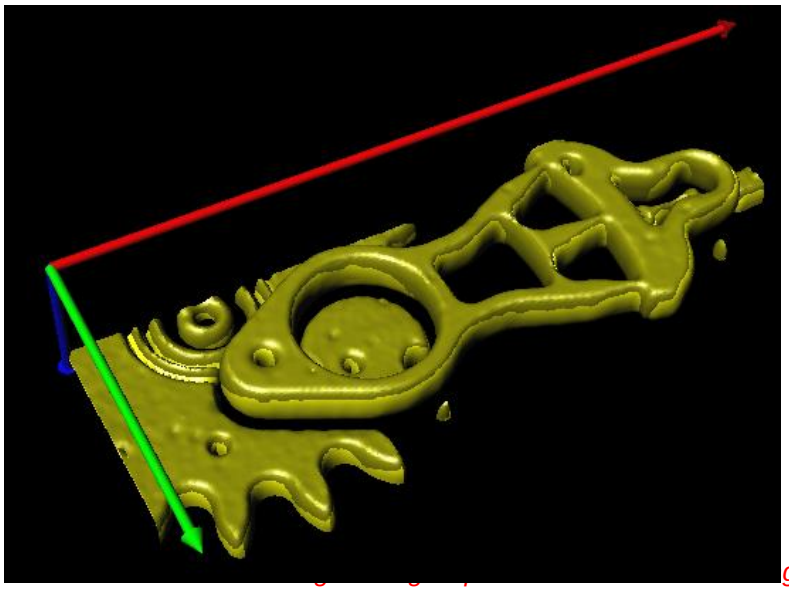
Macroscale



Mesoscale



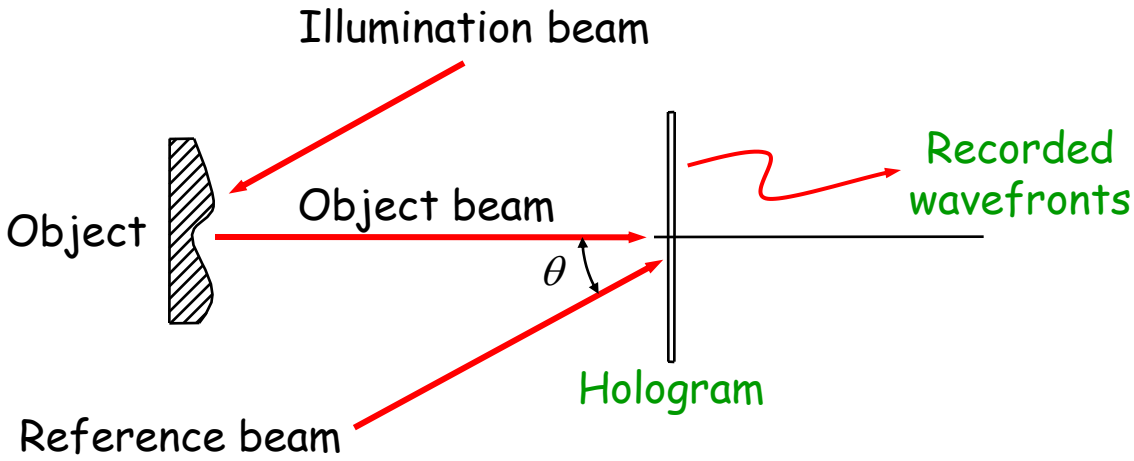
Microscale
and
Nanoscale



Classic Holographic Interferometry

Recording and reconstruction of a hologram

Recording

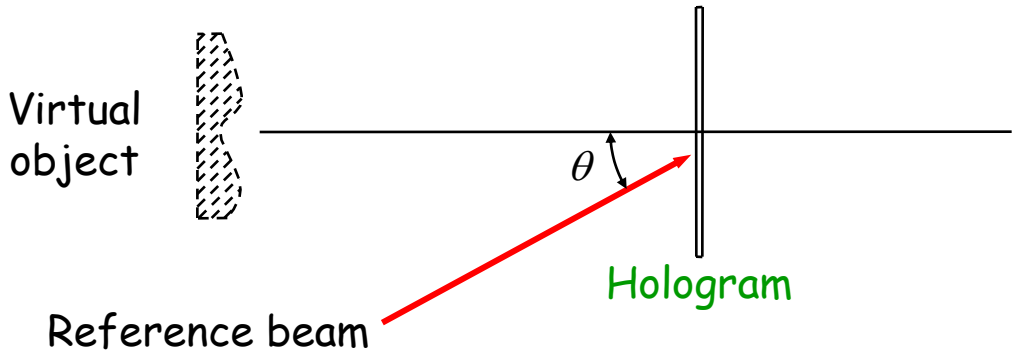


The word "holograph" comes from "holo" meaning entire or whole and "graph" meaning writing, *so a hologram is the entire writing or the entire information.*

Classic Holographic Interferometry

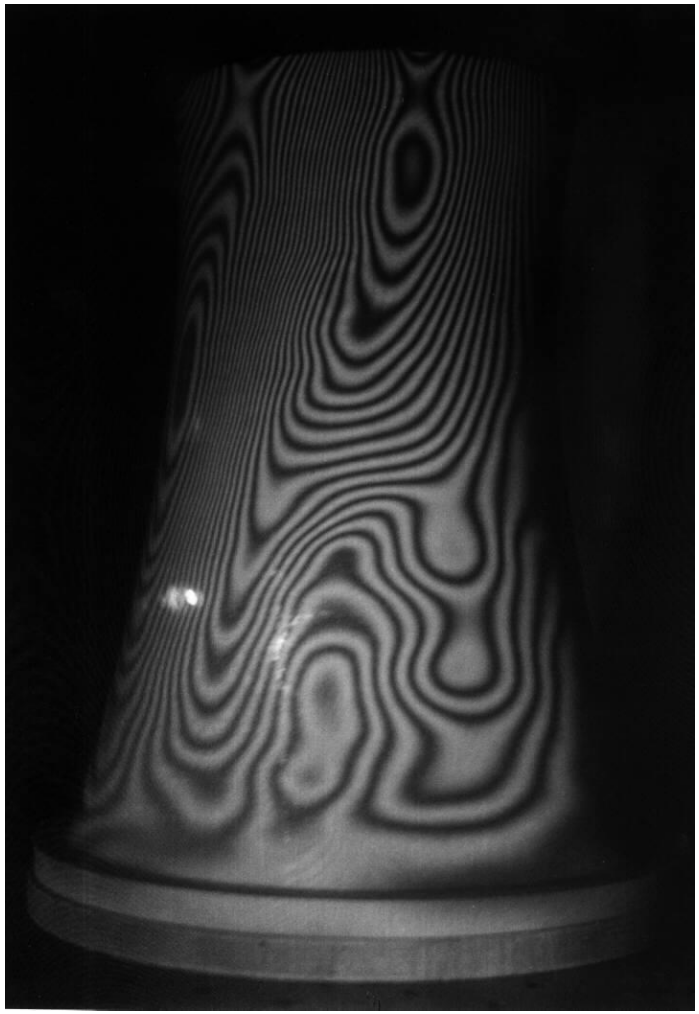
Recording and reconstruction of a hologram

Reconstruction



Applications: NDT of structures

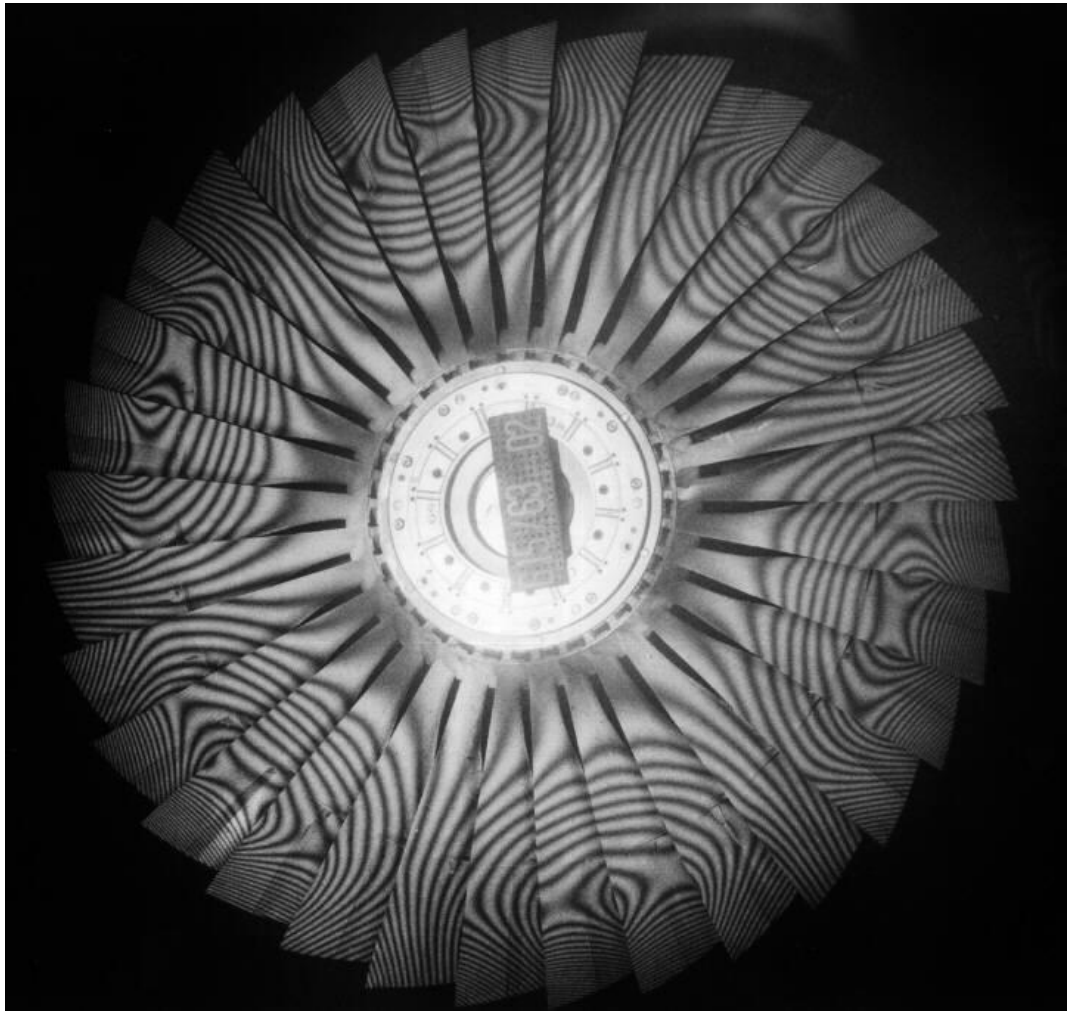
Cooling tower A



Cooling tower B

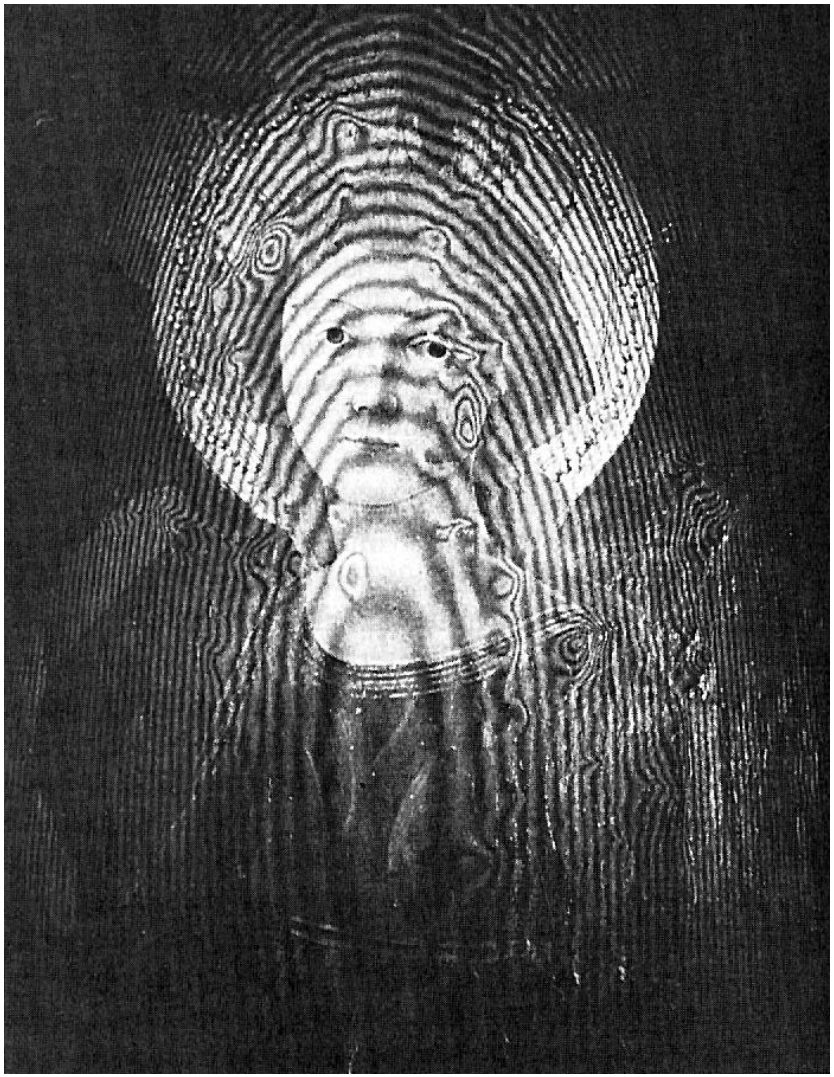
Applications: NDT of structures

Study of vibrations in turbine blades: Elinevskii et al., 1976



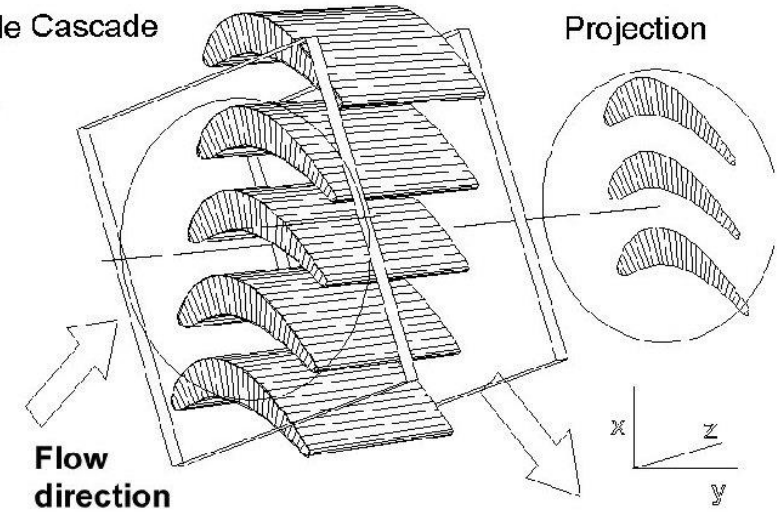
Applications: NDT in art conservation

Holographic interferogram indicating delaminations in a fifteenth century panel painting: S. Amadesi et al., *Appl. Opt.*, **13**, 2009-2013, 1974

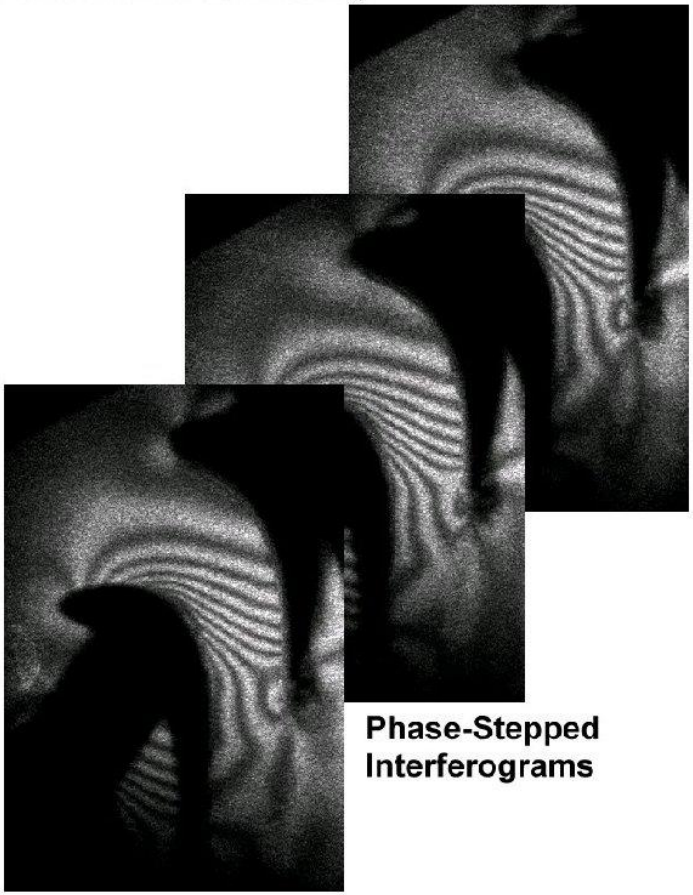


Applications: fluid flow investigations

Phase-Stepped Holographic Interferometry

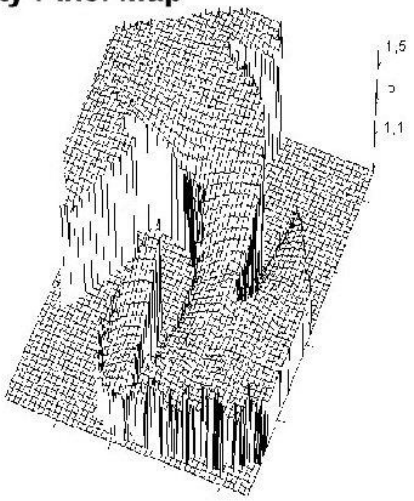


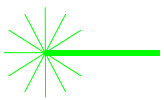
Pulsed Laser Recording



Phase-Stepped Interferograms

Digital Evaluation Density Pixel Map





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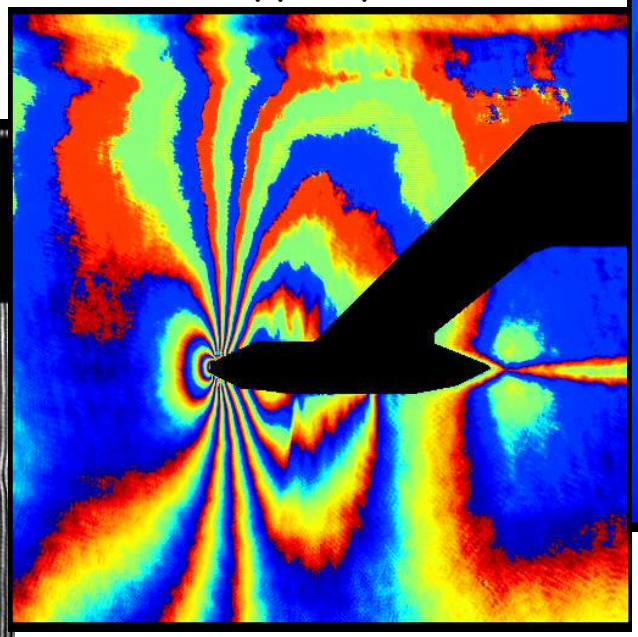
Applications: fluid flow investigations

