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Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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INTERFEROMETRY: CONCEPTS AND APPLICATIONS

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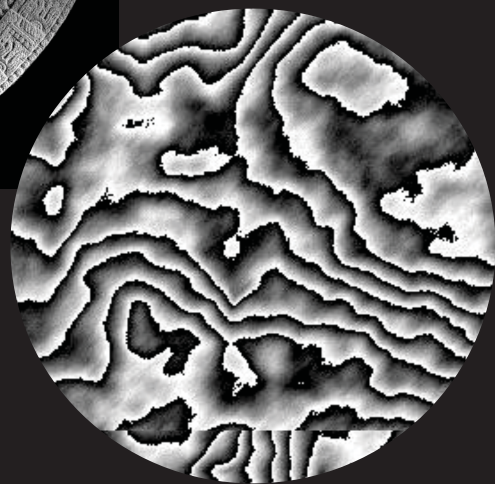
INTERFEROMETRY: CONCEPTS AND APPLICATIONS



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WINTER COLLEGE ON OPTICS
ICTP, TRIESTE
13-14 February 2013

Outline of Presentation

1. Principles of Interferometry
2. Some examples of Interferometric Systems
3. ESPI and Digital Holographic Interferometry

Recommended Literature:

1) Optical Metrology, K.J. Gasvik
2) Optics, M.V. Klein
3) Fundamentals of Optics and Modern Physics, H.D. Young
4) T. Kreis, "Handbook of Holographic Interferometry" WILEY-VCH Verlag GmbH & Co.KGaA, 2005

Definitions

Interferometry: superposition of n E-M beams in space. The result of interefrence depends on the phase relations between the beams.

Interefrence relates to the interaction betwen propagating beams ,

while refraction, scattering and diffraction depend on the interaction between a beam and matter.

A short history of interferometry

1. XVIIc. – R. Boyle, R. Hook, observation and analysis of interference effects in a thin air layer limited by two glass plates which demonstrated the wave nature of light

2. 1690 – C. Huygens, Huyghens theorem (beginning of the wave theory of light)

   Each element of a wavefront may be regarded as the center of a secondary disturbance which gives rise to spherical wavelets and *the position of the wevefront at any latter time is the envelope of such wavelets*

3. 1738 T. Young experiment confirmed Huyghens' hipothesis and gave the basis to modern theory of light coherence

4. 1818 – A. Fresnel – extension of Huyghens theorem, leading to so-called Huyghens-Fresnel principle - great importance in the diffraction theory and the basic postulate of the wave theory of light, development of stellar interferometry

1a. 1874 Lord Rayleigh used for the first time **moire phenomenon**

A short history of interferometry

5. 1881 – Michelson experiment (speed of light) and his further works on interferometry, stellar interferometry, high resolution interferometric spectroscopy - he is considered as the father of interferometry (Nobel prize 1907)
6. 1916 – F. Twyman modifications of Michelson ineterferometer
7. 1960 – invention of laser: Schawlow, Maiman, Townes, Prochorow….
8. 1948 – Gabor principles of holography
9. 1962 -Leith and Upatnieks off-axis holography and development of holographic interferometry (works of Burch, Brooks, Collier, Stetson…)
10. 1970 – Archbold, Leendertz speckle interferometry and speckle photography
11. 1982- ..Development of phase based interferogram analysis methods

11\. 1995-….Rapid progress in digital holography

12\. 2000-…Rapid progress in active interferometry and holography

Fundamentals of interferometry

Vector of electric field

$$\bar{E}_i(\bar{r},t)=\bar{E}_{i0}\exp[i(\varphi_i(\bar{r})-\omega_i t)]$$

Resultant vector in two beam interferometry

$$\bar{E}(\bar{r},t)=\sum_i \bar{E}_i(\bar{r},t); \qquad i=1,2$$

Result of two beam interference (E field intensity):

$$I(r)\,\alpha\,\left|\bar{E}\right|^2=\left|\bar{E}_1+\bar{E}_2\right|^2=\left(\bar{E}_1+\bar{E}_2\right)\left(\bar{E}_1+\bar{E}_2\right)^*=\bar{E}_1\bar{E}_1^*+\bar{E}_2\bar{E}_2^*+\bar{E}_1\bar{E}_2^*+\bar{E}_1^*\bar{E}_2$$

$$I(\bar{r})=I_1+I_2+I_{12}=I_1+I_2+2\sqrt{I_1I_2}\cos[(\varphi_1(\bar{r})-\varphi_2(\bar{r}))-(\omega_1 t-\omega_2 t)]$$

Conditions for stationary interference field:

$$\omega_1=\omega_2$$

$$\varphi_1(\bar{r})-\varphi_2(\bar{r})=\text{const.}$$

Recommended: parallel polarization of beams

Fundamentals of interferometry

For $\omega_1 = \omega_2$ (usually one source applied)

$$I(\bar{r}) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\varphi_1(\bar{r}) - \varphi_2(\bar{r})\right) = a(\bar{r}) + b(\bar{r})\cos\varphi(\bar{r}) \cong 1 + \gamma(\bar{r})\cos\varphi(\bar{r})$$

Where a(r) and b(r) are background and fringe modulation functions

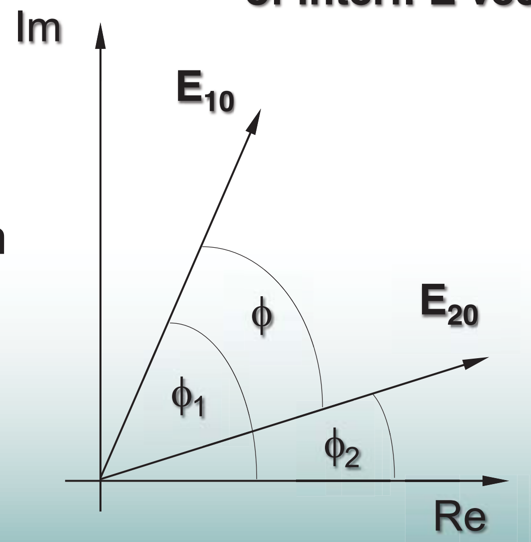
$$\gamma = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}$$

is contrast of interferogram

$$\varphi(\bar{r}) = \varphi_1(\bar{r}) - \varphi_2(\bar{r})$$

is phase difference between the interfering beams

Graphic representation of interf. E vectors



The observable physical quantity is the intensity,

$$I = |a|^2 = (a_1 + a_2)(a_1^* + a_2^*) =$$

$$A_1^2 + A_2^2 + A_1 A_2\, e^{i\,(\varphi_2 - \varphi_1)} + A_1 A_2\, e^{-i\,(\varphi_2 - \varphi_1)} =$$

$$I_1 + I_2 + 2\sqrt{I_1 I_2}\ \cos\Delta\varphi \qquad (3)$$

where $\Delta\varphi = \varphi_1 - \varphi_2$.

Output: interferogram

Modifications of interferograms help to retrieve phase

$$I(x,y,t) = a(x,y) + b(x,y)\cos[2\pi\,[(f_{ox}x + f_{oy}y) + \nu_o(t)] + \alpha(t) + \boldsymbol{\varphi}(x,y)]$$

Required controlled modifications of phase in FP:

$\nu_0(t)$ – introduces temporal heterodyning (running fringes)

$\alpha(t)$ – introduces controled phase shifts

f_{0x}, f_{0y} – introduce spatial carrier fringes (spatial heterodyning)

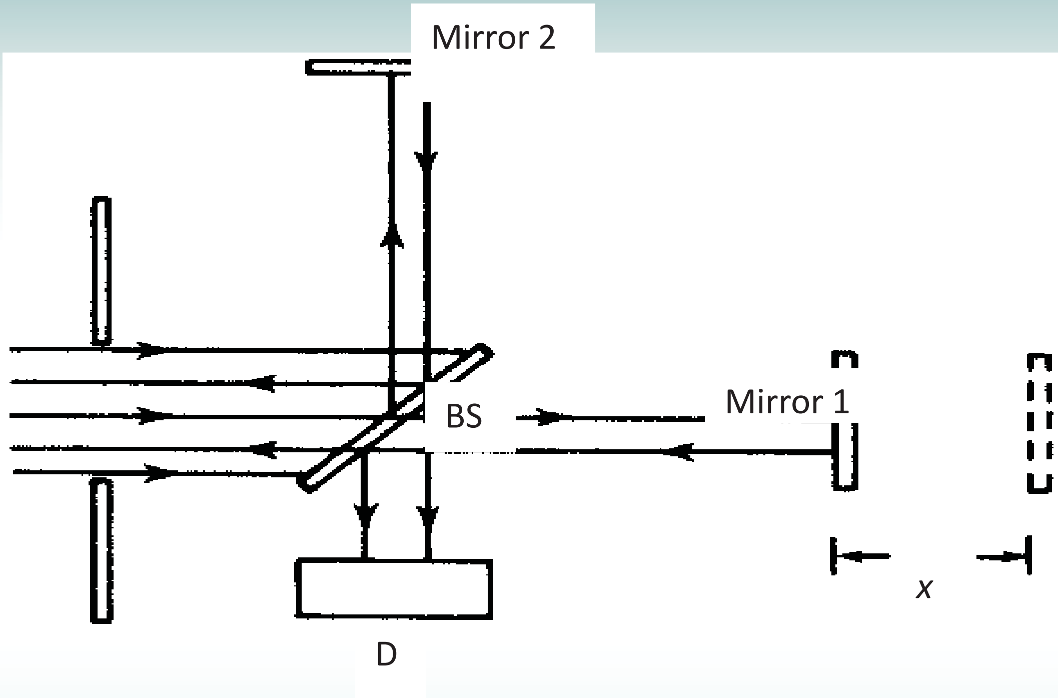
This will be discussed on Thursday

However the requirement to get a high quality interferogram:

Source with spatial and temporal coherence:

Let’s use the Michelson interferometer to determine the coherence length of a laser source

Michelson Interferometer



The length 2x for which we obtain the accepted contrast of fringes is considered as the coherence length of the source.

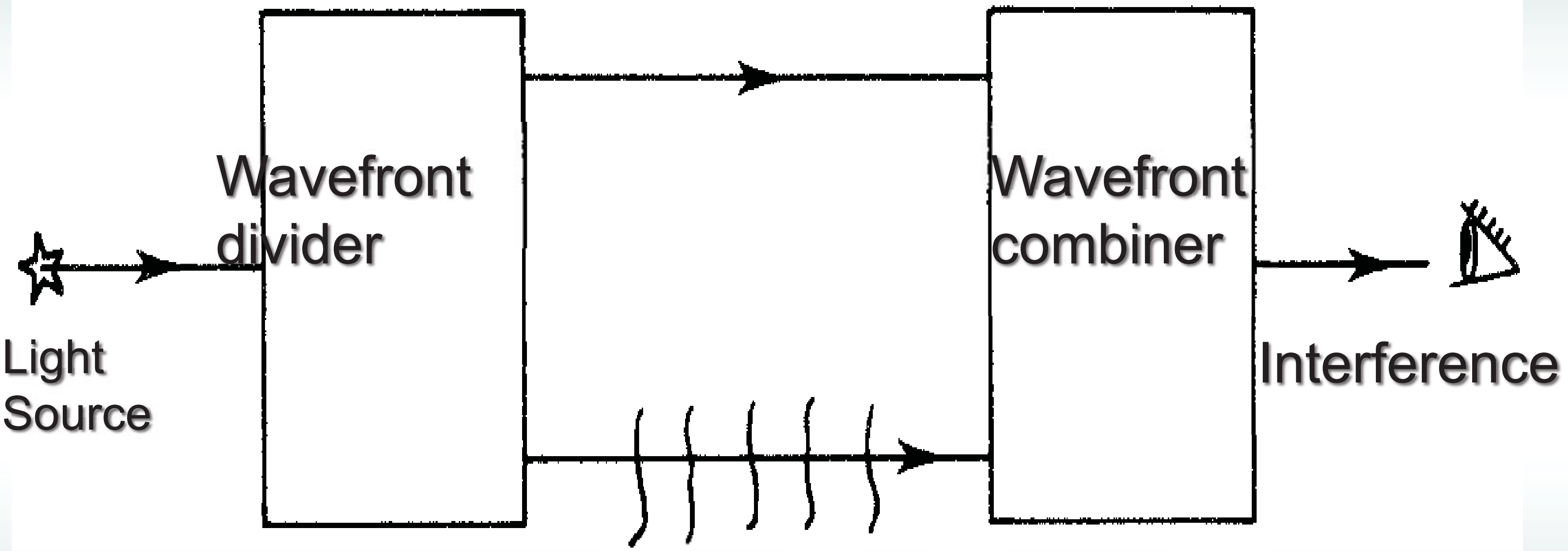
For white light : 1 µm, single mode stabilized He-Ne: 6km

3. Useful Interferometers

Amplitude and Wavefront Division……though there are other types (only a few)

“Light waves can interfere only if they are emitted by the same source”

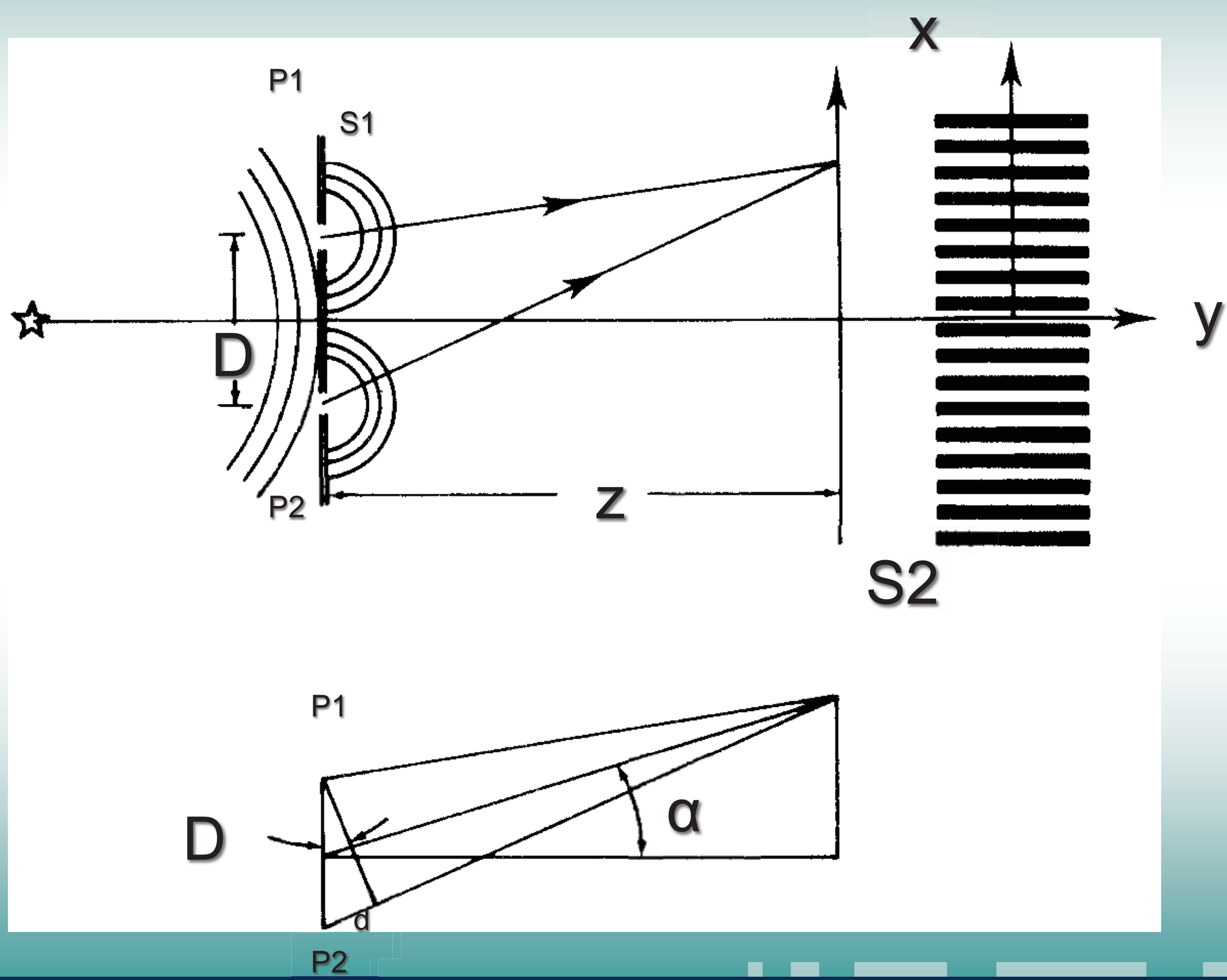
Interferometers



Phase (optical path) difference

Wavefront Division

T. Young (1801)



if $z \gg D$, then

$$\frac{d}{D} = \frac{x}{z} \rightarrow d = \frac{Dx}{z} \therefore$$

$$\Delta\theta = \frac{2\pi Dx}{\lambda z}$$

On substituting into eq (3)

$$I(x) = 2I(1 + \cos\left(\frac{2\pi Dx}{\lambda z}\right)) \quad (8)$$

This equation represents a fringe pattern parallel to the y axis, with period $\left(\frac{D}{\lambda z}\right)^{-1}$.

The Thomas Young interferometer is being used in FEL to measure its coherence!

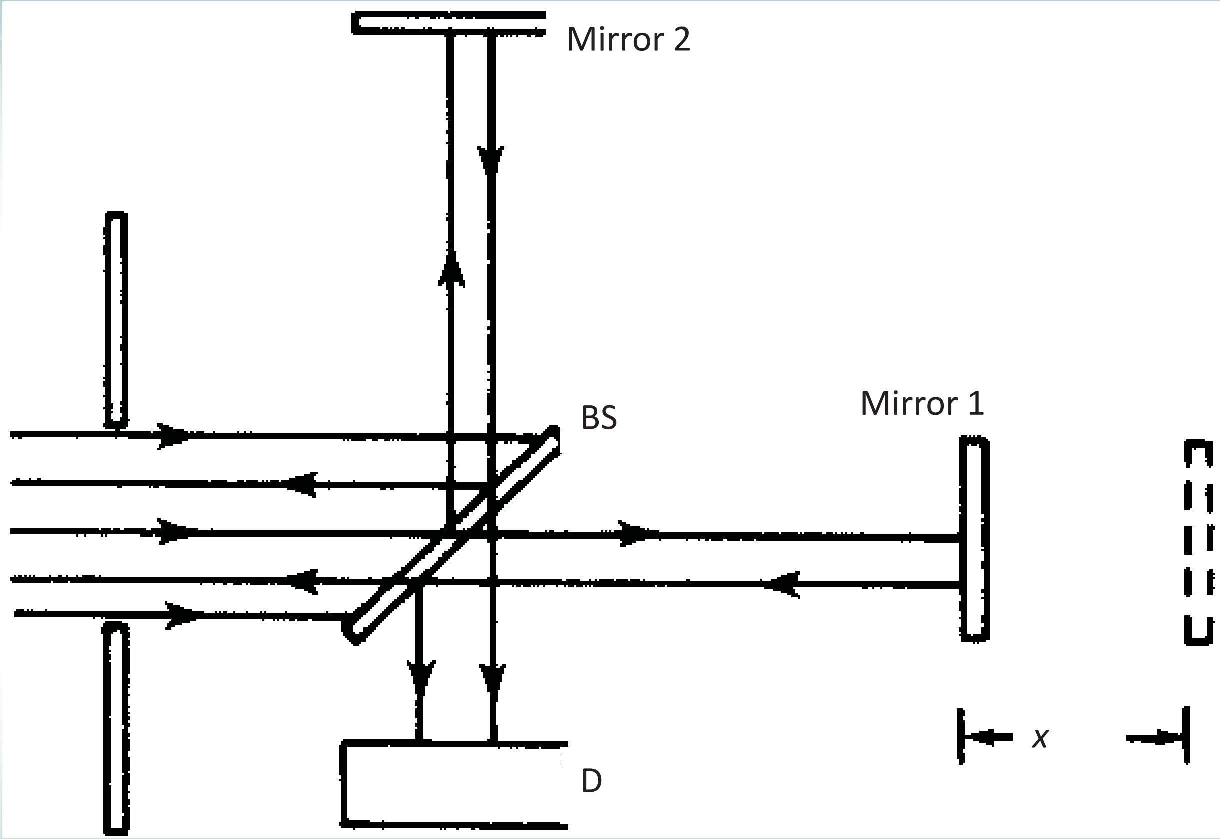
An adaptation of Young's interferometer is used in Michelson' stellar interferometer to measure star diameters.

Other types of wavefront division interferometer are:

- Fresnel biprism
- Lloyd's mirror
- Michelson stellar

Amplitude Division

Michelson Interferometer



if mirror M2 is translated a distance x, the optical path difference with respect to mirror M1 is 2x, thus

$$\Delta\theta = \left(\frac{2\pi}{\lambda}\right) 2x$$

That gives a total intensity on the detector,

$$I(x) = 2I\left(1 + \cos\left(\frac{4\pi x}{\lambda}\right)\right) \quad (9)$$

As the mirror 2 is translated a certain distance *d*, and by counting the number of maxima (bright fringe) per unit time it is possible to measure the speed of an object.

The Michelson Interferometer used with a low coherence source gives way to: low coherence reflectometry, LCR, and Optical Coherence Tomography, OCT. Study of semitransparent materials, biological tissues!

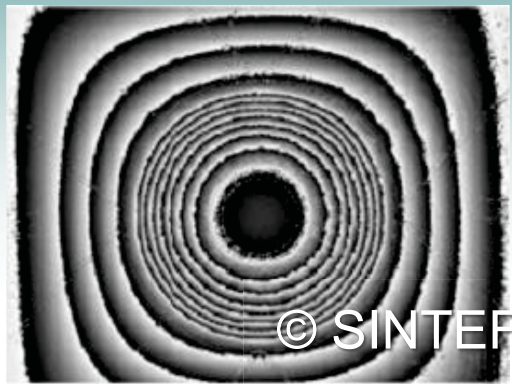
Other good examples of amplitude dividing interferometers are:

- Mach-Zehnder…QO Applications, NEW: 3 arms (as proposed by Prof. Mataloni)!; Microchannel fabrication (Prof. Ramponi)

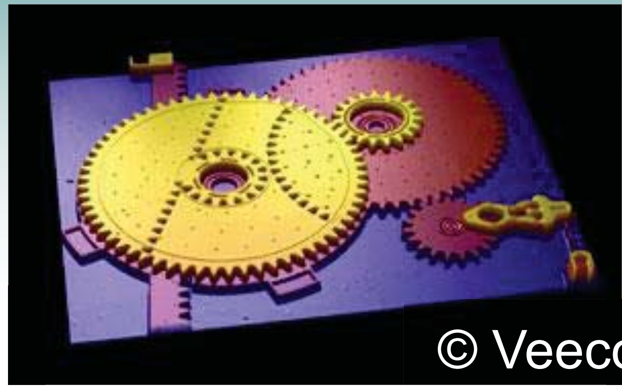
- Twyman-Green…optical shop testing

- Fizeau…flat mirror in FEL

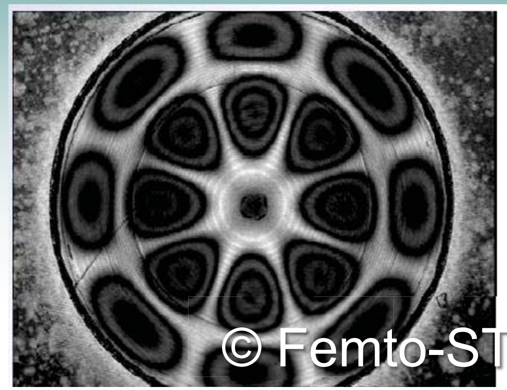
Challanges for interferometry
Example: M(O)EMS Characterisation



deformation
(laser interferometry)

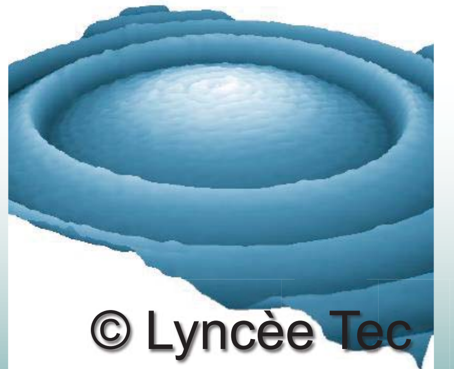


dimensions/shape
(white light interferometry)

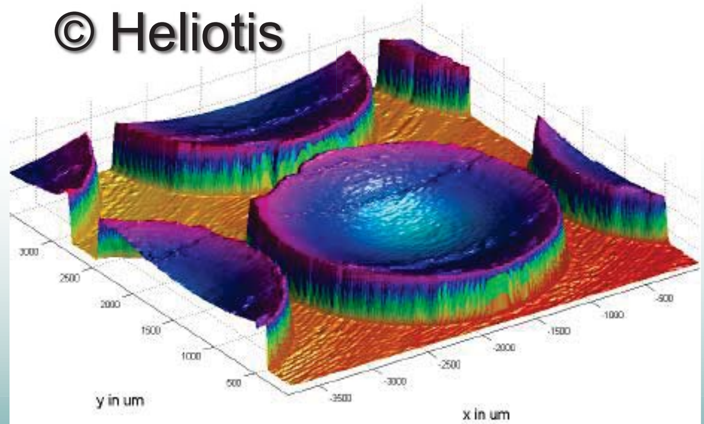


vibration (time average
laser interferometry)

and
many more ...



