Tomographic imaging of displacement and strain fields: Current techniques and applications

Pablo D. Ruiz
Wolfson School of Mechanical and Manufacturing Engineering

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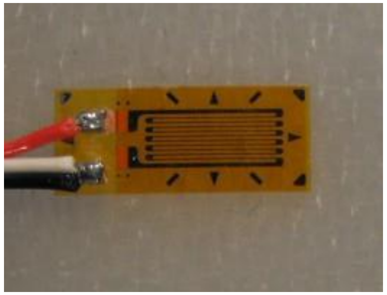
Outline

- 1-D to 3-D displacement/strain measurement
- Why 3-D strain?
- Techniques
- Comparative table
  - Spatial resolution, strain range, materials, penetration depth

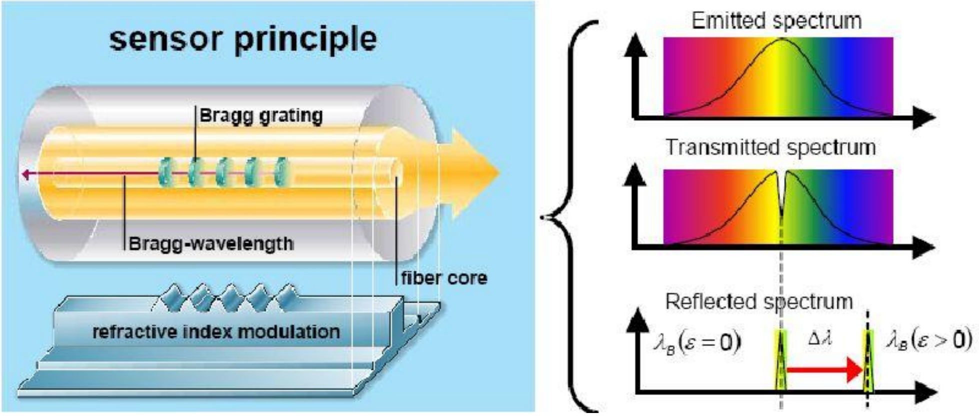
1-D strain measurement

- Extensometer

- Resistive strain gauge



- Fibre Bragg sensors

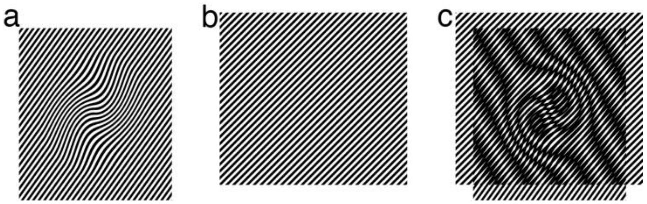


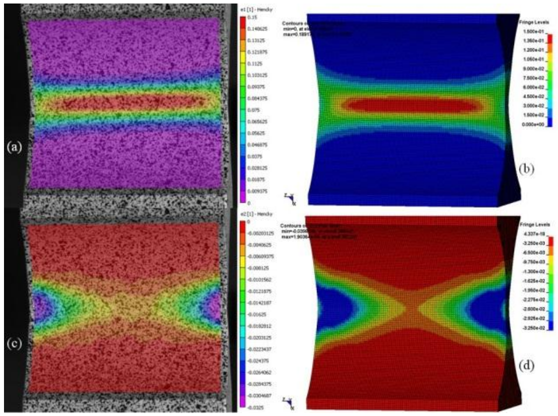
Cai, J et al. **Structural Health Monitoring for Composite Materials** *DOI: 10.5772/48215*

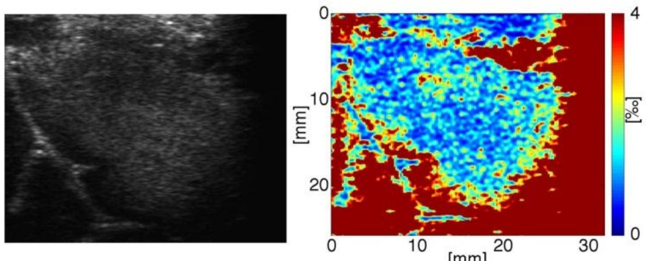
2-D strain measurement

- Arrays of 1-D sensors
- Grid method, Moiré
- Triangulation, photogrammetry
- Digital Image correlation
- Neutron diffraction
- X-ray diffraction
- Ultrasound
- Thermal stress analysis
- Photoelasticity
- Moiré Interferometry
- Speckle Interferometry

In-plane, out-of-plane and slope sensitivity







- **Static and dynamic applications**

Cai, J et al. **Structural Health Monitoring for Composite Materials** *DOI: 10.5772/48215*

3-D displacement measurement

- 1-D embedded detector arrays (SGs and FBGs)
- 3-D strain gauge rosette
- Ultrasound
- X-Ray micro CT + DVC
- Magnetic Resonance Elastography
- OCT + DVC
- Wavelength Scanning Interferometry
- Tilt Scanning Interferometry
- 3-D Photoelasticity
- Other varieties of tomographic methods with DVC (PET, acousto-optic, ND, XD, FBG arrays, etc.)

Methods for 3-D strain imaging

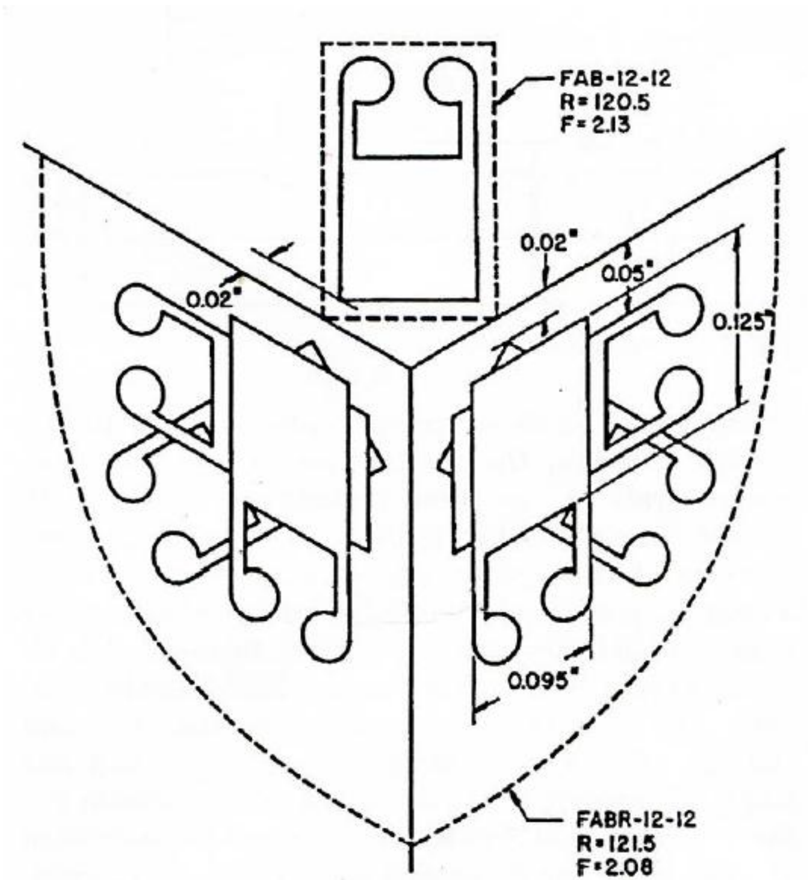
- **Algorithms**
  - Correlation
  - Phase detection

- **Mechanical Stimuli used for perturbation**
  - Quasi Static
  - Low frequency vibration (compressive/shear)

Why 3-D?

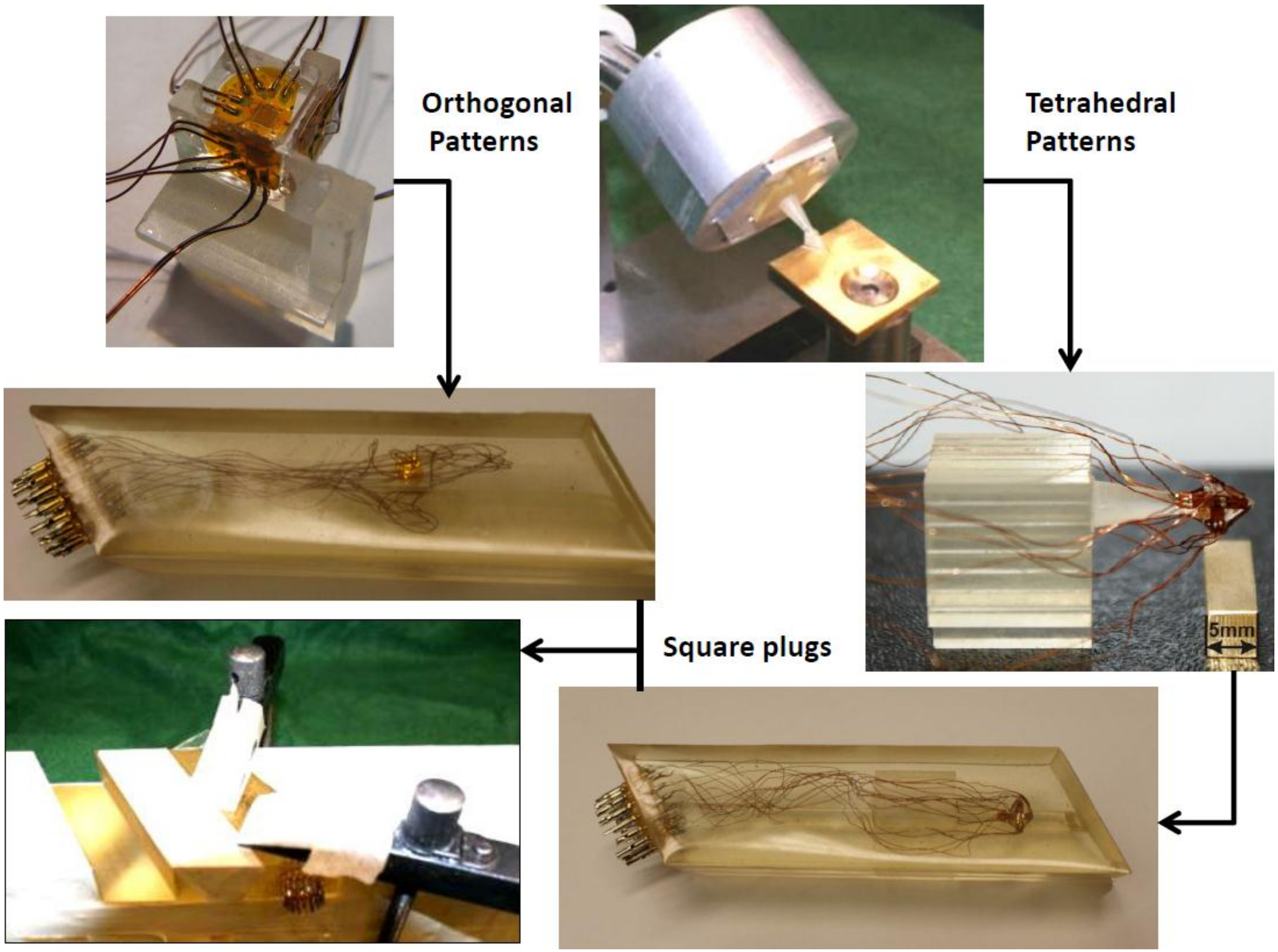
- **Experimental data** is needed to define and validate computer models
- **Material characterization / identification** of constitutive parameters. (Uniqueness issues)
- **3-D elastography** (virtual palpation)
- **Relevant in medicine and biology** (shear modulus G*)
  - In soft tissues, G* changes due to: Aging, Alzheimer's disease, Normal pressure hydrocephalus, Tumours, Multiple sclerosis, Scarring
- **Engineering** (Composites, functional materials, damage characterization, anisotropy)

The 3-D strain rosette, 1963



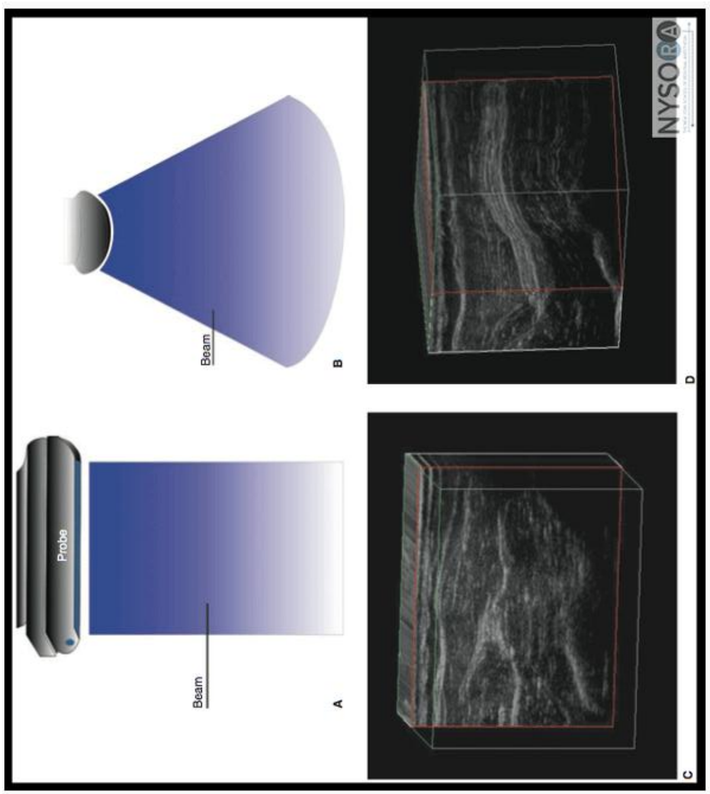
Baker, W. E. and R. C. Dove, "Construction and evaluation of a three-dimensional strain rosette." Experimental Mechanics, 3, 201-206 (1963)