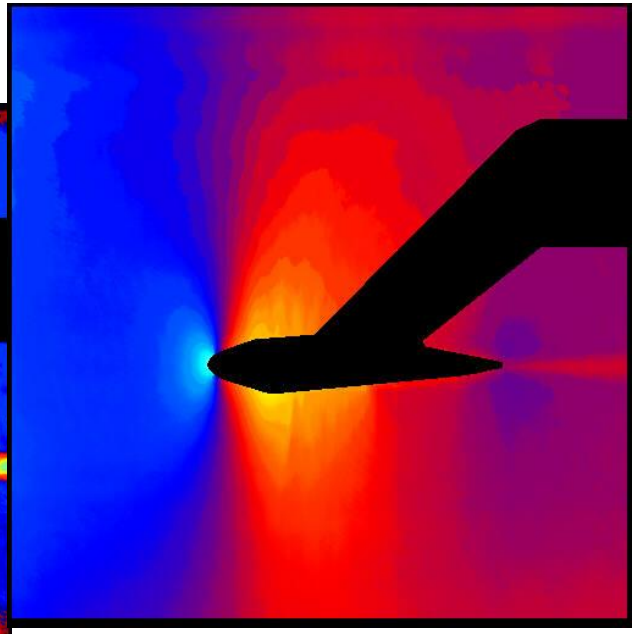
Holographic interferometry can be applied to the study of heat, mass, and momentum transfer phenomena

Fringe pattern

Wrapped phase

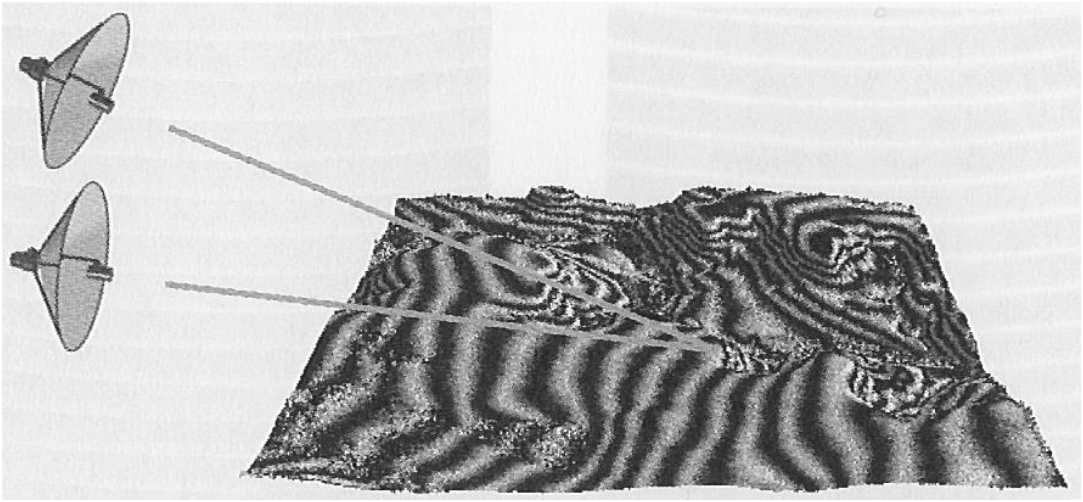


Unwrapped phase: related to properties of the fluid flow

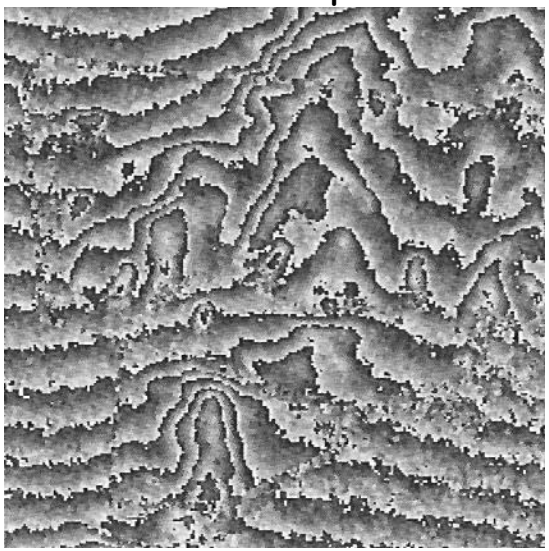


Applications: SAR interferometry

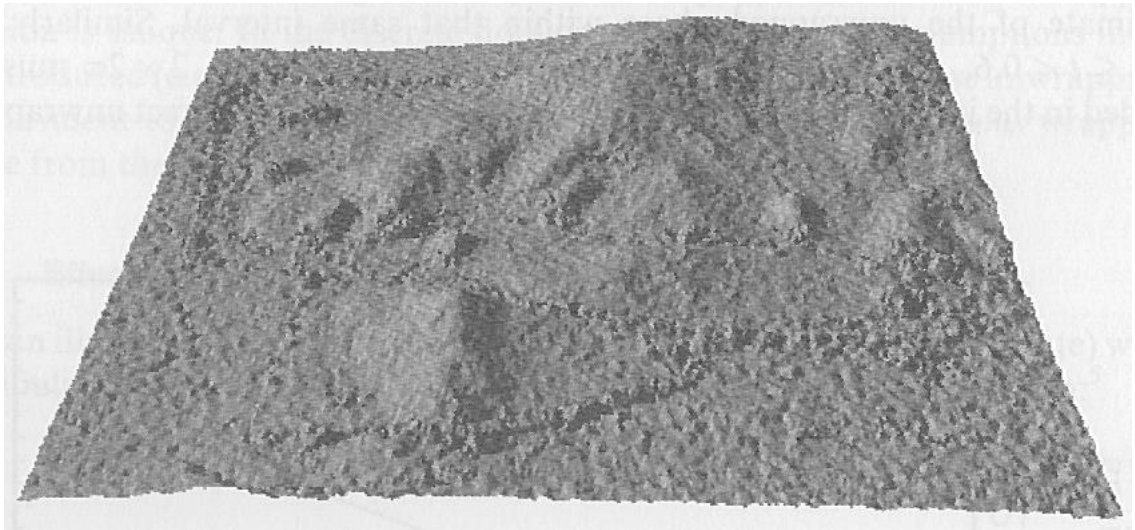
SAR interferogram of undulating terrain: Ghiglia et al., 1998



Recovered phase

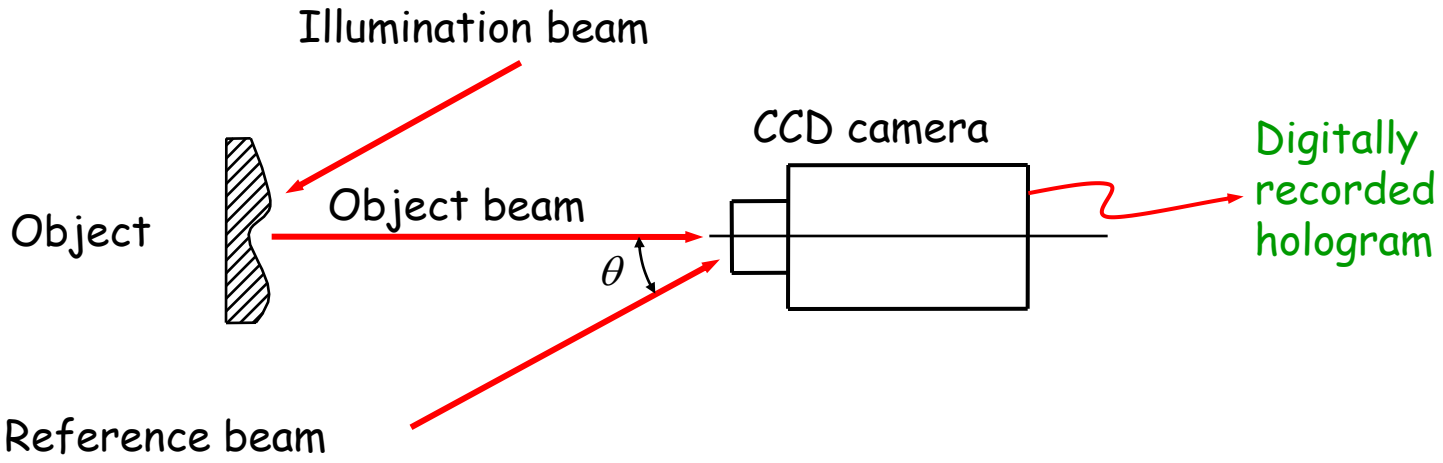


Topography



Digital holography: high-speed measurements

Recording



Reconstruction by application of numerical methods:

- Fresnel integral
- Convolution
- Spatial or phase-shifting methods

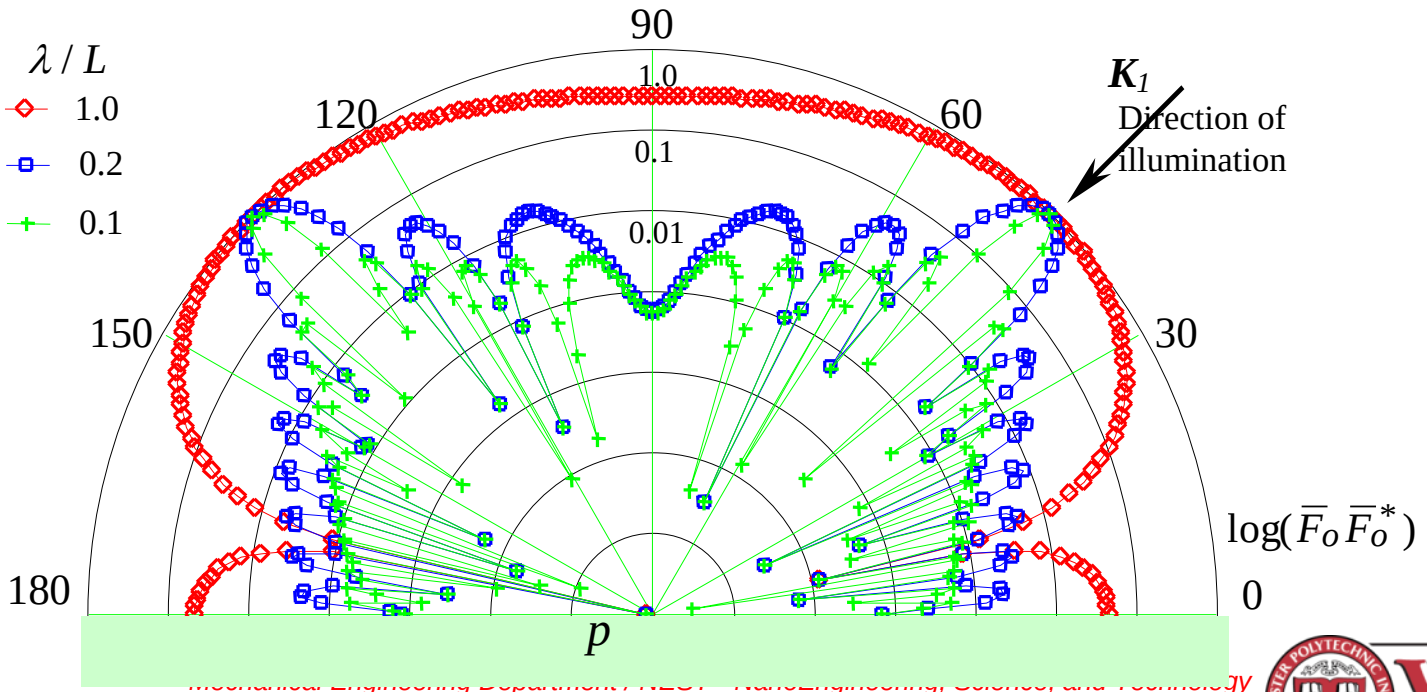
Scattering + diffraction + absorption of light waves

- The complex amplitude of the scattered light, F_o, at point p, can be predicted using the Kirchoff integral

$$F_o = \frac{1}{4\pi}\left\{\iint_s \frac{1}{r}\exp(-jkr)\nabla U \cdot d\boldsymbol{S} - \iint_s U\ \nabla\left[\frac{1}{r}\exp(-jkr)\right]\cdot d\boldsymbol{S}\right\}$$

- Imaging the scattering and absorption of light allows quantification of physical quantities

Light scattering diagram: λ is the wavelength of the light source, L is the dimension of the domain



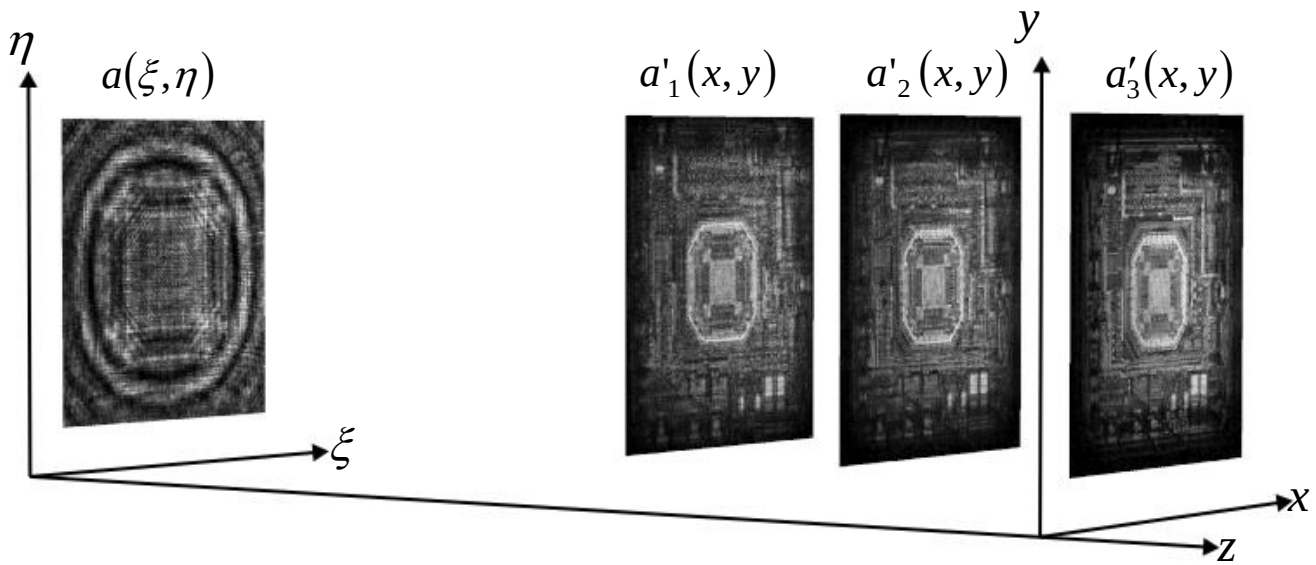
Lensless digital holography

Principle of operation: **numerical reconstruction** of digital holograms

Numerical reconstruction of intensity and phase at any plane along the direction of light propagation:

Complex light distribution: $a(\xi,\eta) = (I_1 - I_3) + i(I_4 - I_2)$

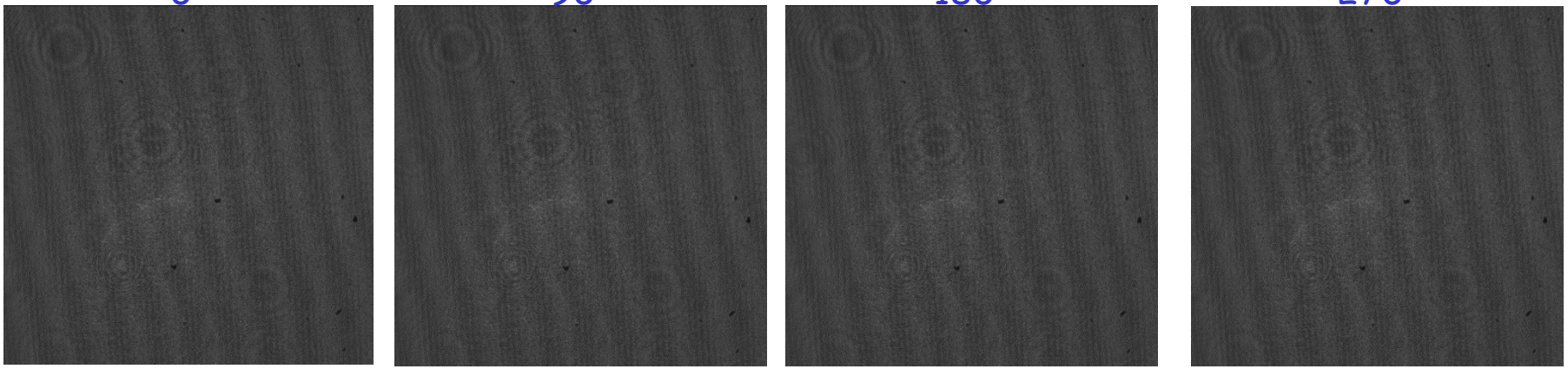
Rayleigh-Sommerfeld integral: $a'(x,y) = \frac{1}{i\lambda}\iint a(\xi,\eta)\,\frac{1}{r}\exp(-ikr)\cos\Theta\; d\xi\, d\eta$