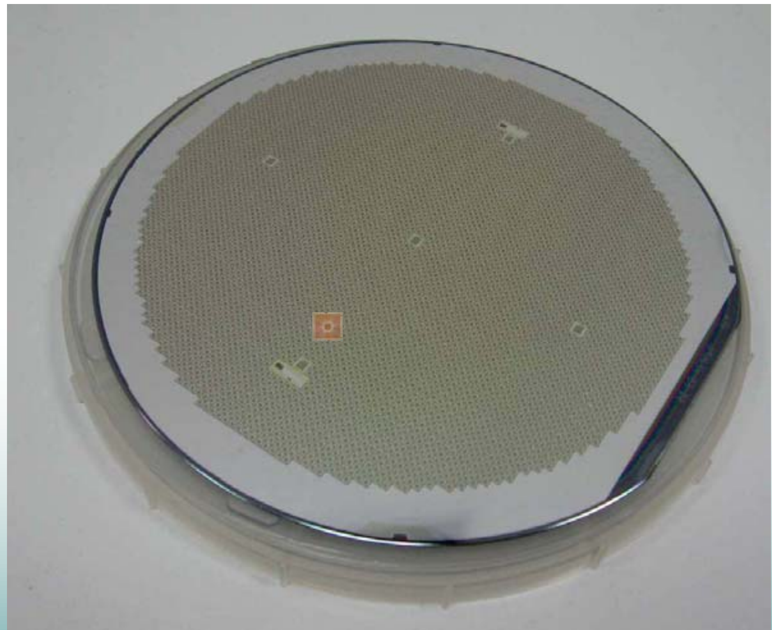
topography
(digital holography)



topography - inner structure
optical coherence tomography

Main challenge in M(O)EMS inspection

- Wafer size increases – current diameters 6”, 8”, 12’’
- Up to several thousands structures on one wafer (time issues)
- Feature size decreases – typically <10mm^2
- Inspection ratio: 10^{-3} to 10^{-7}
- 100% M(O)EMS inspection

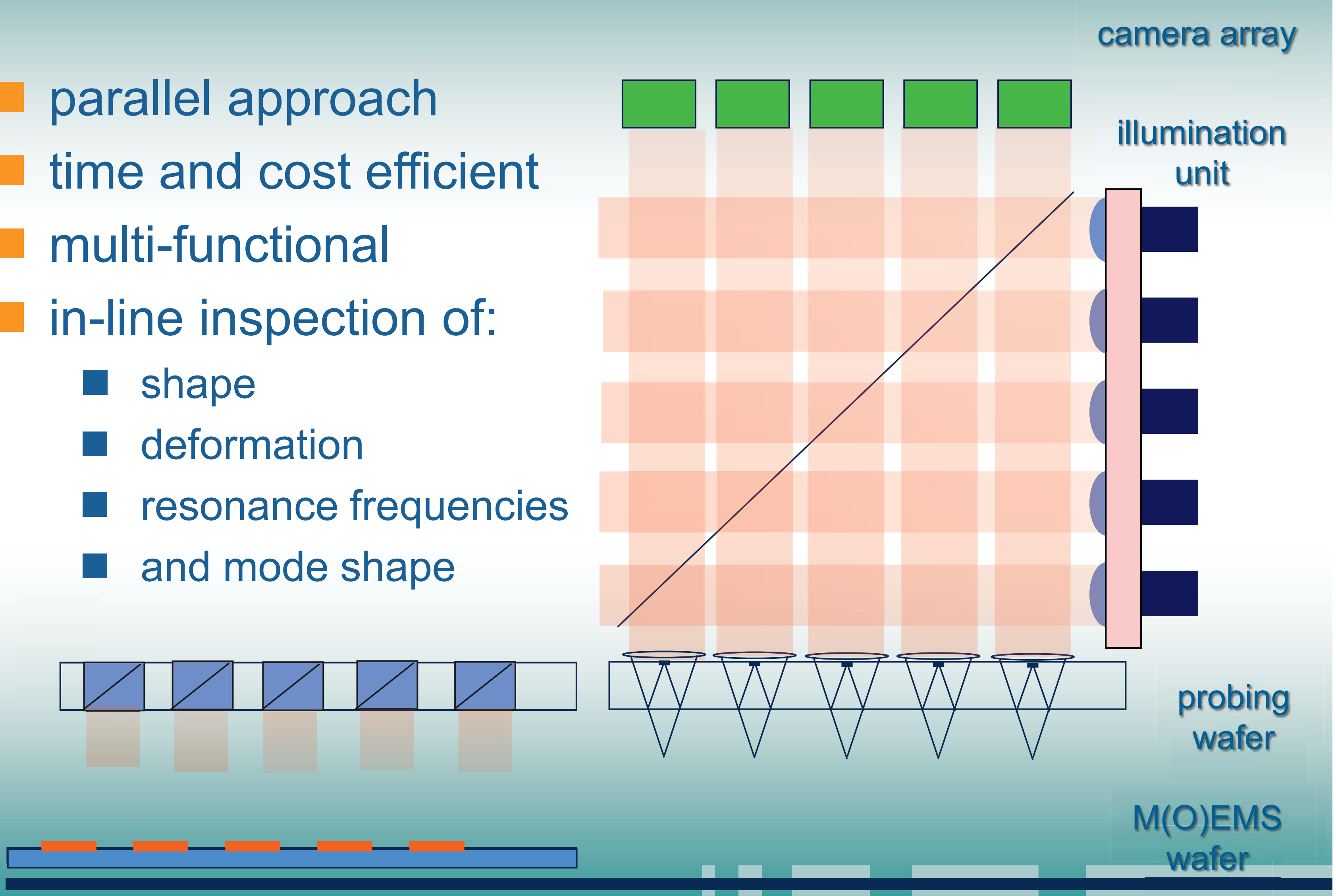


15cm

700µm

Parallel Inspection concept

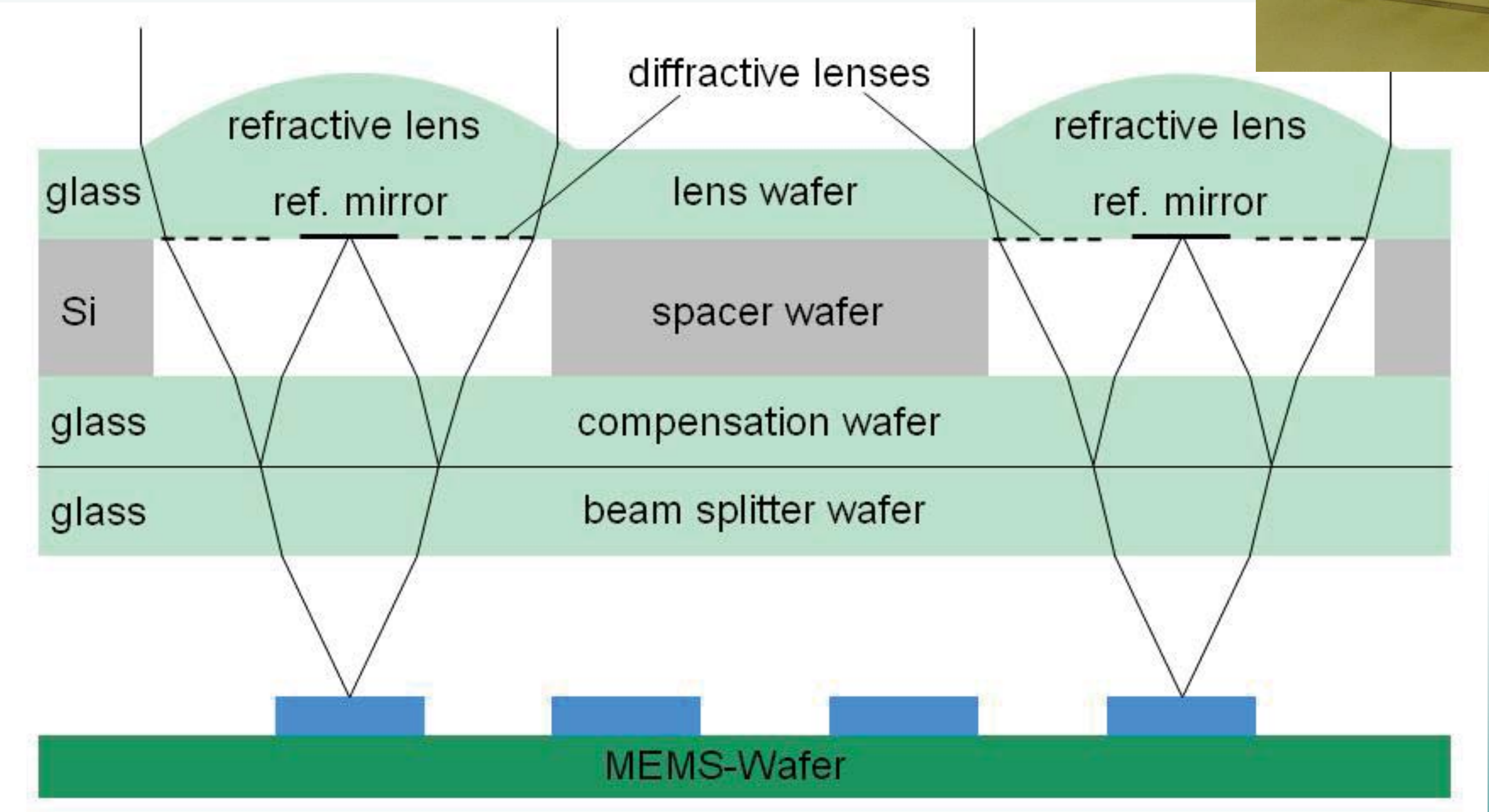
- parallel approach
- time and cost efficient
- multi-functional
- in-line inspection of:
  - shape
  - deformation
  - resonance frequencies
  - and mode shape

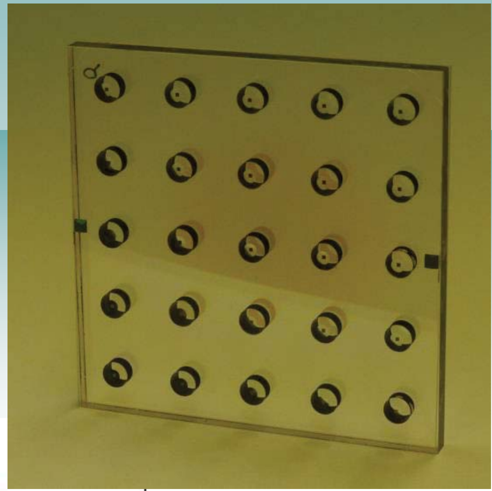


J. Micromech. Microeng. **22** , 015018 , 2012

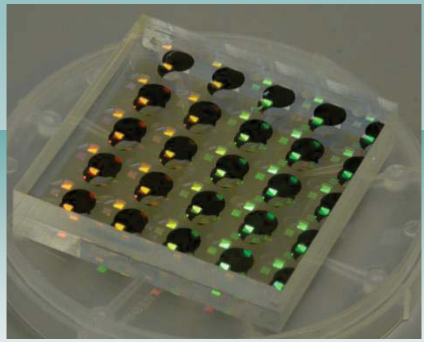
Micro optical LCI array

- Mirau type

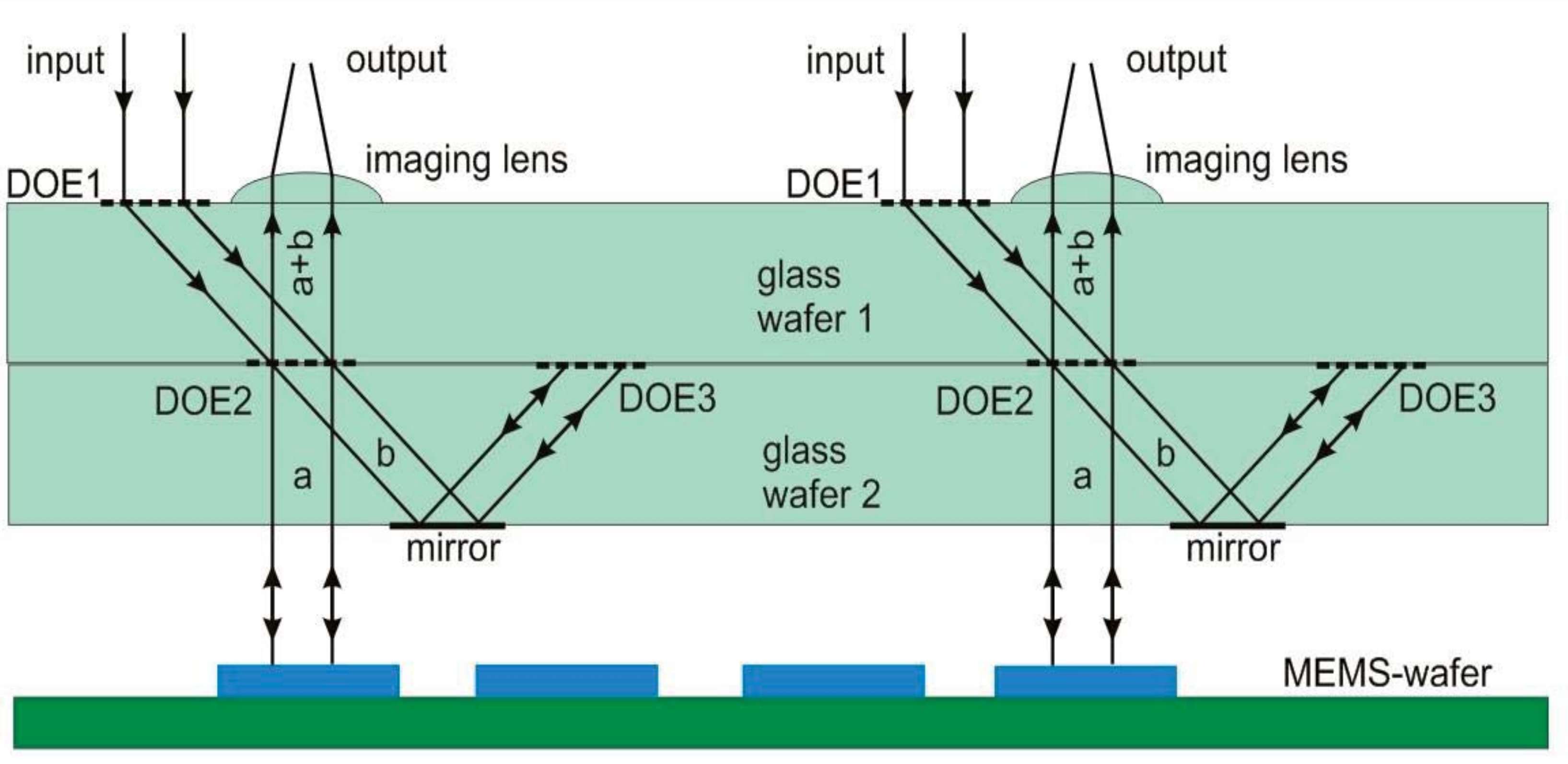




Micro optical LI array



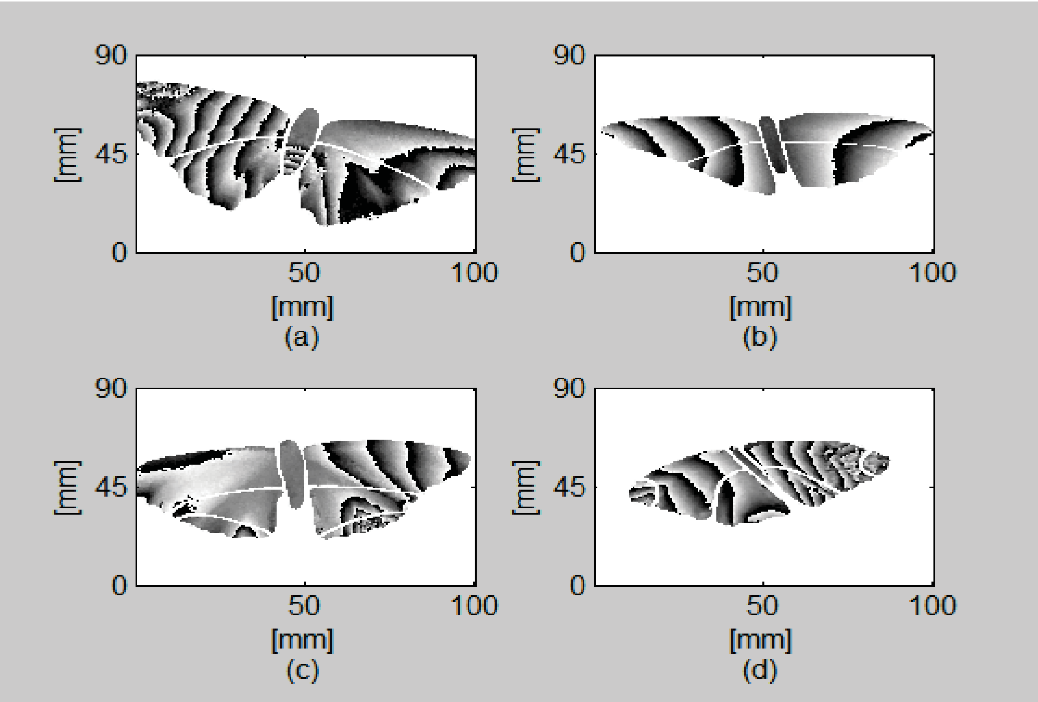
- DOE based Twyman Green type



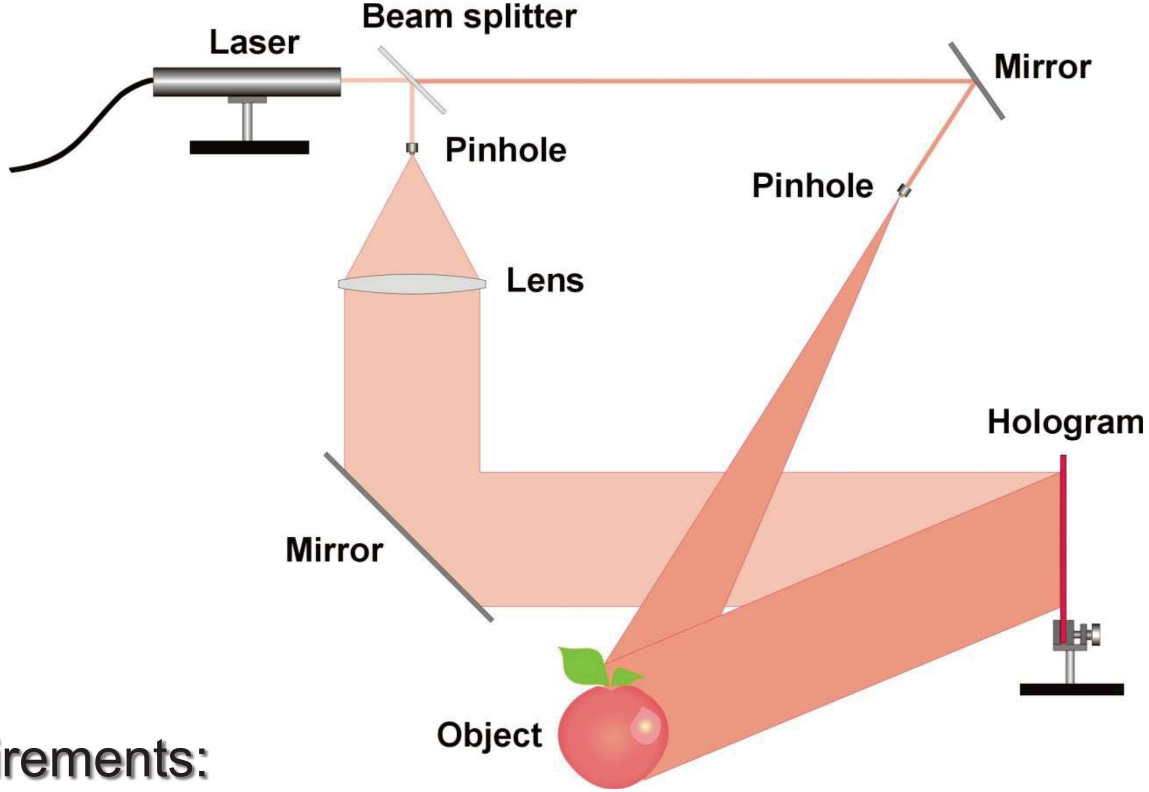
Instrument plattform

© SUSS Test Systems
Cascade Microtech

Holography and speckle techniques
Holographic and speckle interferometry



Registration of optical hologram basic setup



Requirements:

1. Need to have equal optical paths of reference and object beams (within coherence length of laser)
2. During recording the phase between object and reference beams cannot change more than $\Delta\phi_{\max} < 0.2\pi$

Basic Theoretical Considerations

Two wave addition: Object and Reference

$$U_T = U_o + U_r \qquad (1)$$

Intensity/Irradiance on the CCD sensor is proportional to

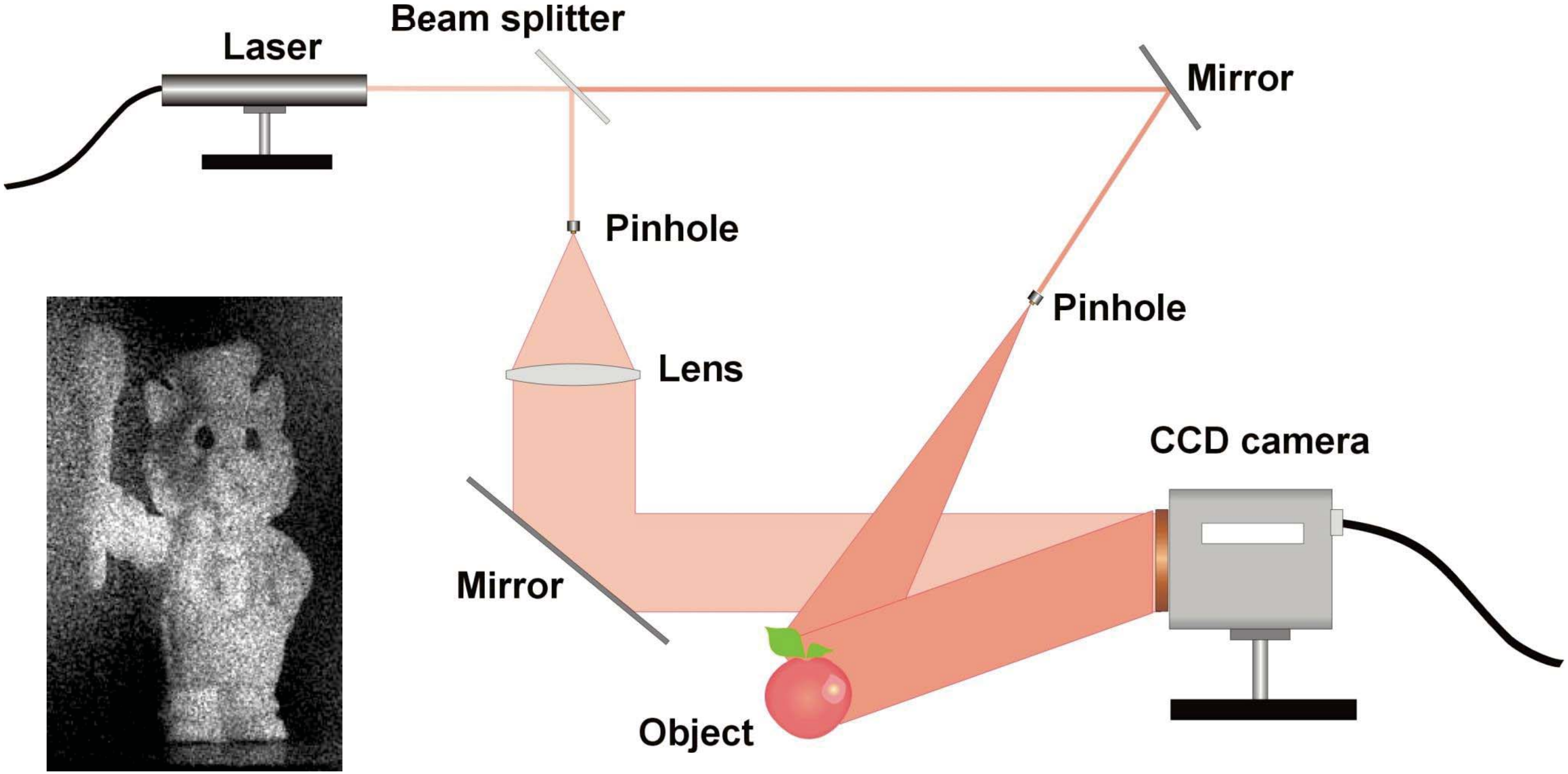
$$I_T = U_o^* U_o + U_r^* U_r + U_o U_r^* + U_r U_o^* \qquad (2)$$

Apart from a scale factor, the third term is identical to the original object

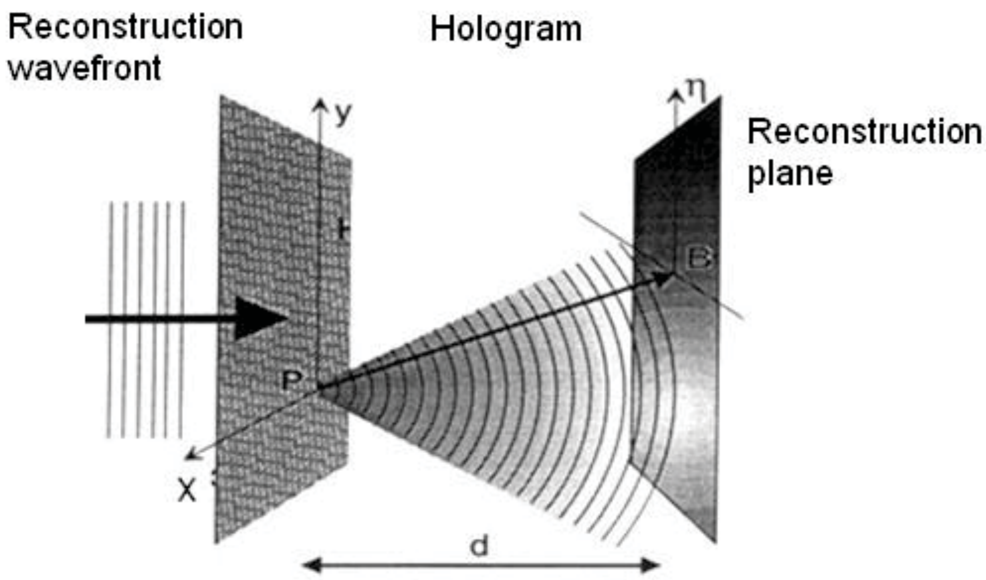
Gabor D., A new microscopic principle, Nature 161, 777-778 (1948).