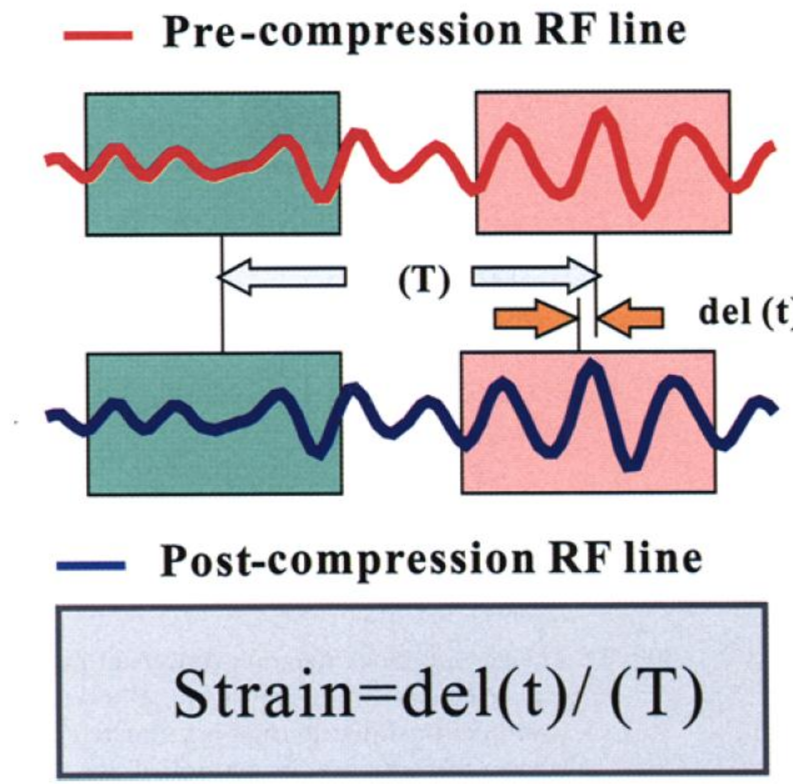
The 3-D strain rosette, 2011



Mulvihill, D.M., et al., *A Comparison of Various Patterns of Three-Dimensional Strain Rosettes.* Strain, 47, e447-e456,(2011)

Ultrasound



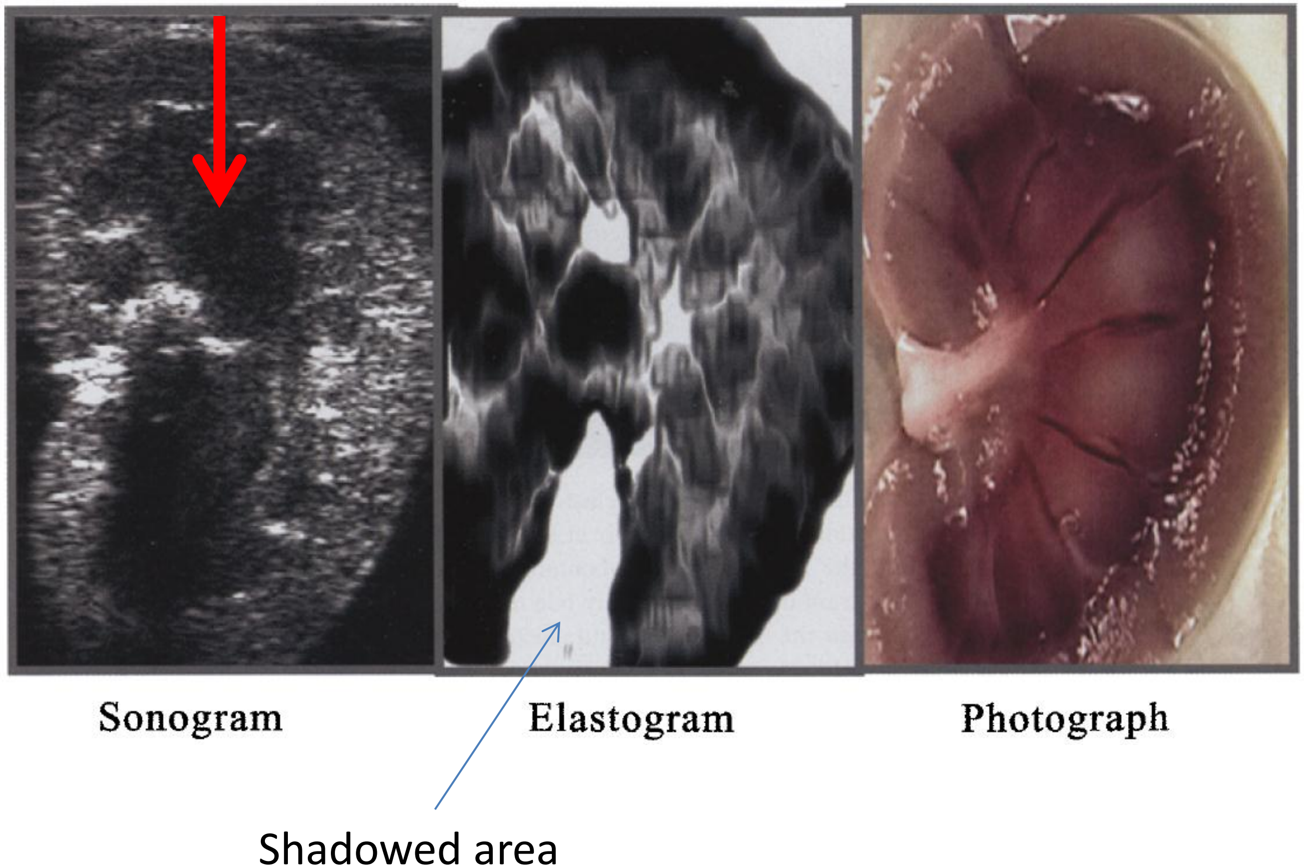


- Send acoustic pulse (few MHz) and measure echo delay
- Compare 2 states to measure displacement
- Compare displacement at 2 points to measure strain

http://www.NYSORA.com
Ophir, J., et al., *Elastography: Imaging the elastic properties of soft tissues with ultrasound.* J. Med. Ultr., **29**, 155-171 (2002).

Ultrasound elastography example

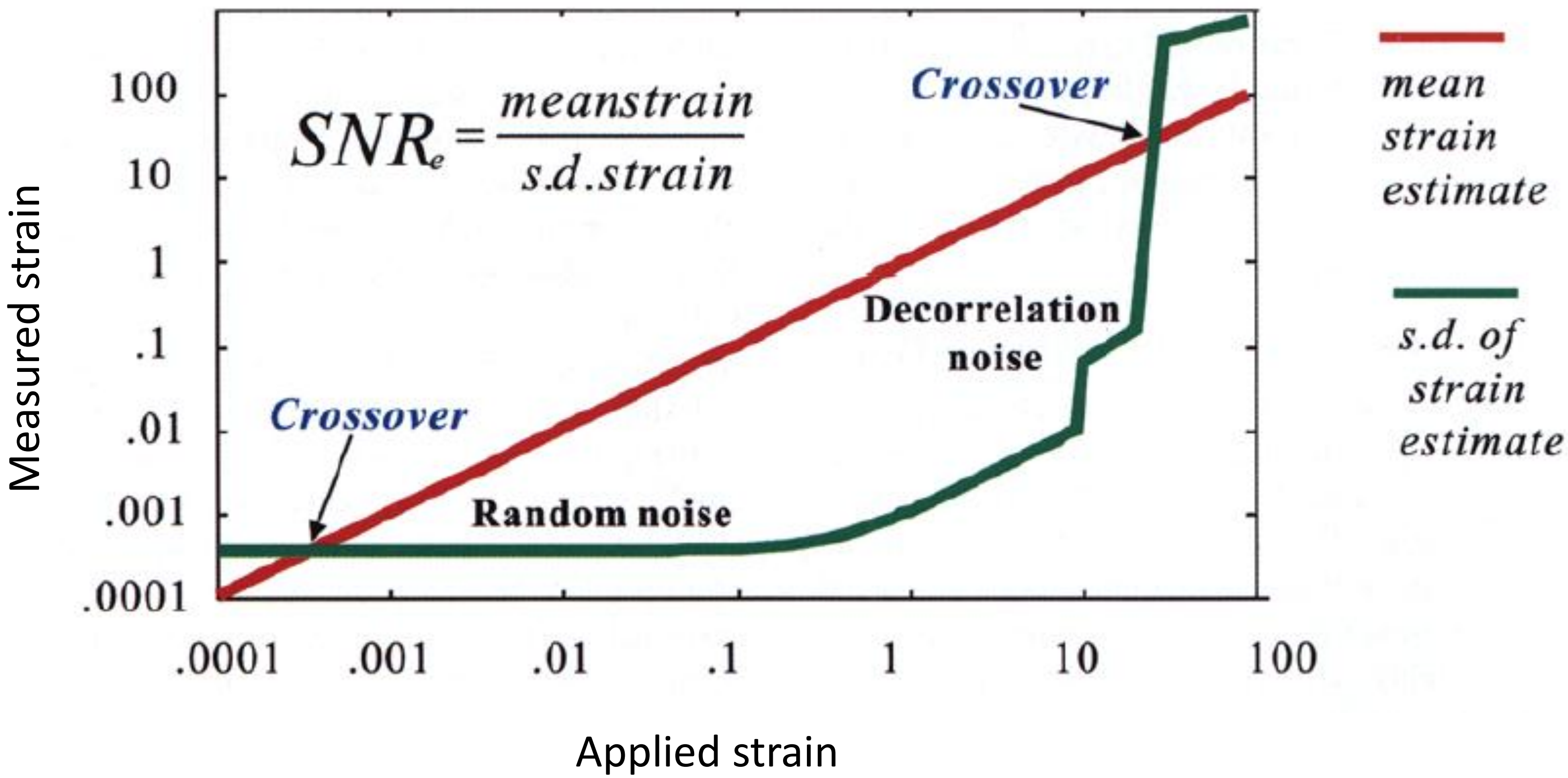
- Ovine kidney in-vitro
- Bright = 'soft'; dark = 'stiff'



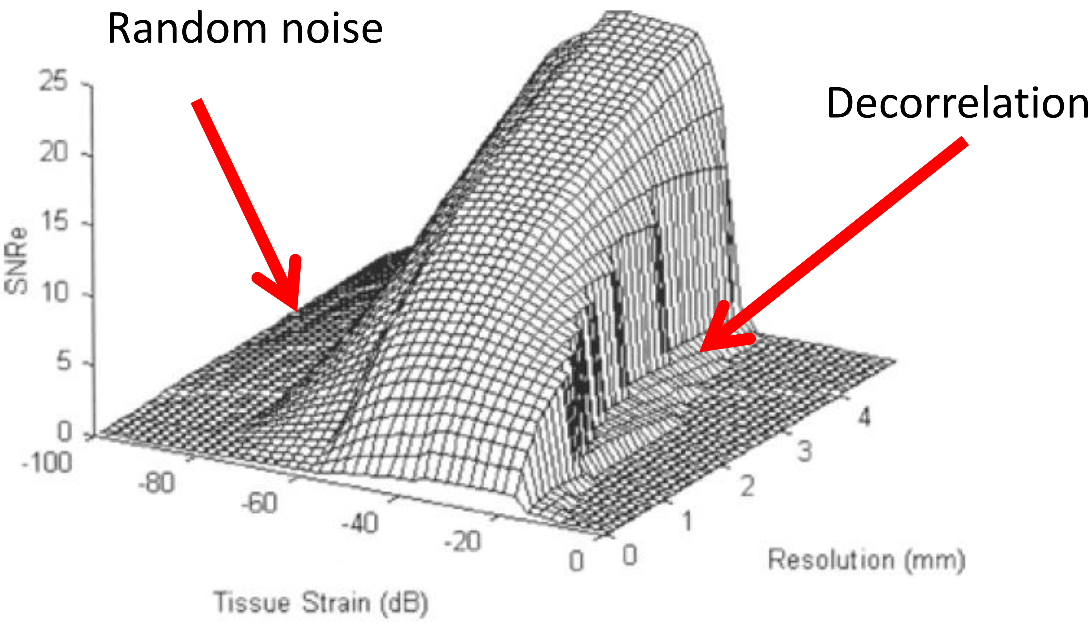
Ophir, J., et al., *Elastography: Imaging the elastic properties of soft tissues with ultrasound.* J. Med. Ultr., **29**, 155-171 (2002)

Ultrasound

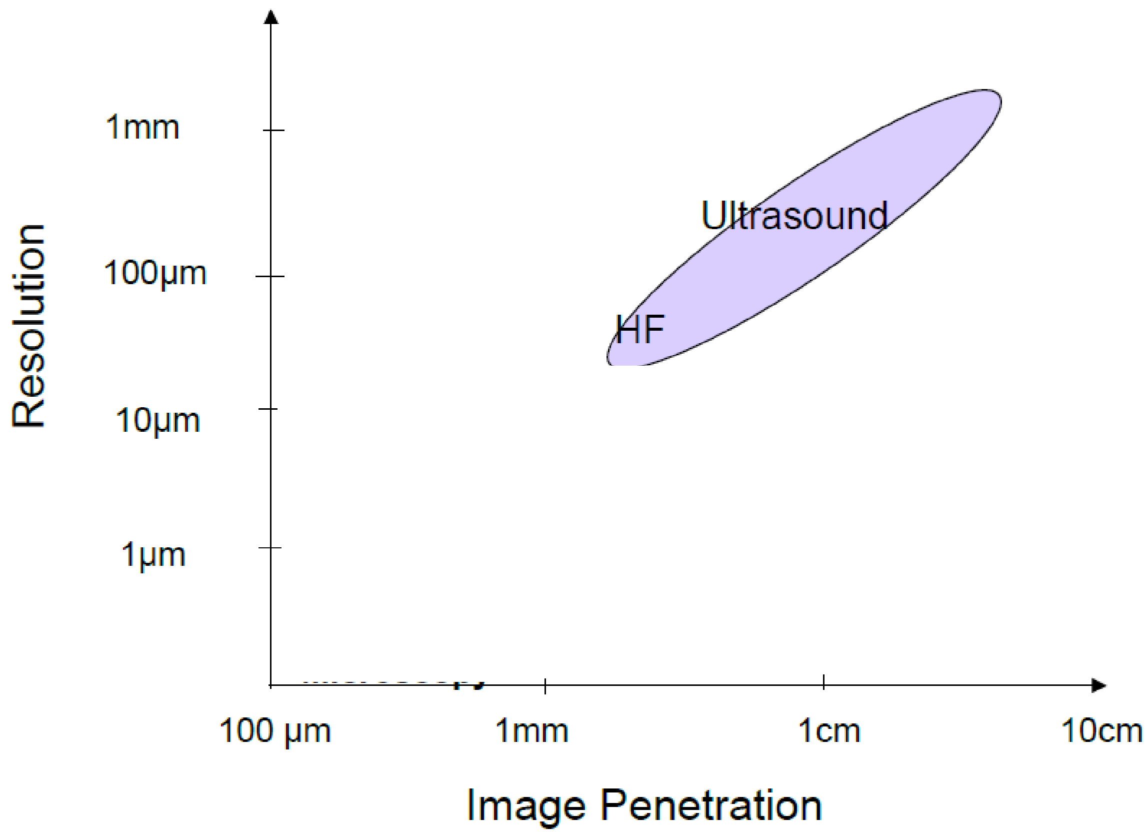
- In soft tissues: $K \sim 2\rho c$ (ρ: density, c:wave velocity ~1540m/s)
- Most attempts to map K distributions failed, as c nearly uniform in tissues (low contrast-to-noise ratio).
- Shear modulus G is the main parameter identified in US elastography.