Digital holography: recording

Phase-shifted digital holograms

0° 90° 180° 270°

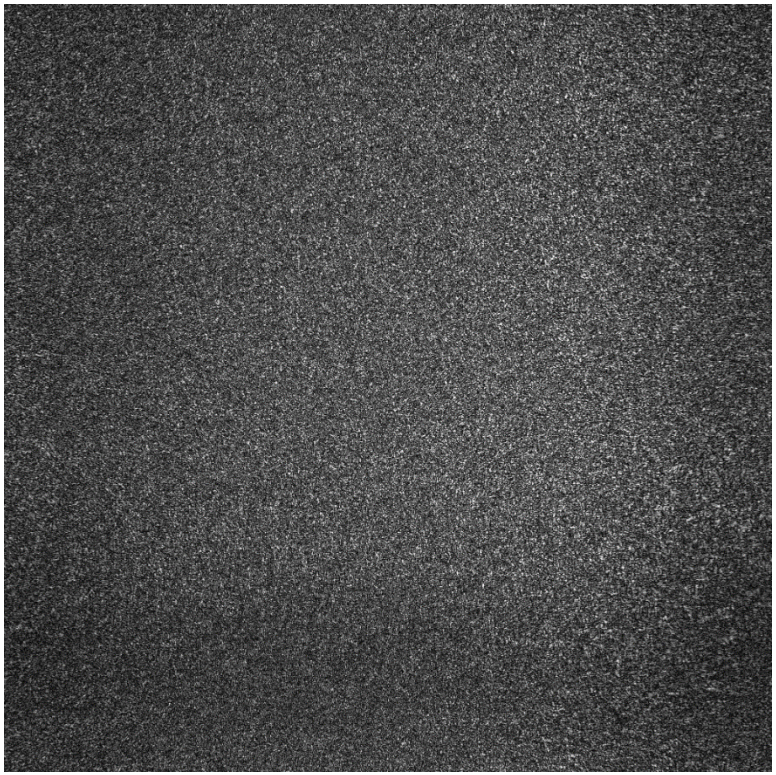


Recording conditions:

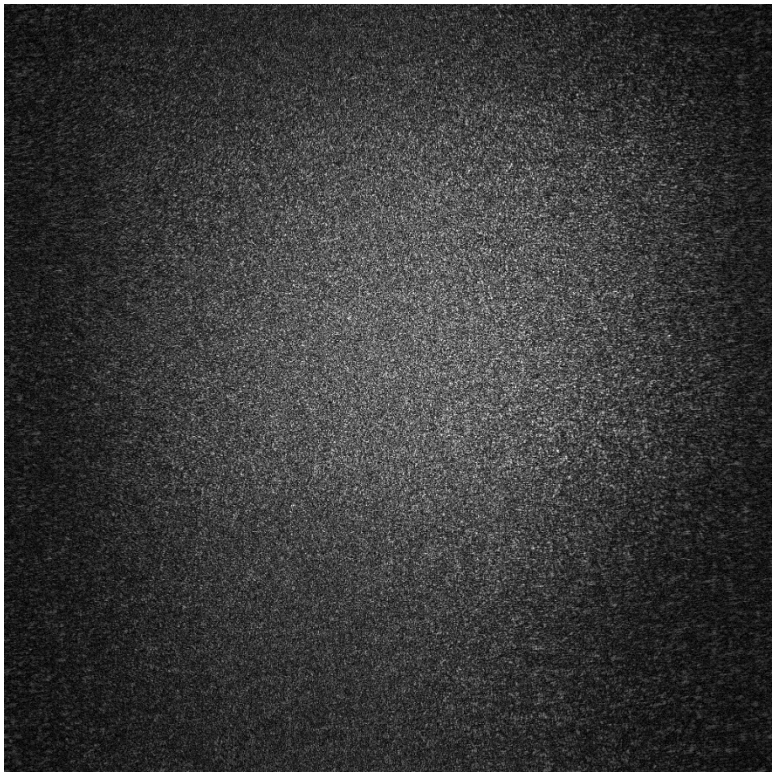
- Wavelength: 782 nm
- Digital CCD camera: 10-bit, 1024 x 1024 pixels
- Pixel size of CCD: 6.24 x 6.24 μm^2
- Parallel illumination and observation conditions
- Distance between object and CCD: 330 mm
- Characteristic dimension of object: 30 mm

Digital holography: reconstruction (numerical)

Reconstruction distance: 30 mm

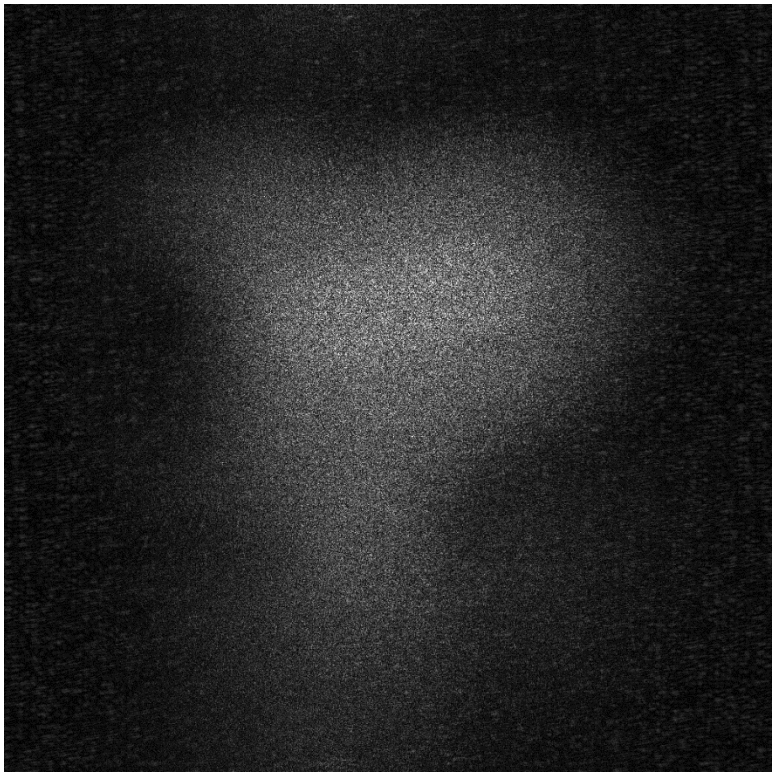


Reconstruction distance: 45 mm

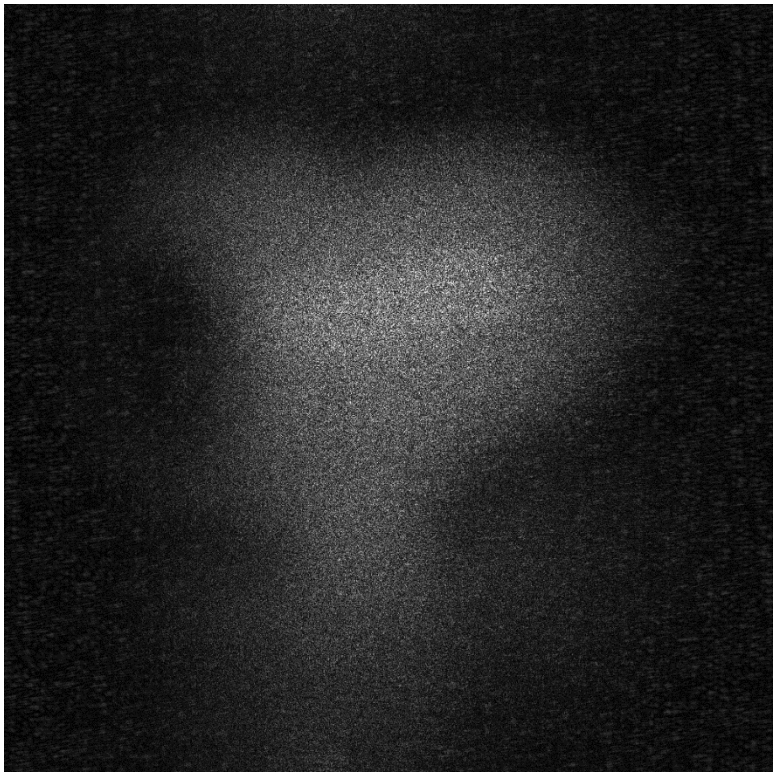


Digital holography: reconstruction (numerical)

Reconstruction distance: 125 mm

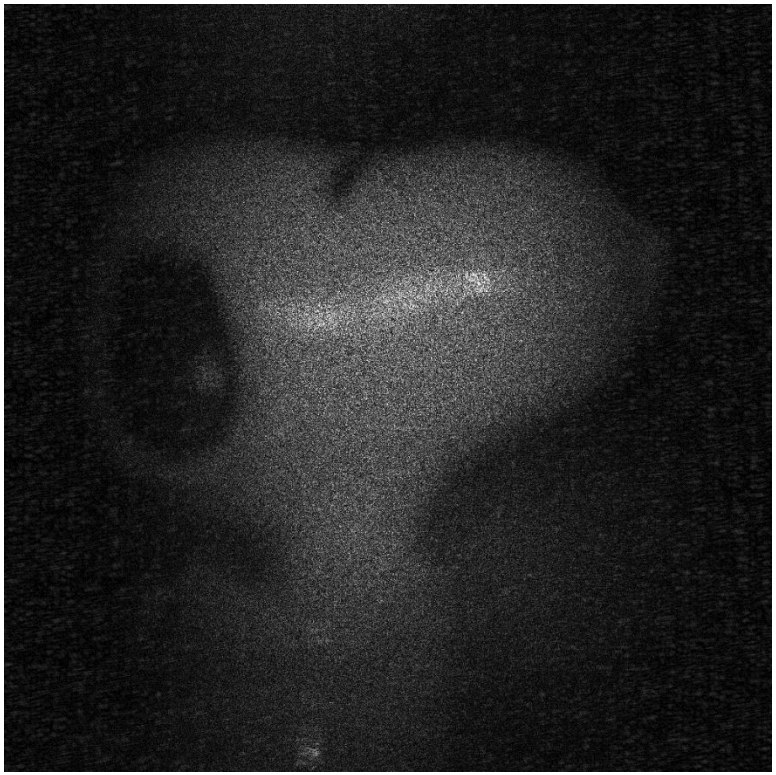


Reconstruction distance: 140 mm

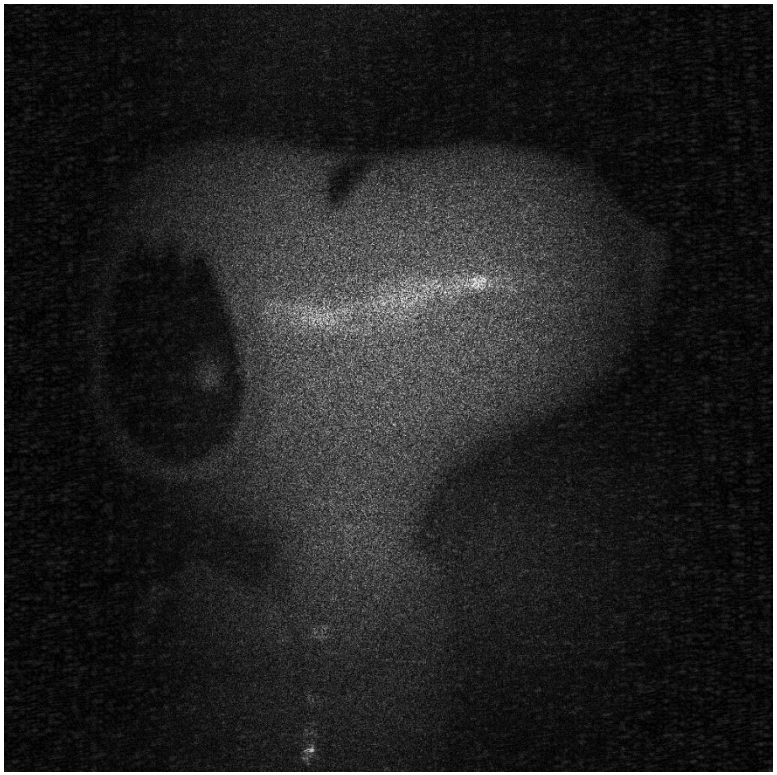


Digital holography: reconstruction (numerical)

Reconstruction distance: 220 mm

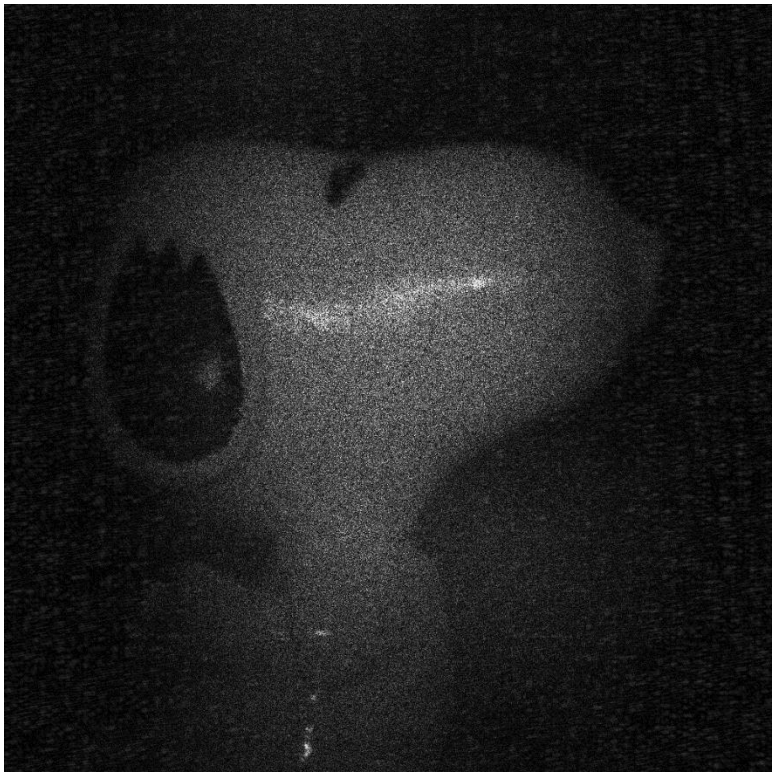


Reconstruction distance: 250 mm

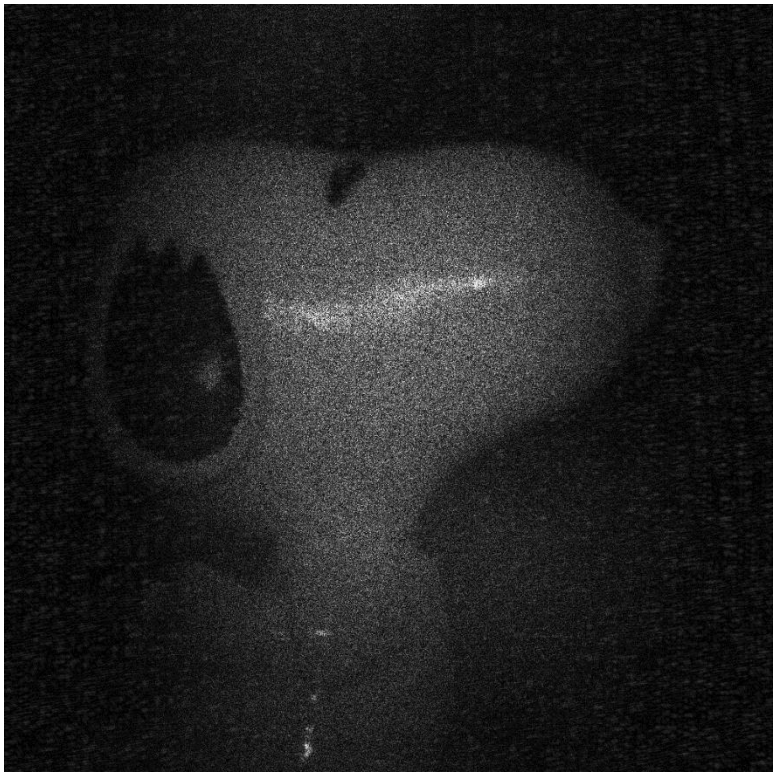


Digital holography: reconstruction (numerical)

Reconstruction distance: 326 mm



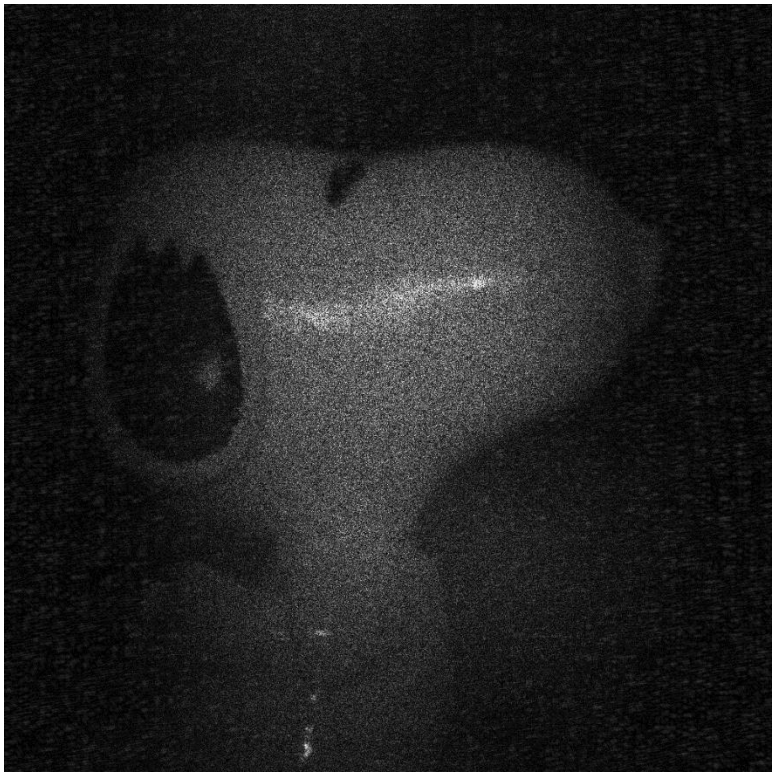
Reconstruction distance: 330 mm



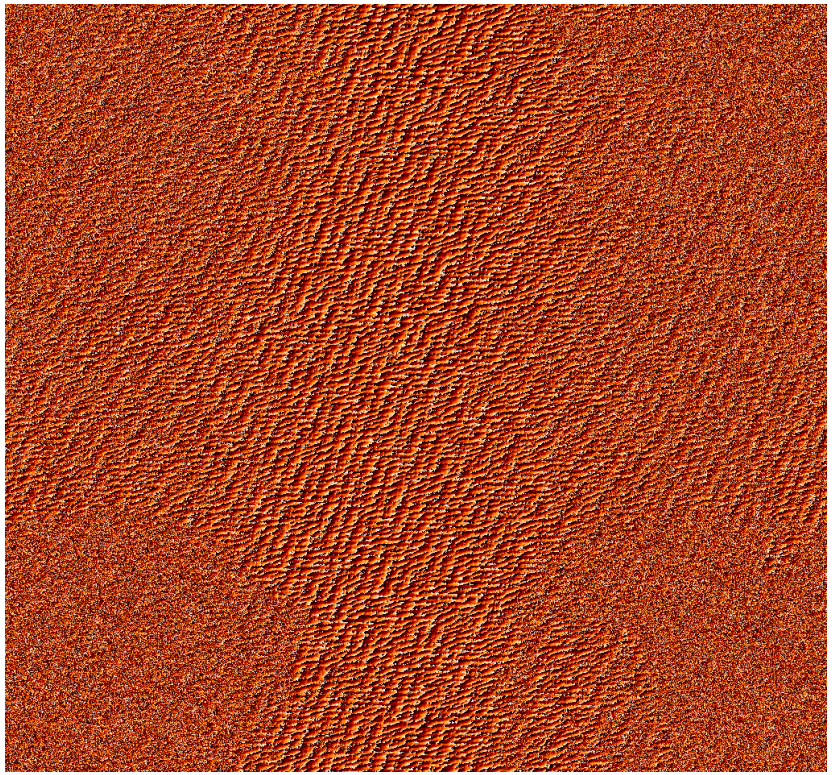
Digital holography: reconstruction (numerical)