Registration of digital hologram

Photographic (analog) material is replaced by CCD or CMOS matrix



Scheme for numerical reconstruction of digital hologram



Diffraction of plane wave at hologram is given by Fresnel-Kirchoff integral.

Due to small size of CCD camera versus the distance camera (hologram)-object we can use here Fresnel approximation given by:

$$U(\xi,\eta;d)=\frac{iU_0}{\lambda d}\exp\left[-i\frac{\pi}{\lambda d}\left(\xi^2+\eta^2\right)\right]\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}h(x,y)\exp\left[-i\frac{\pi}{\lambda d}\left(x^2+y^2\right)\right]\times\exp\left[i\frac{2\pi}{\lambda d}(x\xi+y\eta)\right]dxdy$$

where : (x,y), (ζ,η) are coordinates, h(x,y) is the amplitude transmittance of hologram, U_0 – is the real amplitude of reconstructing wavefront

Sampled version of the reconstructed field

The hologram function is sampled by CCD camera in MxN points with sampling periods Δx and Δy. Then the numeric representation of the previous equation is given as:

$$U(m,n;d) = \exp\left[-i\frac{\pi}{\lambda d}\left(m^2\Delta\xi^2 + n^2\Delta\eta^2\right)\right]\sum_{k=0}^{M-1}\sum_{l=0}^{N-1} h(k,l)\times\exp\left[-i\frac{\pi}{\lambda d}\left(k^2\Delta x^2 + l^2\Delta y^2\right)\right]\exp\left[i2\pi\left(\frac{km}{M}+\frac{\ln}{N}\right)\right]$$

Where Δζ and Δη are the sizes of pixels in reconstructed images.

Intensity of the object field at distance d

$$\mathrm{I}(\xi,\mathrm{n};\mathrm{d}) = \mathrm{Re}^2\left[U(m,n;d)\right] + \mathrm{Im}^2\left[U(m,n;d)\right]$$

Phase of the object field at distance d

$$\phi(\xi,\eta;\mathrm{d}) = \arctan\frac{\mathrm{Im}\left[\mathrm{U}(\mathrm{m},\mathrm{n};\mathrm{d})\right]}{\mathrm{Re}\left[\mathrm{U}(\mathrm{m},\mathrm{n};\mathrm{d})\right]}$$

So we can reconstruct numerically all information about an object

Limitations of digital holography

The recording medium has to fulfil the Nyquist condition !
Each fringe has to be sampled by at least two pixels of CCD matrix

CCD cameras;
- resolution 1024x1534;
- Pixel size Δ=9μm; for 4.5 μm
- Spatial resolution - ap. 111 lines/mm, 220l/mm
  holographic materials (plates) - >3000 lines/mm). → Limitations

$\delta = \lambda / (2\sin(\gamma/2))$

Assumption.: $\gamma \approx \sin\gamma \approx \tan\gamma$
For small γ

$\gamma \leq \lambda / (2\Delta)$

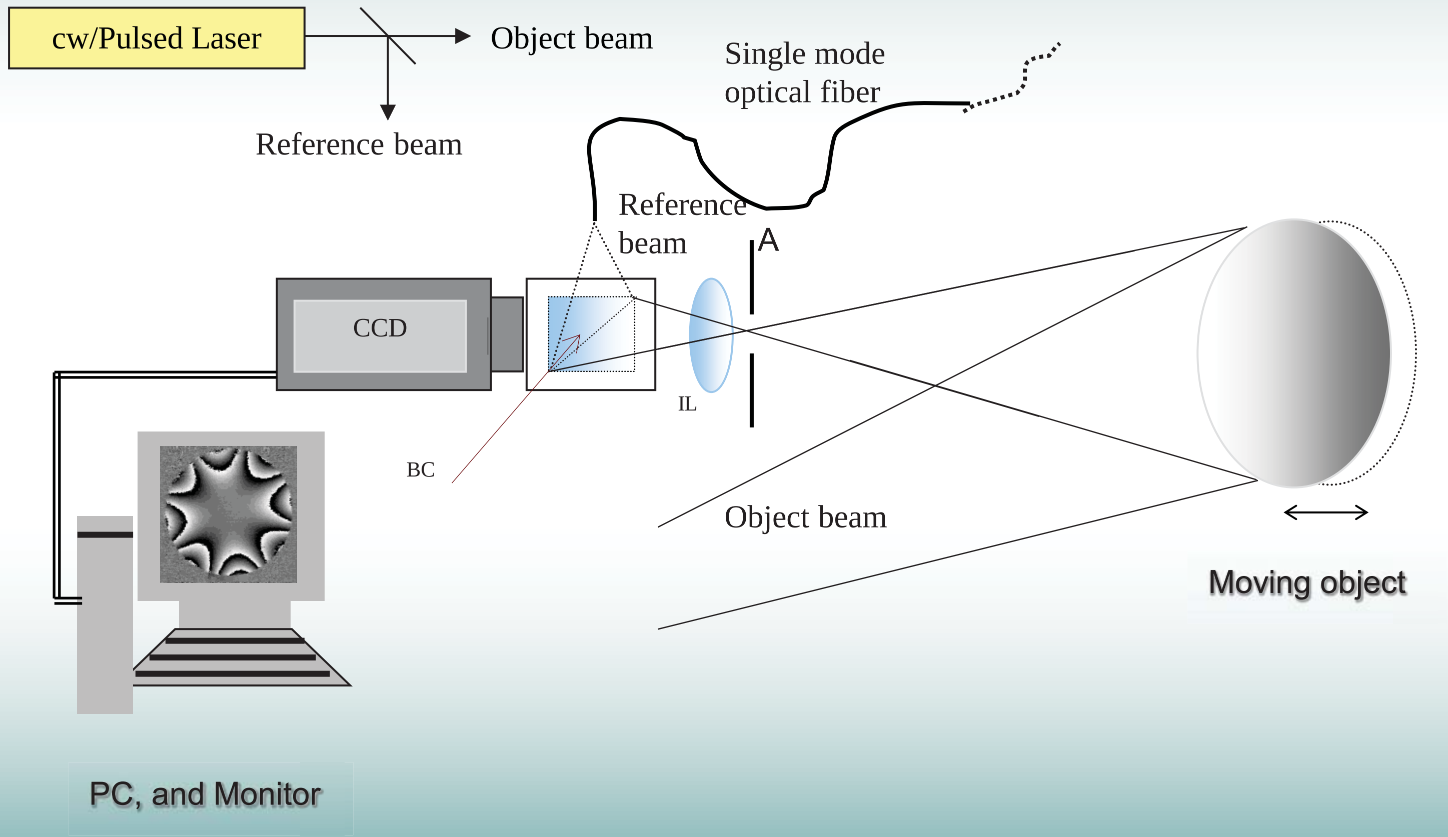
$2\Delta \leq \delta$

=>

for λ=632.8nm and Δ=9μm, $\gamma \approx 3.5°$

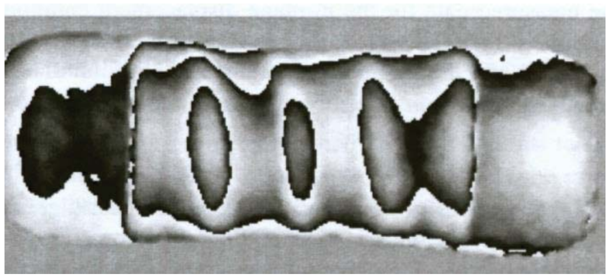
Conclusion: SMALL angular size of object (a few degrees) i.e.
SMALL OBJECT or Object SITUATED FAR from CAMERA

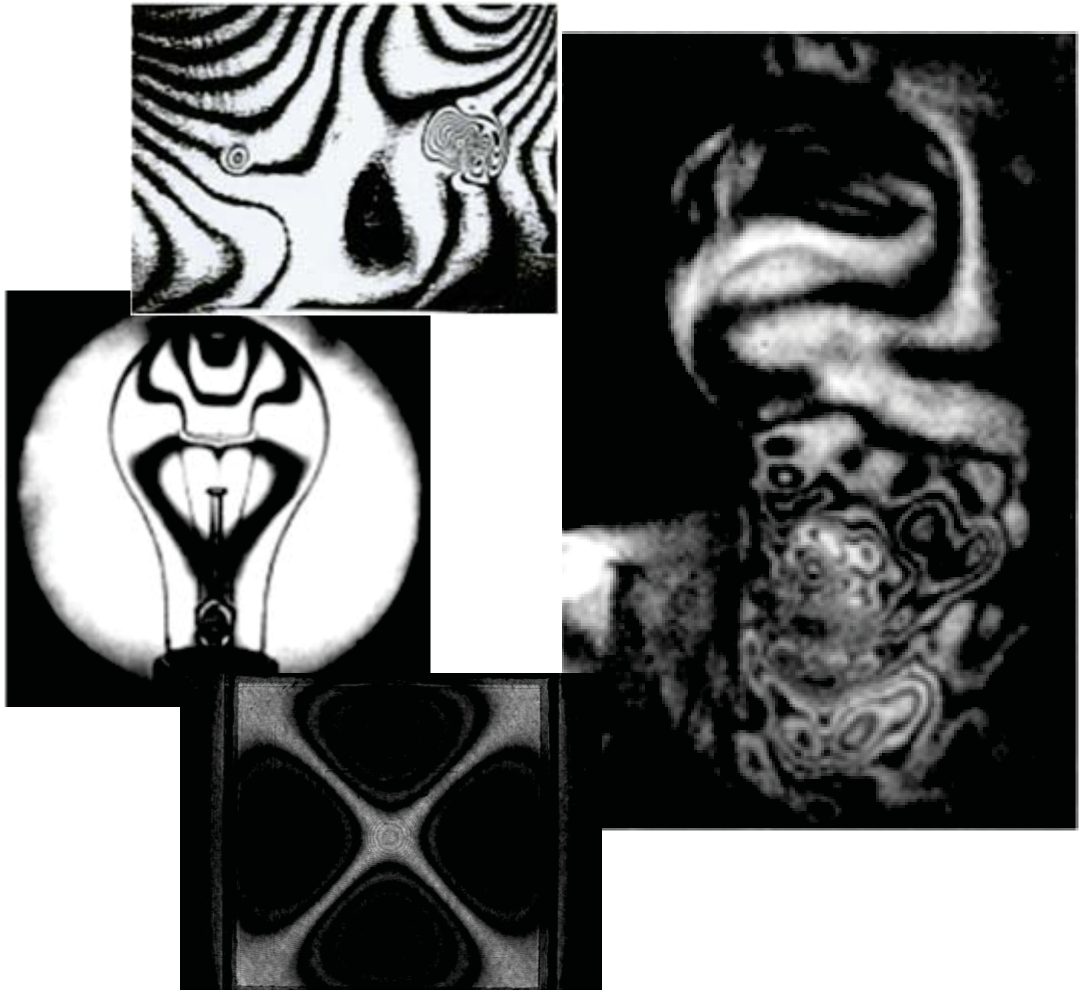
4. ESPI/TV H set-up



HOLOGRAPHIC INTERFEROMETRY

- Classical
- Digital





C. M. Vest, *Holographic interferometry,* J. Wiley and Sons, New York, 1979
P. K. Rastogi (ed), Holographic interferometry, Springer, 1994
I. Yamaguchi, T. Zhang, Phase shifting digital holography, Opt. Lett., 22, 1268-1270, 1997
T. Kreis, "Handbook of Holographic Interferometry" WILEY-VCH Verlag GmbH & Co.KGaA, 2005

Classical holographic interferometry

Each holographic system can be used to compare optical wavefronts formed by an object in different states (physical conditions)

Let initial state of an object is**:** $$E_{p1}(P) = A_{p1}(P)\exp[i\phi(P)]$$

After providing load (or other changes) $$E_{p2}(P) = A_{p2}(P)\exp i[\phi(P) + \Delta\phi(P)]$$

If the object (load) is stationary we may compare these wavefronts by:

-double exposure holographic interferometry,

-real time holographic interferometry.

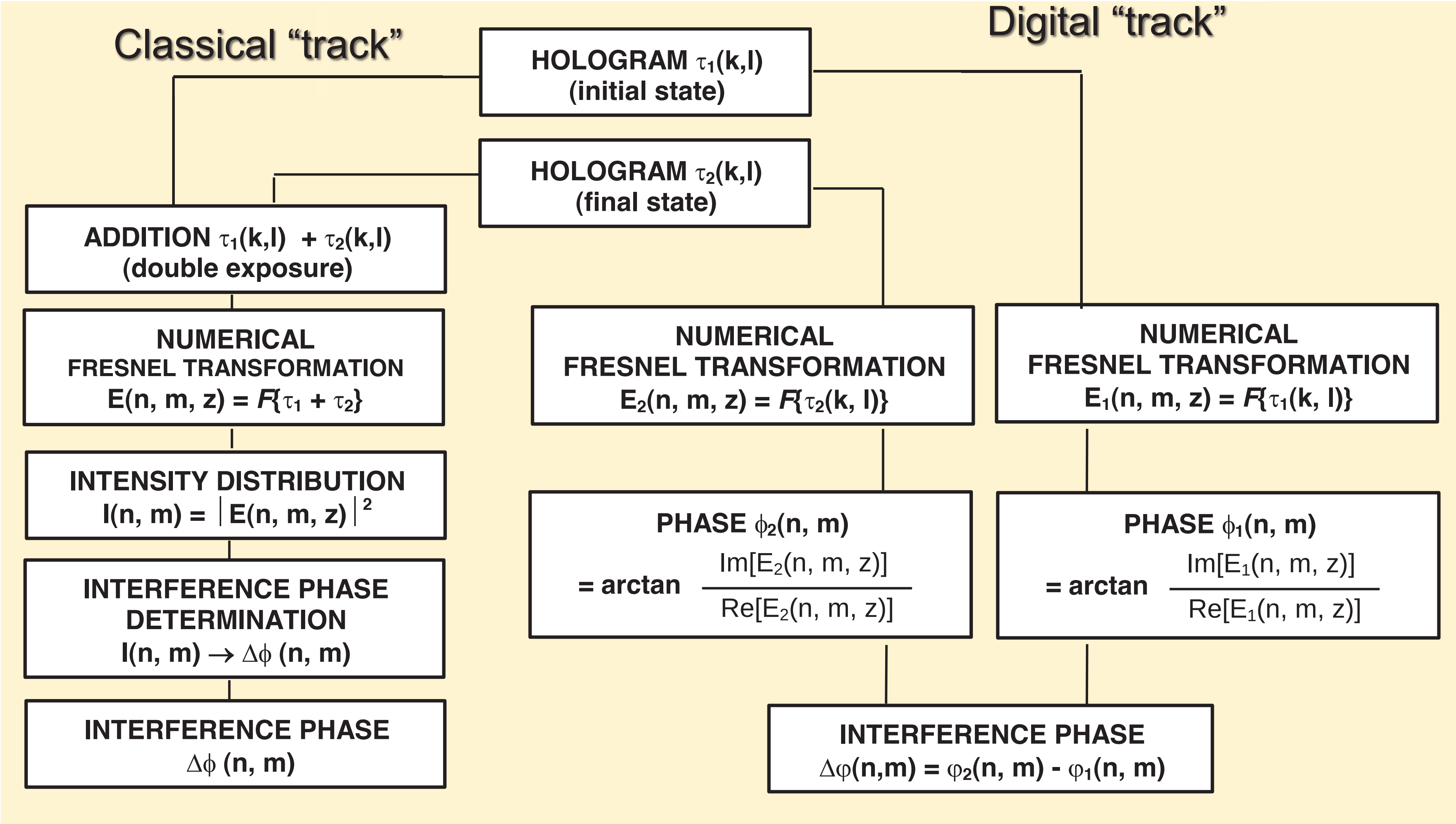
If the object is vibrating we use:

-Time averaged holographic interferometry

-Stroboscopic holographic interferometry

In the case of dynamic object investigation we use impulse double exposure HI

PRINCIPLES OF DIGITAL HOLOGRAPHIC INTERFEROMETRY

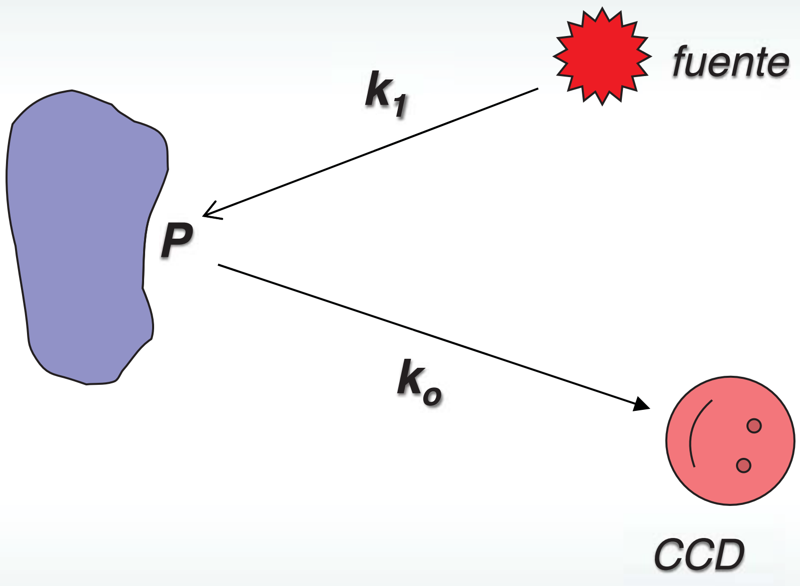


$$\Delta\phi(m,n) = \begin{cases} \phi_2(m,n) - \phi_1(m,n) & \text{if} \quad \phi_2(m,n) \geq \phi_1(m,n) \\ \phi_2(m,n) - \phi_1(m,n) + 2\pi & \text{if} \quad \phi_2(m,n) < \phi_1(m,n) \end{cases} .$$

No intermediate state: sequential monitoring by phase substraction

X, Y, Z, Displacement Acquisition

see for instance: S. Schedin, et.al., Appl Opt, **38**, pp. 7056-7062 (1999), y Mendoza, et. al.., Meas. Sci. And Tech., **10**, pp. 1305-1308 (1999).



$k_1 = P - F_1$

$k_o = C - P$

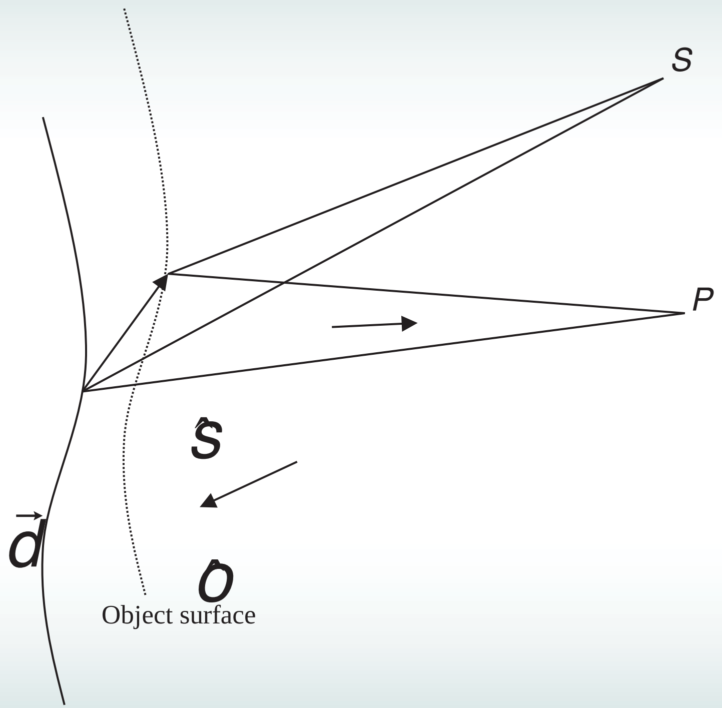
P, punto en el Objeto

F_1, posición de la fuente

C, Posición de la CCD

Note: Object has to be illuminated from three different positions

Sensitivity vector



Phase difference due to surface displacement

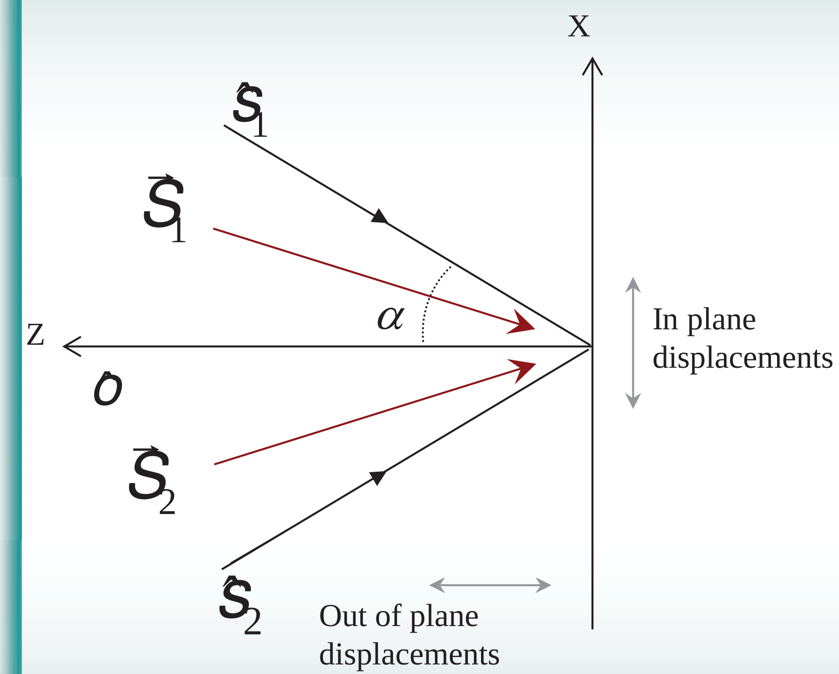
$$\Delta\phi = \frac{2\pi}{\lambda}\vec{S}\cdot\vec{d}$$

Sensitivity vector as a function of the unity illumination and observation vectors

$$\vec{S} = \hat{s} - \hat{o}$$

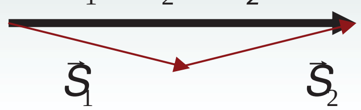
2D measurements (an in plane and an out of plane component)

2D evaluation requires two independent sensitivity vectors



Out of pane sensitivity

$$\vec{S}_1 + \vec{S}_2 = \vec{S}_z$$

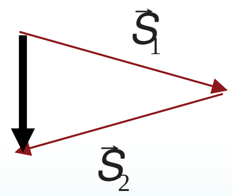


From equation (7)

$$\phi_z = \phi_2 + \phi_1 = \frac{2\pi}{\lambda}\vec{d}\cdot\vec{S}_z \qquad (9)$$

In plane sensitivity

$$\vec{S}_1 - \vec{S}_2 = \vec{S}_x$$



$$\phi_x = \phi_2 - \phi_1 = \frac{2\pi}{\lambda}\vec{d}\cdot\vec{S}_x \qquad (10)$$