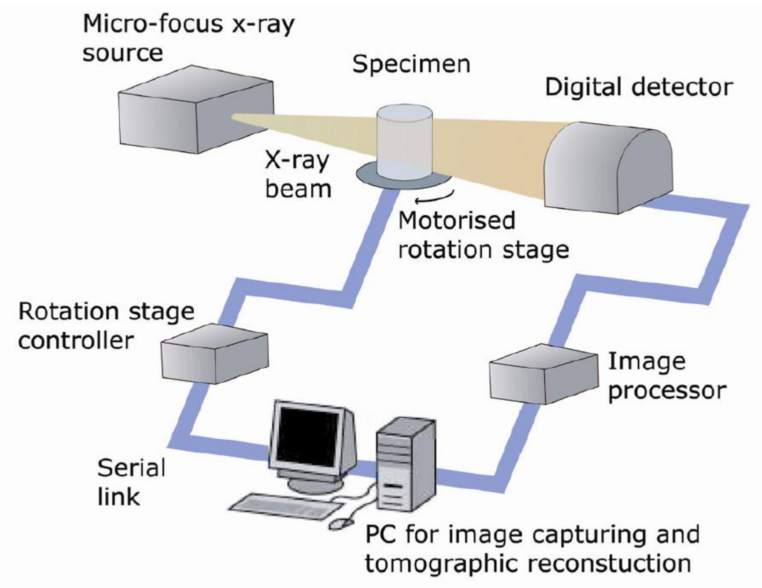
Strain Filter concept

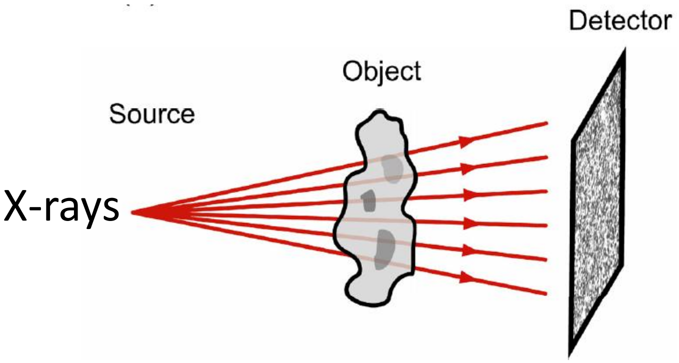


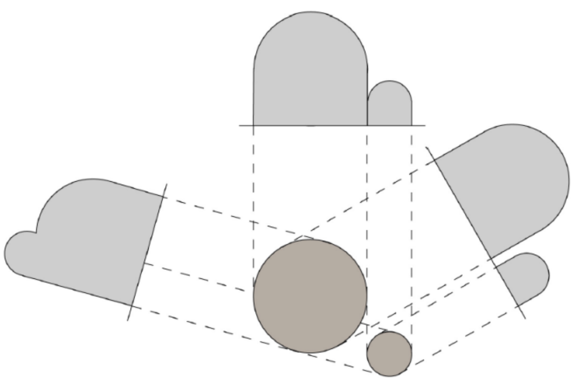
Depth and resolution

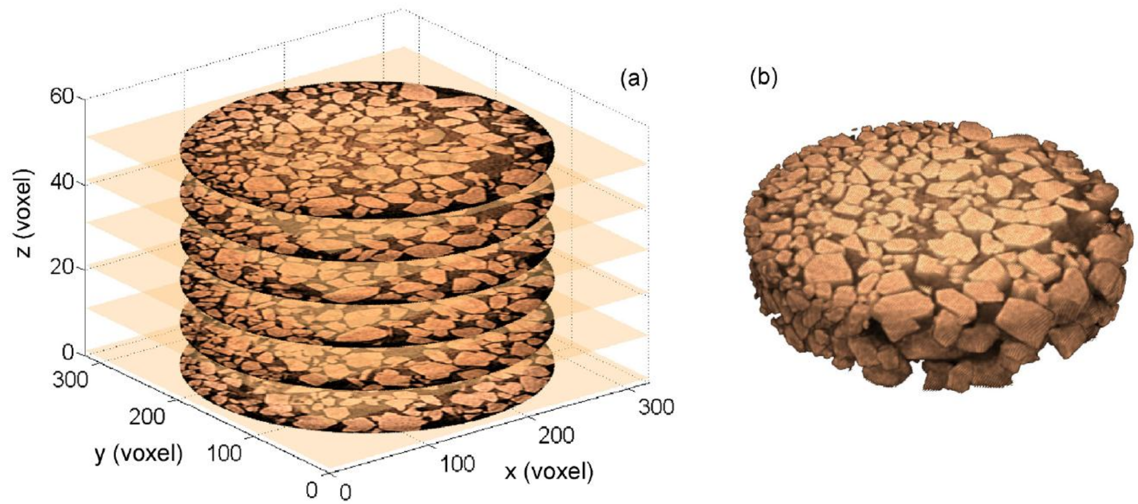


X-ray micro CT





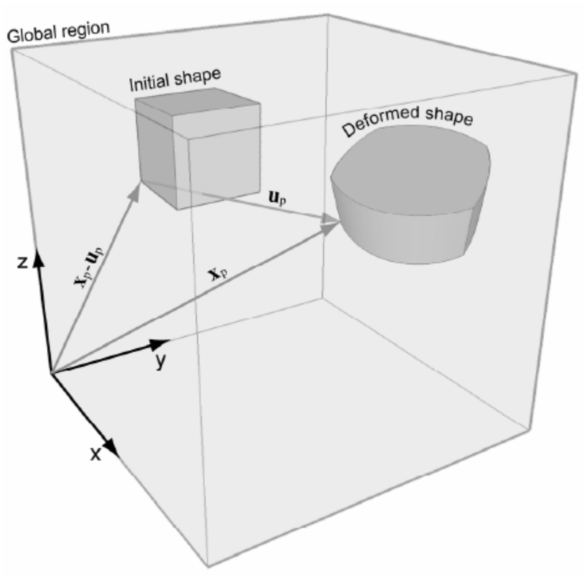


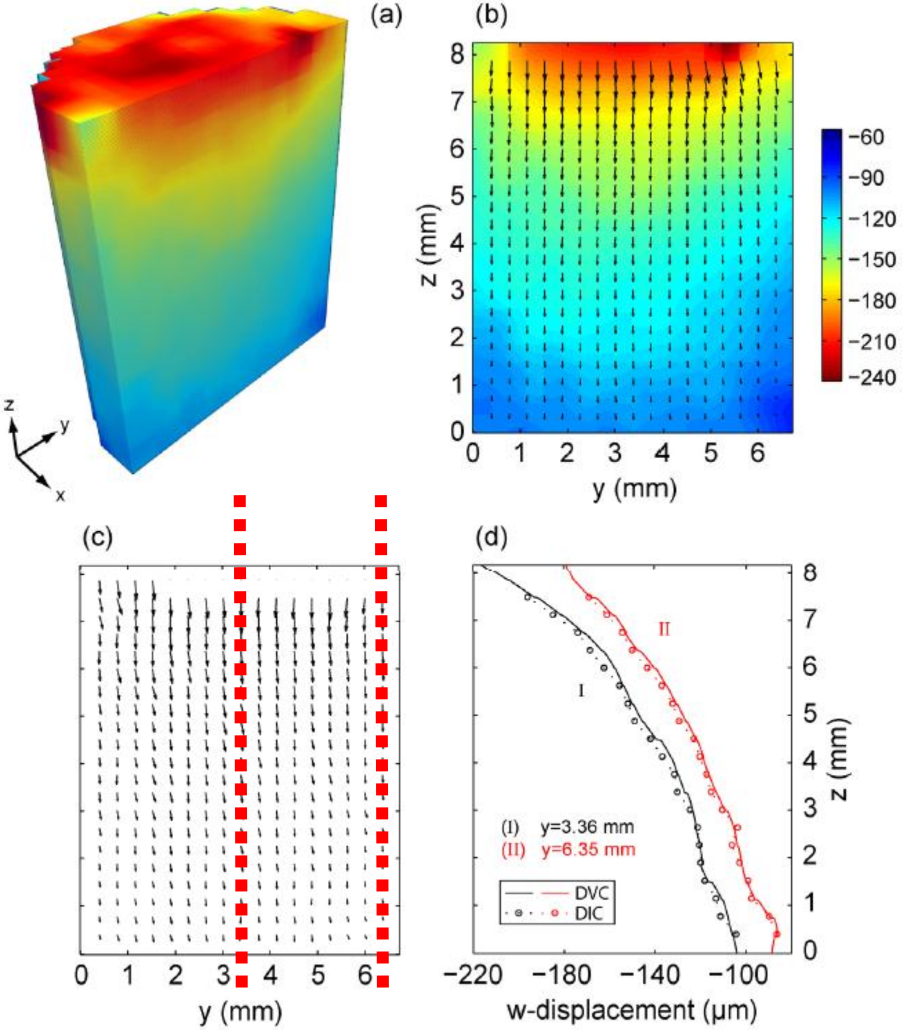


Dr. Fredrik Forsberg, PhD Thesis, Lulea University, 2008

X-ray micro CT

- Digital Volume Correlation





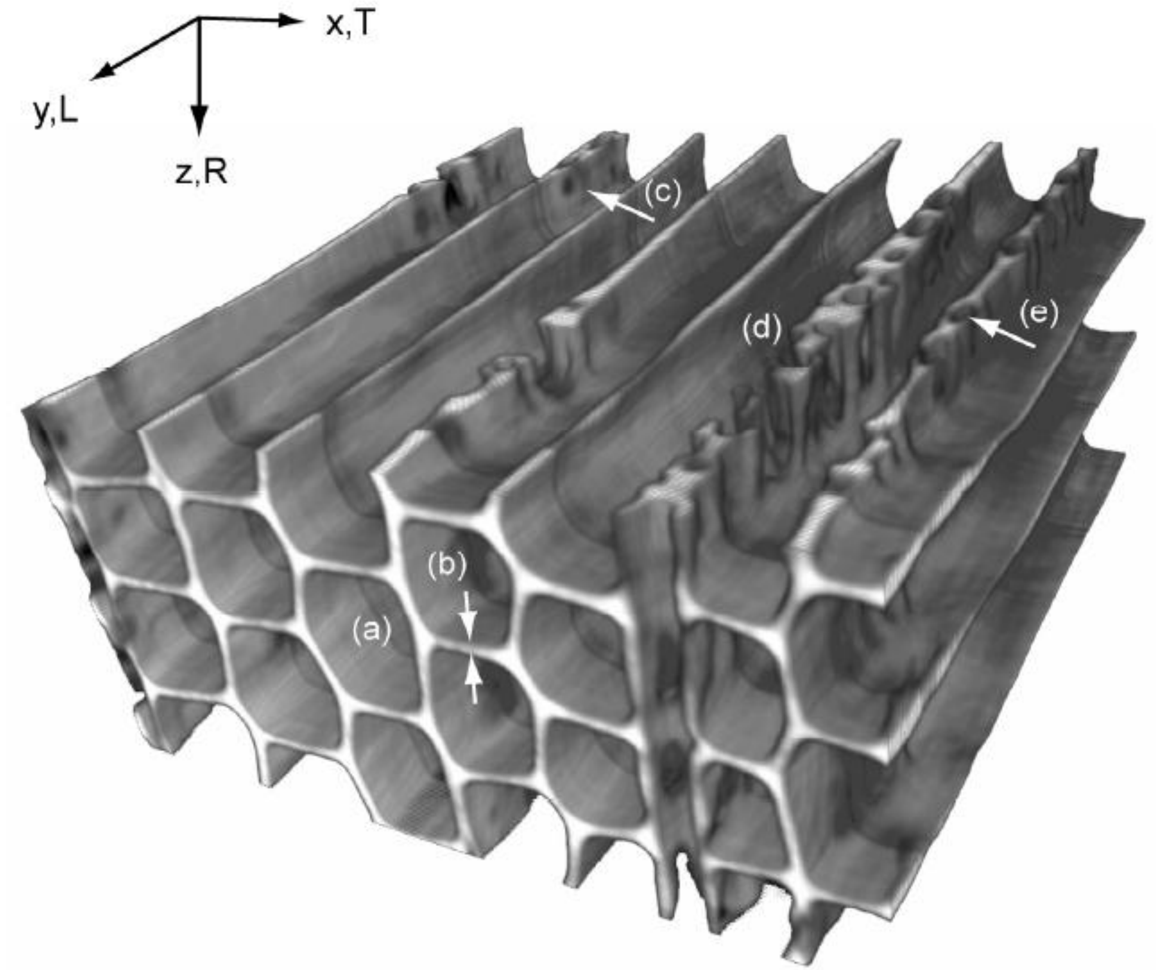
Dr. Fredrik Forsberg, PhD Thesis, Lulea University, 2008