Reconstructed intensity: $I(x,y) = I_B + I_M \cos[\Delta\varphi(x,y)]$

Intensity: $I(x,y)$

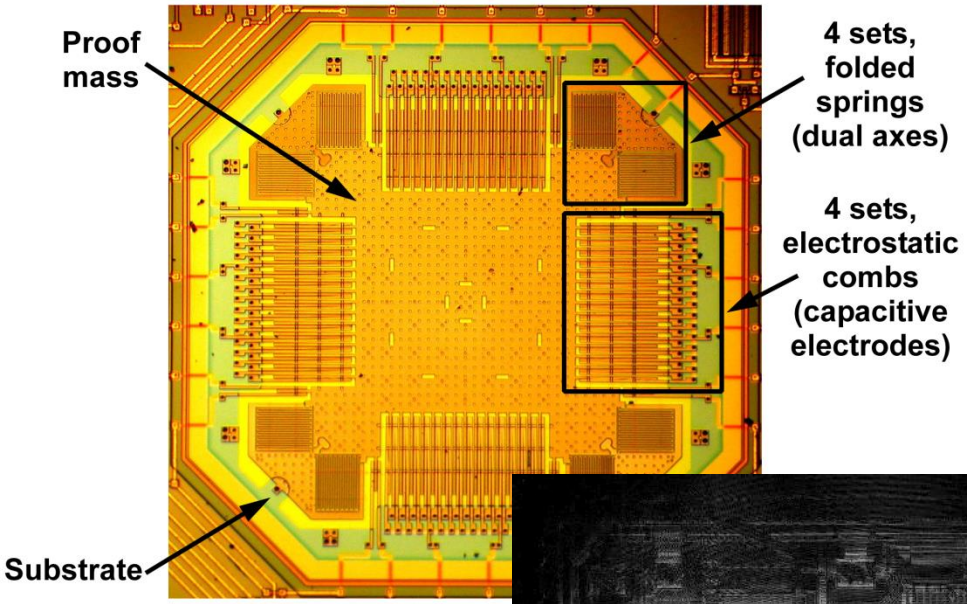


Phase: $\Delta\varphi(x,y) \in [-\pi, \pi]$

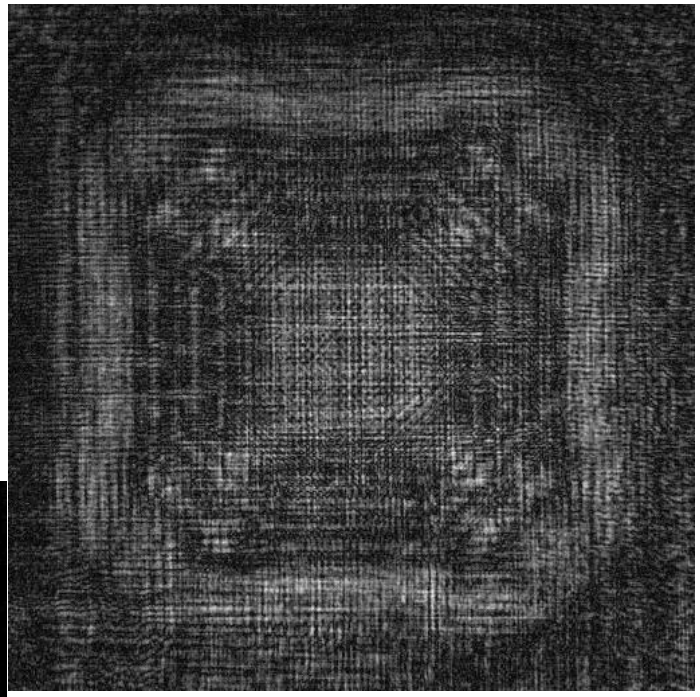


Lensless digital holography: 532 nm laser source

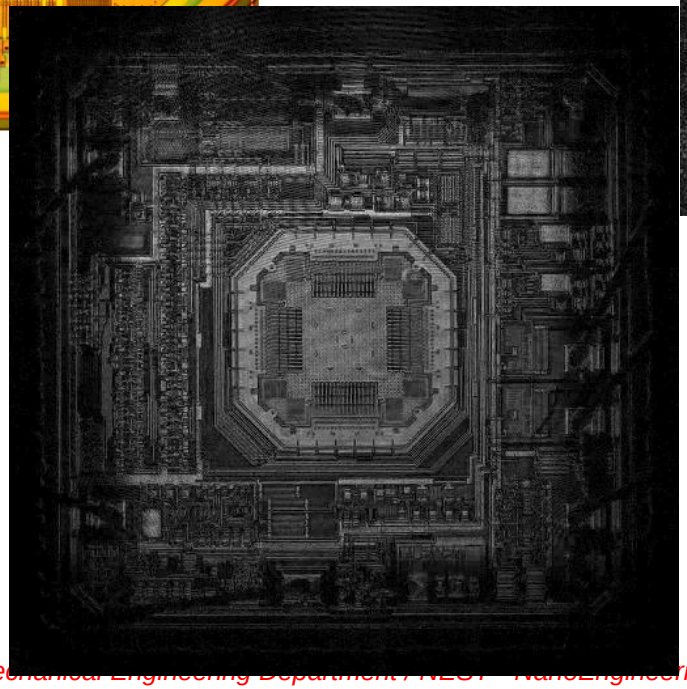
ADXL202 dual-axes accelerometer die



Numerical reconstruction



Numerical magnification

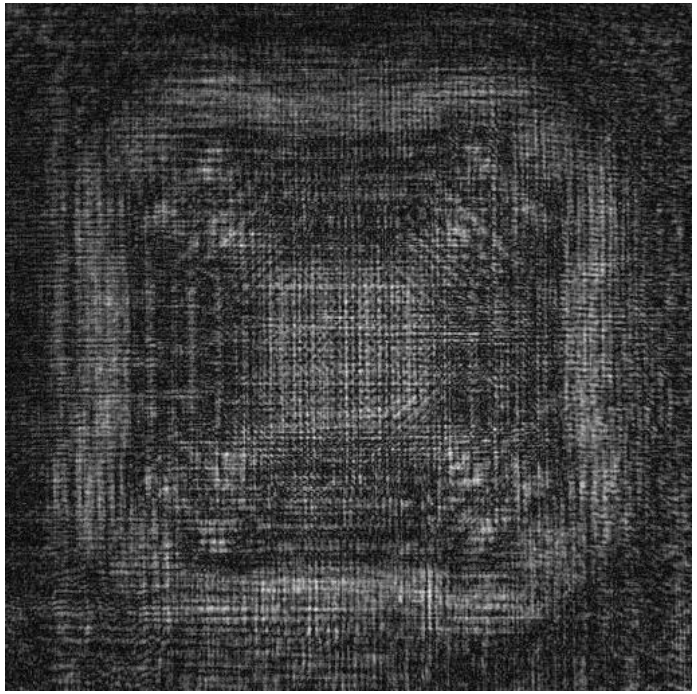


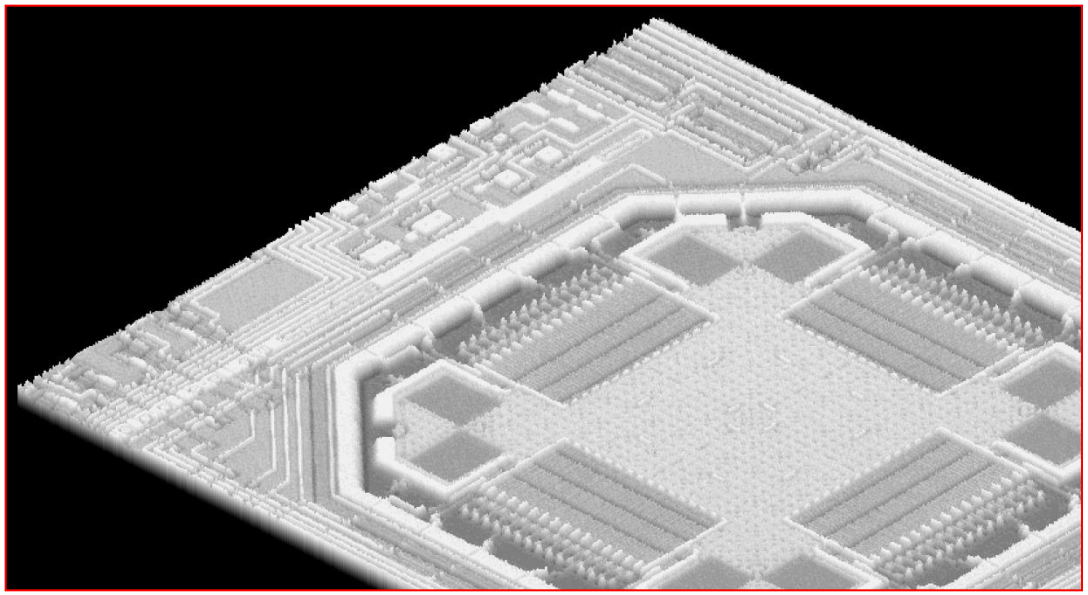
Lensless digital holography, tomographic measuring mode

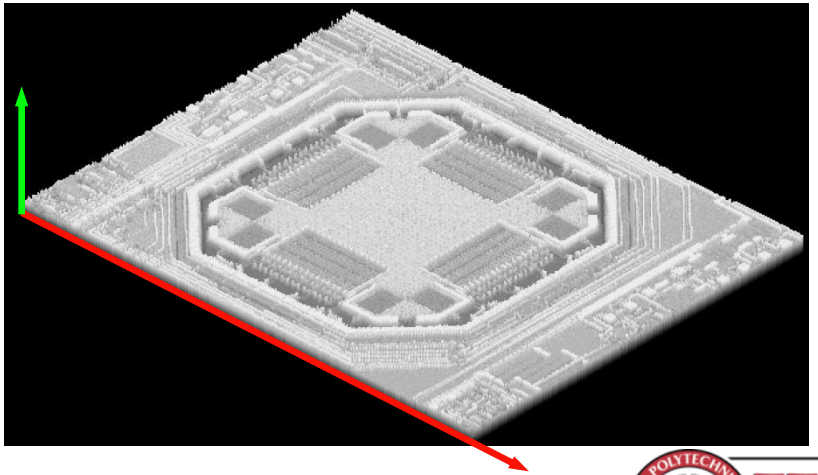
Phase, Intensity, and Time-in-Flight analyses

Reconstruction of a digital hologram

Numerical reconstruction





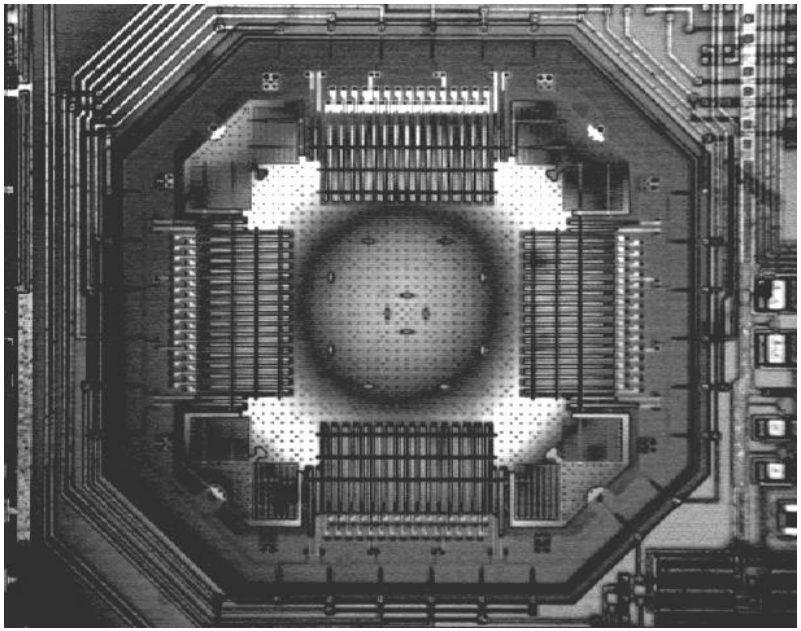


Recovered shape with a resolution on the order of 1 nm

Full-field-of-view characterization of mode shapes

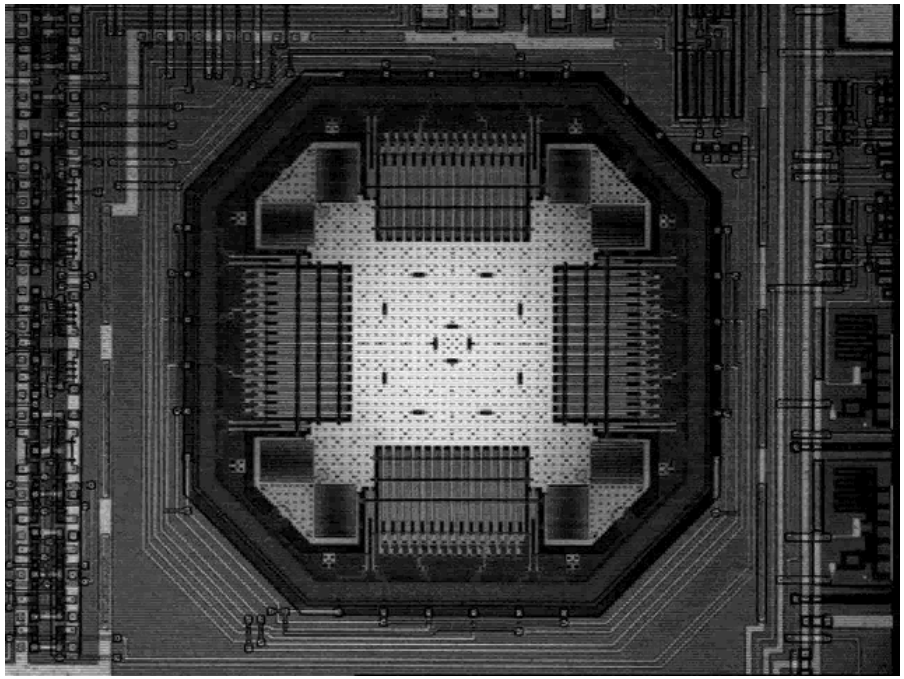
Fundamental frequency is related to the measuring accuracy of the MEMS device

Observed fundamental mode at 10.65 KHz



Continuous full-field-of-view measurements

Frequency scan: 10 kHz – 11 kHz



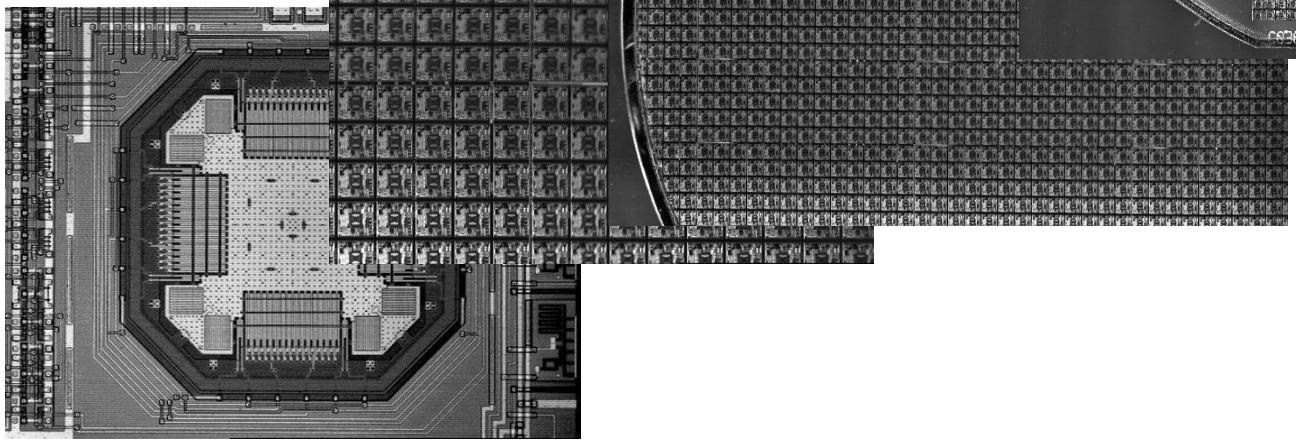
Testing at the wafer level: inspecting an ADXL202 wafer