Sensitivity vectors

$$\vec{S}_1 = (-\sin\alpha, 1+\cos\alpha)$$

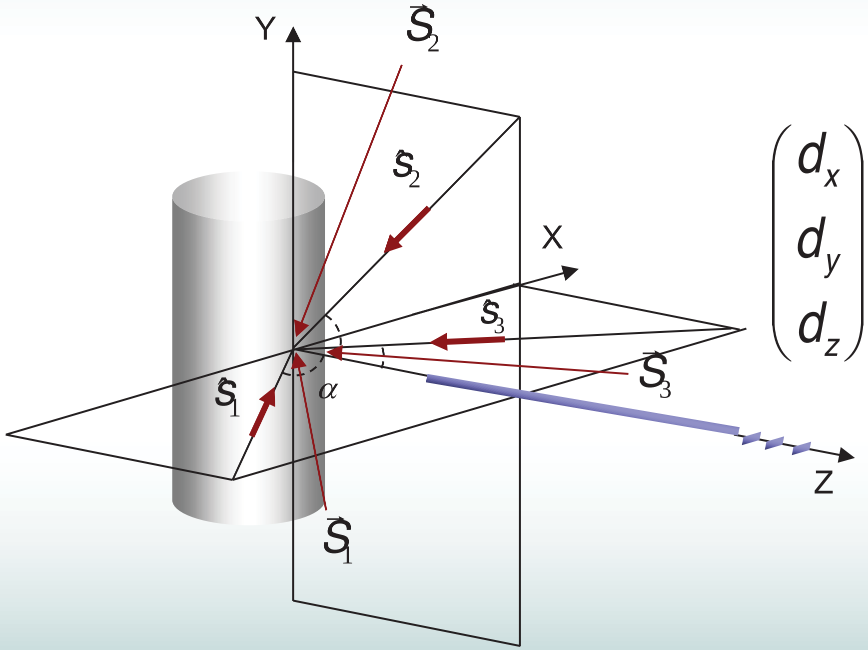
$$\vec{S}_2 = (\sin\alpha, 1+\cos\alpha)$$

From eq. (7) →

$$\begin{pmatrix} d_x \\ d_z \end{pmatrix} = \frac{\lambda}{2\pi}\begin{pmatrix} -sen\alpha & 1+\cos\alpha \\ sen\alpha & 1+\cos\alpha \end{pmatrix}^{-1}\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \end{pmatrix} \qquad (11)$$

3D Sensitivity

3D evaluation requires three sensitivity vectors



$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \frac{\lambda}{2\pi} \begin{pmatrix} -\sin\alpha & 0 & 1+\cos\alpha \\ 0 & -\sin\alpha & 1+\cos\alpha \\ \sin\alpha & 0 & 1+\cos\alpha \end{pmatrix}^{-1} \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \end{pmatrix} \quad (12)$$

Deformation components are evaluated at each point of the object's surface

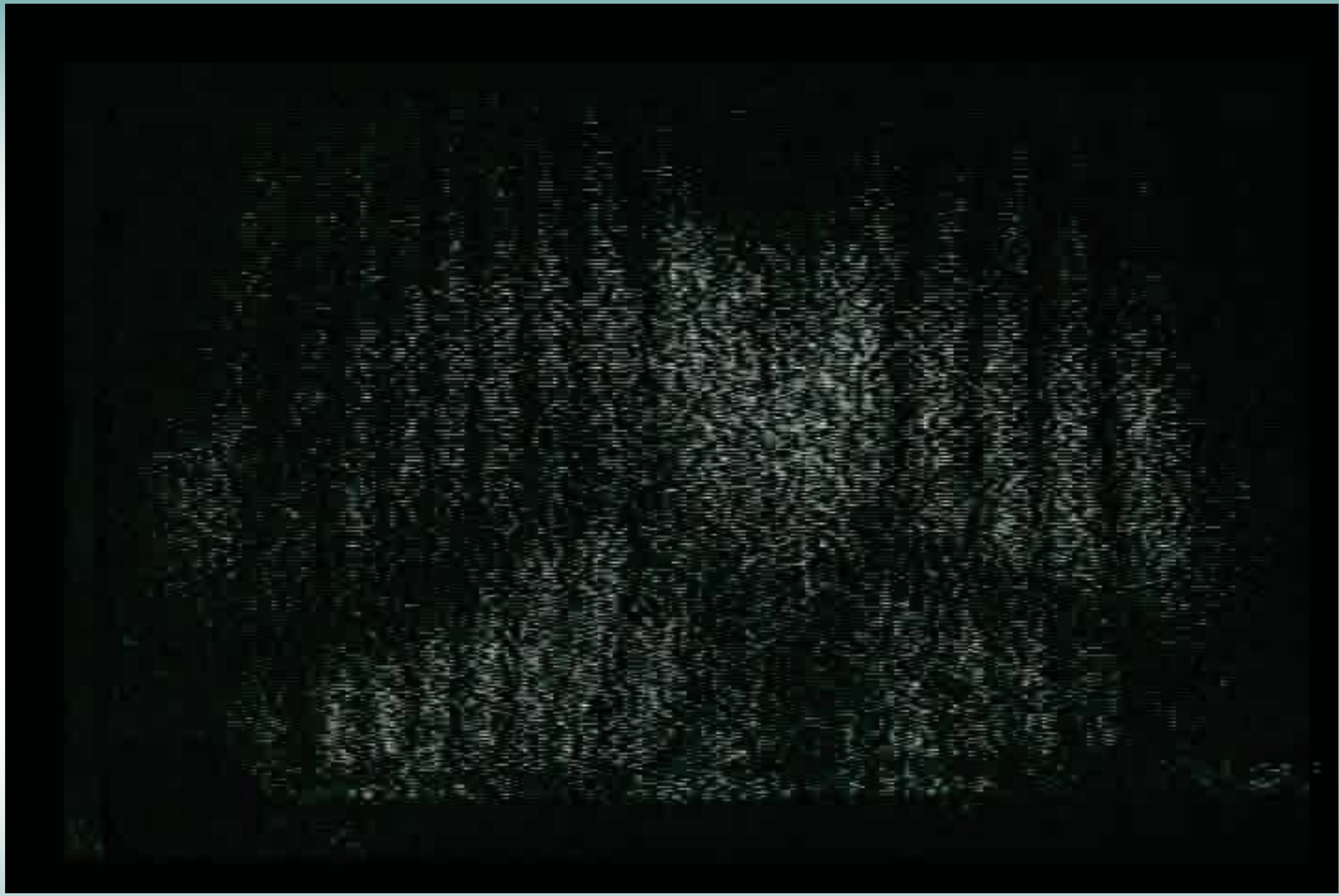
The displacement information must now be drawn on the ***Object Contour (shape)***, which may be found using any of several different/complementary (optical and non-optical) techniques, viz.,

Pedrini, et. al., App Opt, **38**, pp. 3460-3467 (1999)
Rodriguez, et. al. JOSA, **A 9**, pp. 2000-2008 (1992)

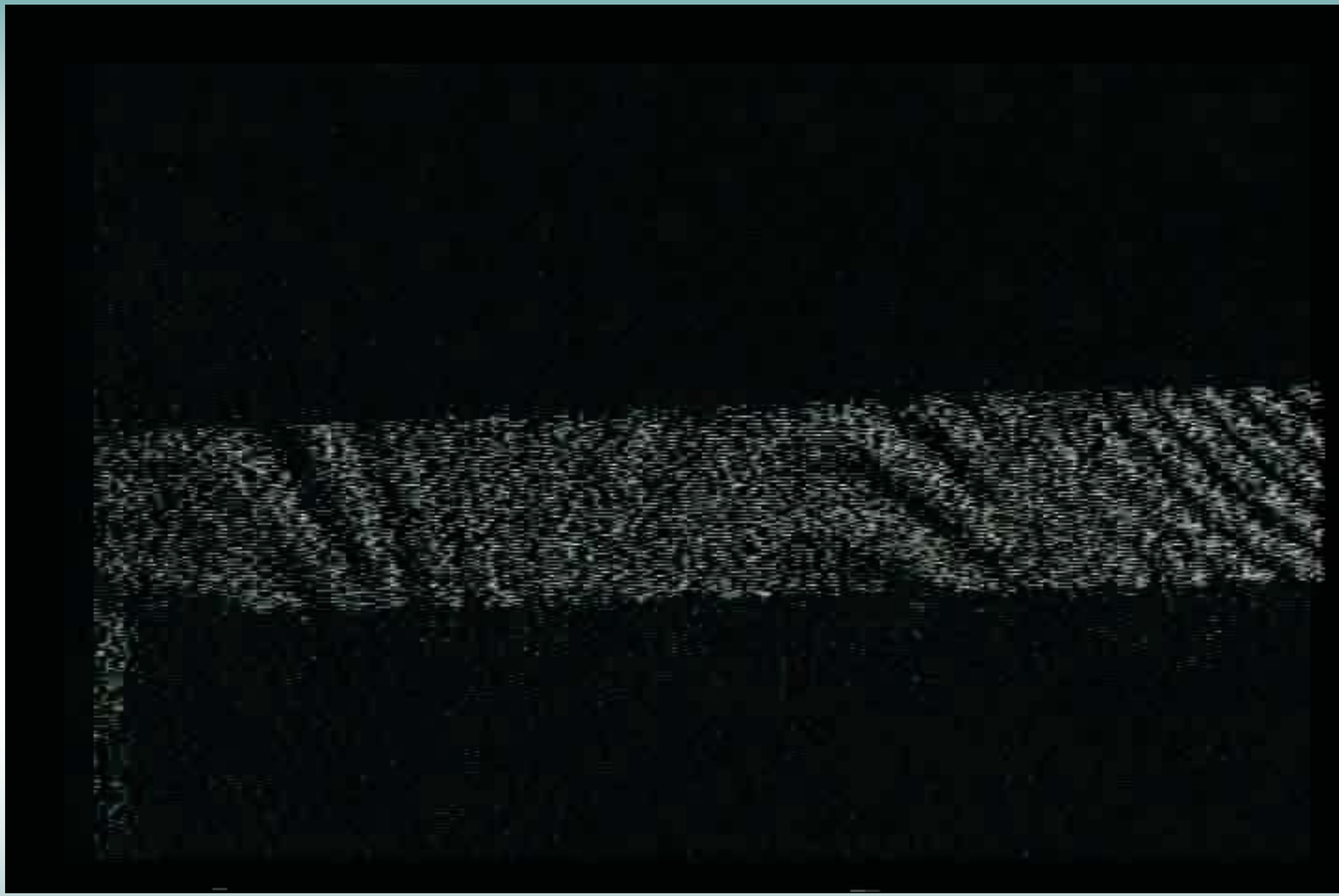
RESULTS

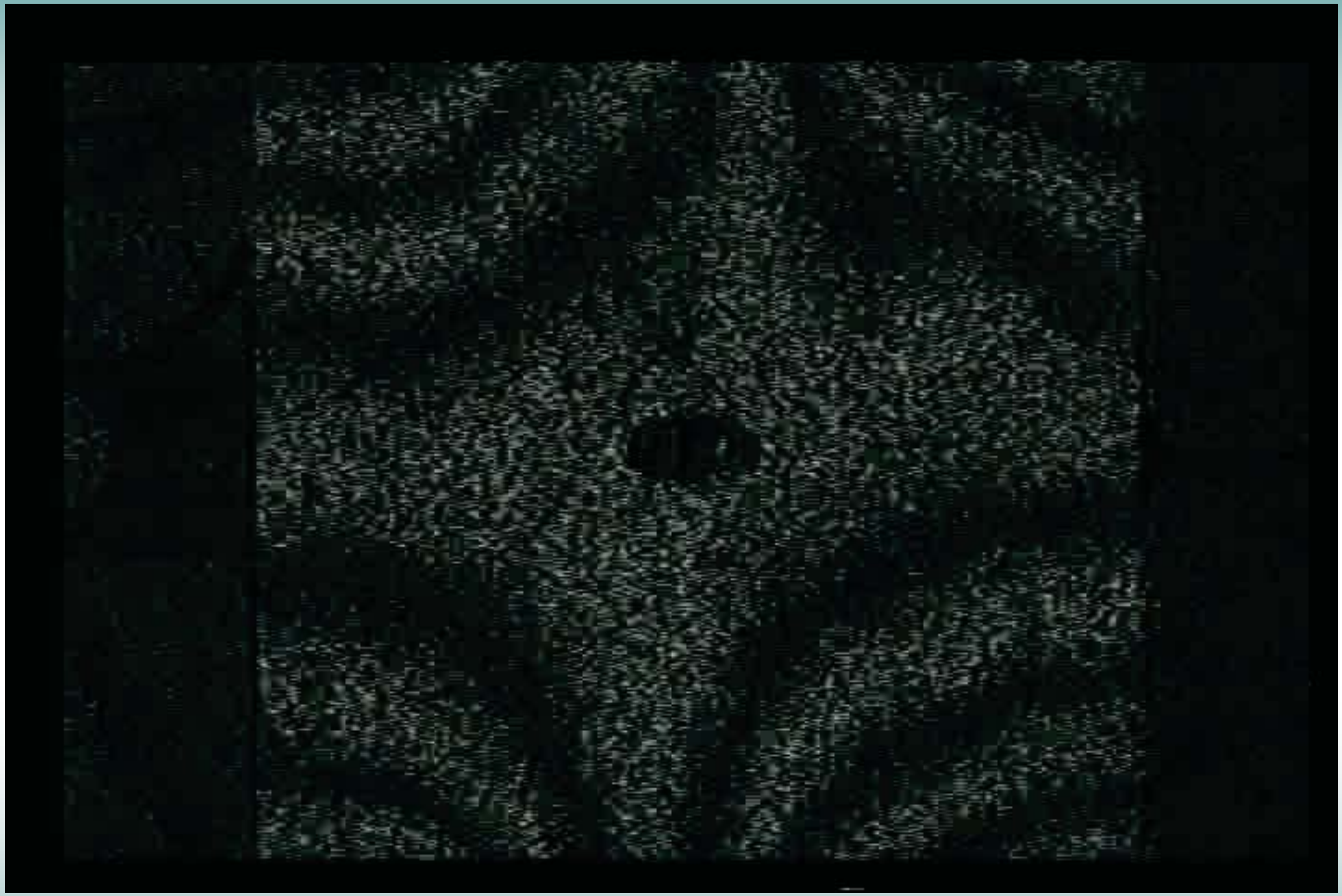
ESPI

- A) Underwater Sonar at 3KHz
- B) Traveling wave
- C) In-plane harmonic oscillation at 33 and 37 KHz



Journal of Sound and Vibration, **172** (4), pp. 433-448 (1994).



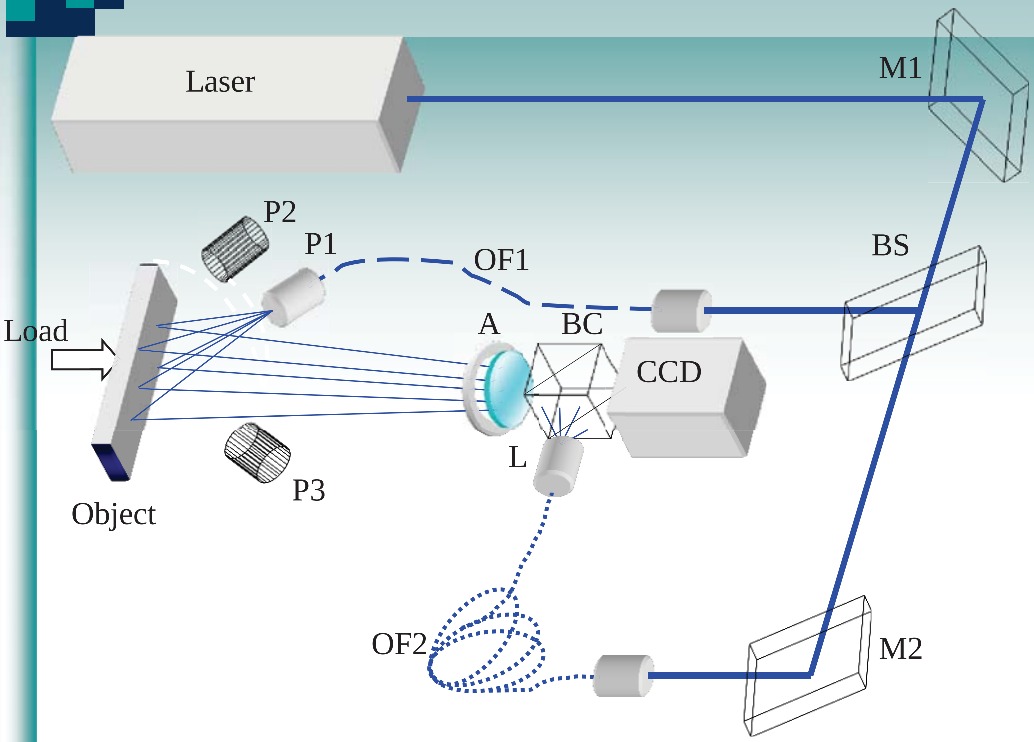


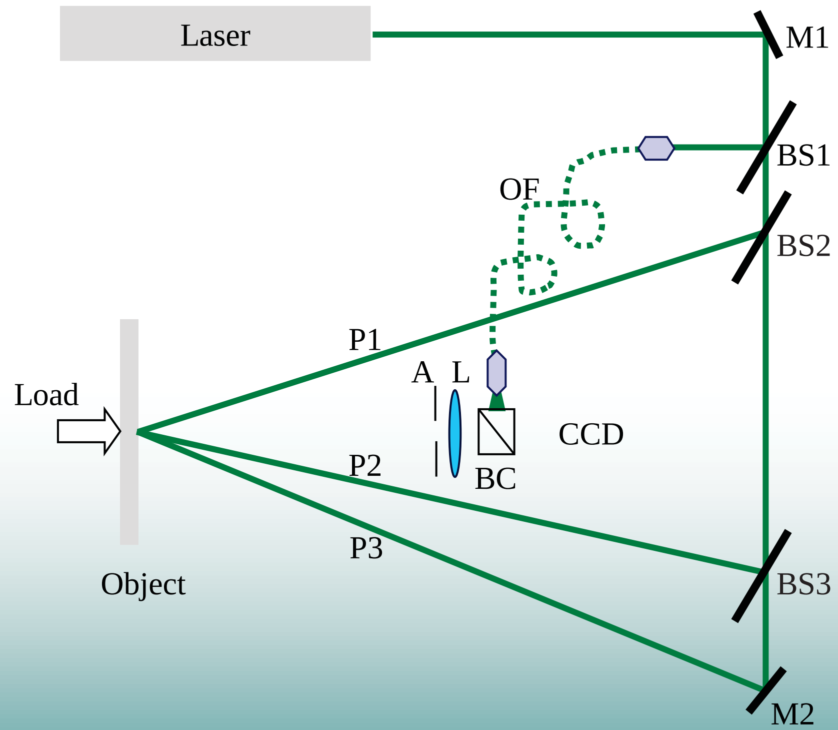
Applied Optics, **30** (7), pp. 717-721 (1991).

DHI

- A) 2D/3D set up, Dedicated software
- B) 3D component separation
- C) Tympanic membrane
- D) Tumor detection
- E) Vocal Chords
- F) Biomechanics

Experimental set up





Digital holographic interferometry

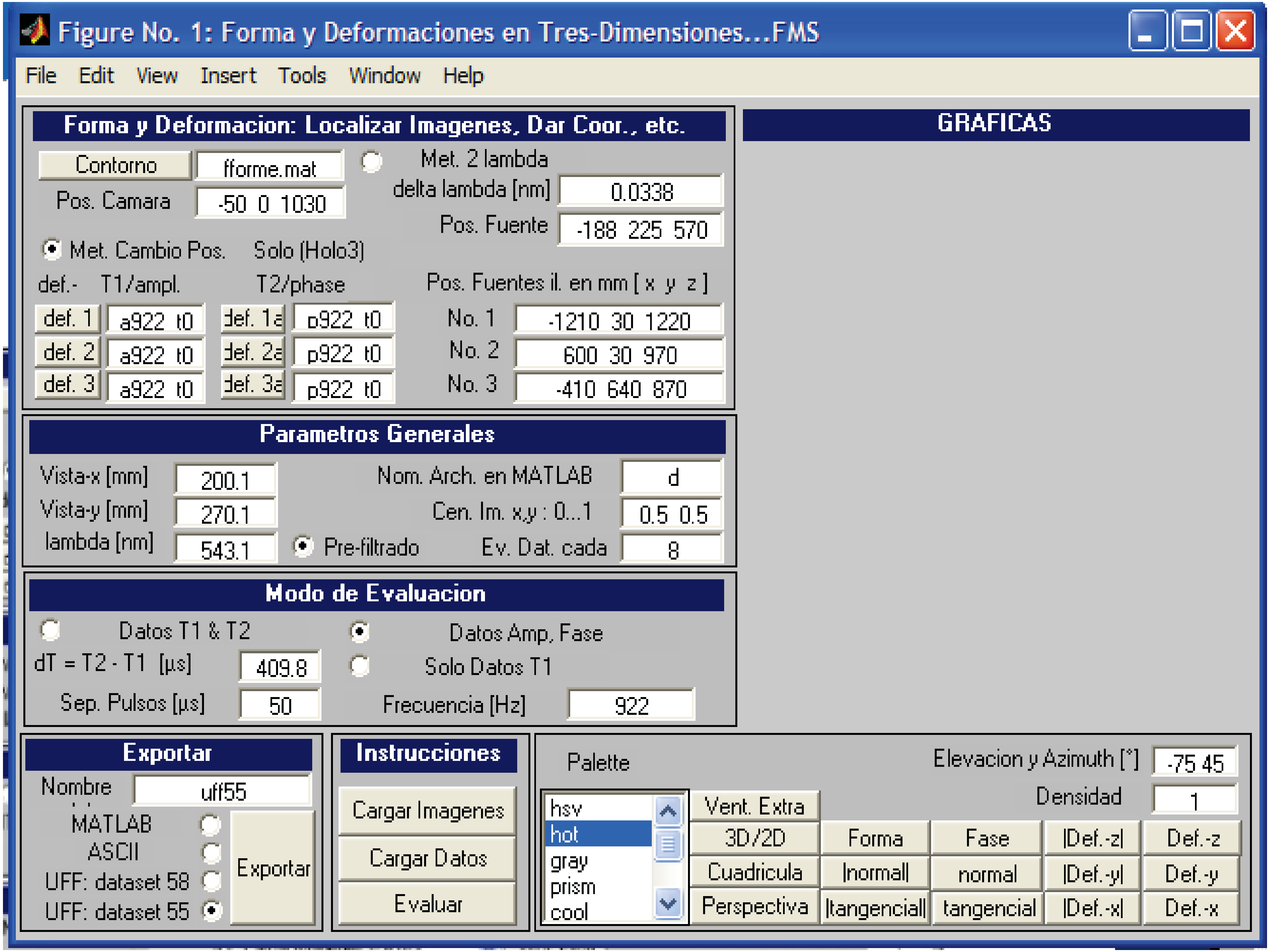
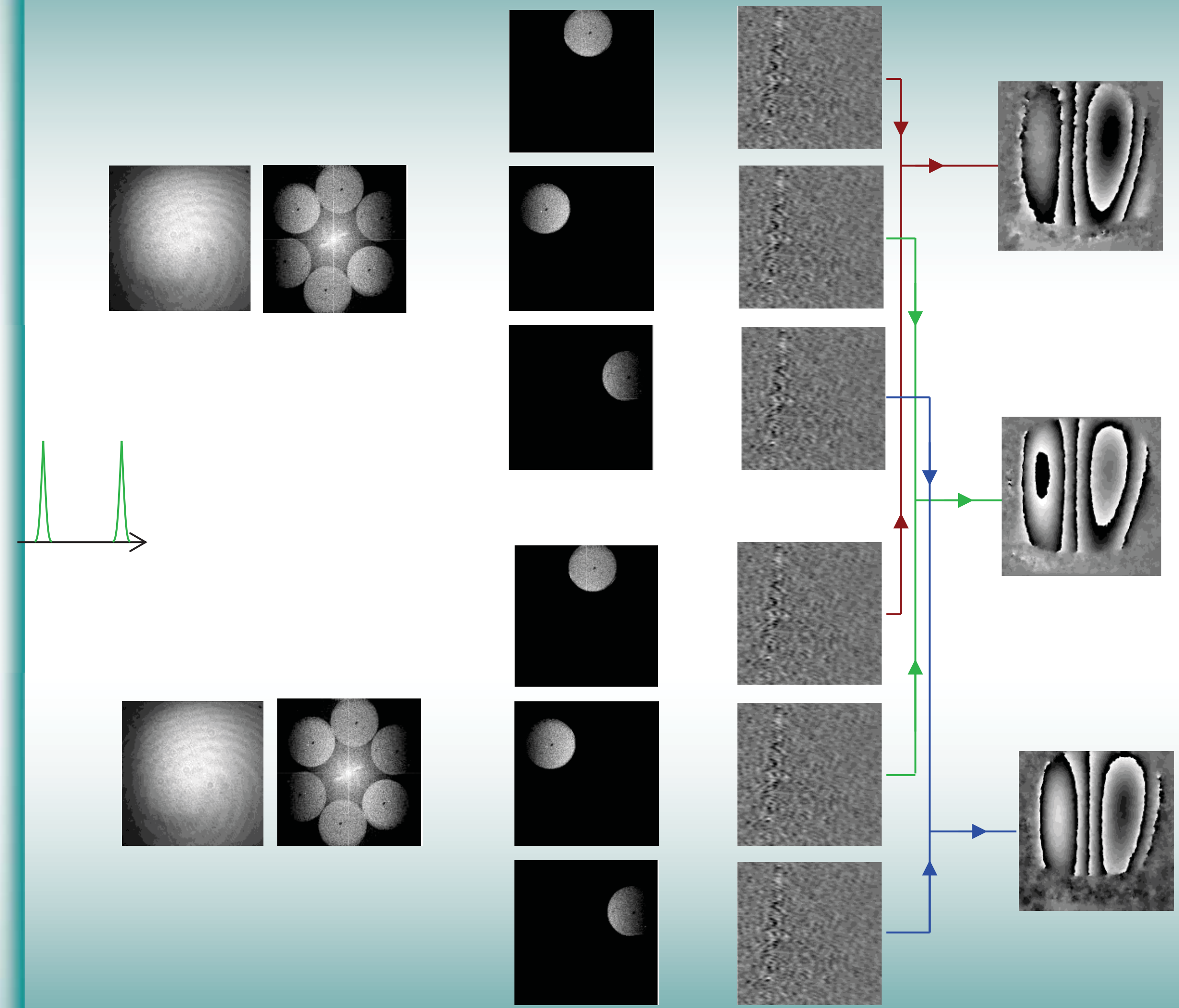