X-ray intense source

- Synchrotron facility
  - Dynamic applications at high resolution

Dr. Fredrik Forsberg, PhD Thesis, Lulea University, 2008

X-ray micro CT



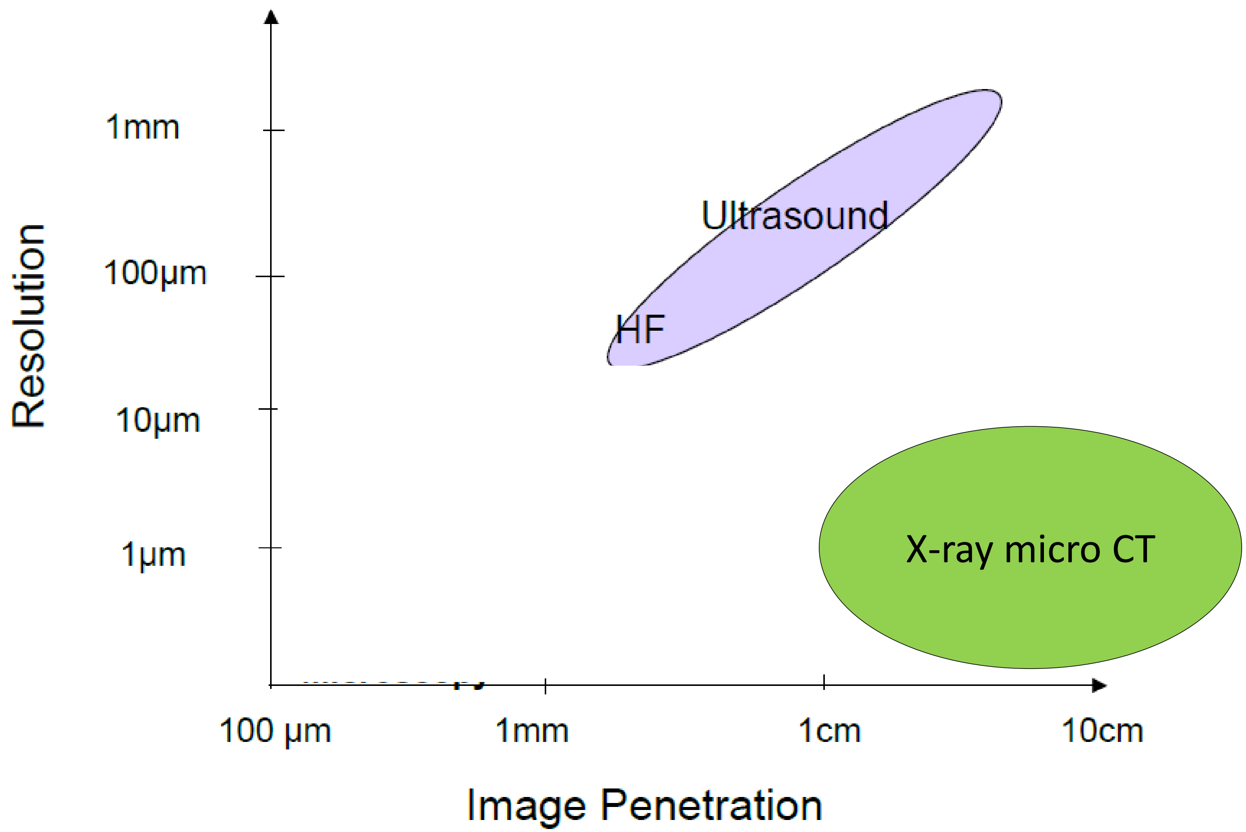
Wood microstructure, 112 × 112 × 56 μm^3

Dr. Fredrik Forsberg, PhD Thesis, Lulea University, 2008

X-ray micro CT

	Synchrotron	Desktop systems
Sample average diameter	<50 mm	<200 mm
Spatial resolution max / typical	0.2 µm / 0.2 µm	0.5 µm / 5-10 µm
Scan time	1 sec - 10 minutes	1-2 hours

Depth and resolution



Magnetic Resonance Elastography

MRI

- Measure nuclear spin precession
- Encode position using magnetic field gradients (frequency proportional to magnetic field)
- Non-magnetic samples

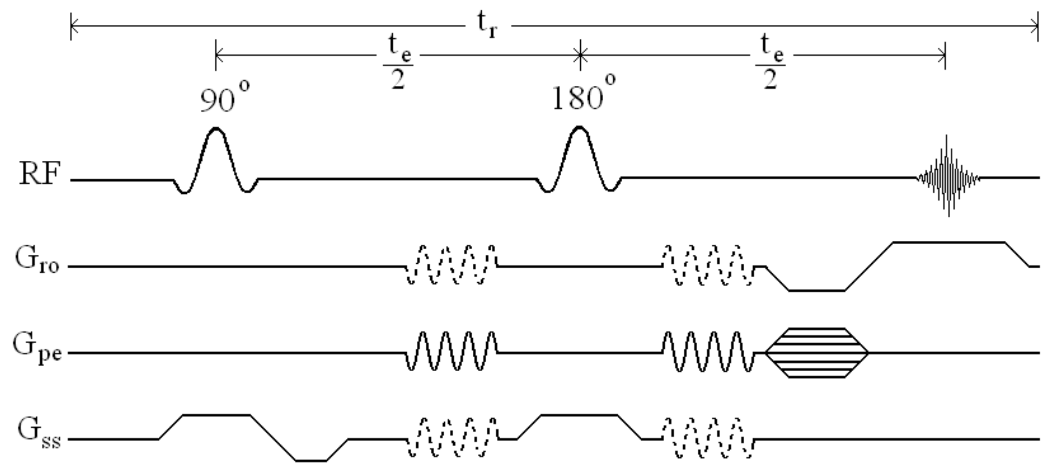
MRE

- Visualize **mechanical waves** in tissue
- Wave velocity and wavelength depend on **elastic modulus**

Phase contrast measurement of shear waves

Pulse sequence

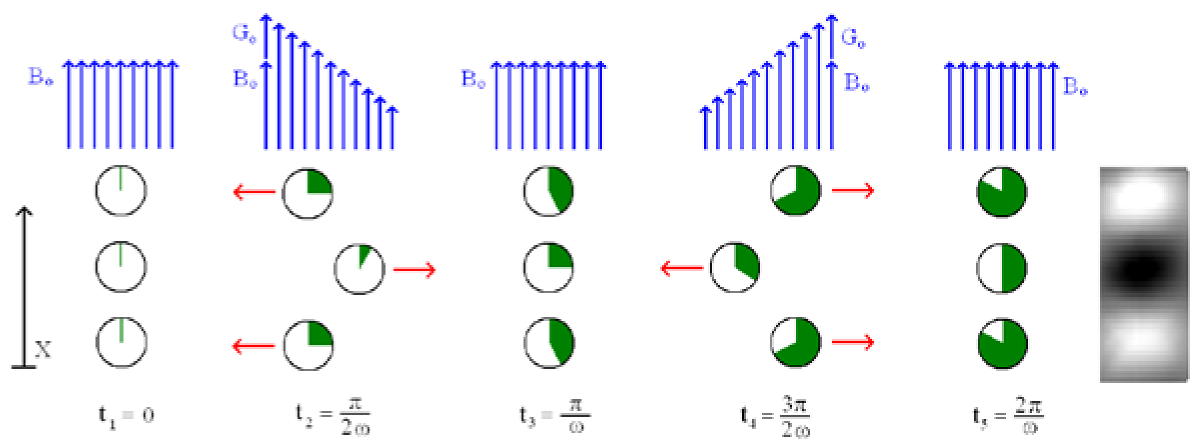
Oscillating gradients



Phase accumulation

Proportional to

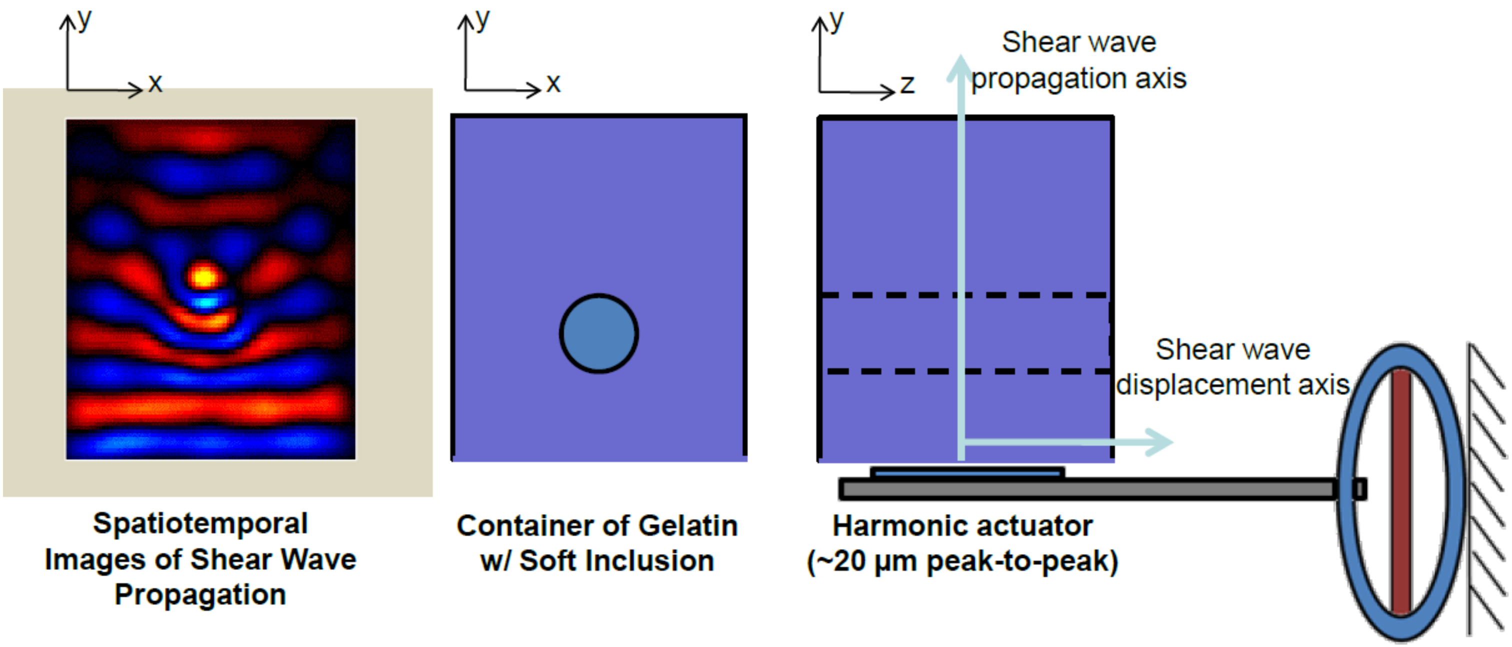
displacement



Atay, S.M., et al., *Measurement of the Dynamic Shear Modulus of Mouse Brain Tissue In Vivo by Magnetic Resonance Elastography.* Journal of Biomechanical Engineering, 2008. **130**(2): p. 021013-021013.

MRE

- Detection of mm-amplitude harmonic motion requires synchronous actuation



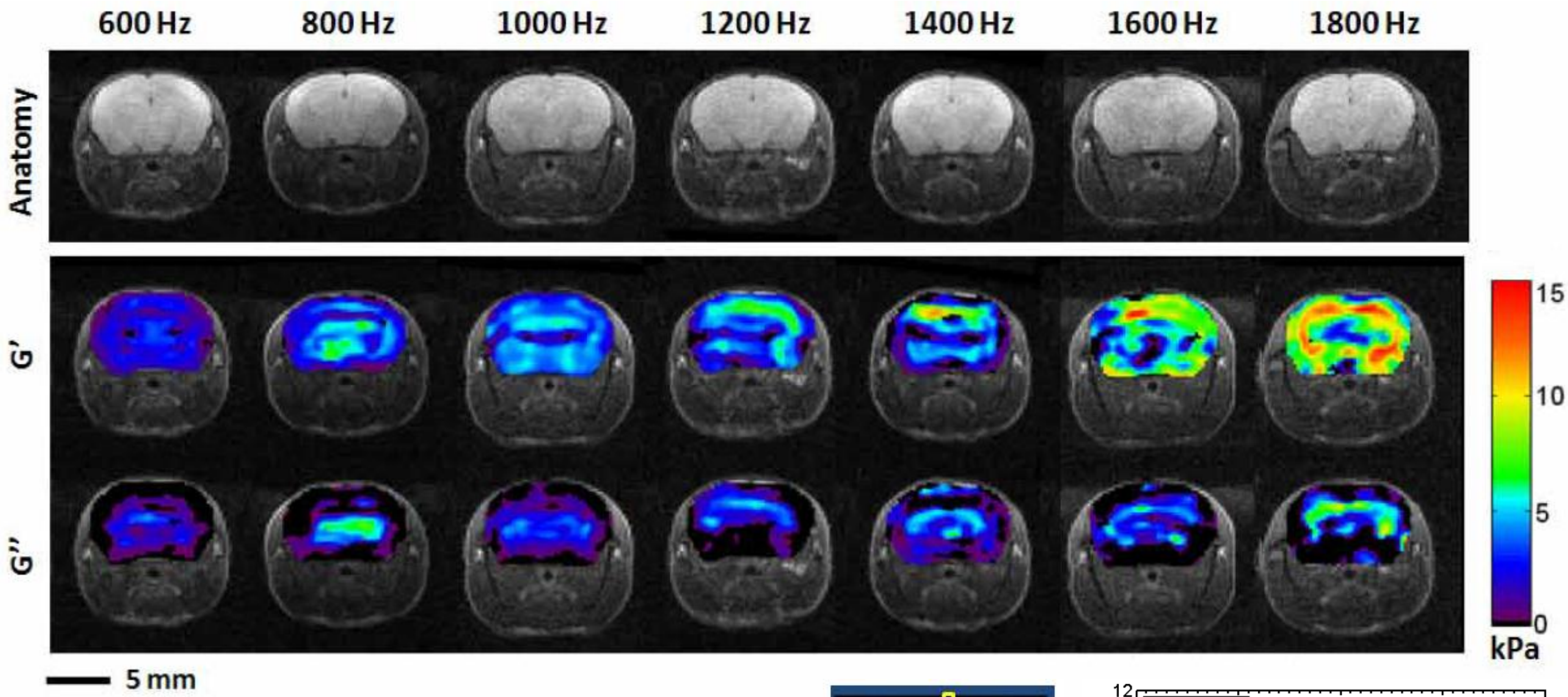
Spatiotemporal Images of Shear Wave Propagation