Multi-scale approach

Level-3: stitching patches of Level-2

Level-2: stitching individual die measurements

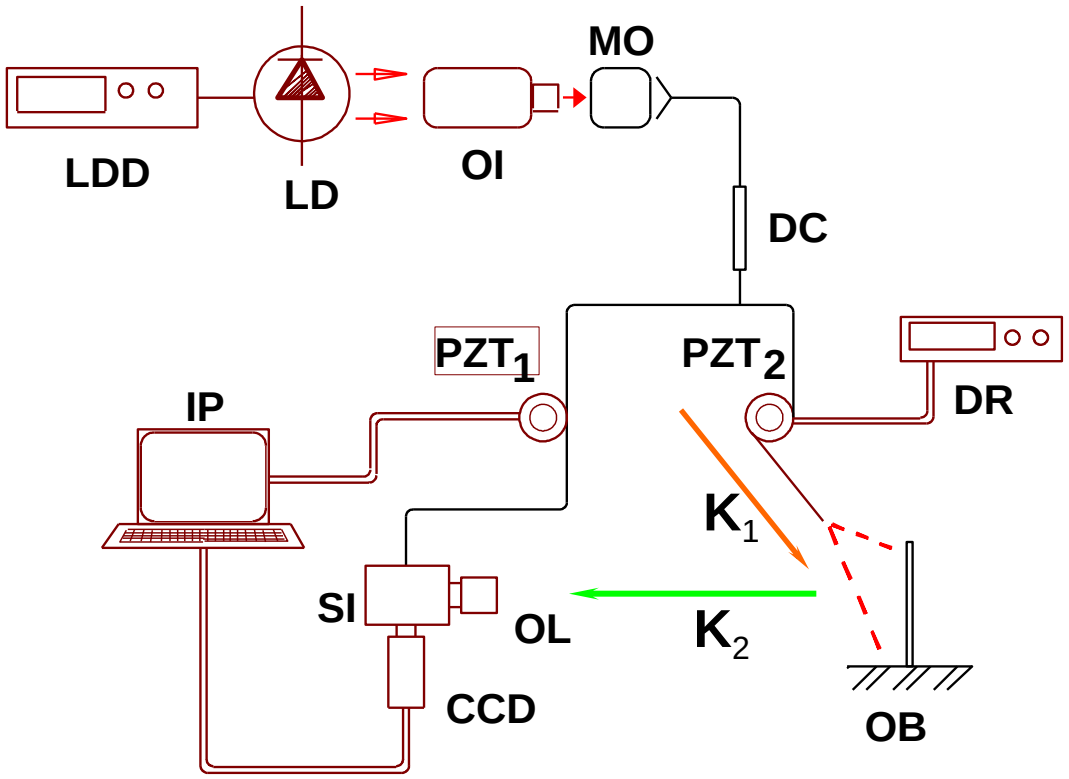
Level-1: measurement of individual dies



Level- 4: stitching patches of Level-3

Fiber-optic based optoelectronic holography (FOBOEH)

Single camera configuration



$\mathbf{K}_1$ - DIR OF ILLUMINATION

$\mathbf{K}_2$ - DIR OF OBSERVATION

$$\mathbf{K}_2 - \mathbf{K}_1 = \mathbf{K}$$

$\mathbf{K}$ - SENSITIVITY VECTOR

$\mathbf{L}$ - DISPLACEMENT VECTOR

$$\mathbf{K} \bullet \mathbf{L} = \Omega$$

Ω - FRINGE-LOCUS FUNCTION

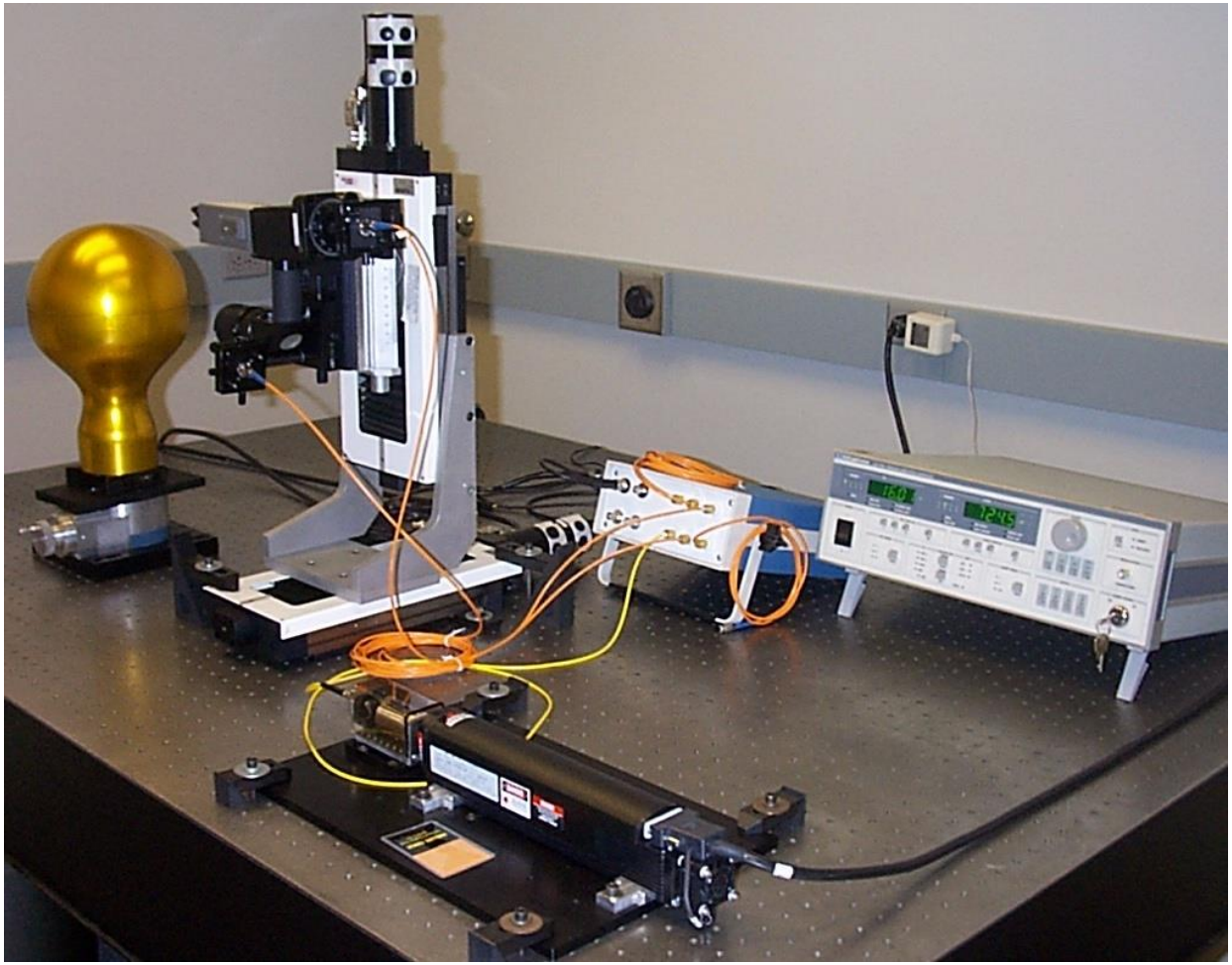
$$[\mathbf{K}] \bullet \mathbf{L} = (\Omega)$$

$$[\mathbf{K}]^{\mathrm{T}} [\mathbf{K}] \bullet \mathbf{L} = [\mathbf{K}]^{\mathrm{T}} (\Omega)$$

$$\mathbf{L} = \left[[\mathbf{K}]^{\mathrm{T}} [\mathbf{K}] \right]^{-1} \left([\mathbf{K}]^{\mathrm{T}} (\Omega) \right)$$

FOBOEH

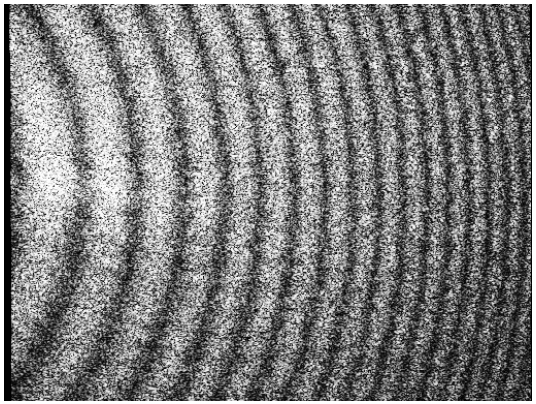
Typical experimental setup



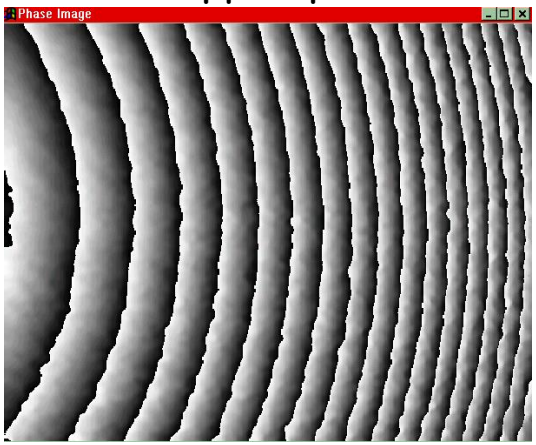
Typical phase analysis results

Tile #8: contour depth is 1.81 ± 0.01 mm

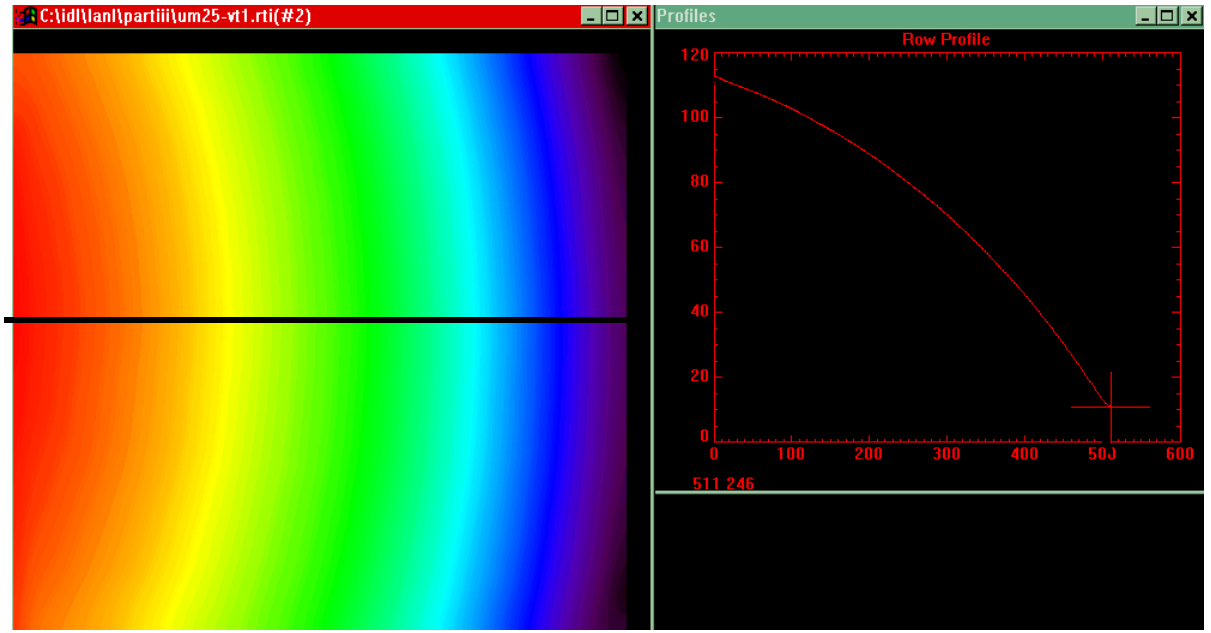
Interferogram



Wrapped phase



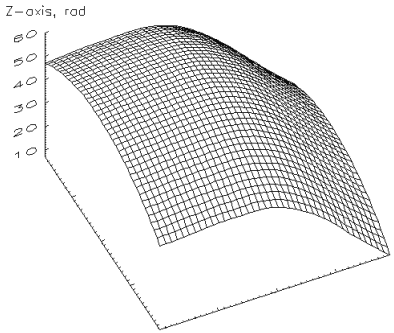
Unwrapped phase

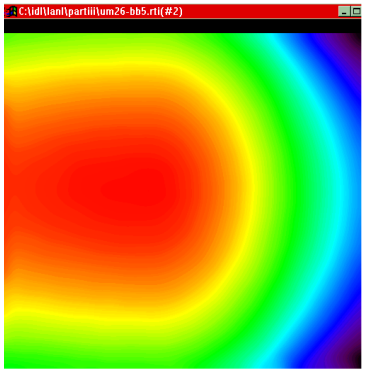


Inspecting using an overlapped tile approach

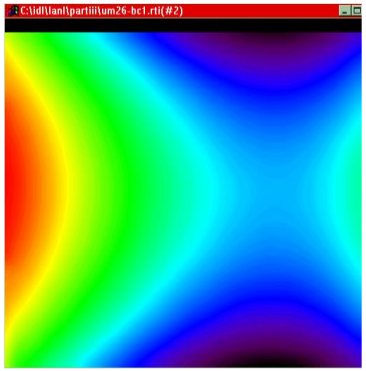
Intermediate tiling steps: algorithm

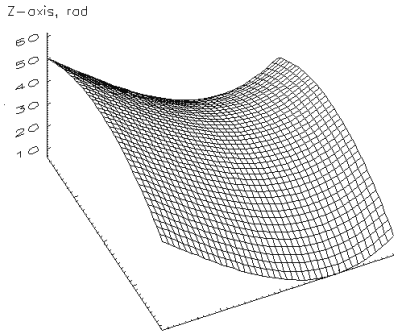
Tile #1



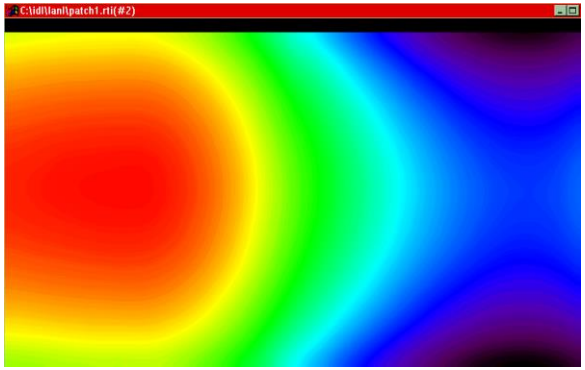


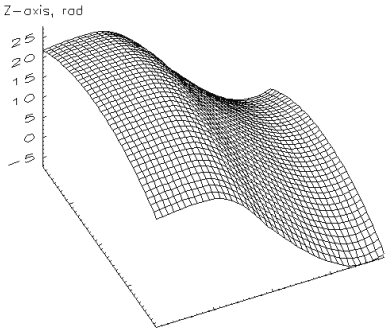
Tile #2





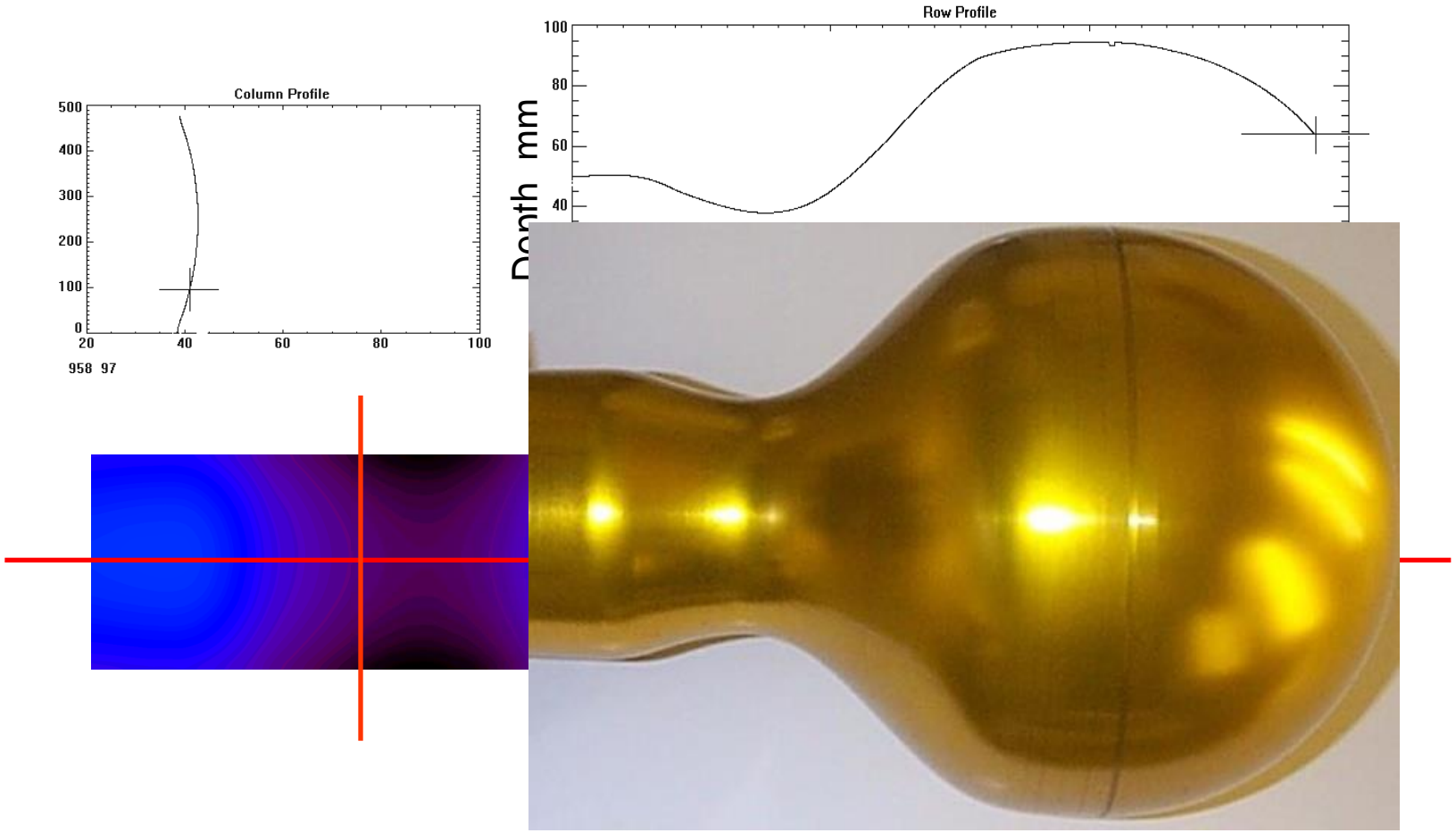
Patch #1





Contoured section

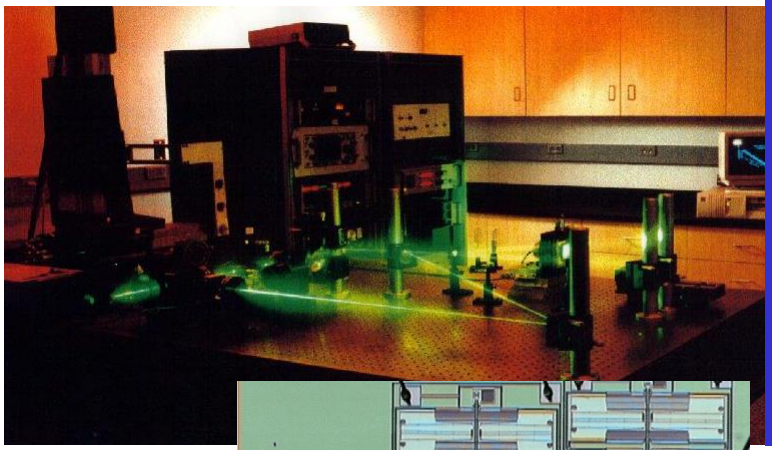
Intermediate tiling step: 33 x 257 mm² longitudinal section