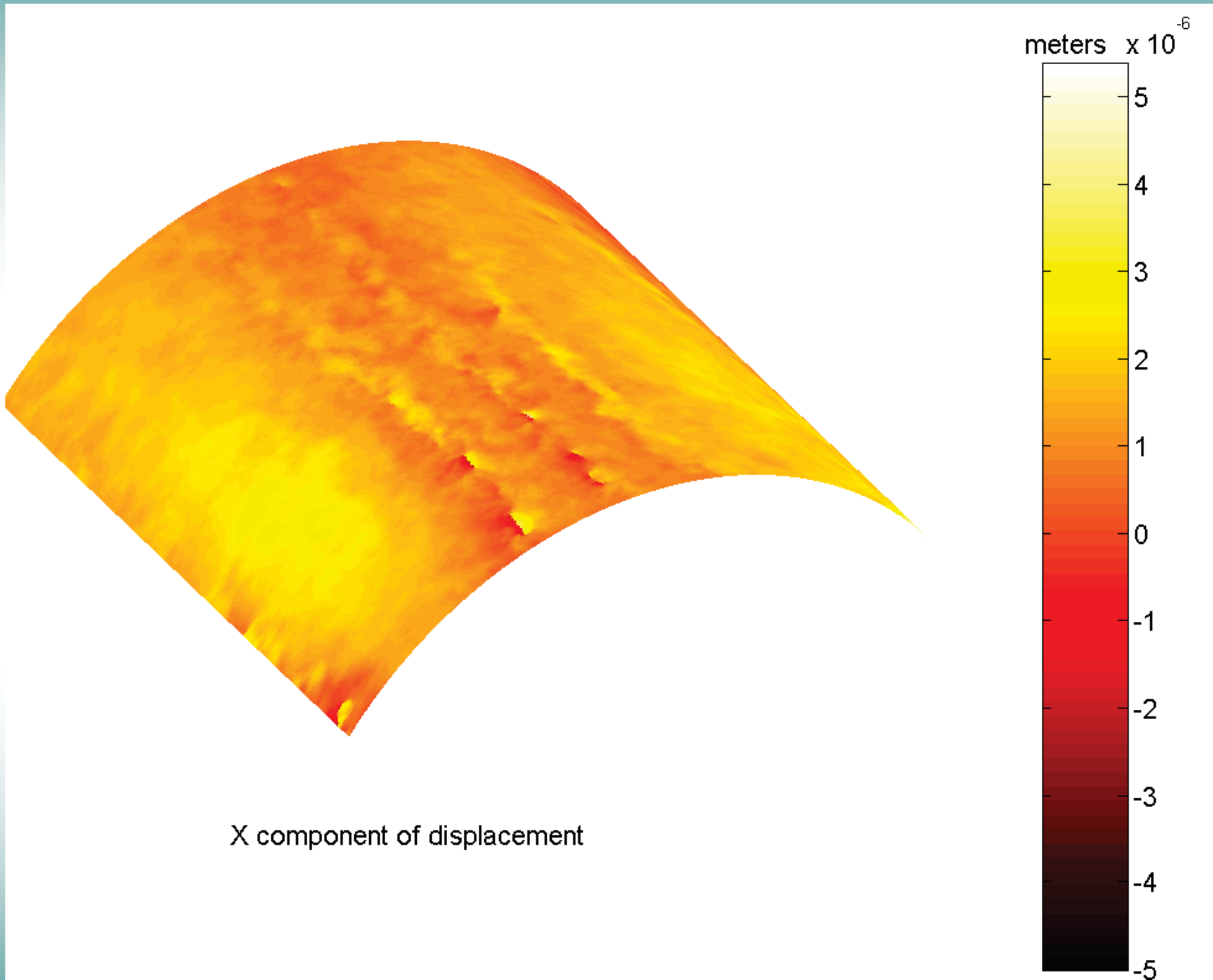
Figure No. 1: Forma y Deformaciones en Tres-Dimensiones...FMS
File Edit View Insert Tools Window Help
Forma y Deformacion: Localizar Imagenes, Dar Coor., etc.
Contorno
fforme.mat
Met. 2 lambda
delta lambda [nm]
0.0338
Pos. Camara
-50 0 1030
Pos. Fuente
-188 225 570
Met. Cambio Pos.
Solo (Holo3)
def.- T1/ampl.
T2/phase
Pos. Fuentes il. en mm [x y z]
def. 1
a922 t0
def. 1a
p922 t0
No. 1
-1210 30 1220
def. 2
a922 t0
def. 2a
p922 t0
No. 2
600 30 970
def. 3
a922 t0
def. 3a
p922 t0
No. 3
-410 640 870
GRAFICAS
Parametros Generales
Vista-x [mm]
200.1
Nom. Arch. en MATLAB
d
Vista-y [mm]
270.1
Cen. Im. x,y : 0...1
0.5 0.5
lambda [nm]
543.1
Pre-filtrado
Ev. Dat. cada
8
Modo de Evaluacion
Datos T1 & T2
Datos Amp, Fase
dT = T2 - T1 [µs]
409.8
Solo Datos T1
Sep. Pulsos [µs]
50
Frecuencia [Hz]
922
Exportar
Nombre
uff55
MATLAB
ASCII
UFF: dataset 58
UFF: dataset 55
Exportar
Instrucciones
Cargar Imagenes
Cargar Datos
Evaluar
Palette
Elevacion y Azimuth [°]
-75 45
Densidad
1
hsv
hot
gray
prism
cool
Vent. Extra
3D/2D
Forma
Fase
|Def.-z|
Def.-z
Cuadricula
|normal|
normal
|Def.-y|
Def.-y
Perspectiva
|tangencial|
tangencial
|Def.-x|
Def.-x

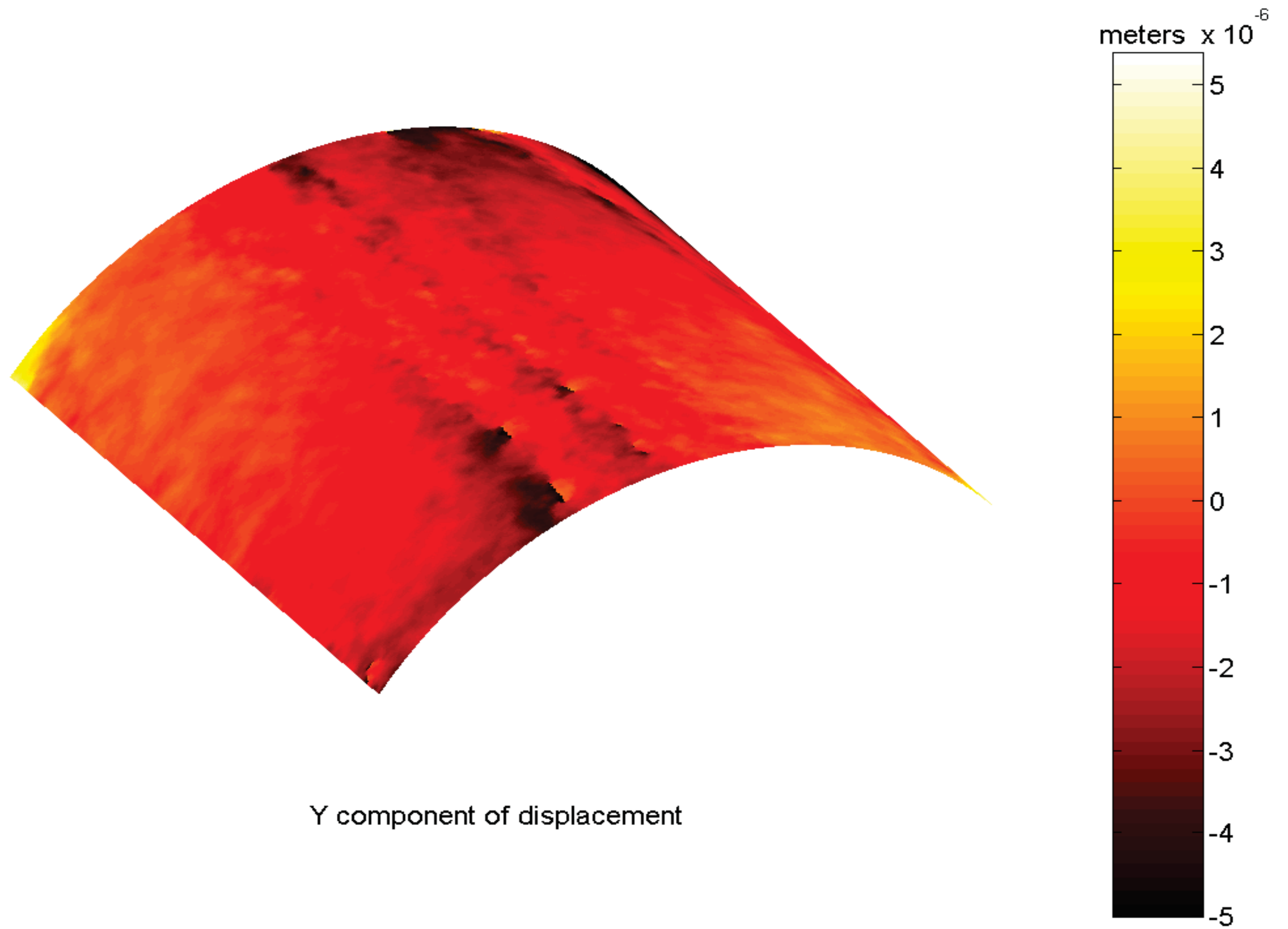
Phase evaluation with 3 holograms

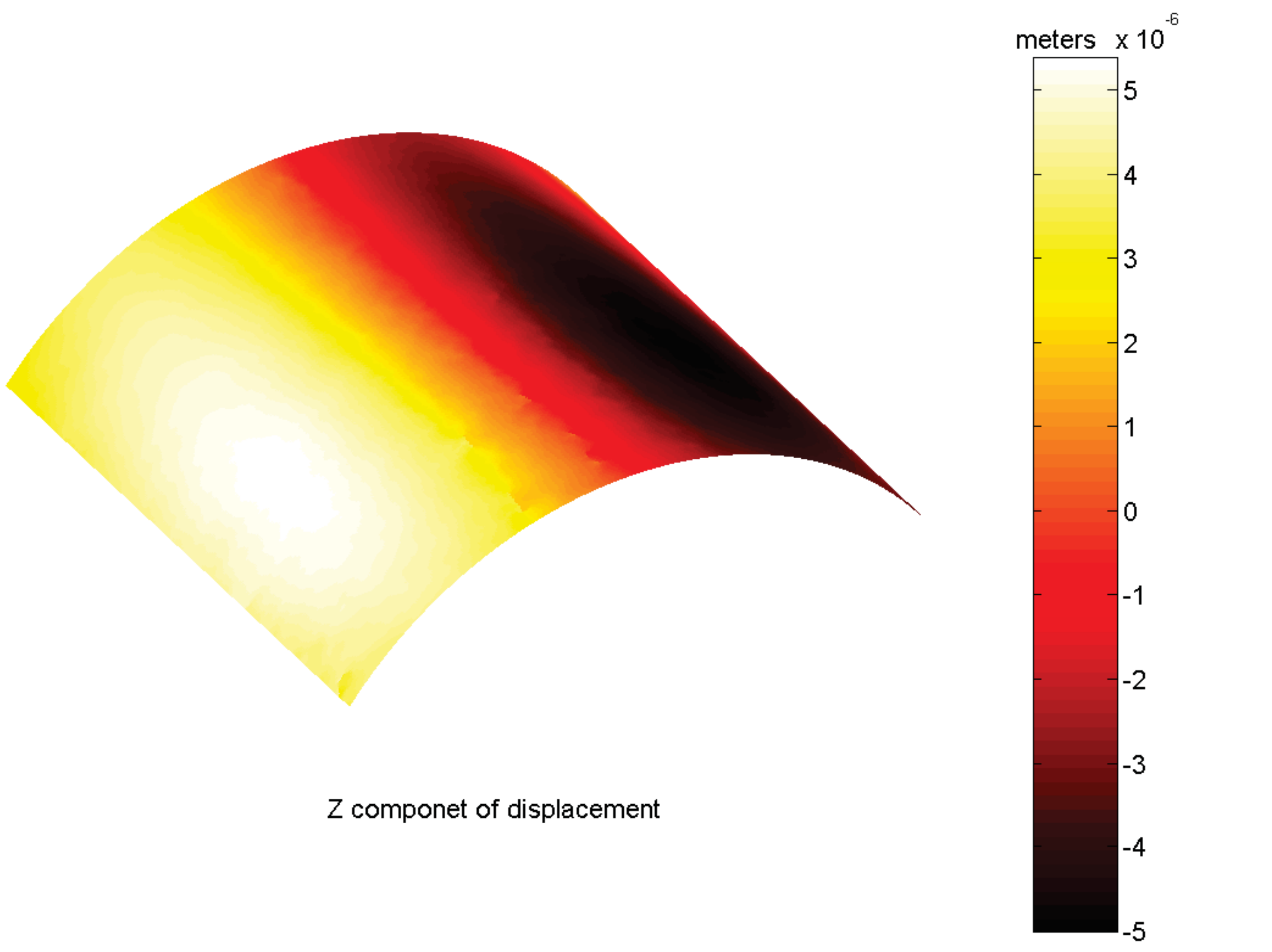


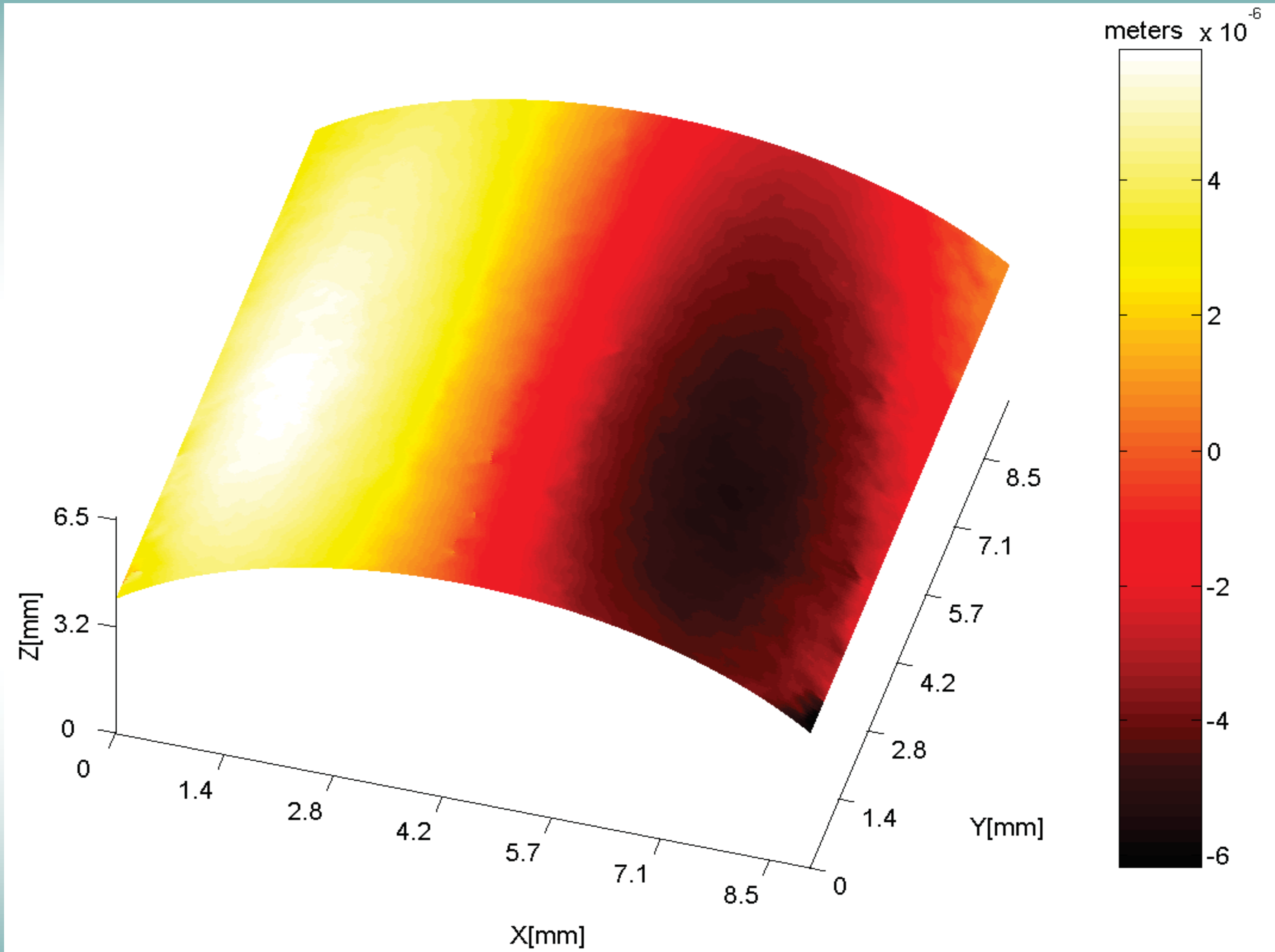
$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} = \frac{\lambda}{2\pi} \begin{pmatrix} S_{1x} & S_{1y} & S_{1z} \\ S_{2x} & S_{2y} & S_{2y} \\ S_{3x} & S_{2z} & S_{3z} \end{pmatrix}^{-1} \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta\phi_3 \end{pmatrix}$$

Separation of individual displacement components

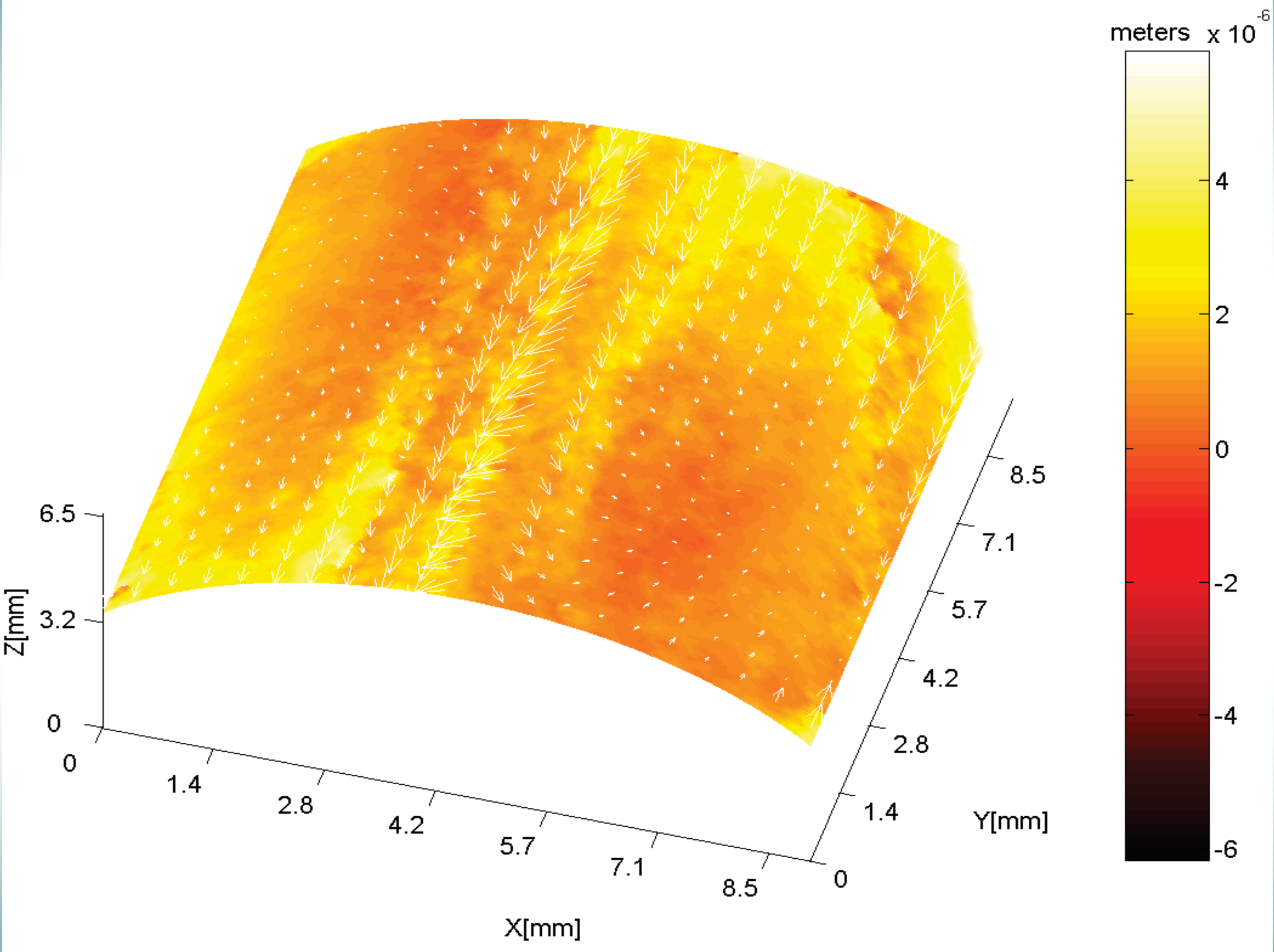



meters x 10^-6
5
4
3
2
1
0
-1
-2
-3
-4
-5
Y component of displacement


meters x 10^-6
5
4
3
2
1
0
-1
-2
-3
-4
-5
Z componet of displacement

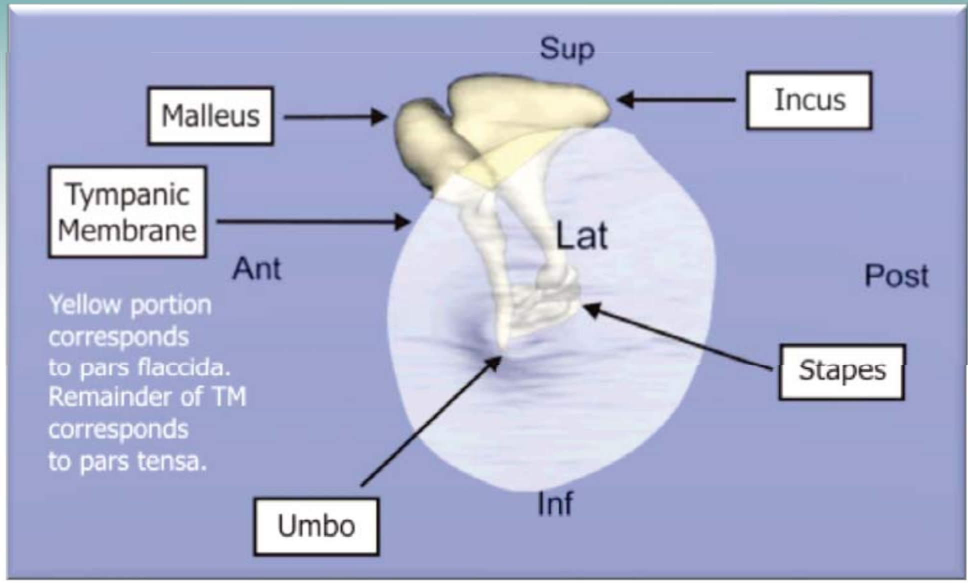


meters x 10^-6
4
2
0
-2
-4
-6
6.5
3.2
0
Z[mm]
0
1.4
2.8
4.2
5.7
7.1
8.5
X[mm]
0
1.4
2.8
4.2
5.7
7.1
8.5
Y[mm]


meters
x 10-6
4
2
0
-2
-4
-6
6.5
3.2
0
Z[mm]
0
1.4
2.8
4.2
5.7
7.1
8.5
X[mm]
0
1.4
2.8
4.2
5.7
7.1
8.5
Y[mm]