Container of Gelatin w/ Soft Inclusion

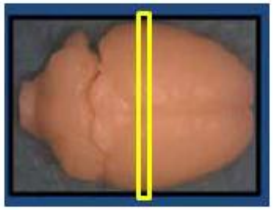
Harmonic actuator (~20 μm peak-to-peak)

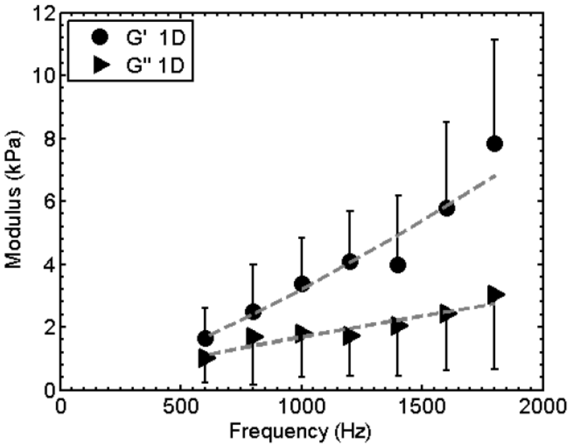
(Erik Clayton)

Mouse brain



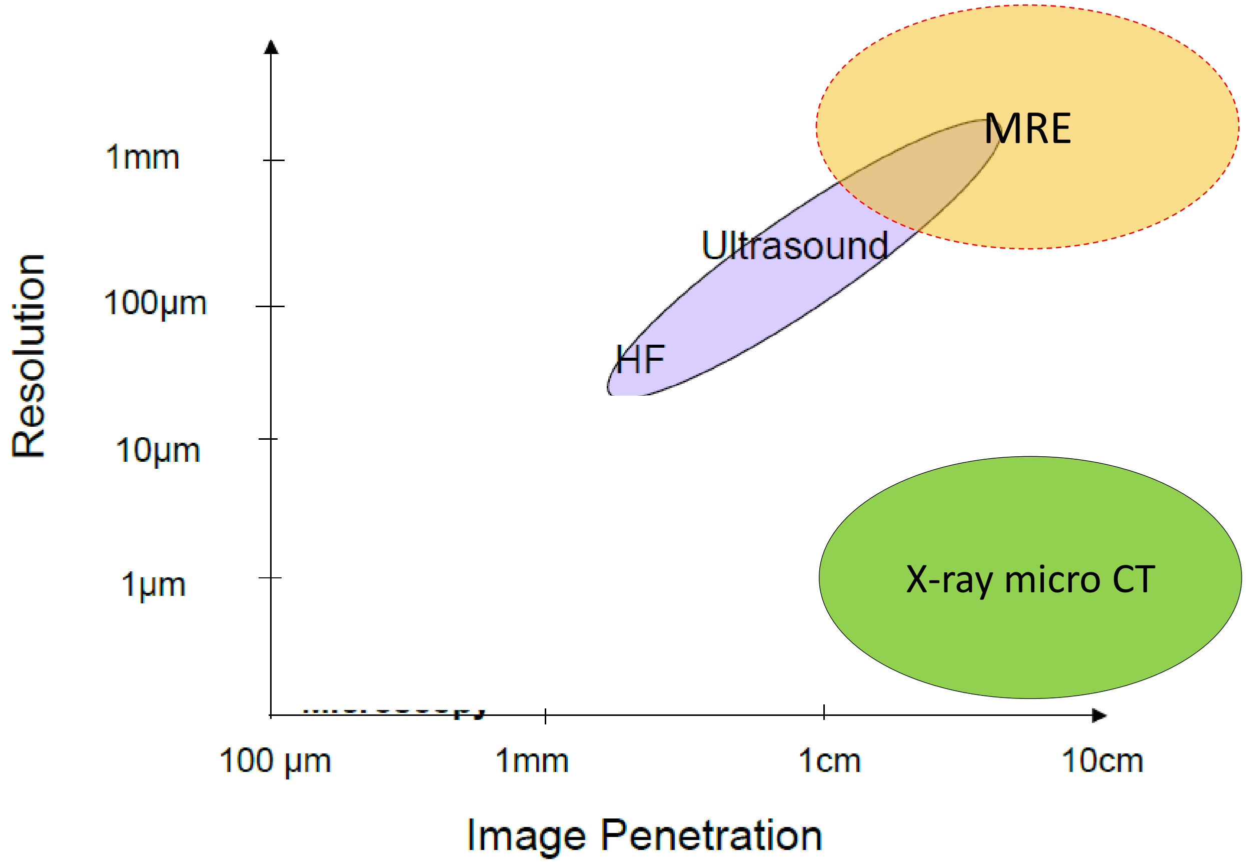
Voxel size: $0.25 \times 0.25 \times 0.25 mm^3$





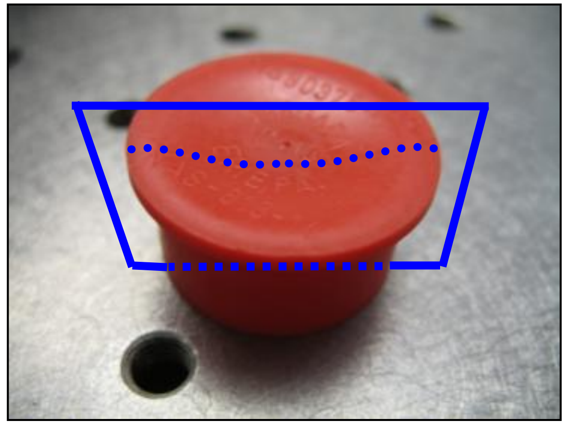
Clayton, E.H., J.R. Garbow, and P.V. Bayly, *Frequency-dependent viscoelastic parameters of mouse brain tissue estimated by MR elastography.* Physics in Medicine and Biology, 2011. **56**(8): p. 2391

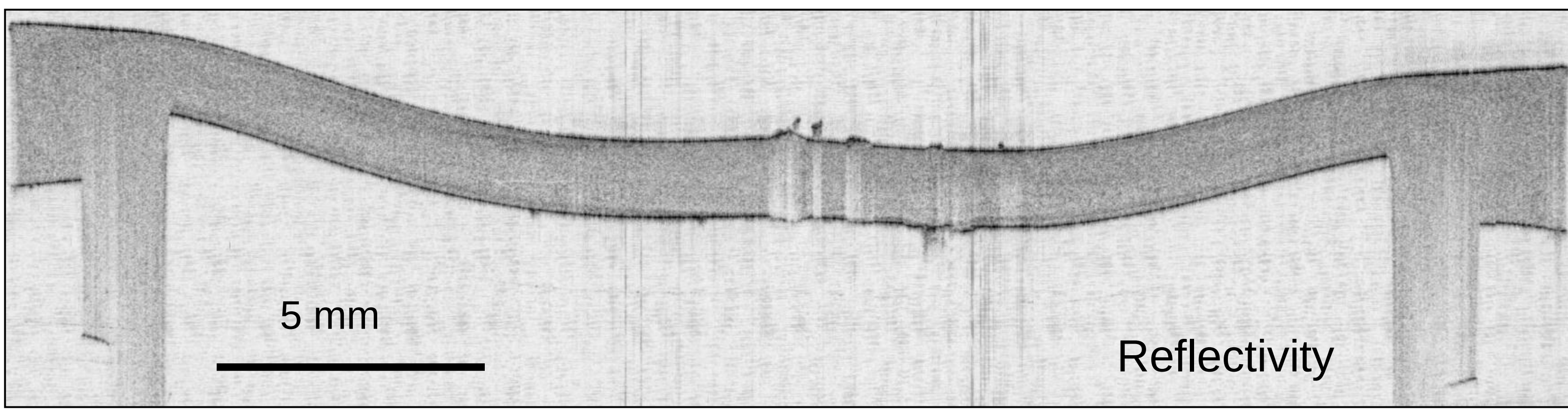
Depth and resolution



Optical Coherence Tomography

polymer injection
moulded part

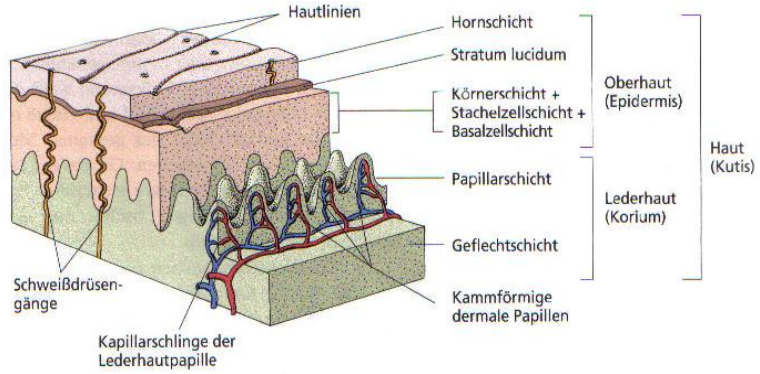


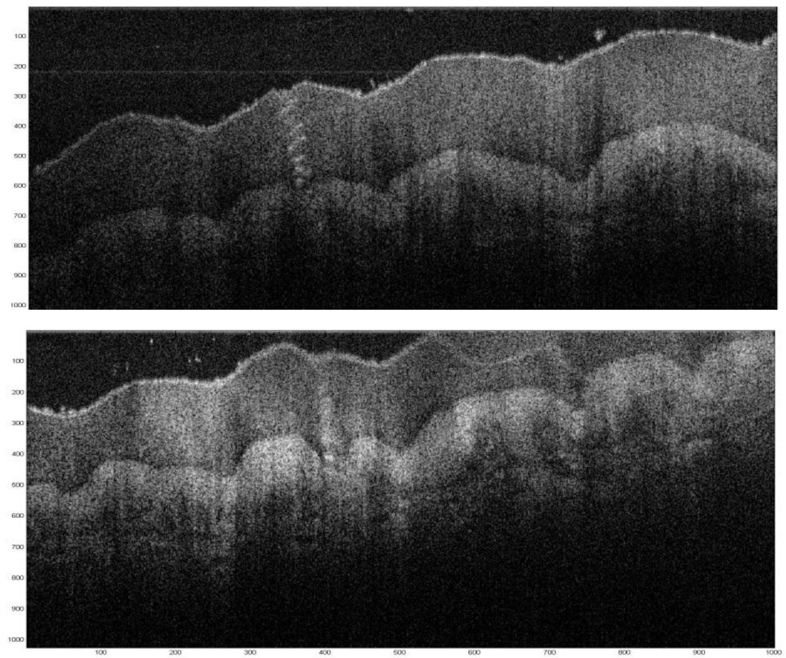


Courtesy David Stifter, Upper Austrian Research GmbH

Optical Coherence Tomography

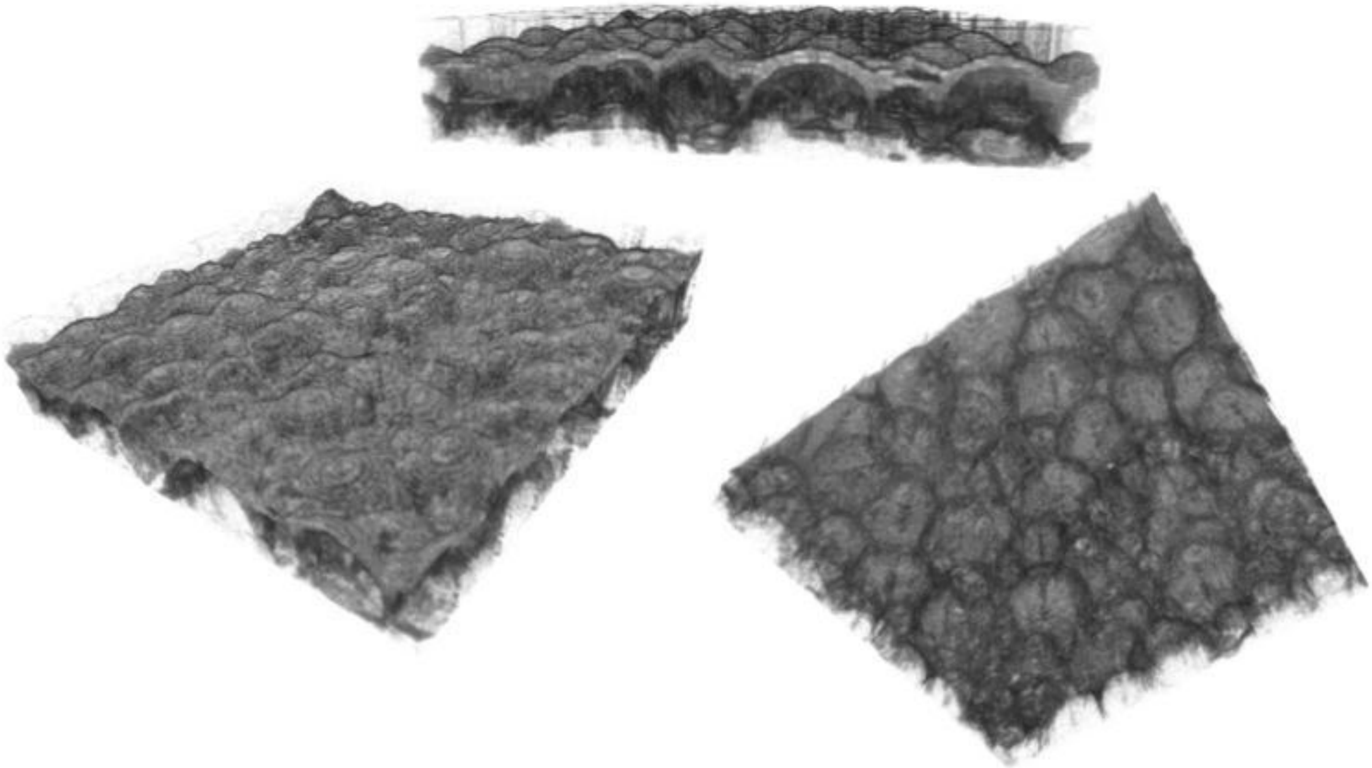
human skin





Courtesy David Stifter, Upper Austrian Research GmbH

Optical Coherence Tomography



Polyolefin foams

Courtesy David Stifter, Upper Austrian Research GmbH

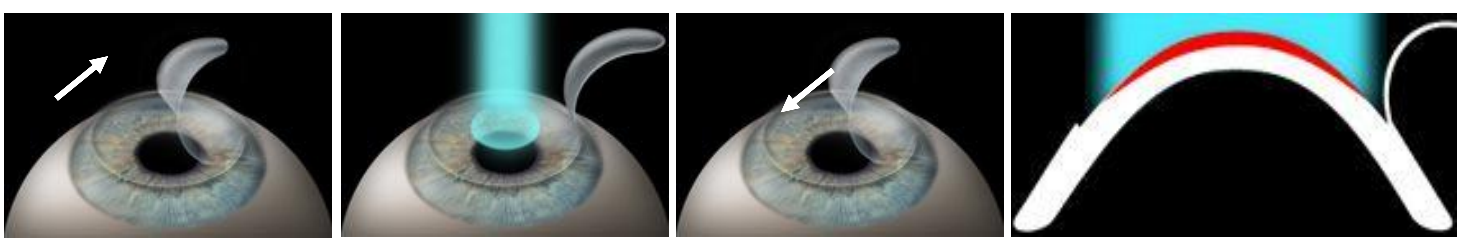
Measurement of 3-D corneal displacements using DVC + OCT