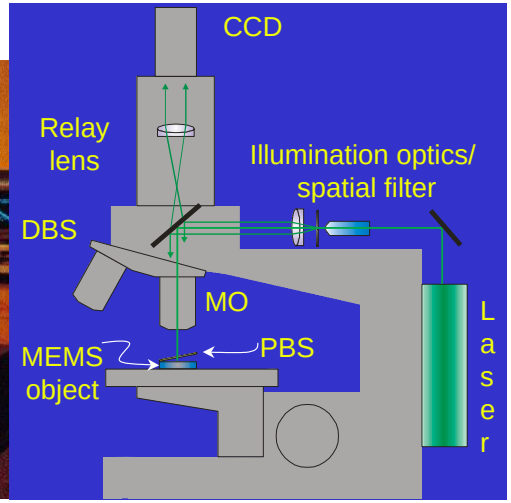


SANDIA Labs 1,000,000 rpm microengine

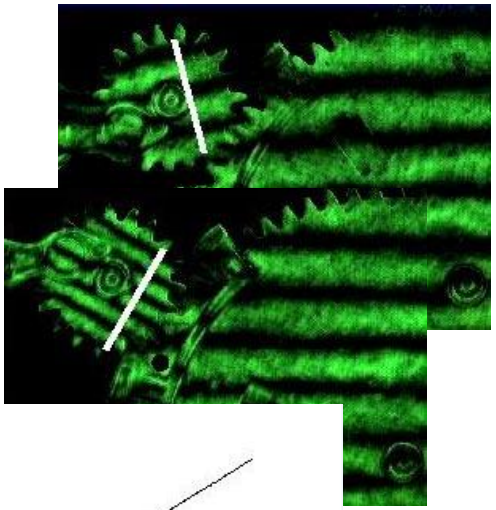
50 μm diameter input gear

CHSLT-NEST Laser Lab for studies of MEMS

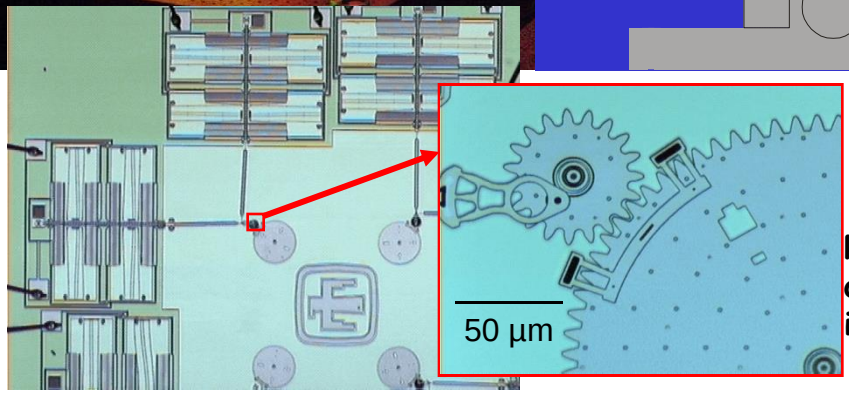




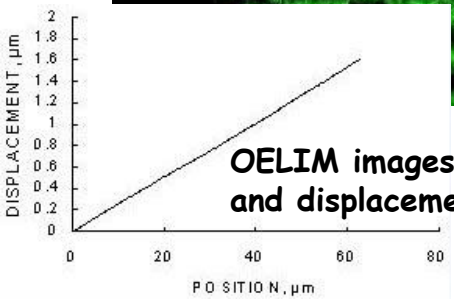
Optoelectronic Laser Interferometry Microscope (OELIM)



Electrostatically driven Sandia MEMS microengine



Region of interest

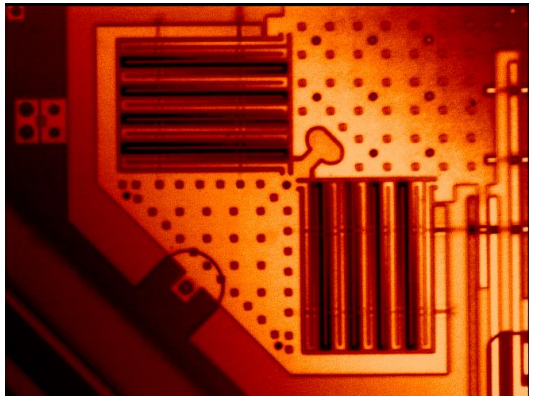


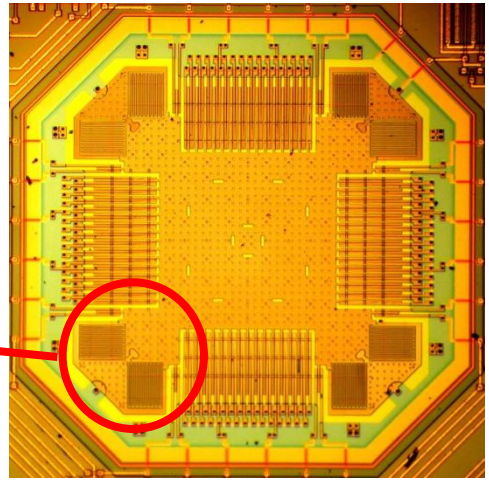
OELIM images and displacements

2-axes MEMS accelerometer: *deformation*

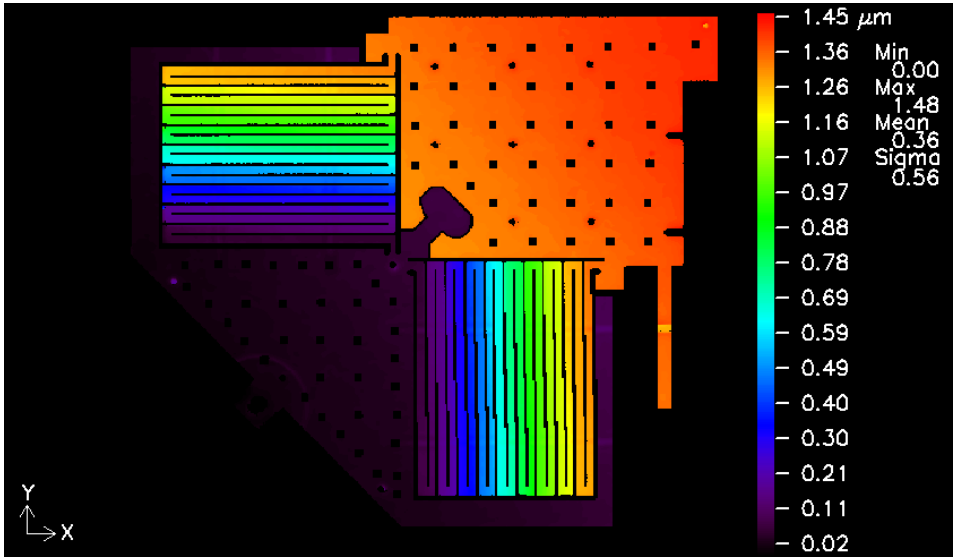
Package in the loaded state: with excitation voltage

Interferogram

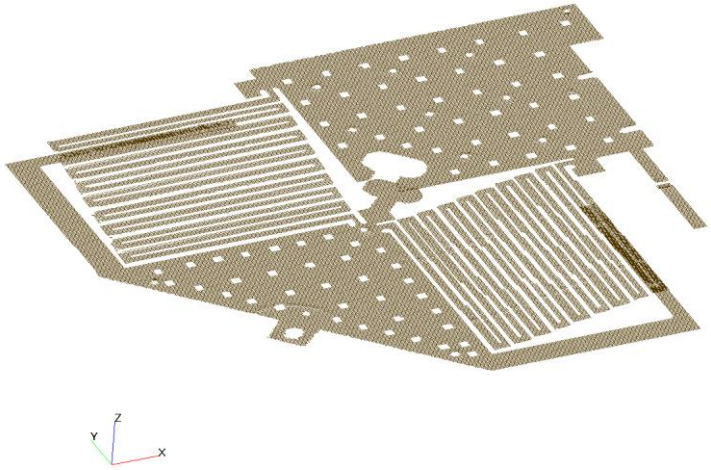




OEH results

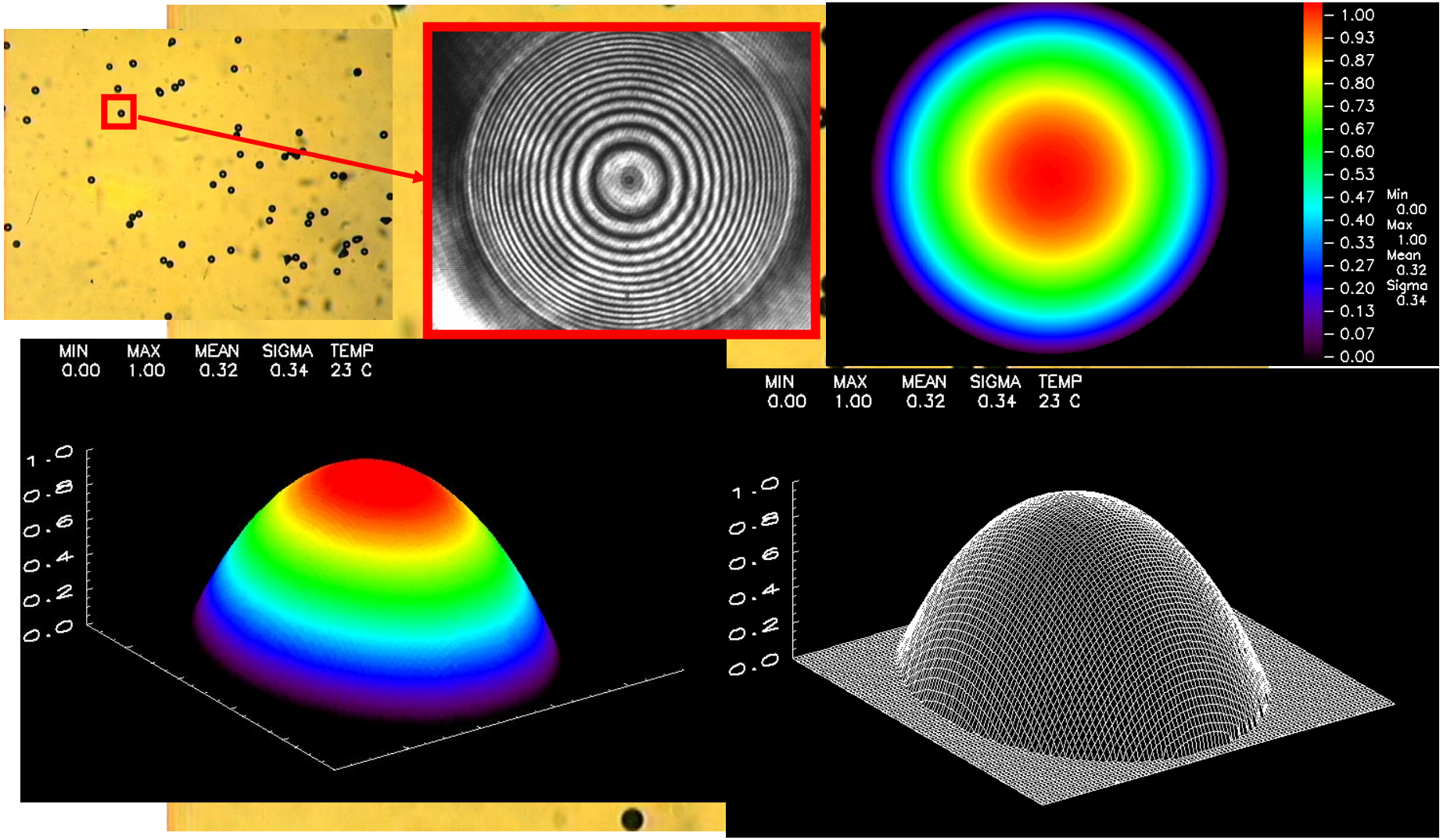


CAD model



Characterization of micro- and nano-particles:

Holographic laser tomography for biological/materials applications

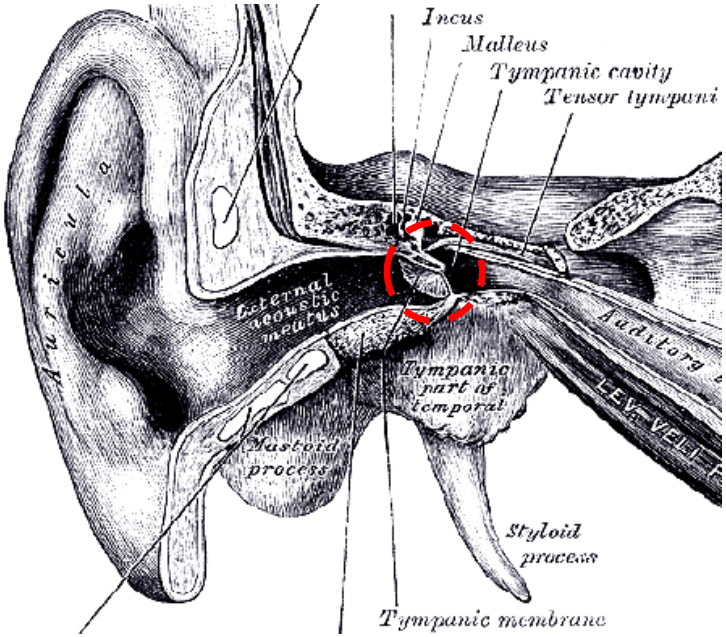


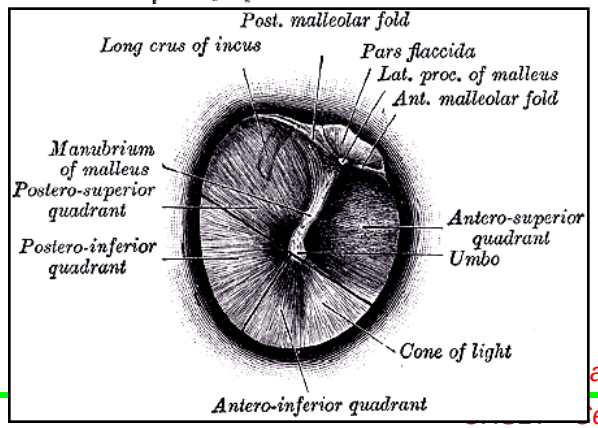
MEMS-based metrology

High-speed measurements in confined volumes

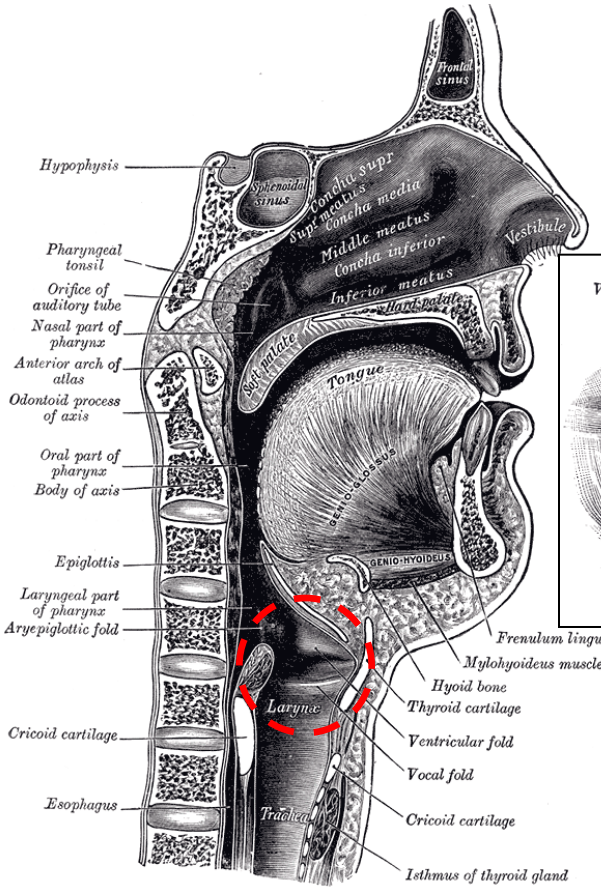
Otolaryngology applications

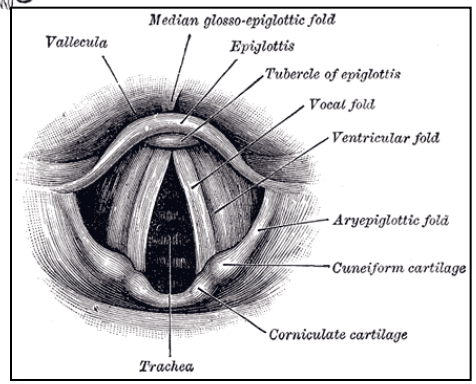
The Human Tympanic Membrane





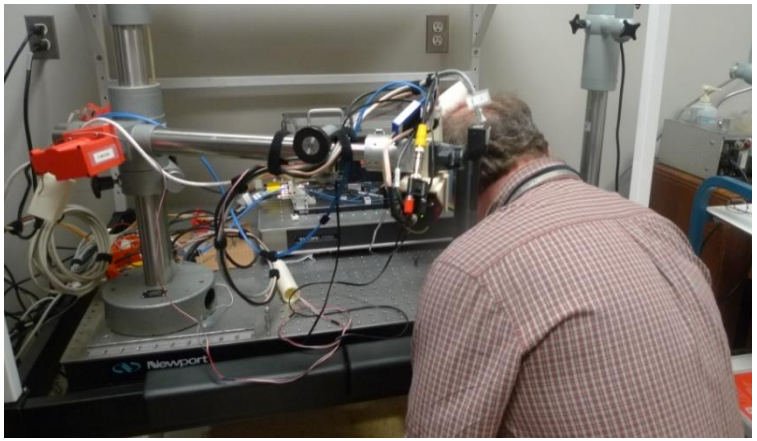
The Human Vocal Cords





Grey's Anatomy, NY, 2000

Holographic otoscope systems deployed in the clinic (MEEI)



MP-FEM
Rapid Pro

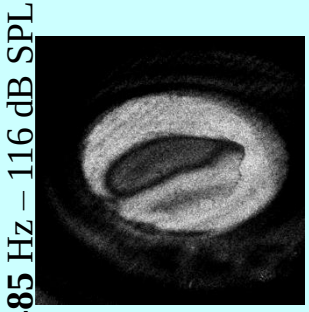
2nd Generation System

Holographic otoscope systems deployed in the clinic (MEEI)