Tympanic Membrane

Endoscopic image of the TM

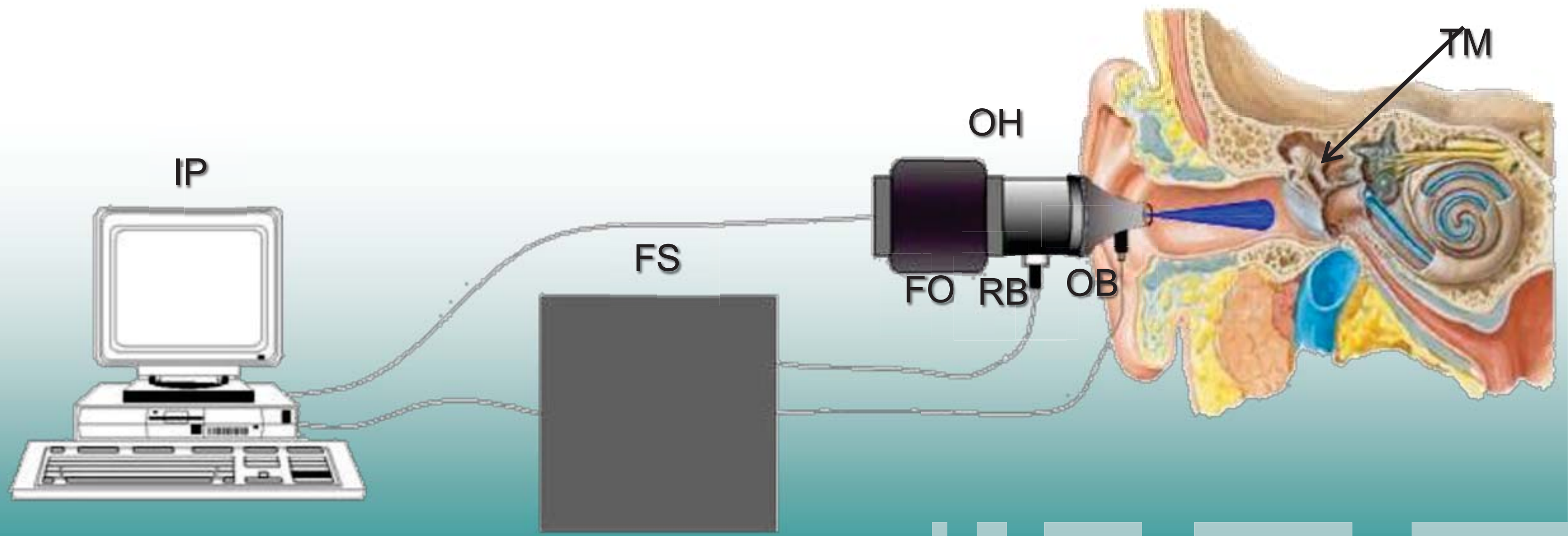


Characteristics of human TM
Semitransparent
Cone shaped
The depth of the cone is about 1.5 mm
Diameter is 8–10 mm
Thickness varies between 55 and 140 μm

OEHO System

The inspection system consists of:

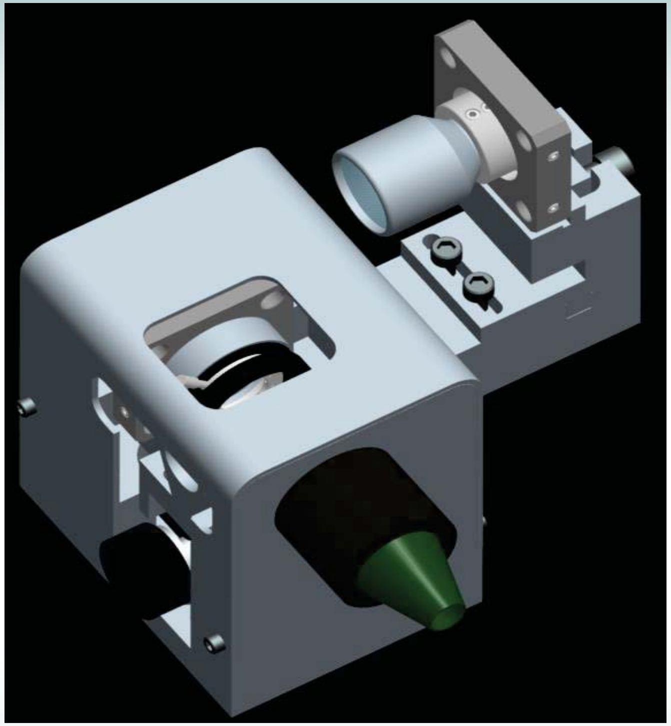
- High speed PC with dedicated software and hardware,
- Fiber optics, FS, and
- A compact optics head resembling an otoscope, OH



Otoscope optics head (OH)

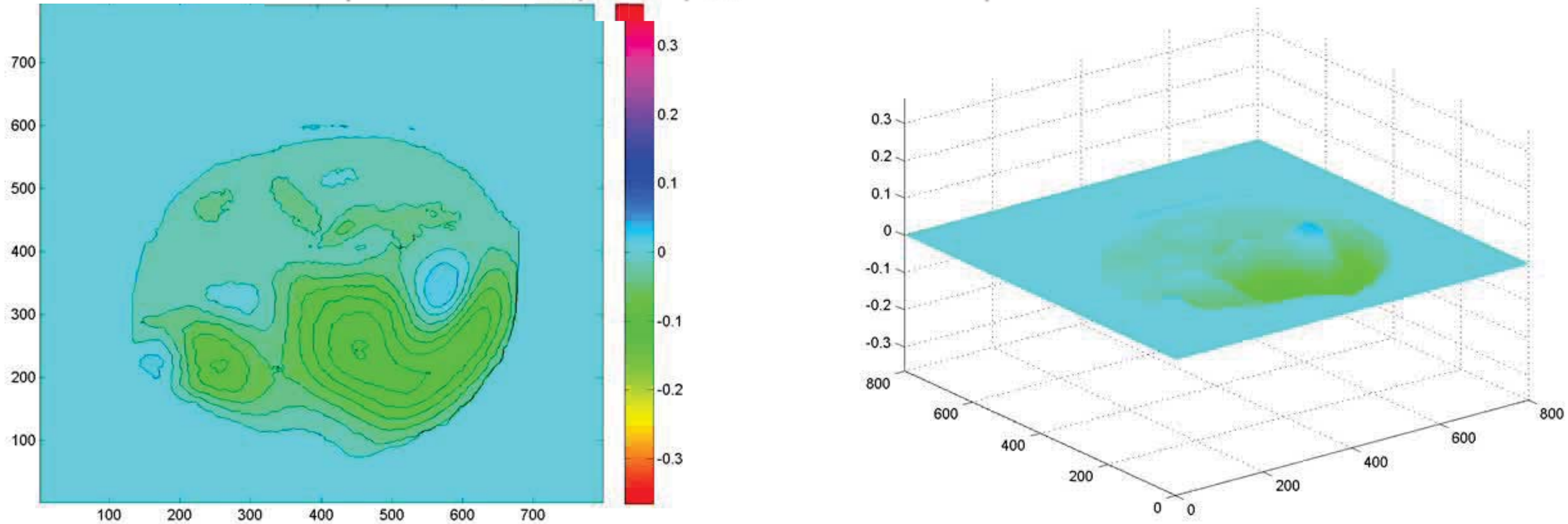
Parameters	Value
FOV	ϕ =10 mm
Magnification	0.4X
DOF	5 mm
Contrast	0.82
MTF	52.0 lp/mm

Field of View (FOV)
10.0 mm
8.5 mm
6.7 mm

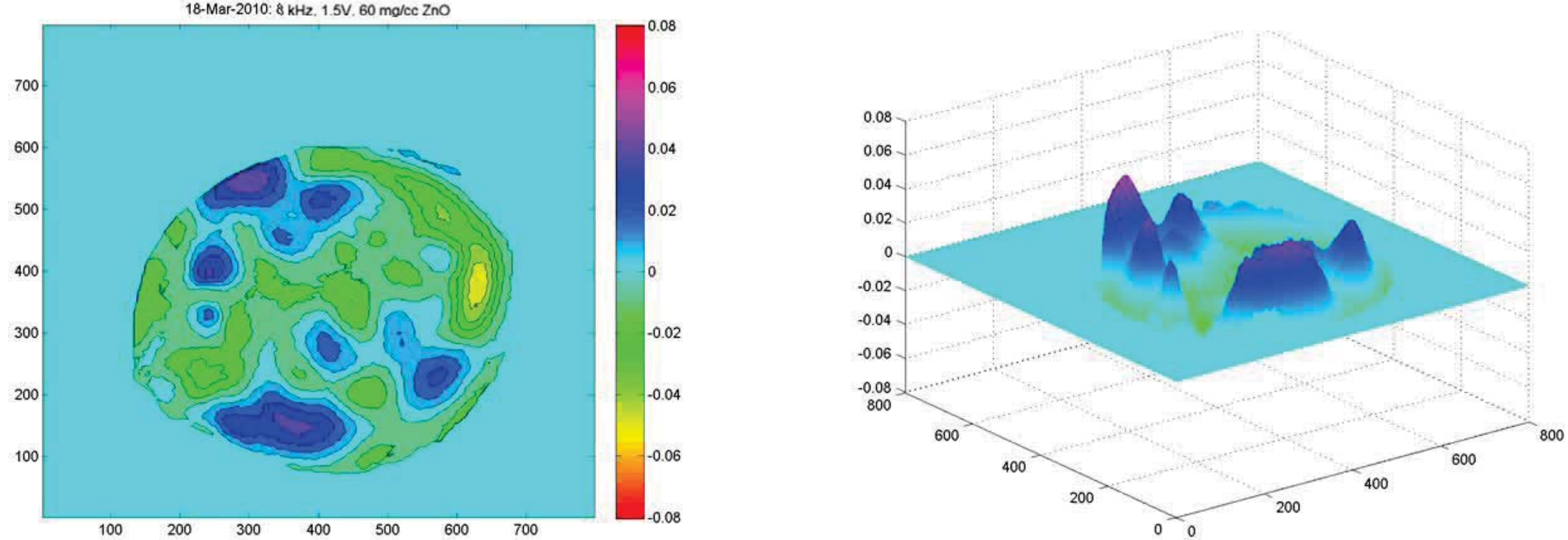


CAD model of compact (OH)

Complex 4 kHz, 2.0 V: peak-to-peak deformation 0.660μm



Ordered 8 kHz, 1.5 V: peak-to-peak deformation 0.080μm



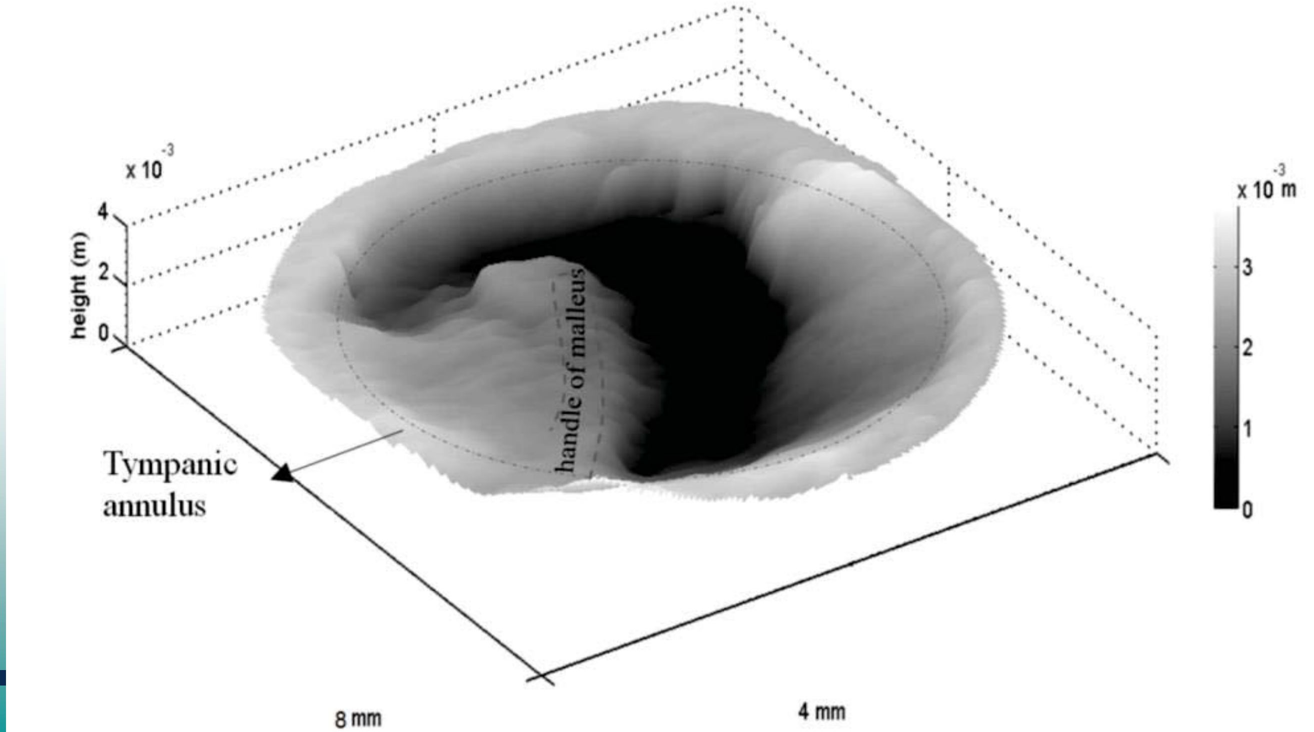
Hear Res **253**, 83-96 (2009)

- Rock…..noisy?

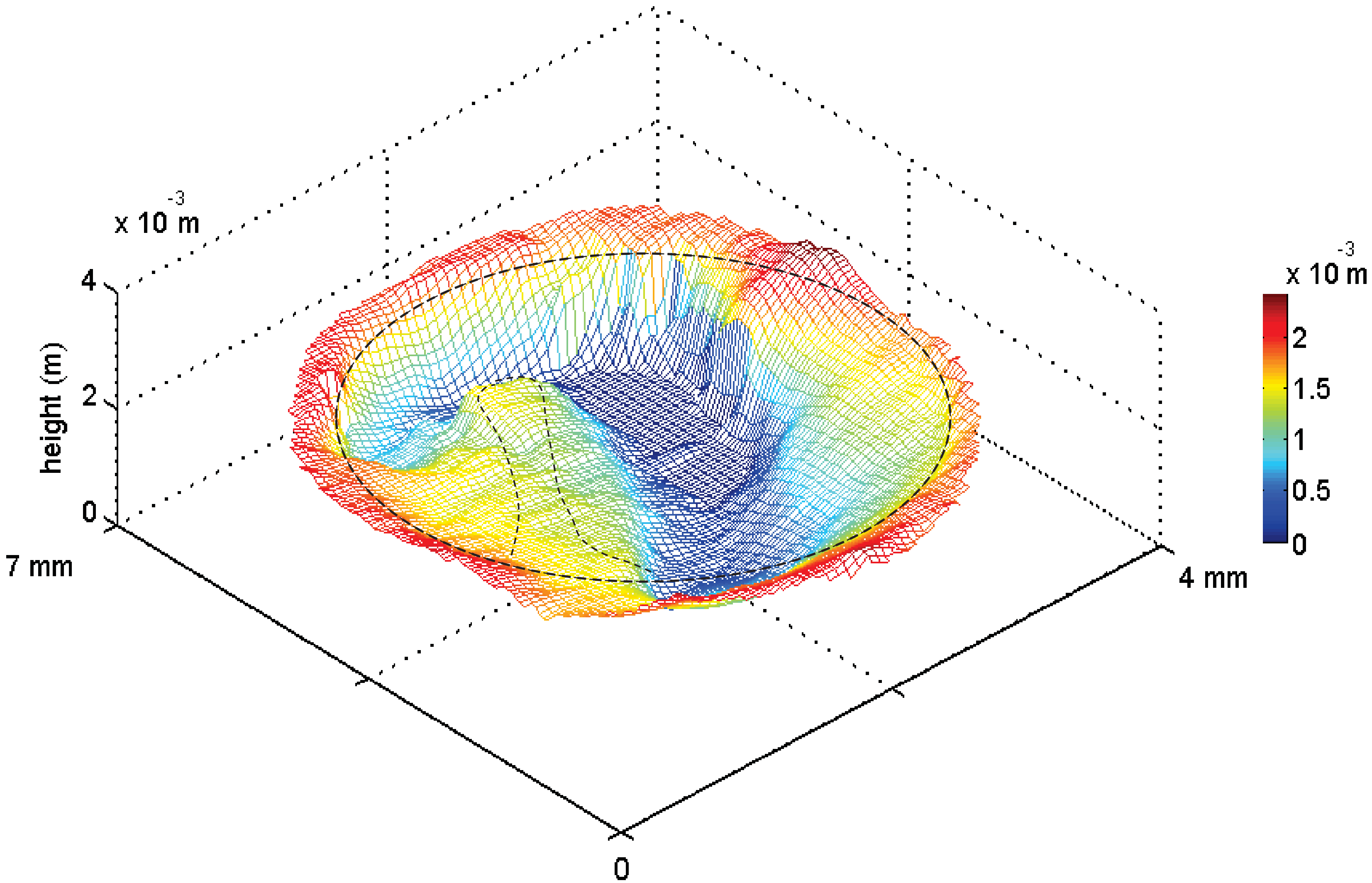
softer…..classical

The TM surface height-change may be found from the difference between the reconstructed phases which are recorded before and after the small tilt of the object illuminating beam by the follow equation:

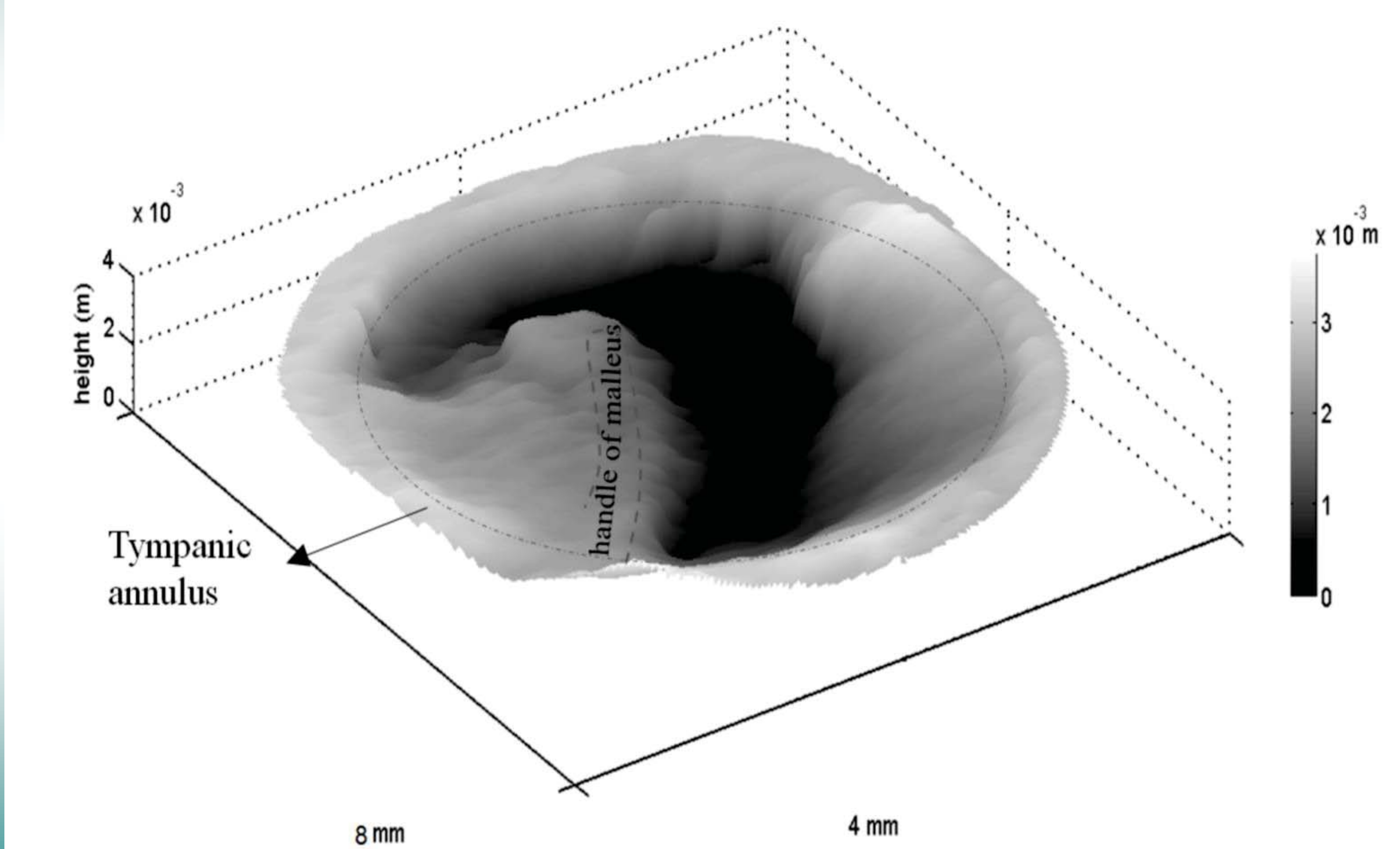
$$\Delta\varphi = 2K\sin\frac{\Delta\theta}{2}\left[x\cos\left(\theta+\frac{\Delta\theta}{2}\right)-h(x)\sin\theta+\frac{\Delta\theta}{2}\right]$$



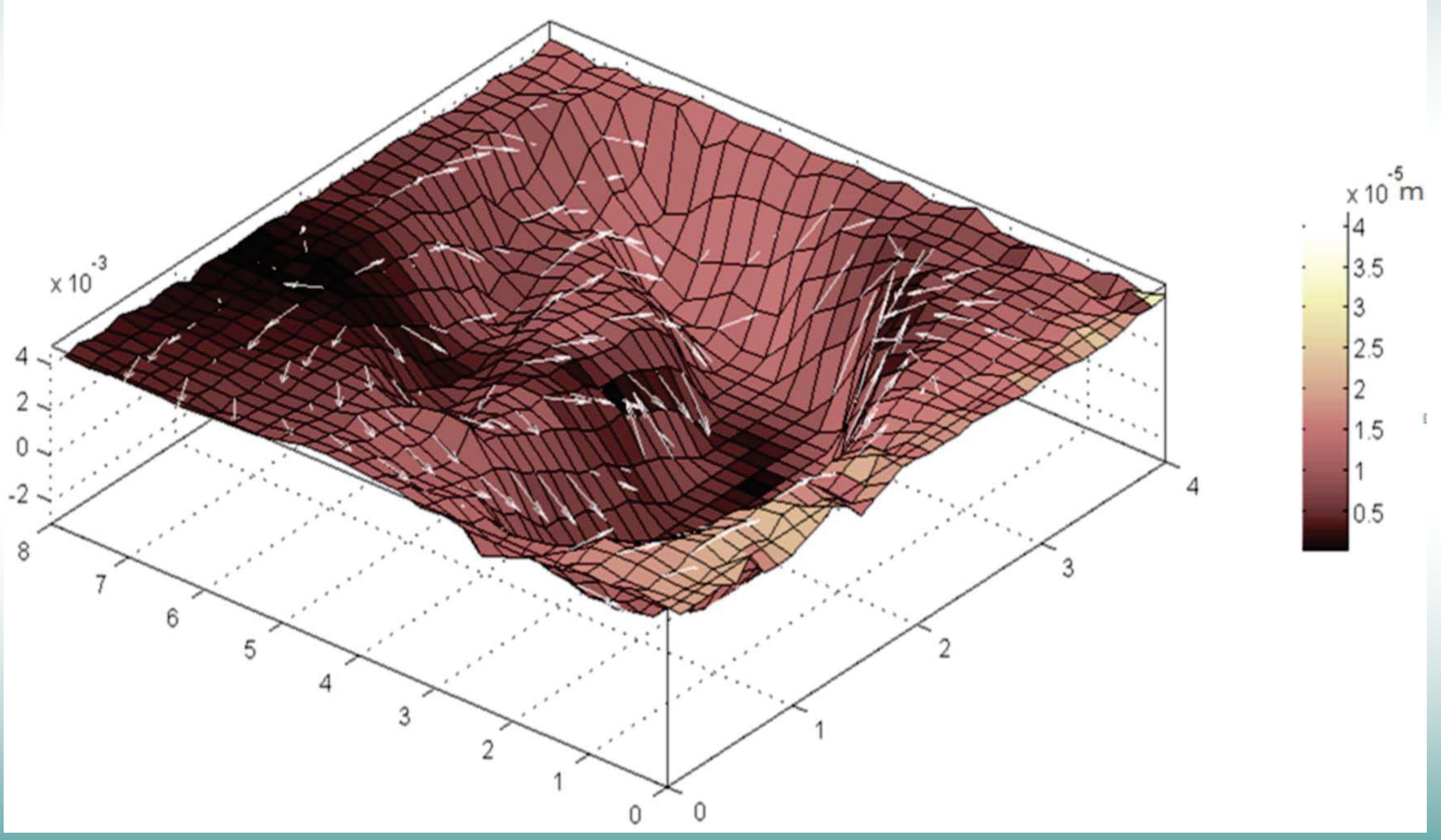
Shown : Tympanic annulus and handle of maleus