Motivation

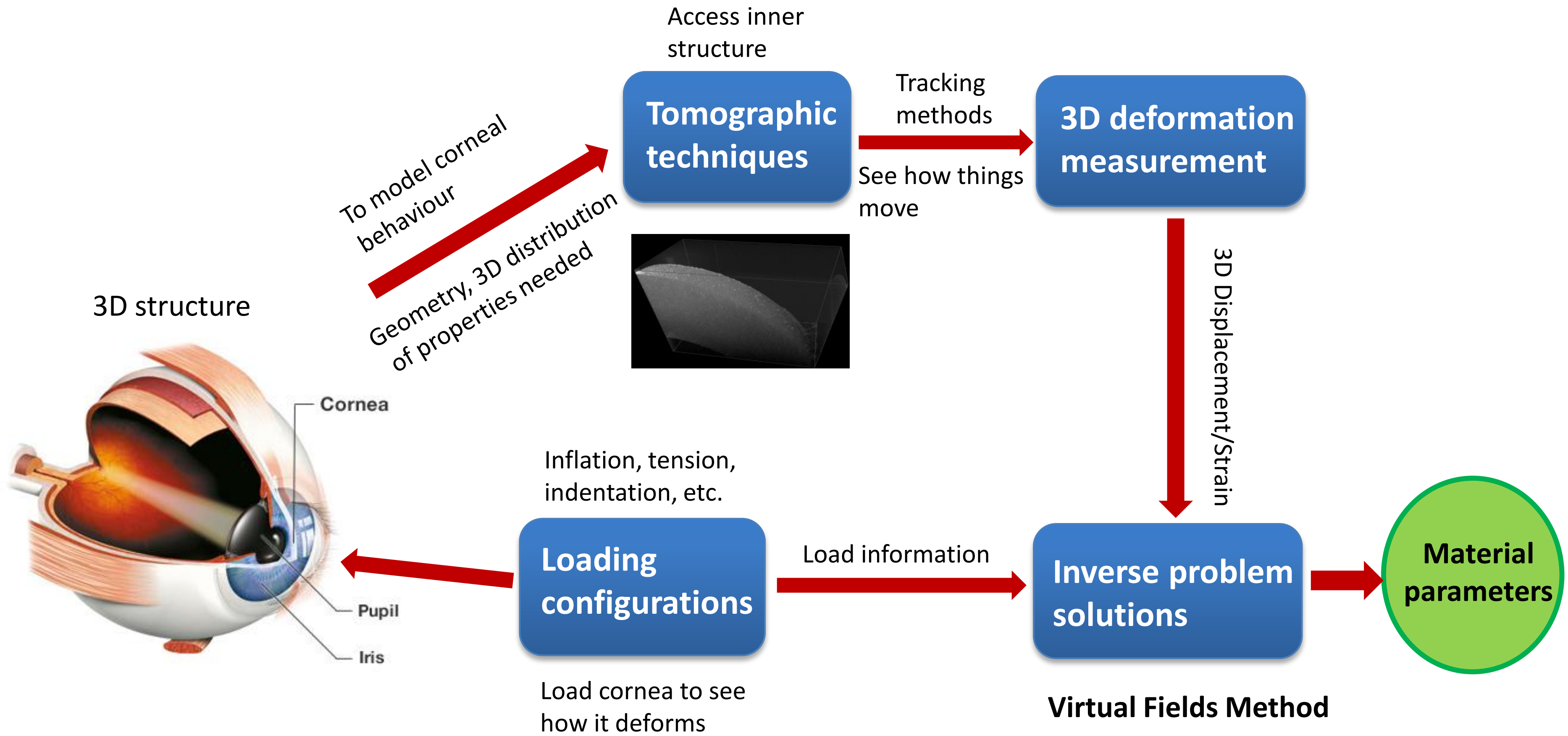
To use corneal mechanical response, rather than only corneal thickness, as the criteria to perform refractive surgery.

Long term objective

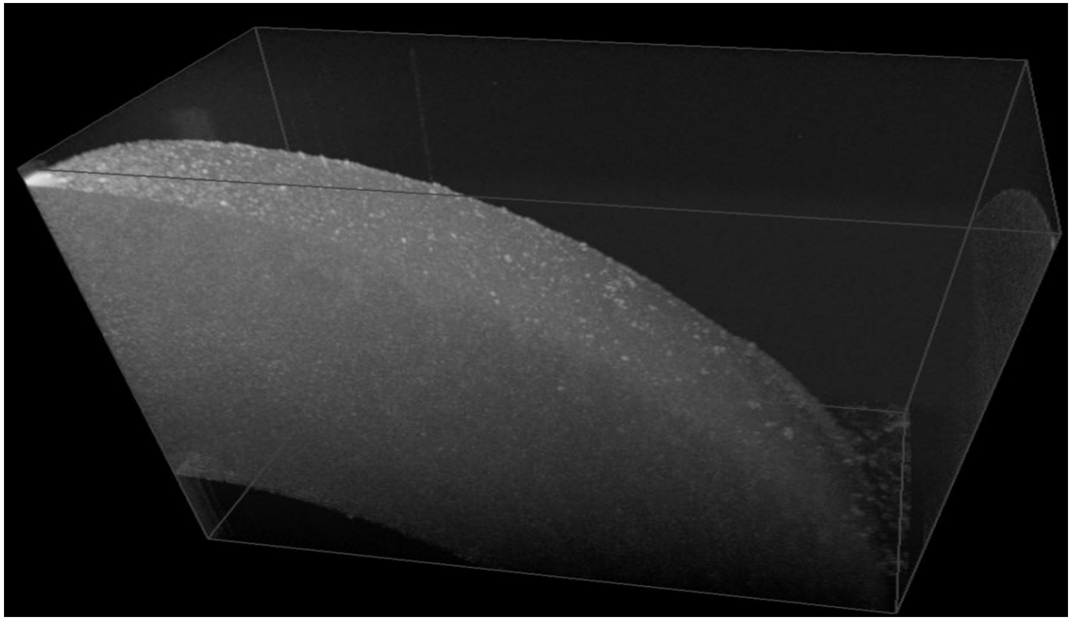
- Measure internal 3D deformation field
- Identify depth-resolved constitutive parameters
- Predict corneal mechanical behaviour during/after ablative surgery

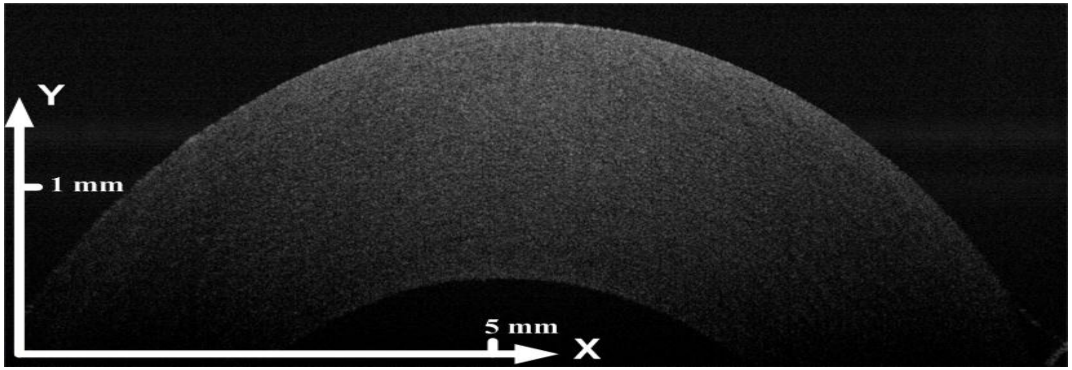


Methodology



Optical coherence tomography



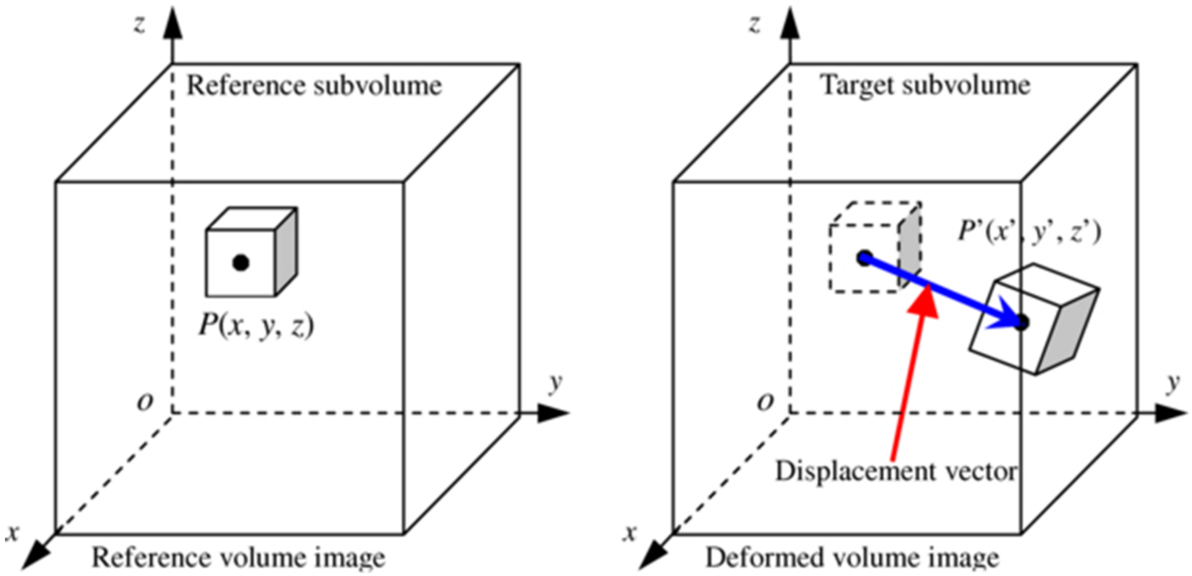


1024 × 512 × 1024 voxels data volume

Acquisition time ~ 3 minutes

3D displacement fields

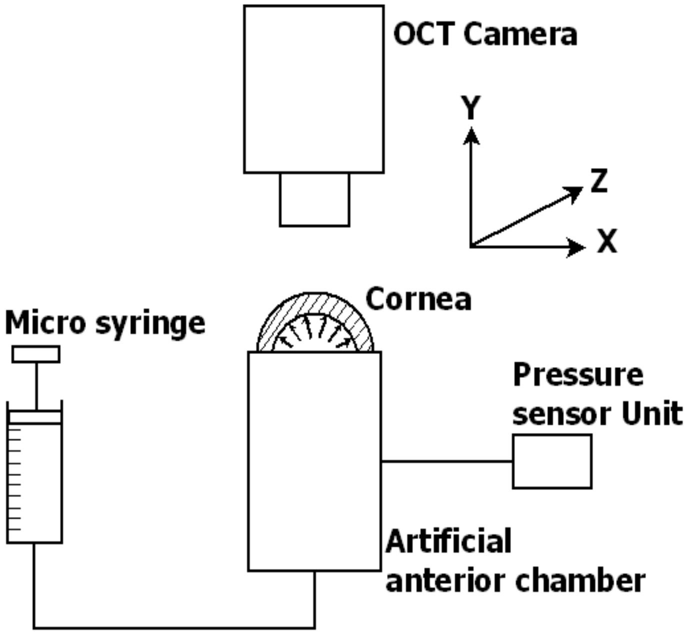
Digital volume correlation

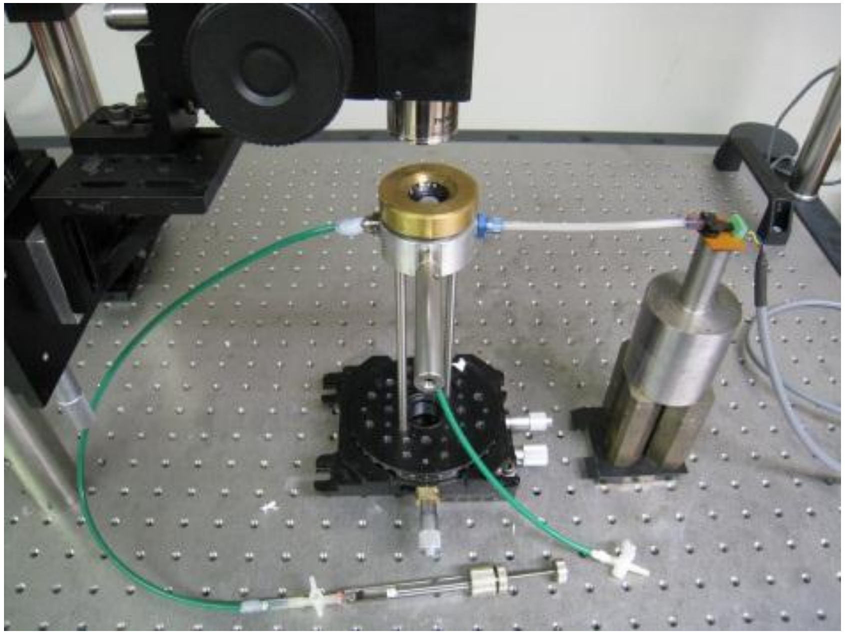


- Volume divided into sub-volumes.
- Displacement vector obtained from tracking and matching voxels between sub-volumes in reference and deformed states