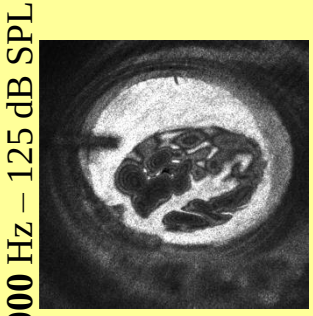
Representative measurements: time-averaged holography

Cat Right Ear

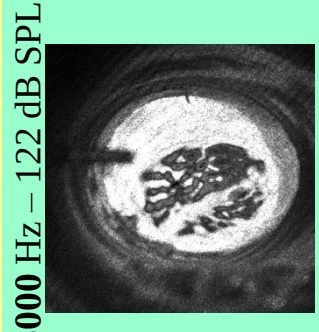
Simple



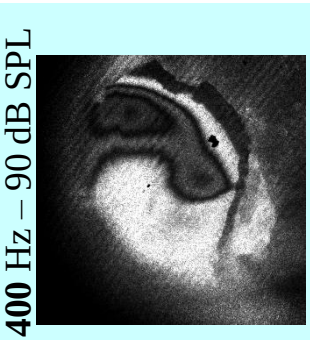
Complex

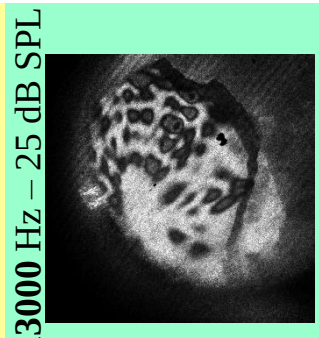


Ordered



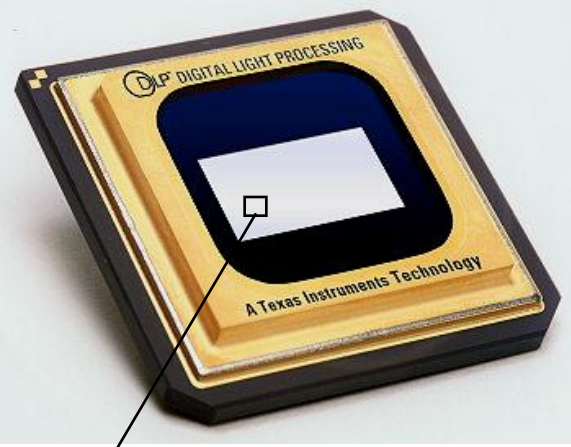
Chinchilla Right Ear



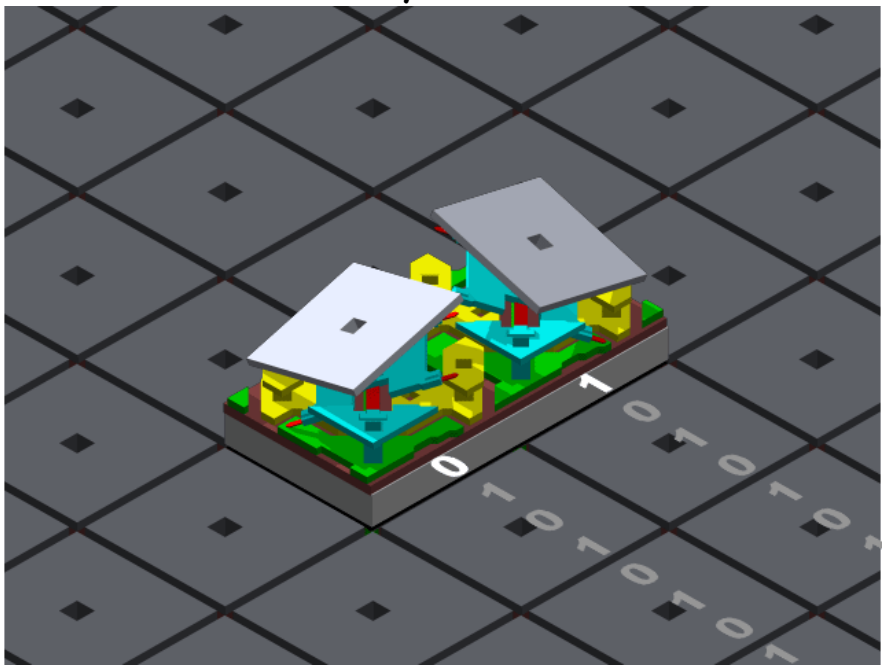


MEMS in optoelectronic metrology: SLM

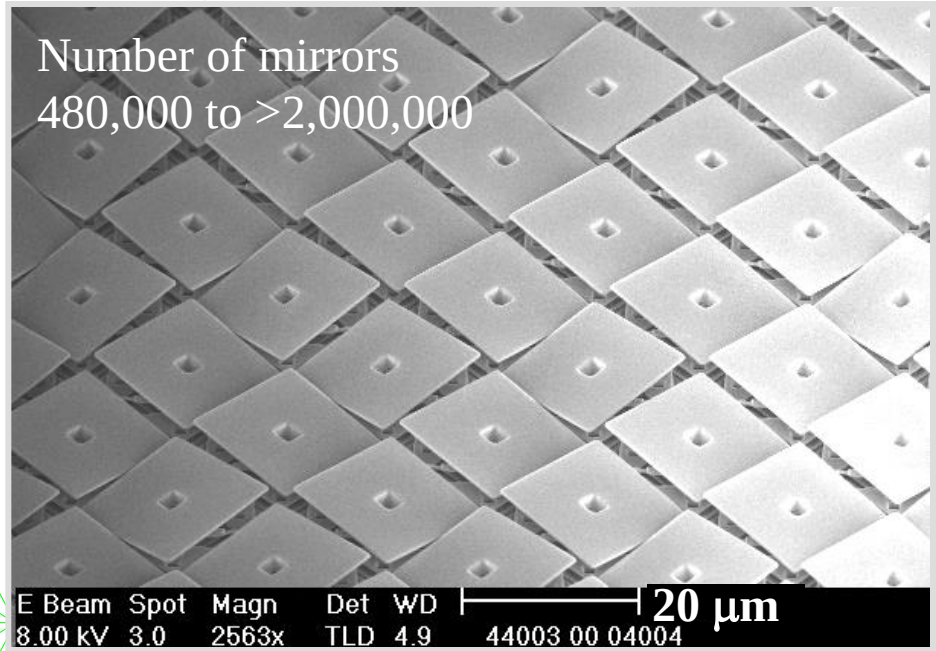
Texas Instrument's DMD

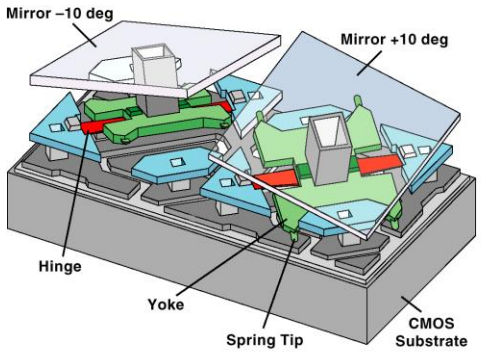


Each mirror of the DMD is individually addressable



Close-up of chip surface

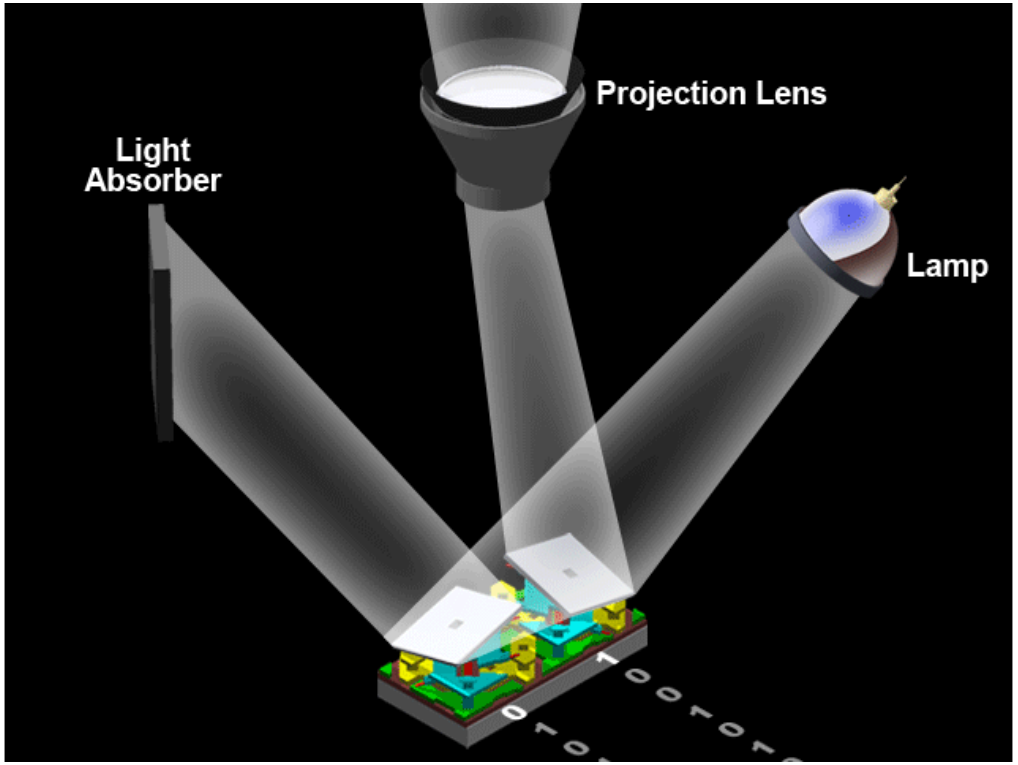


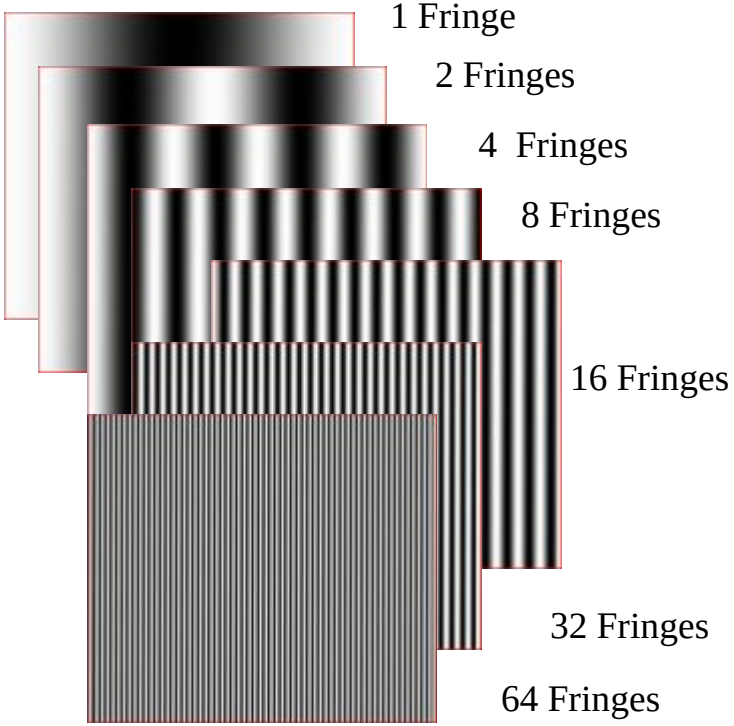


MEMS in optoelectronic metrology

High-speed measurements based on holographic interferometry principles

Use of computer generated holograms





MEMS in optoelectronic metrology

High-speed measurements based on holographic interferometry principles

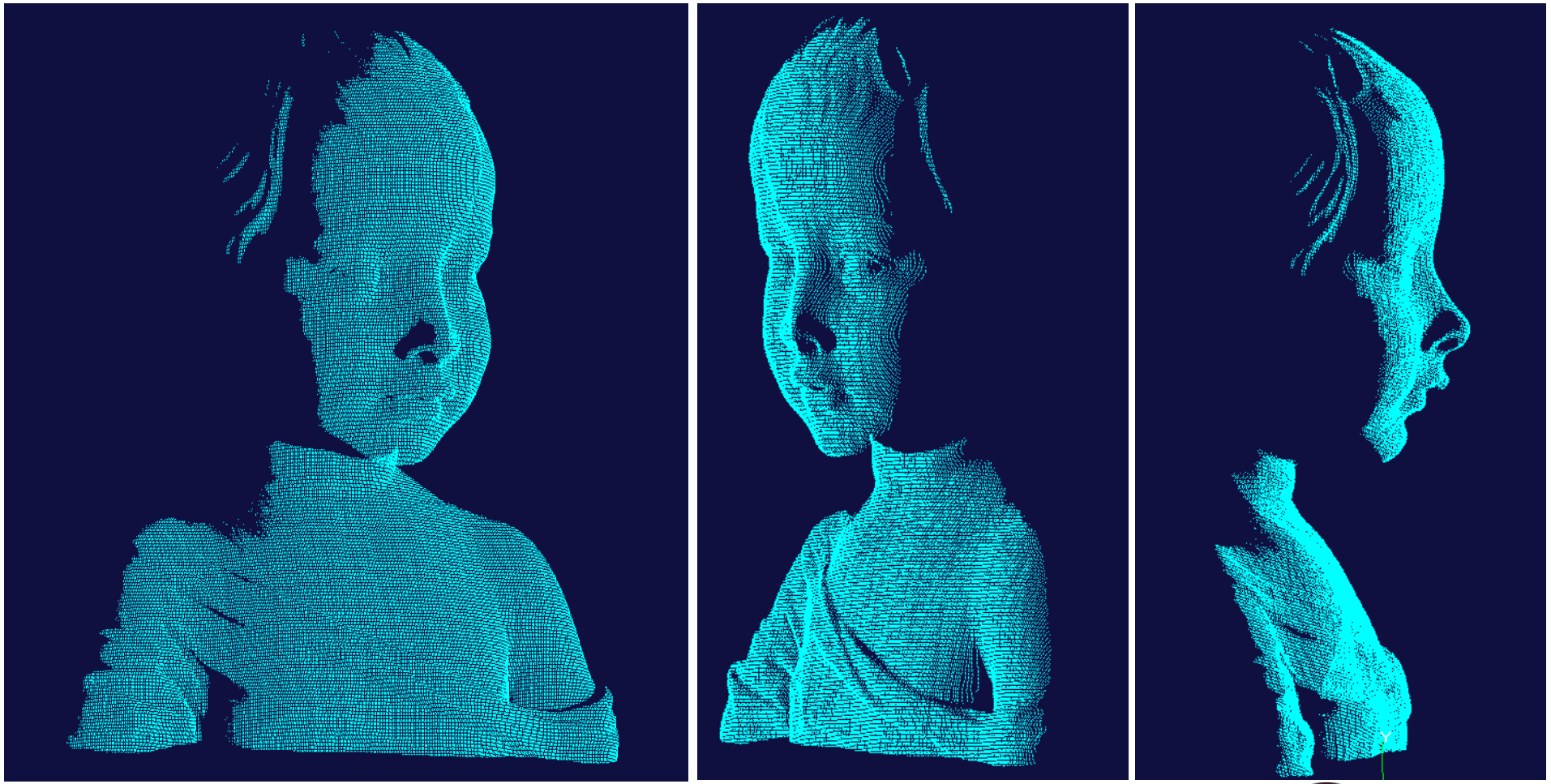
Shape measurements in
'3D inspection applications'

MEMS in optoelectronic metrology

High-speed measurements based on holographic interferometry principles

CAD models for shape measurements in 'art preservation'

Definition of models… for 'video games' development… CAM…



MEMS in optoelectronic metrology

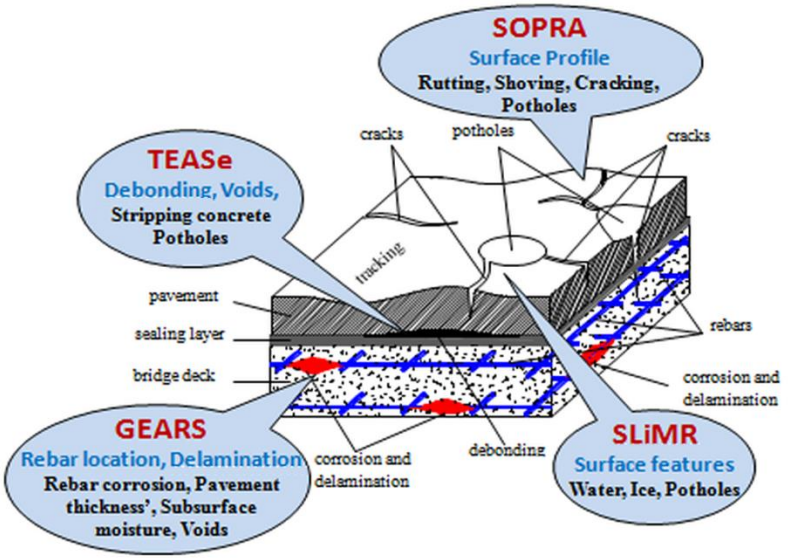
High-speed measurements based on holographic interferometry principles

VOTERS Sensor Systems
Versatile Onboard Traffic Embedded Roaming Sensors

Northeastern University

Mission

- Determine road characteristics
- Integrate state-of-the-art sensing
- Register data geographically
- Support of a national network
- Work with industry partners