3D Displacement on the TM shape



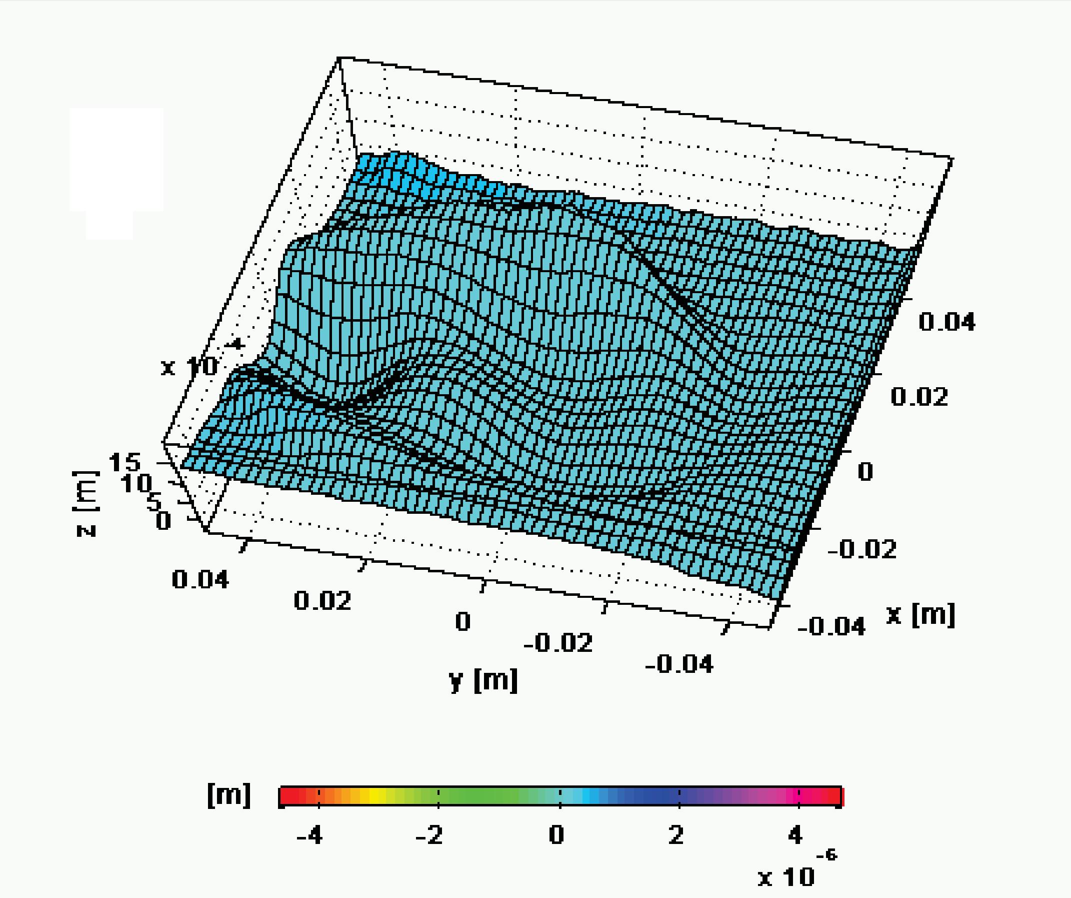
3D Displacement on the TM shape



INHOMOGENEITIES DETECTION (TUMORS)

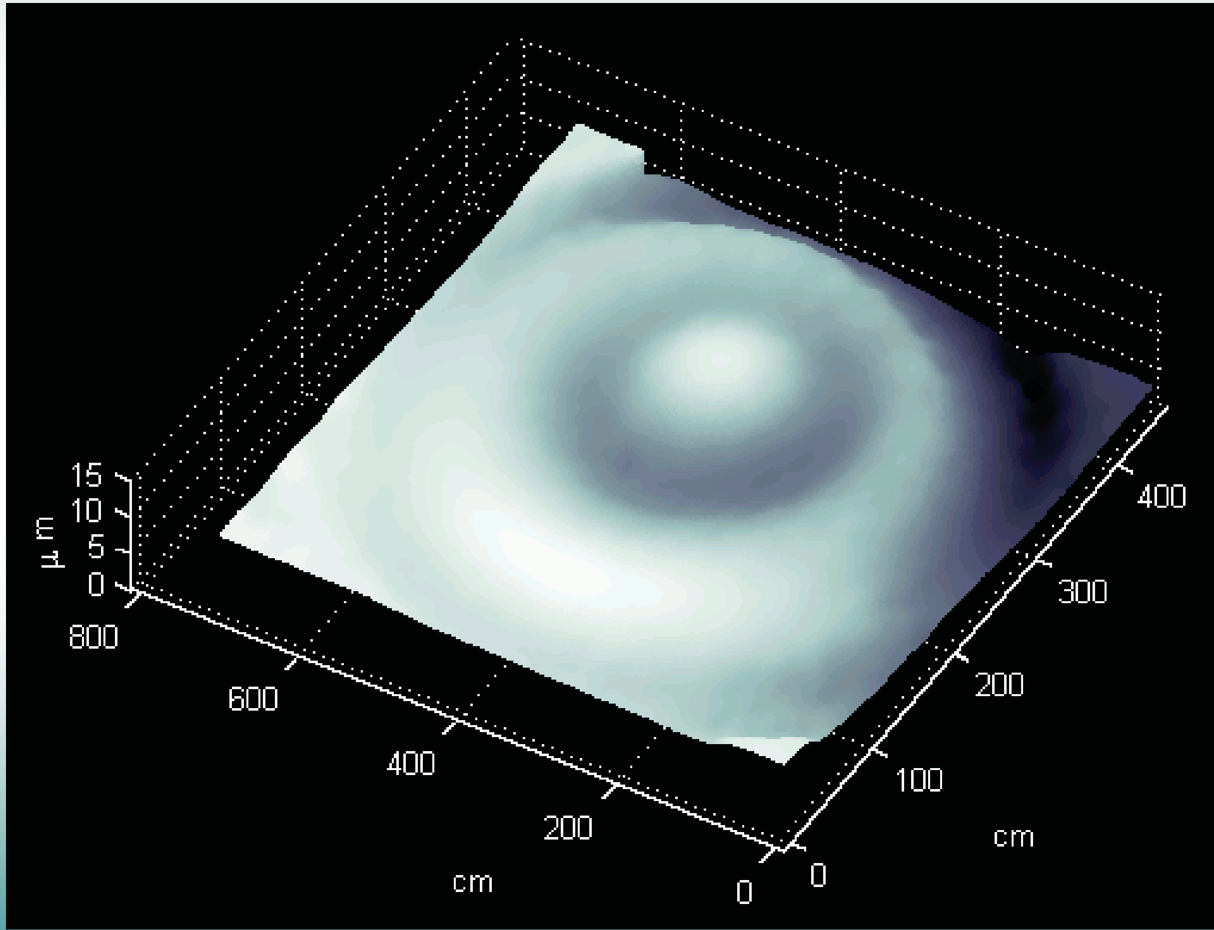
- Input sound power of approximately 661 mW, equivalent to a pressure of 2.3 x 105 pa.
- Laser pulse separation 14 ms, at 532 nm, 15 ns pulse width, 20 mJ/pulse, average power of 0.639 µW/cm^2 at the surface, and 6 m of coherence length.
- CCD with 1024 by 1280 pixels at 12 bits.
- Phantom is a semi sphere with an 8.4 cm in diameter and 4 cm height.

Unwrapped phase map without sound, gel surface free to move due to environmental disturbances

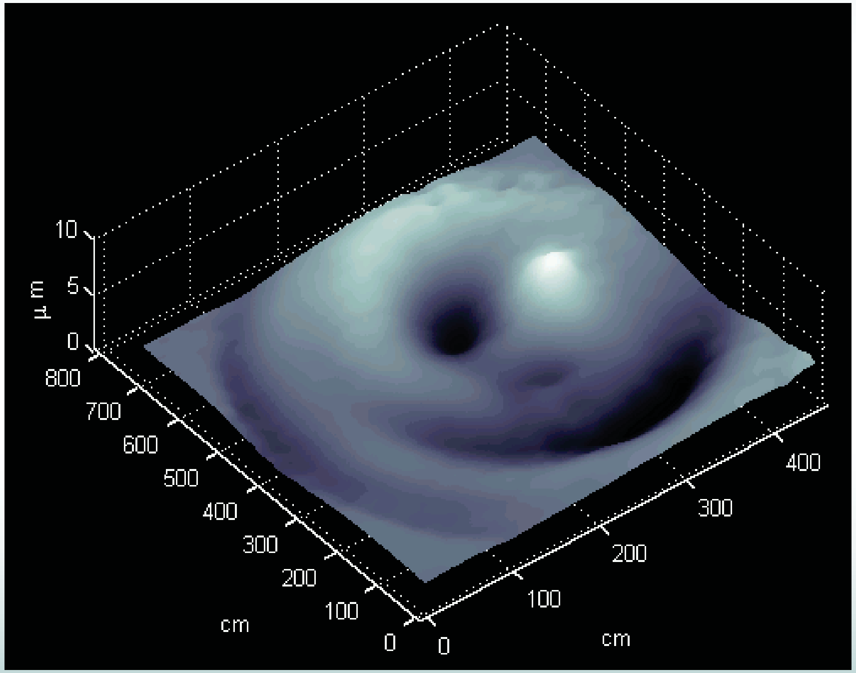


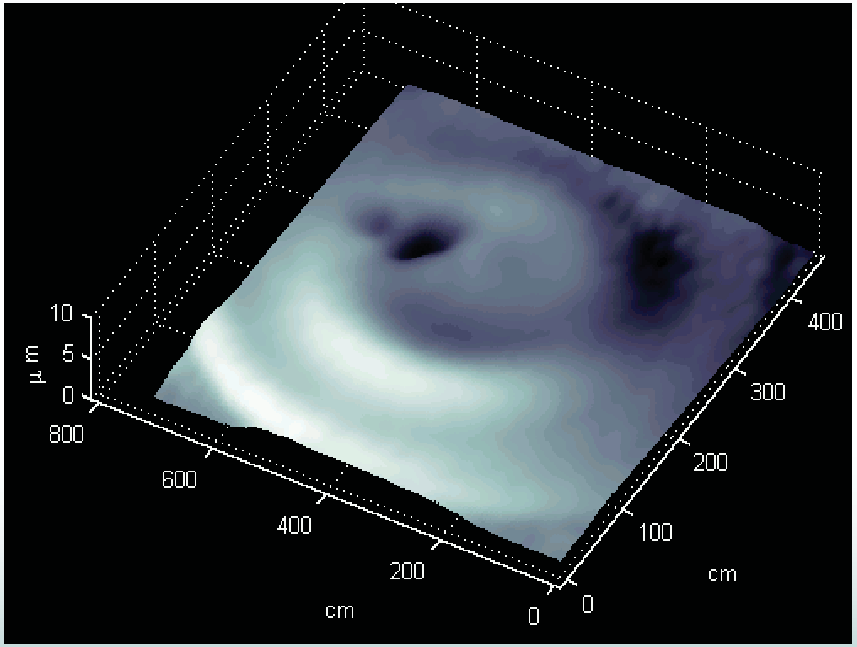
It is not possible to observe whether there is an inhomogeneity in the gel

Without inhomogeneity and sound: resonant mode at 810 Hz.



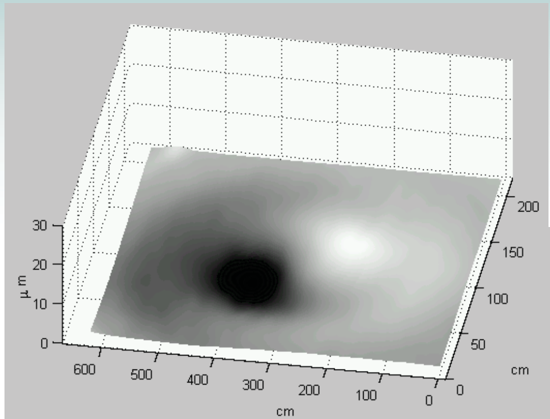
With inhomogeneity: Malignant tumor 10 mm diameter



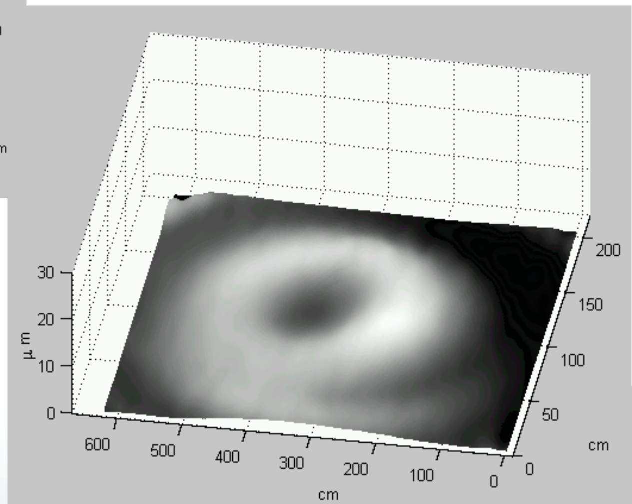


With 3D data the depth of the tumor may be found

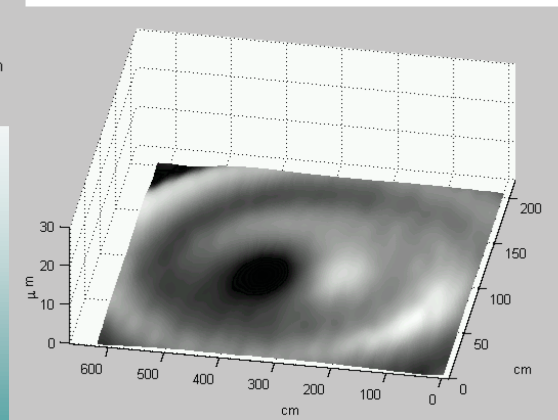
Unwrapped phase maps corresponding to each illumination direction



L

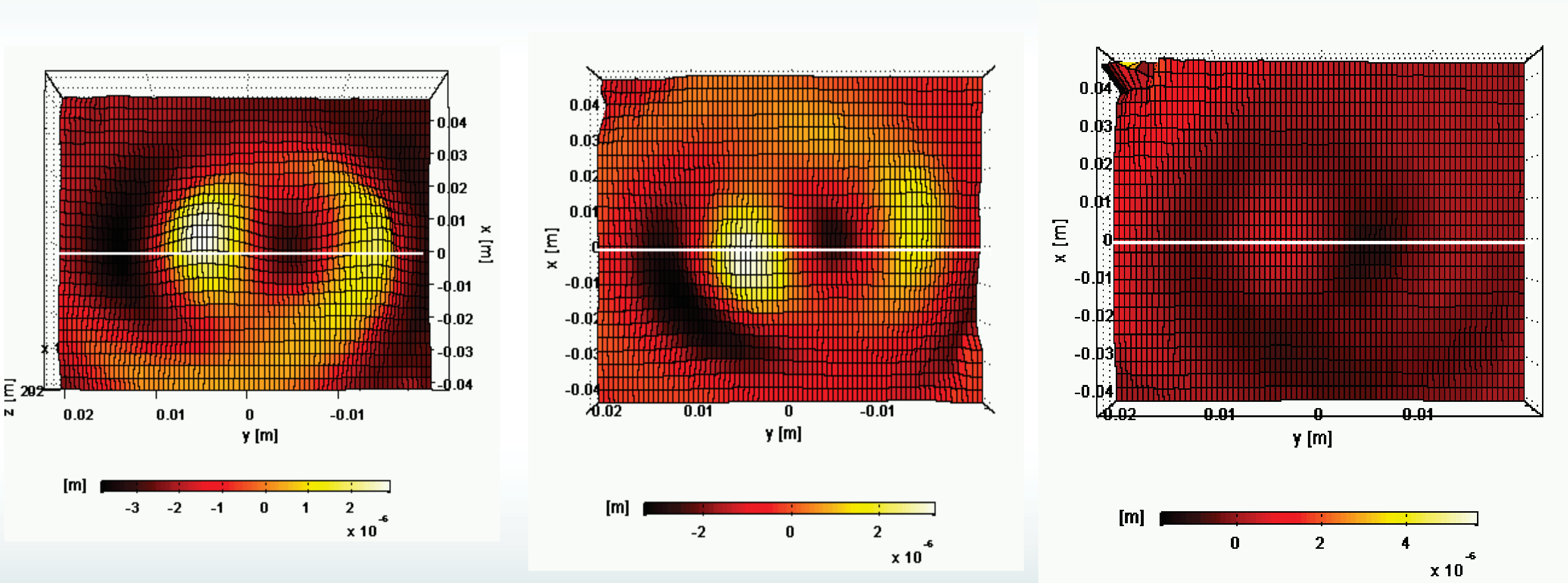


C



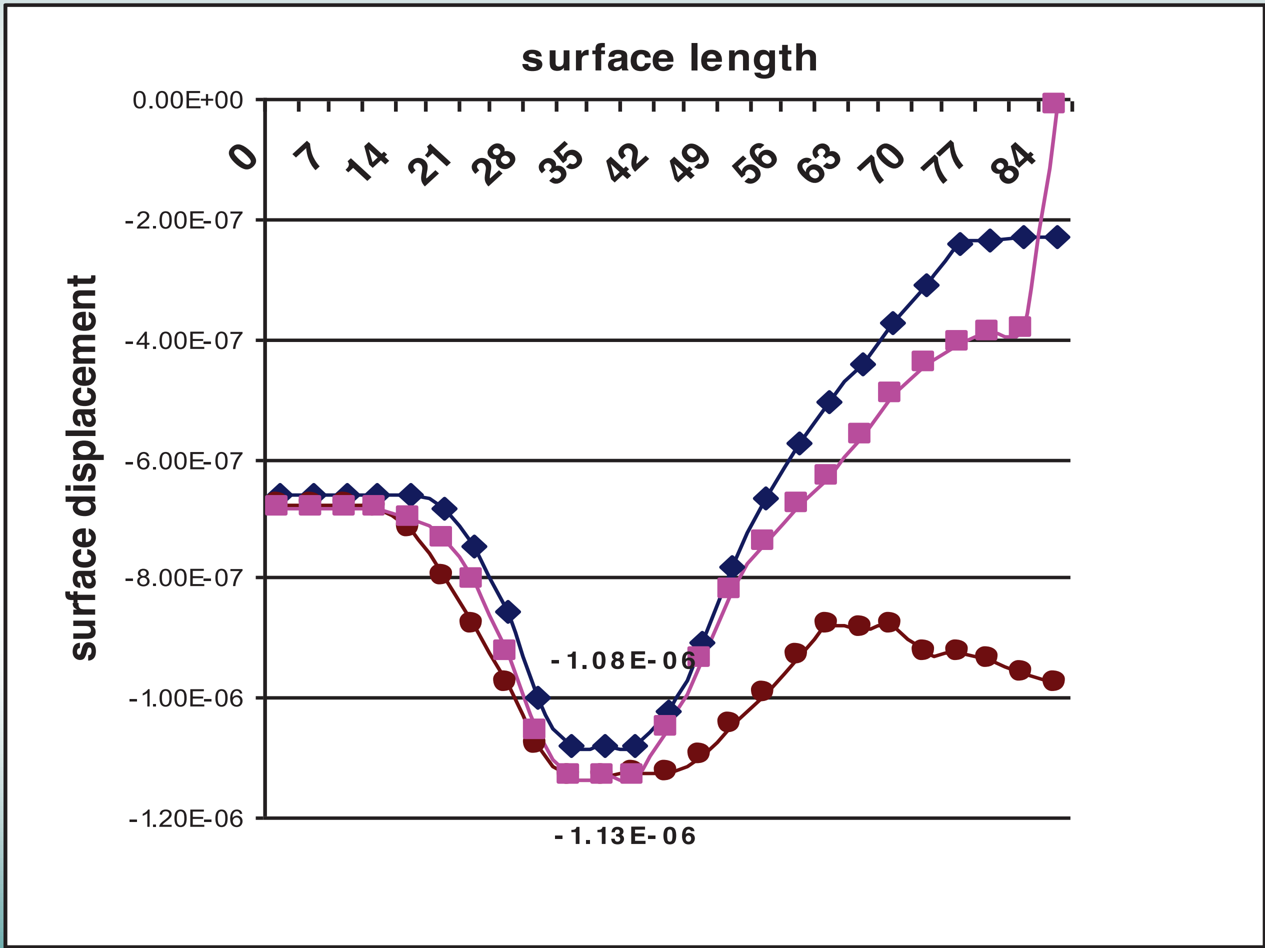
R

Malignant tumor 10 mm diameter, 3D data

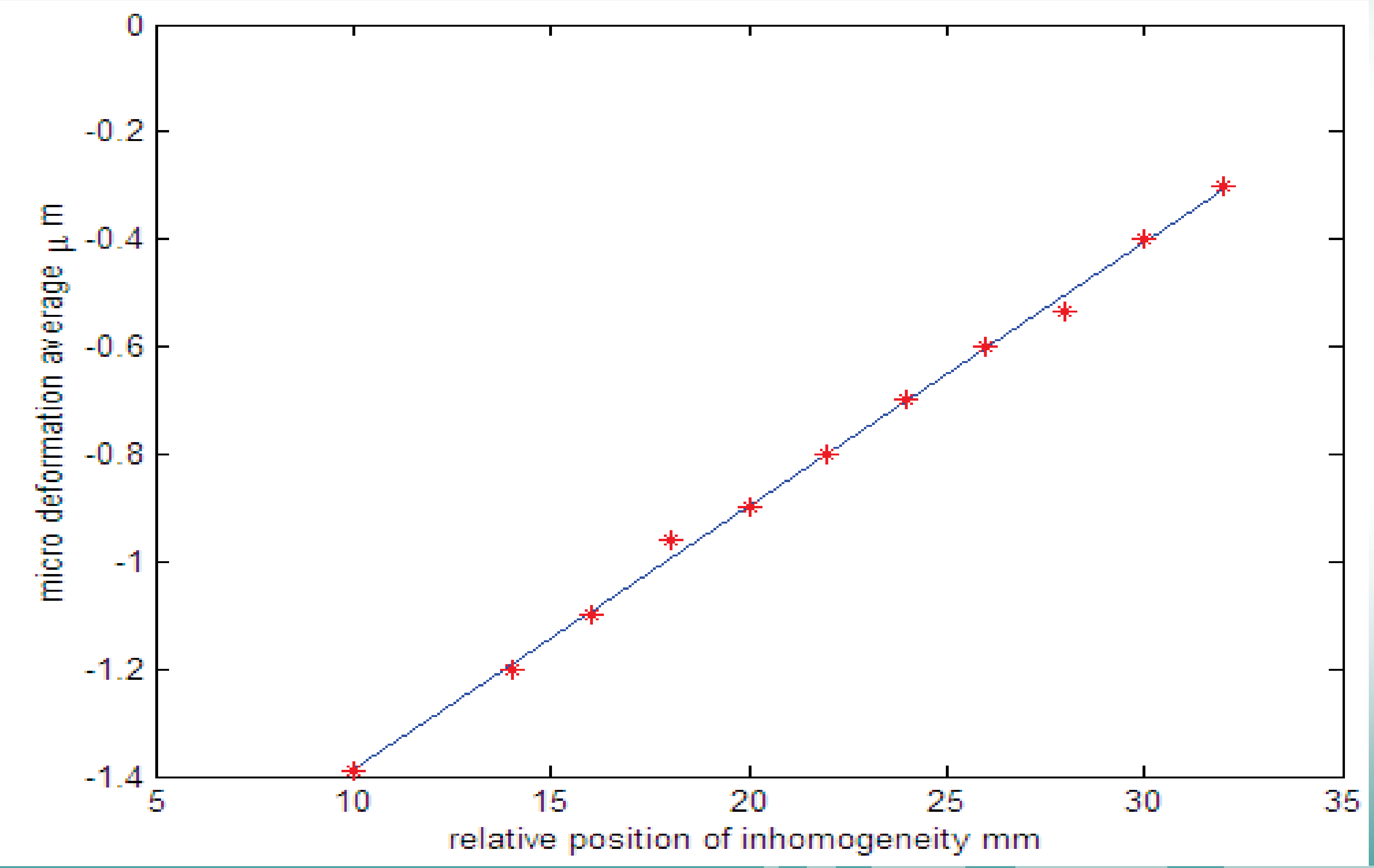


Journal of Biomedical Optics, **12** (2), pp. 024027-1/024027-5 (2007).