LaVision, Digital Volume Correlation (DVC) package

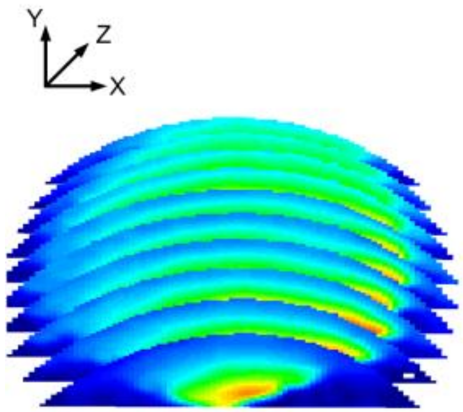
Inflation test

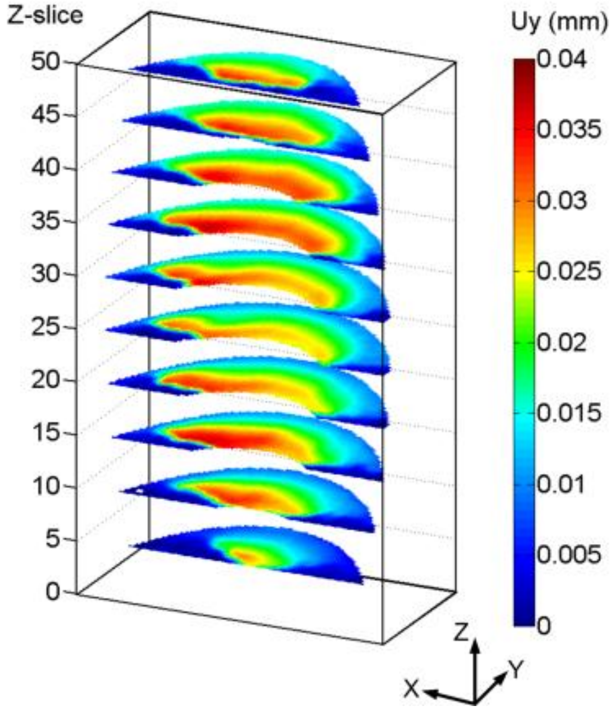


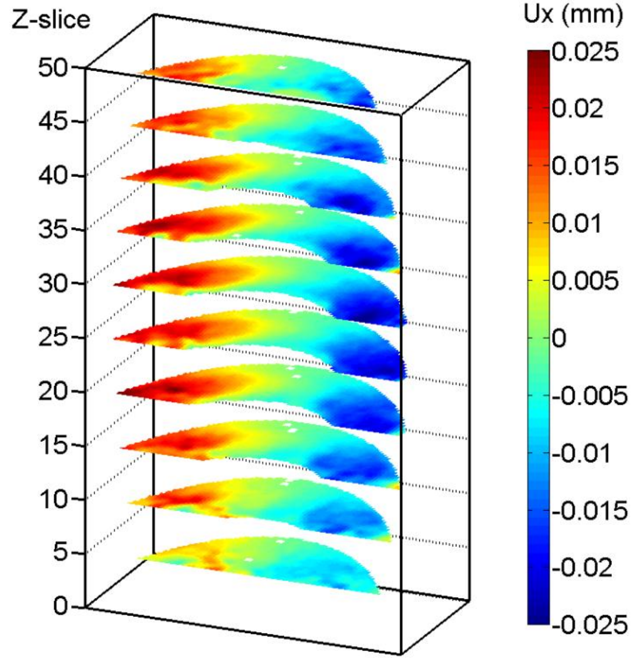


- Swept Source Optical Coherence Tomography system (Thorlabs OCS1300SS).
- Porcine corneas inflated from 2 to 2.5 kPa

Inflation test



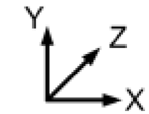




- 24^3-voxel sub-volume, 50% overlap
- Inflated from 2 to 2.5 kPa

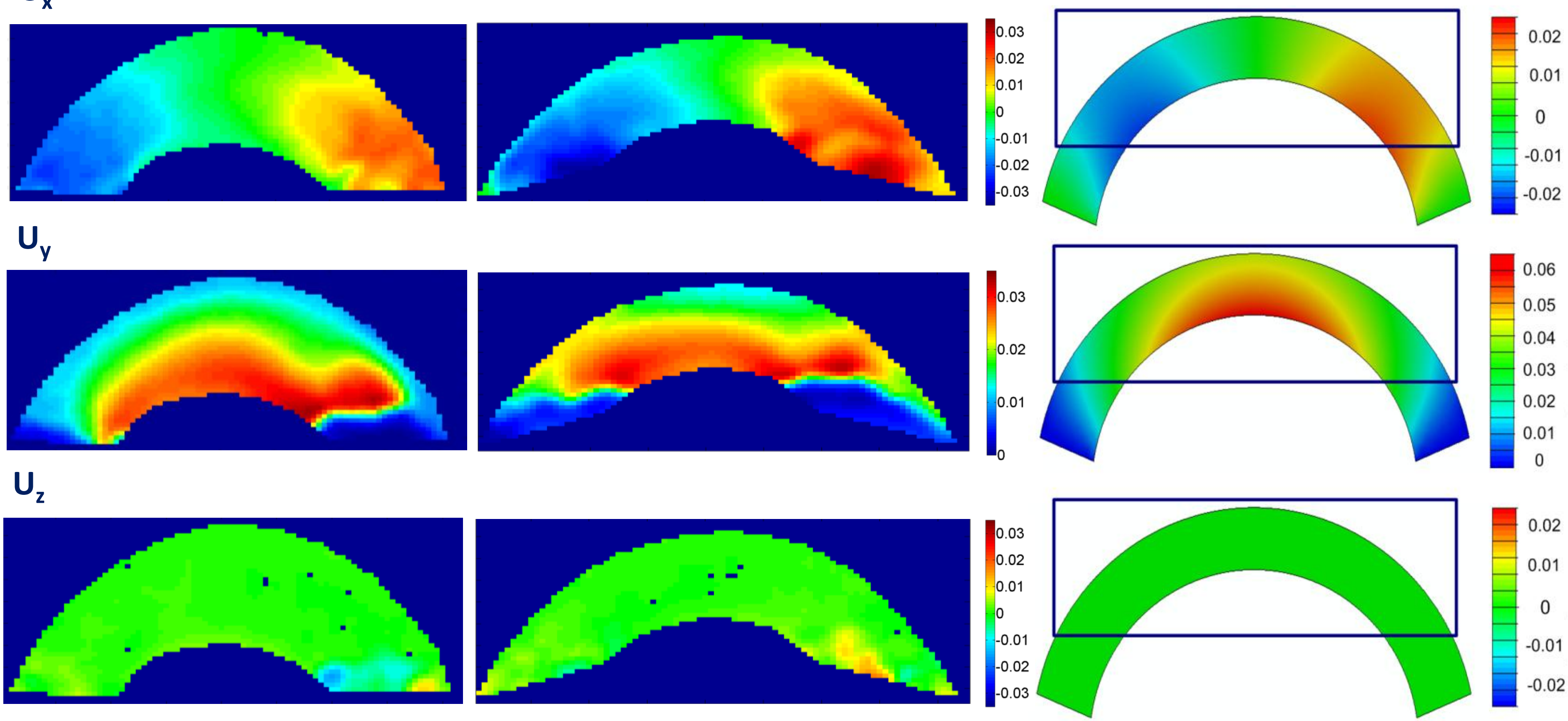
Displacement

Displacement maps for a central z-slice for inflation from 2 to 2.5 kPa



Before refraction correction | **After correction** | **FEM**

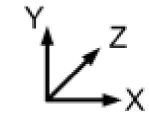
U_x



E=0.3 Mpa; v=0.49 (from literature)