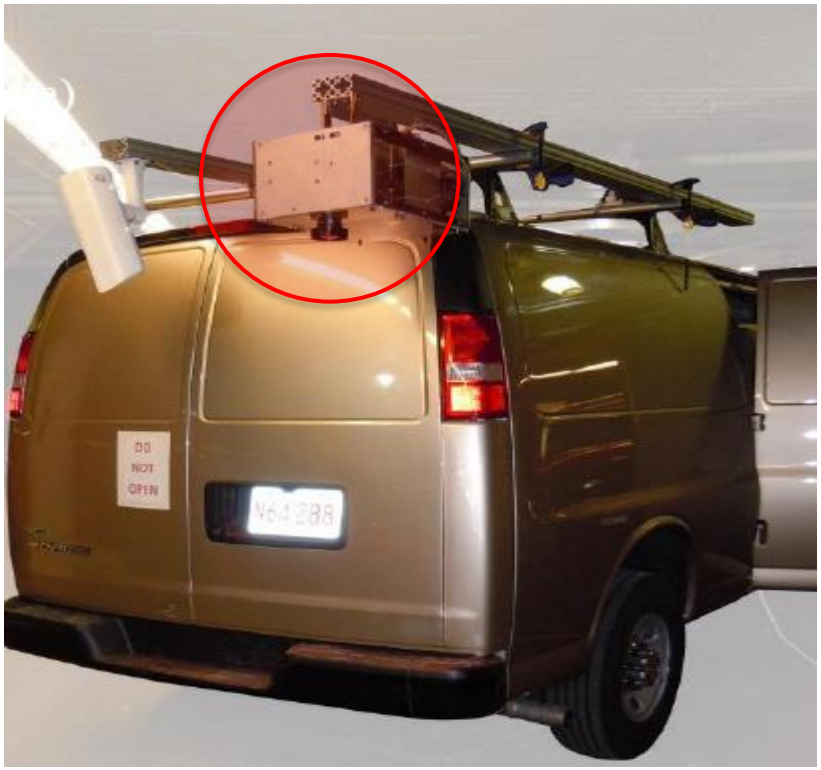
* Courtesy of VOTERS website

MEMS in optoelectronic metrology: SOPRA

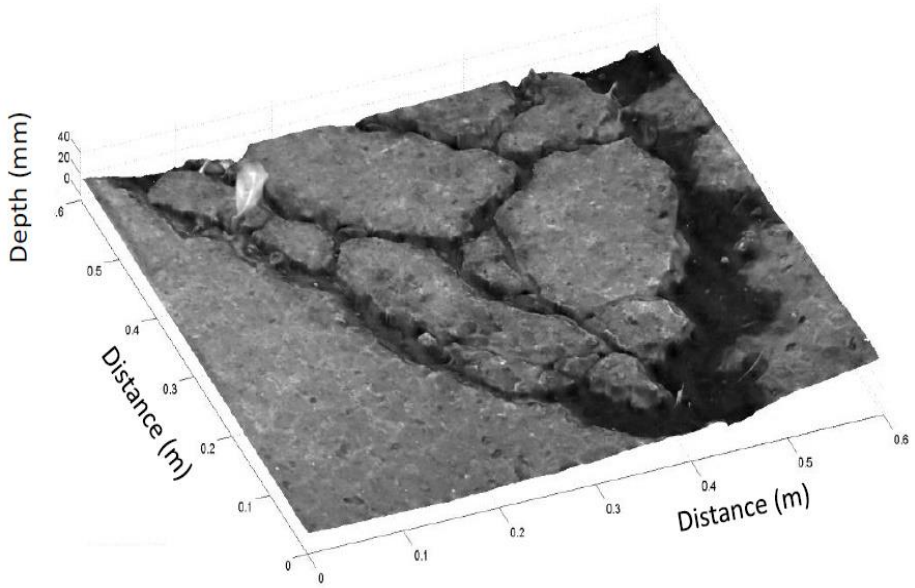
High-speed measurements based on holographic interferometry principles

- A prototype system has been developed and applied to road surface analysis
- We are currently designing a robust, low-cost, projection system that can be deployed in the field for measurements at up 60 mph driving speeds

Prototype projector on a vehicle



Typical surface road measurements

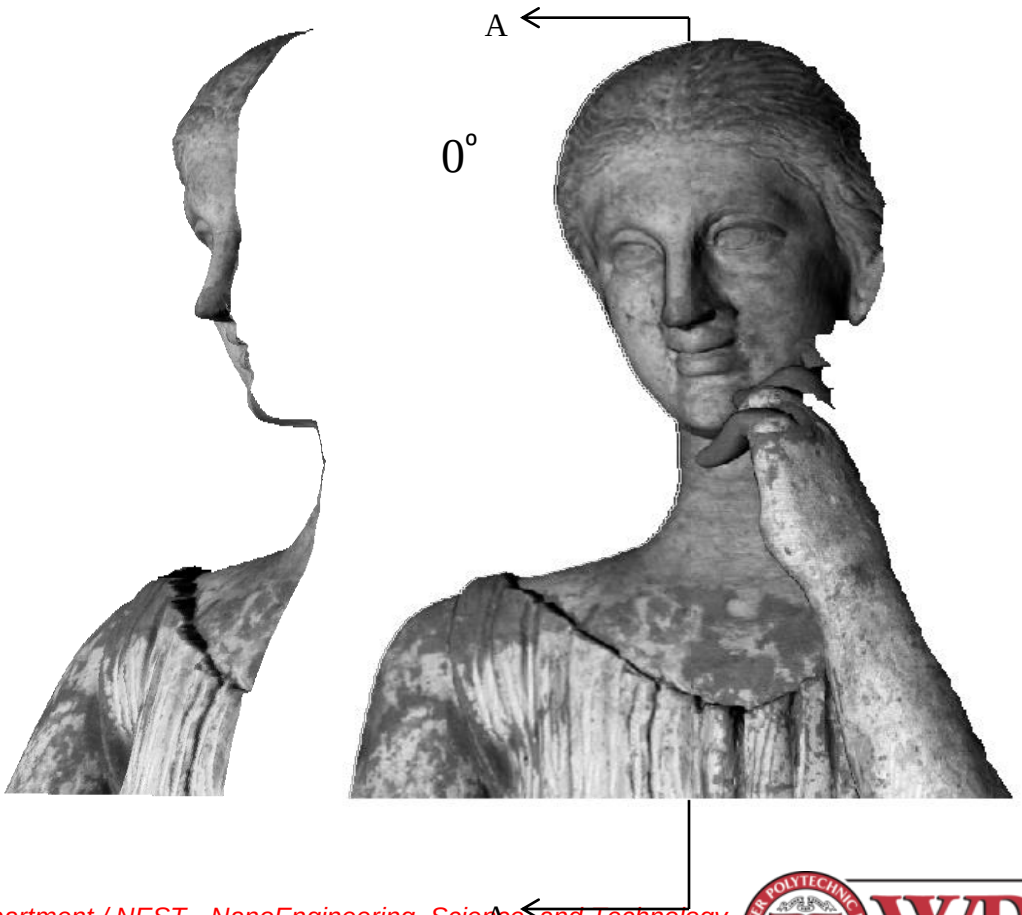


MEMS in optoelectronic metrology: art-conservation

High-speed measurements based on holographic interferometry principles

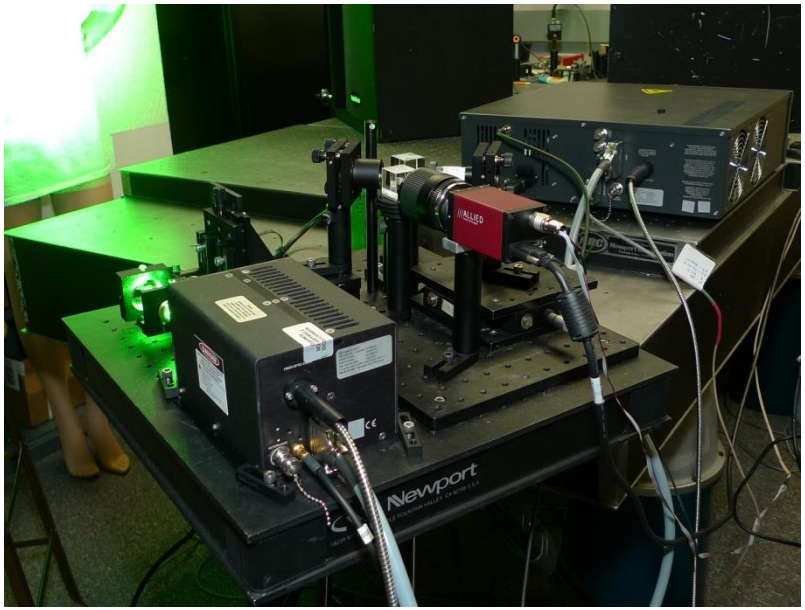
Worcester Art Museum: Sculpture titled "*Funeral of a Young Maiden*" Casona, South Italy. Late 4th Century BCE

Representative Measurements

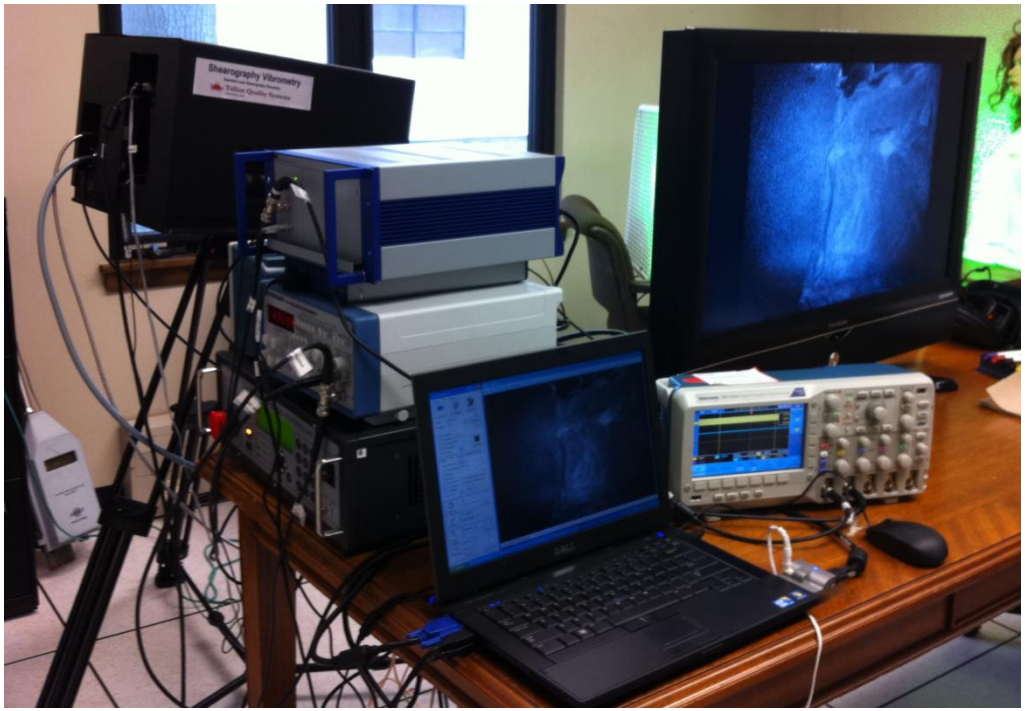


Nondestructive testing: standoff detection
Hidden objects + Internal defects

Realized opto-electronic head with pulsed laser



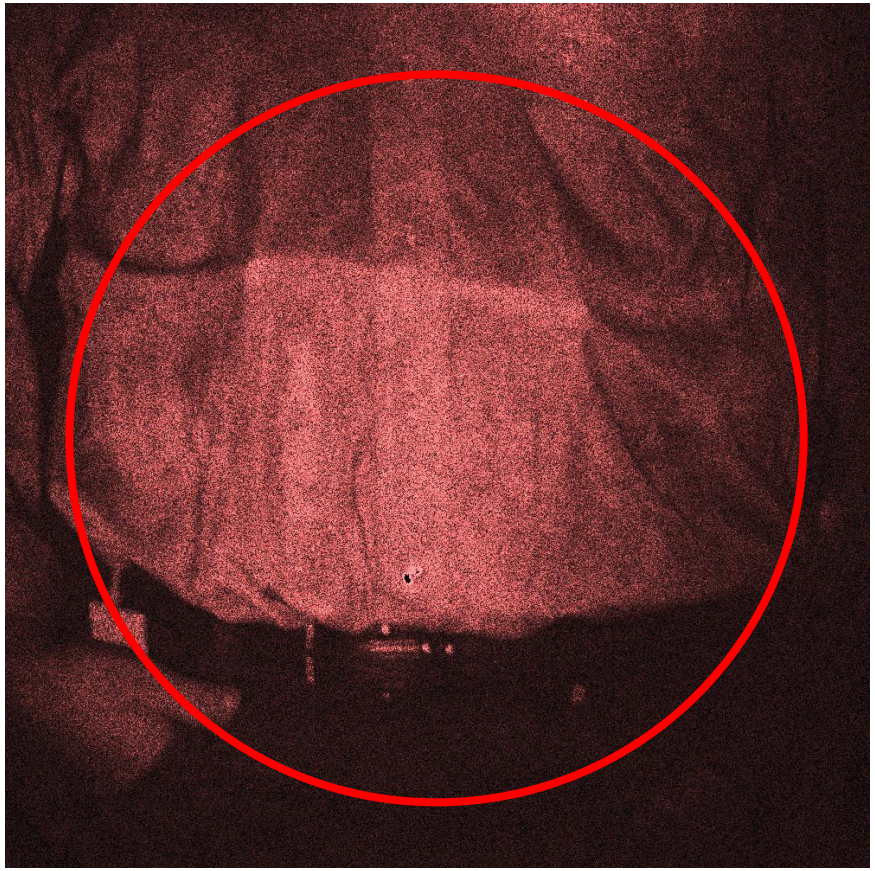
Developed holographic system in the field



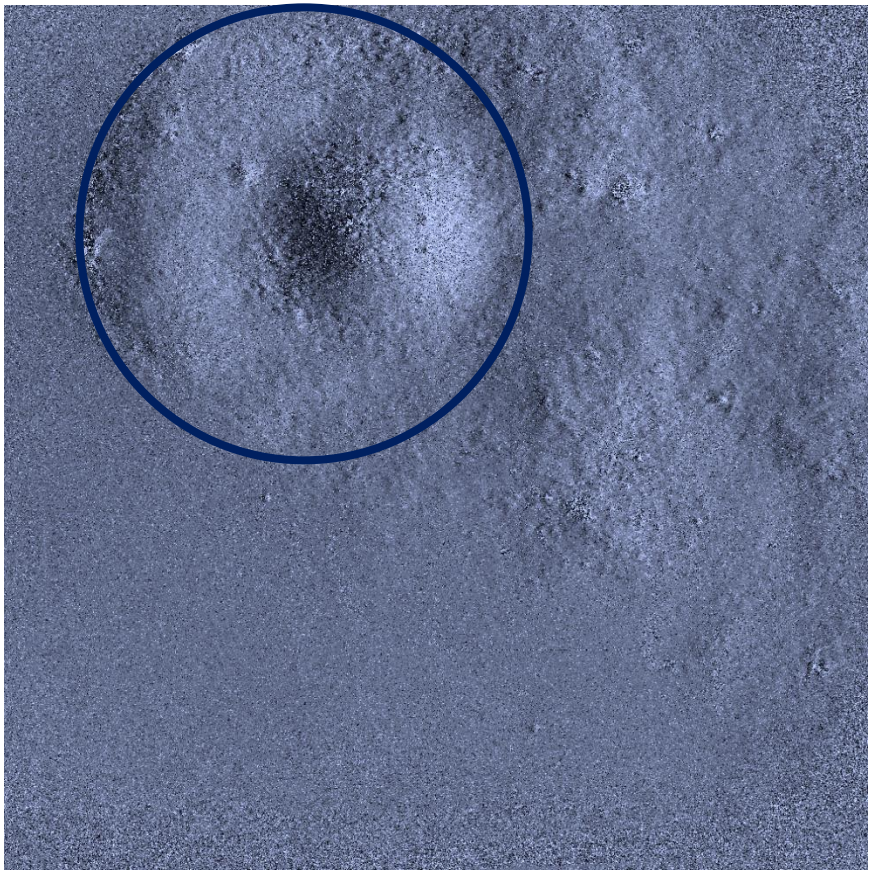
Nondestructive testing: standoff detection

Hidden objects + Internal defects

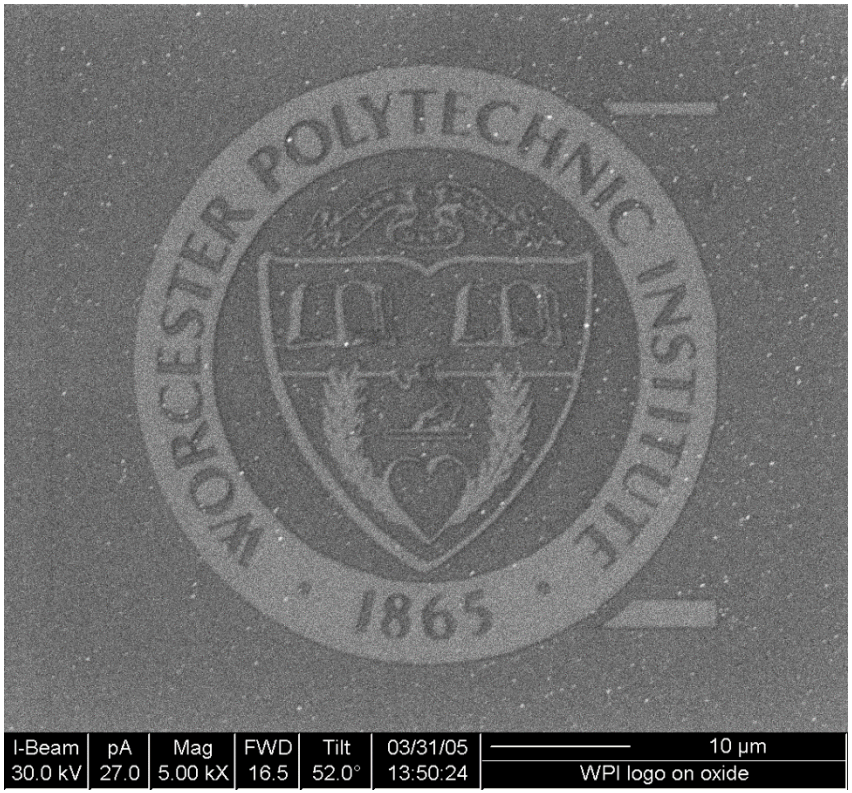
Hidden object under person's shirt



Detected internal defect



Thank you & see you next time !



(WPI's Seal, ~1/4th of the human-air diameter)

Short list of references

- D. Gabor, "A new microscope principle," *Nature*, **161**, 777-778, 1948. (In 1971, Dr. Gabor was awarded the Nobel Prize for his invention and development of the holographic method.)
- D. Gabor, "Microscopy by reconstructed wavefronts," *Proc. Royal Society A*, **197**, 454-487, 1949
- E. N. Leith and J. Upatnieks, "Reconstructed wavefronts and communication theory," *J. Opt. Soc. Amer.*, **53**, 1377-1381, 1963
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- R. L. Powell and K. A. Stetson, "Interferometric vibration analysis by wavefront reconstruction," *J. Opt. Soc. Amer.*, **55**, 1593-1598, 1965
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