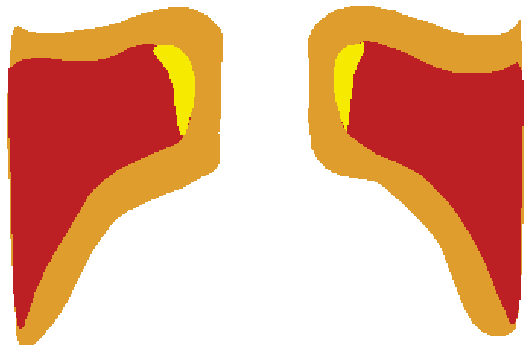
Depth location with respect to the surface



Results fitted to a straight line for calibration purposes

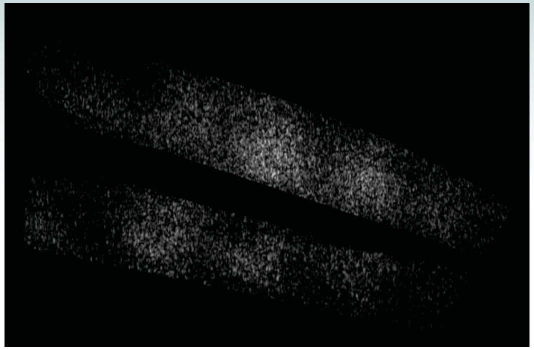


Vocal chords displacements
(Pig's Larinx)

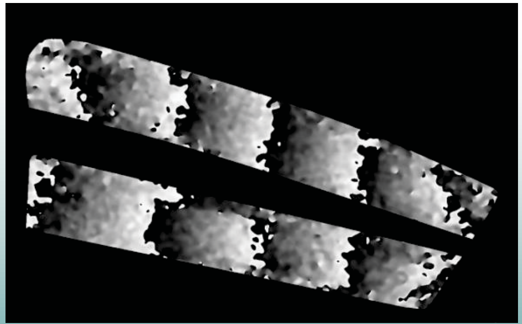


VOCAL CHORDS MOVEMENT

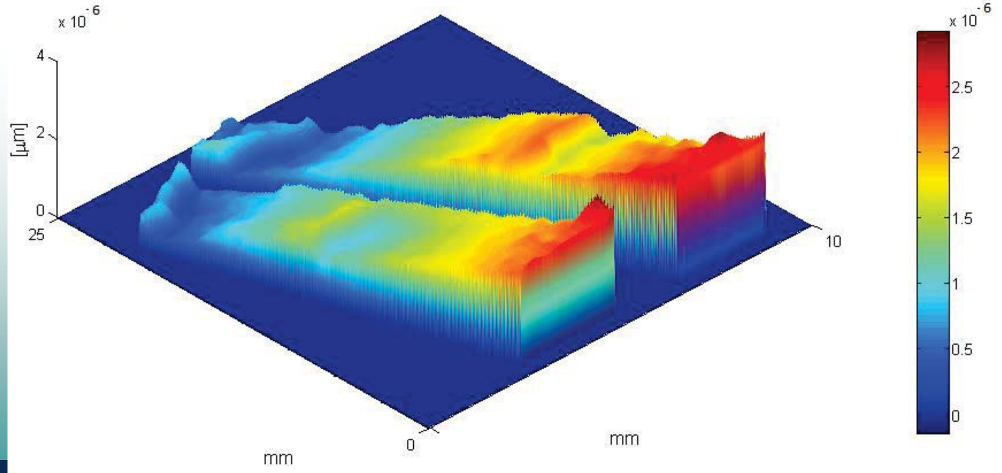
La amplitudes de vibración y las velocidades depende de la fonación. Así como la edad y sexo, determinan sus características fisiológicas de las cuerdas.



FRINGE PATTERN



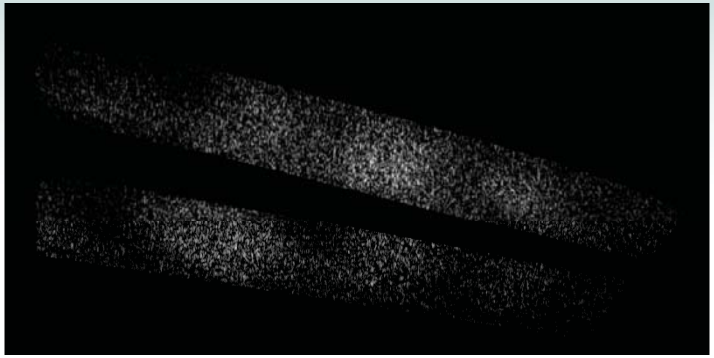
WRAPPED PHASE



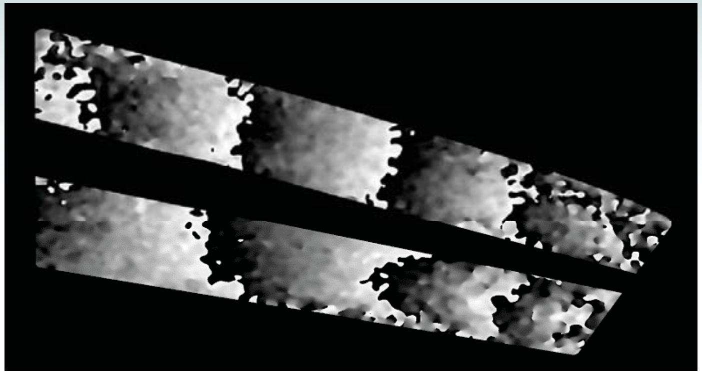
2000 fps

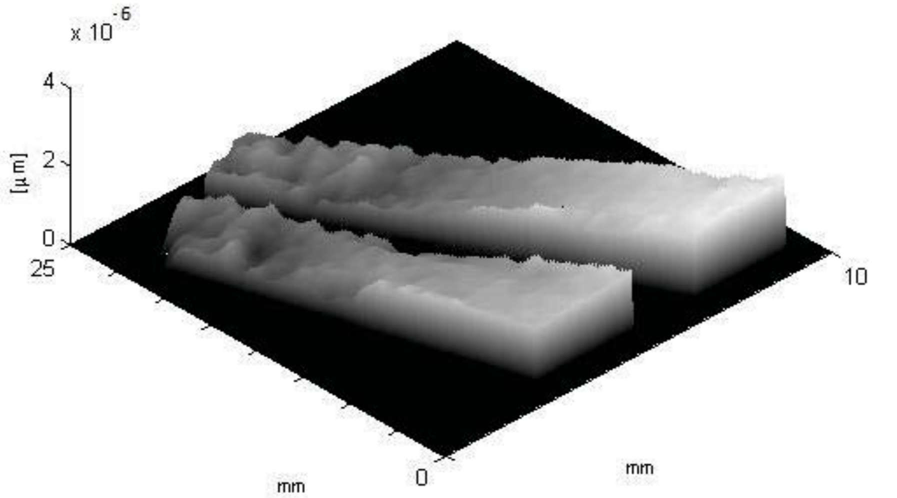
VOCAL CHORDS MOTION

FRINGE PATTERN



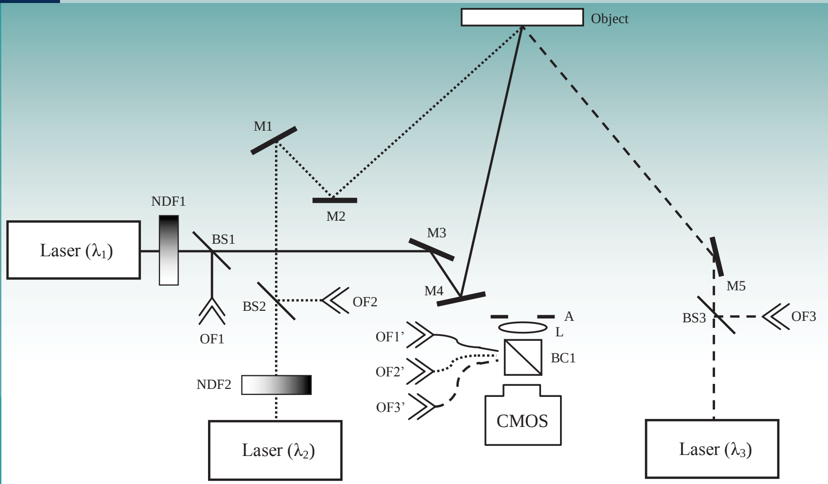
WRAPPED PHASE

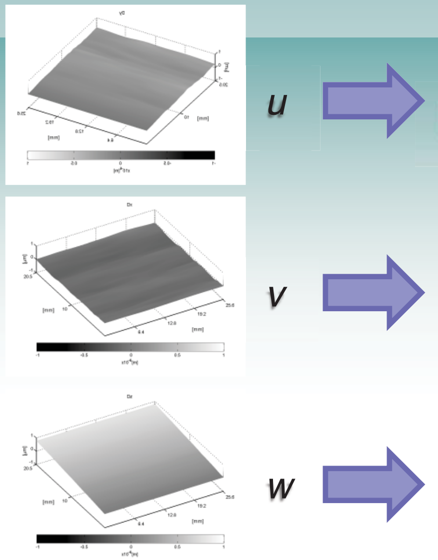




2000 fps

Biomechanics, Stress calculation

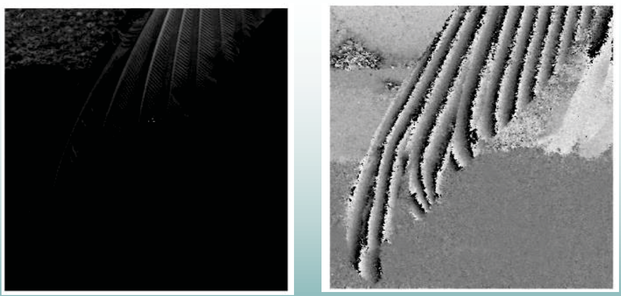




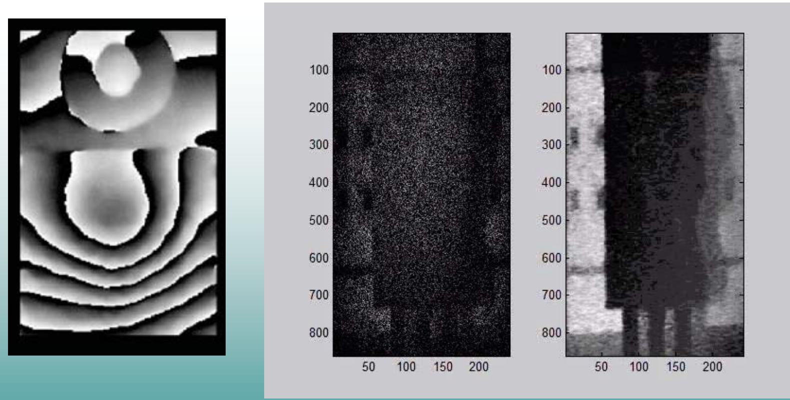
Biomechanical studies*

Strain/Stress

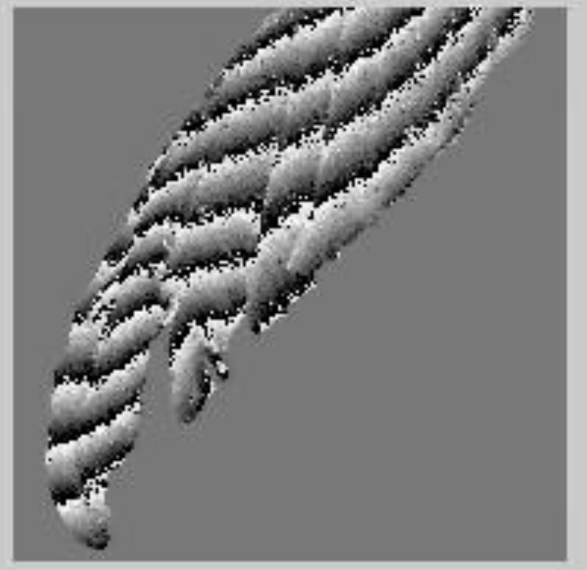
Research on complex organical surfaces

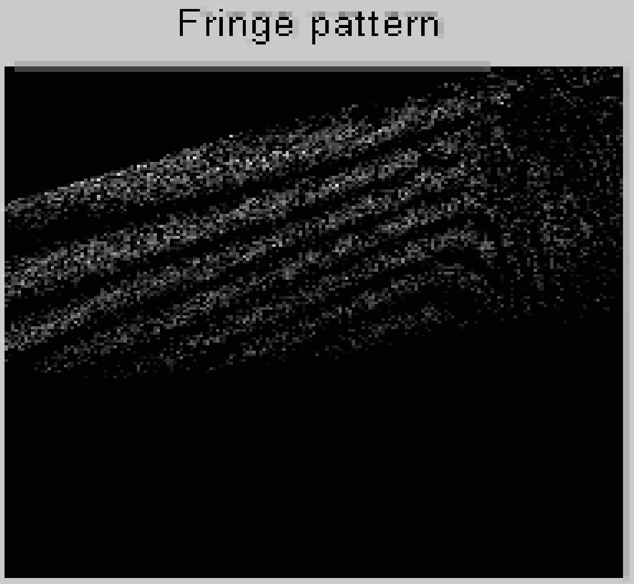


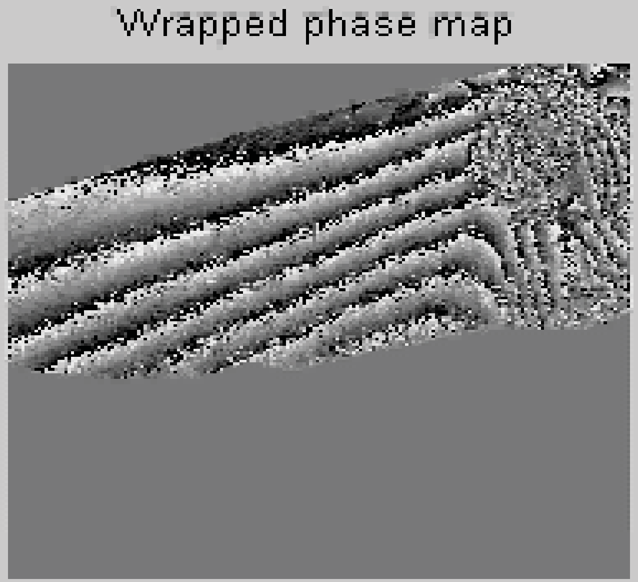
Thermal deformations (transistor)




Fringe pattern


Wrapped phase map


Fringe pattern


Wrapped phase map

Buterflies in-flight

Capture

Fixing

experimental measurement

Comparison among 4 butterflies

Pterourus Multicaudata

Agraulis Vanillae Incarnata

Dannaus Gillipus Cramer

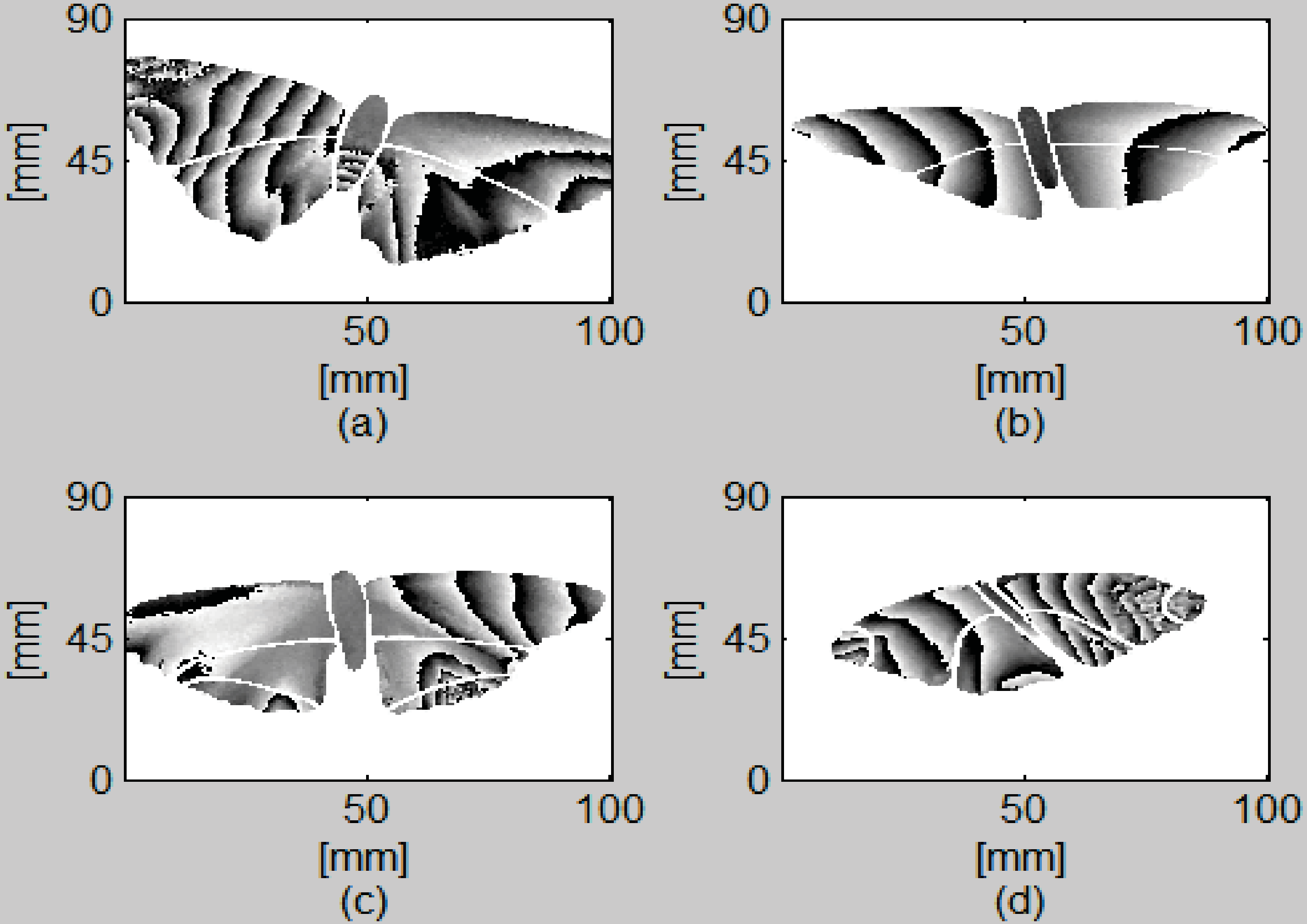
Precis Evarete Felder

- in-vivo experimentation

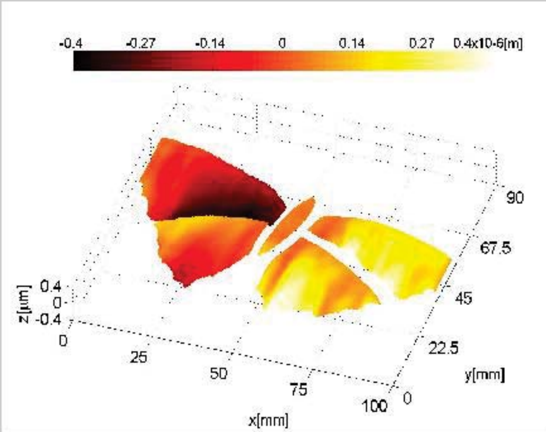
- High speed DHI
- Laser Verdi (Coherent V6)
- Ilumination density on the insecto:
  19.6 mW/cm2

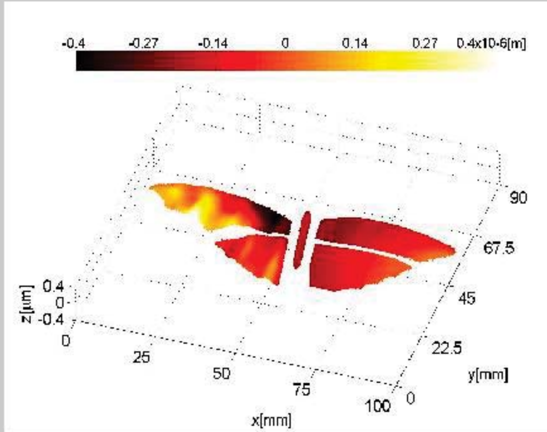
- NAC GX-1 camera
- Recordings at 4000 fps
- FOV: 90 x 100 mm
- 800 x 800 pixeles
- 10 bits dynamic range

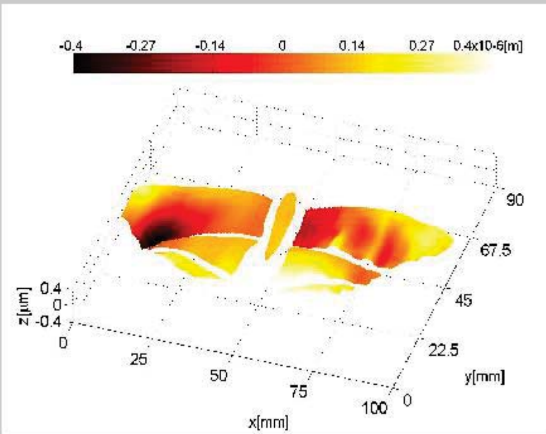
Wrapped phase maps

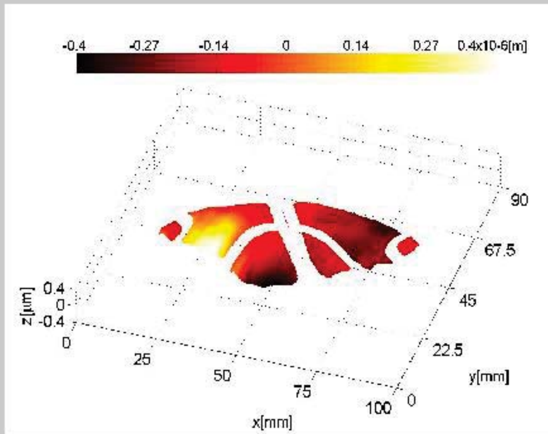


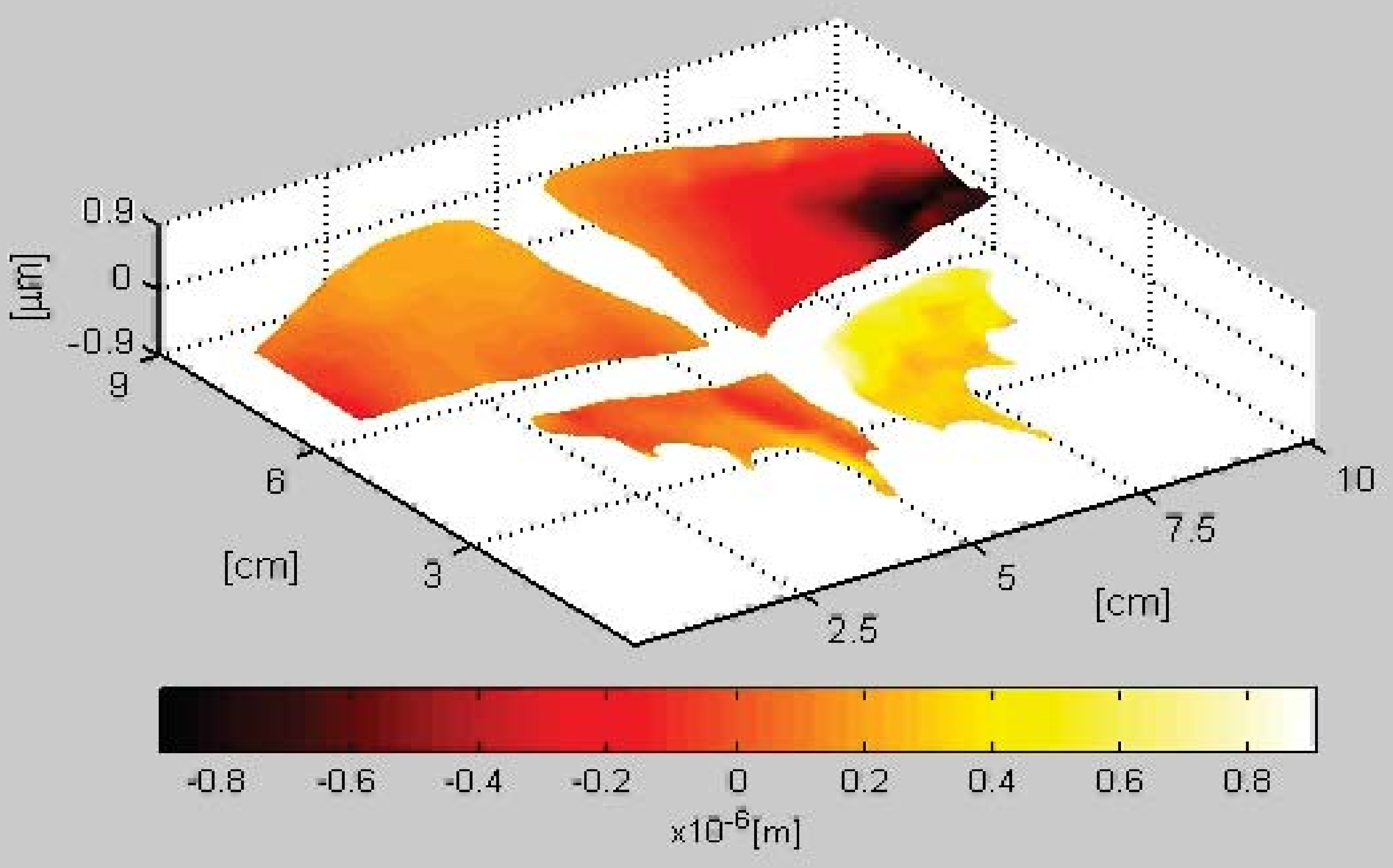
Unwrapped phase maps










0.9
0
-0.9
[µm]
9
6
3
[cm]
2.5
5
7.5
10
[cm]
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
x10-6[m]

Summary

-Interferometry is “not such an old” subject. The first ever experiment, the two slit T. Young’s interferometer, is used in today’s state of the art lasers (FEL).
- Interferometry allows the non contact more accurate measurements known today. Novel approaches are all the time on the way
- Interferometric systems are being used in many areas of Optics and Photonics, from optical shop testing to writing of Bragg gratings, to being incorporated in lab in a chip.
 Electronic Speckle Pattern Interferometry have been successfully used over the last 40 years.
- Digital Holographic Interferometry brought solutions to new challenges

ACKNOWLEDGEMENTS

MY DEEPEST APPRECIATION TO ICTP FOR HAVING INVITED ME TO CO-DIRECT THIS COURSE…….ONLY 32 YEARS AFTER I WAS ATTENDING THE “same” COURSE but as a STUDENT!!

Thank you for your kind attention