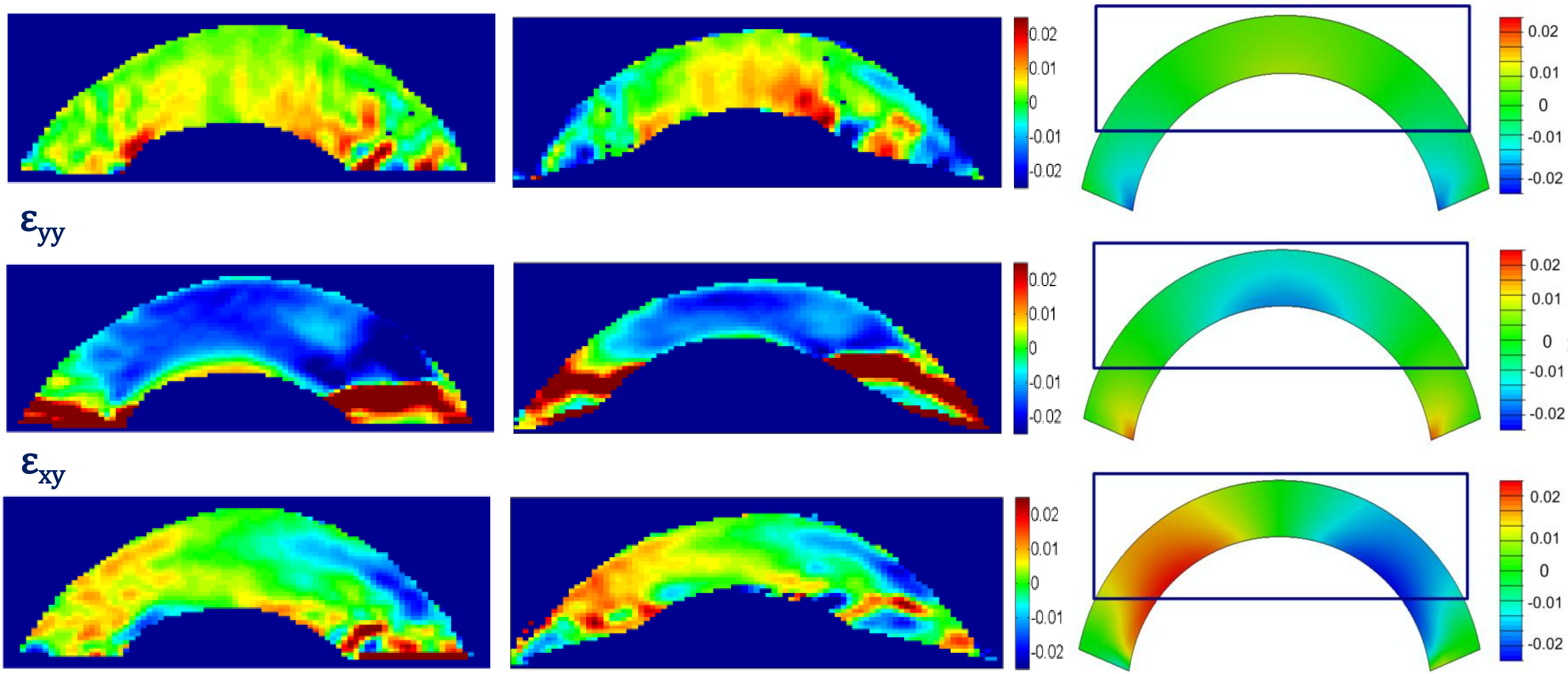
Strain

Strain maps for a central z-slice for inflation from 2 to 2.5 kPa

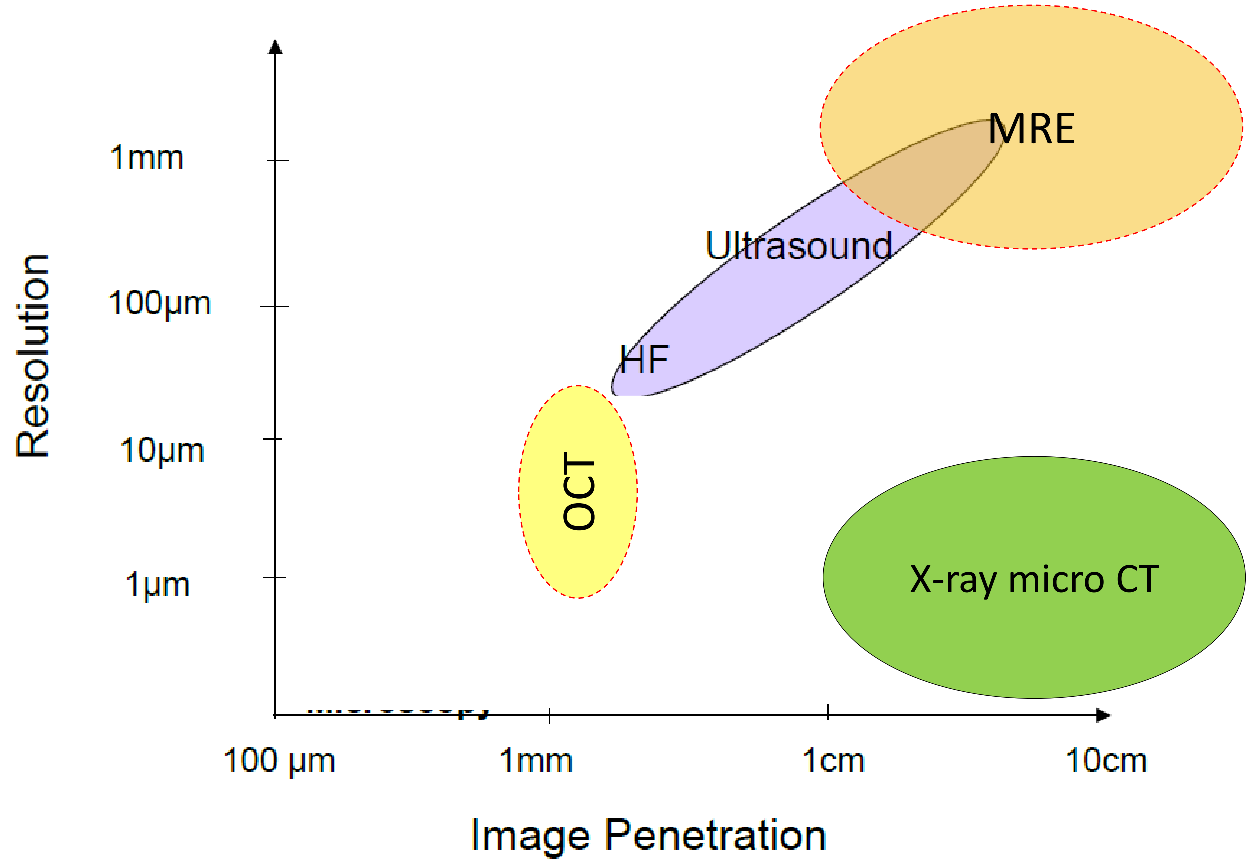


Before refraction correction | **After correction** | **FEM**

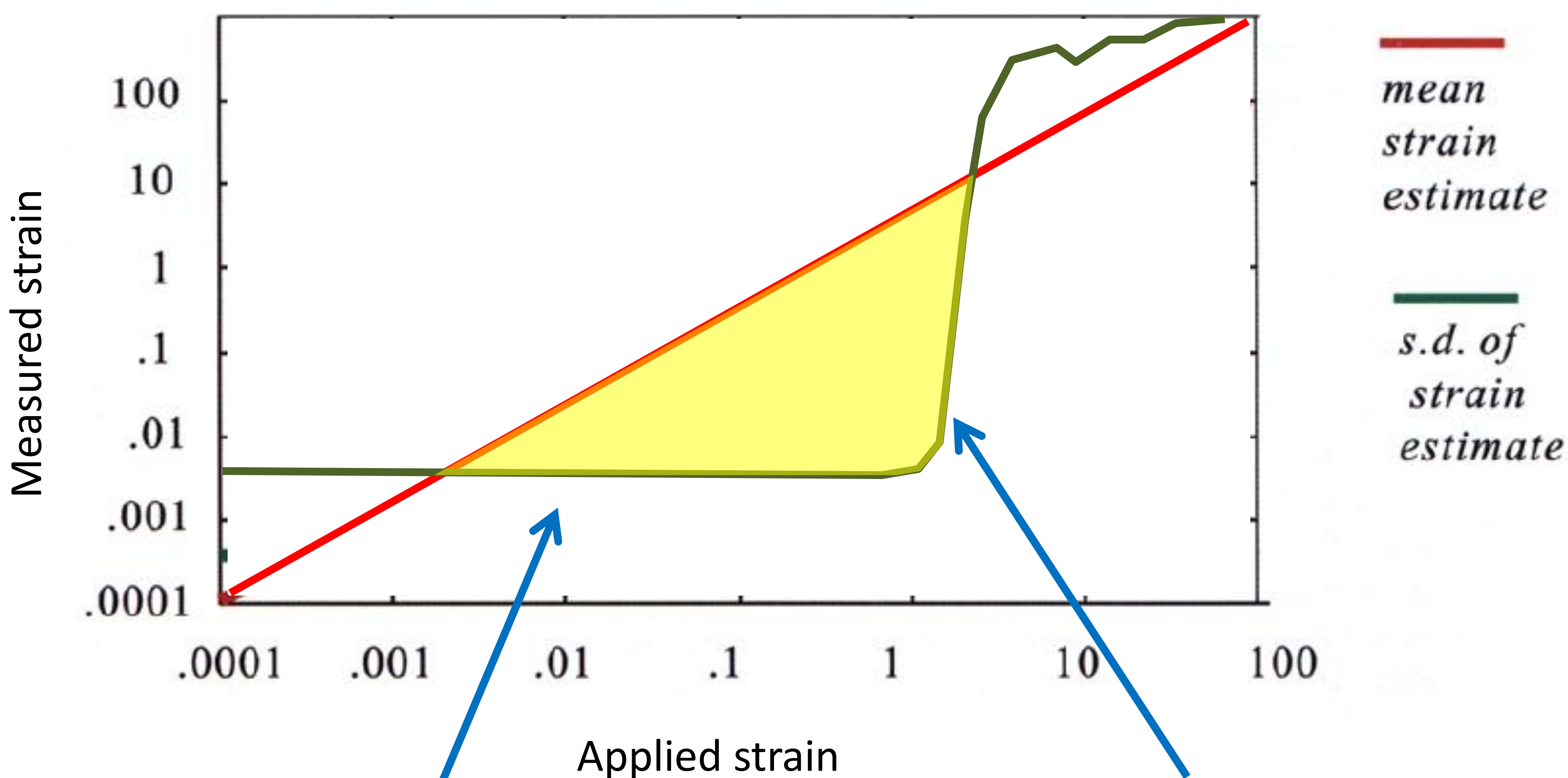
ε_{xx}, ε_{yy}, ε_{xy}



Depth and resolution



OCT & DVC noise study

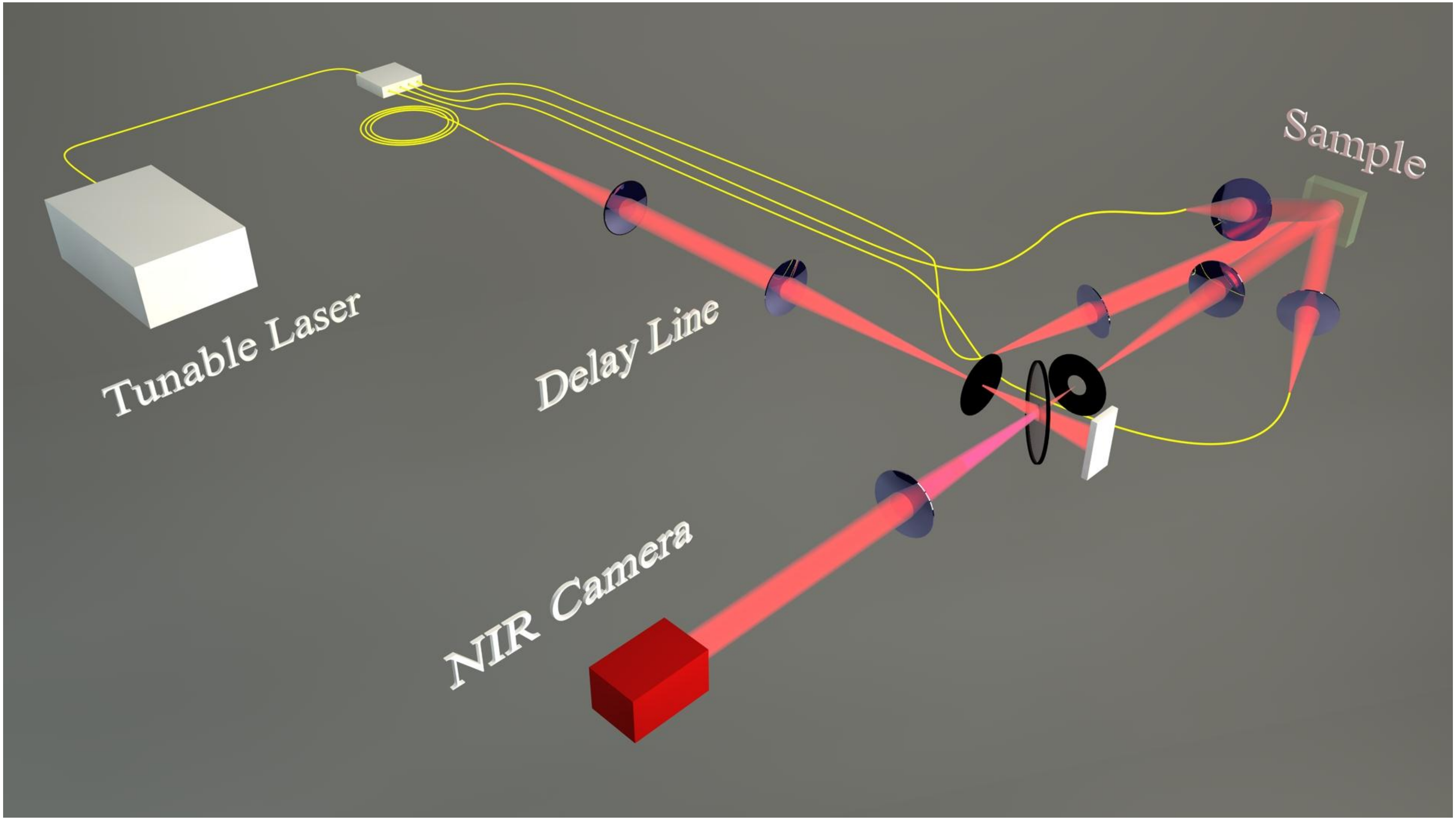


Speckle decorrelation
Strain sd~0.015

Systematic noise
(intensity, electronic, phase jitter)
strain~0.0005

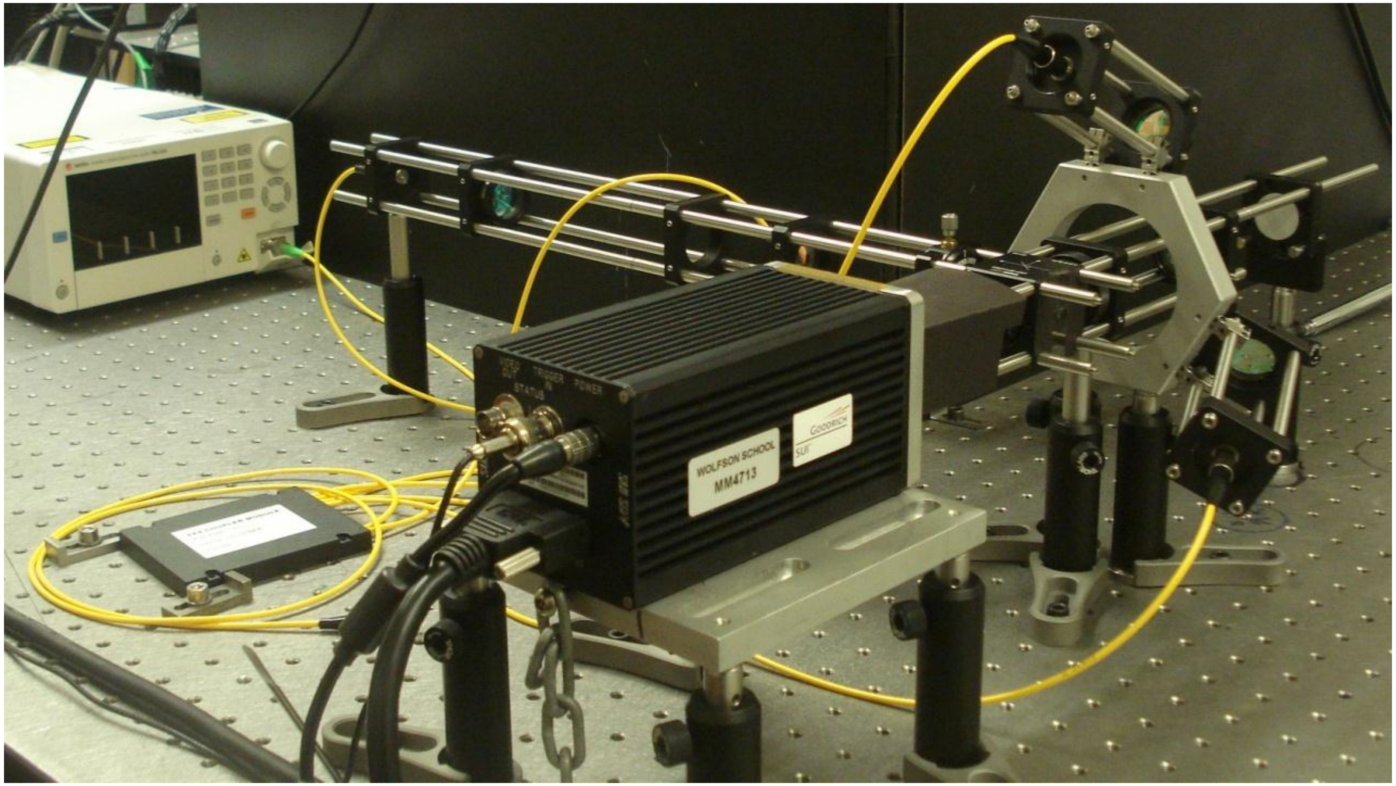
Wavelength scanning interferometry (phase detection) WSI

WSI with multiple illumination directions



3 illumination directions with offset OPDs

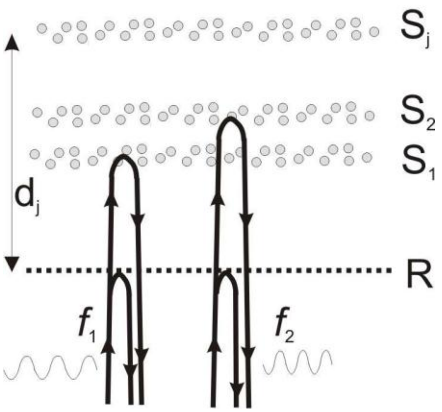
WSI with multiple illumination directions



Full paper:

Chakraborty, S. and P.D. Ruiz, J. Opt. Soc. Am. A, 2012. **29**(9): p. 1776-1785.

Opaque surface, <u>one</u> illumination beam



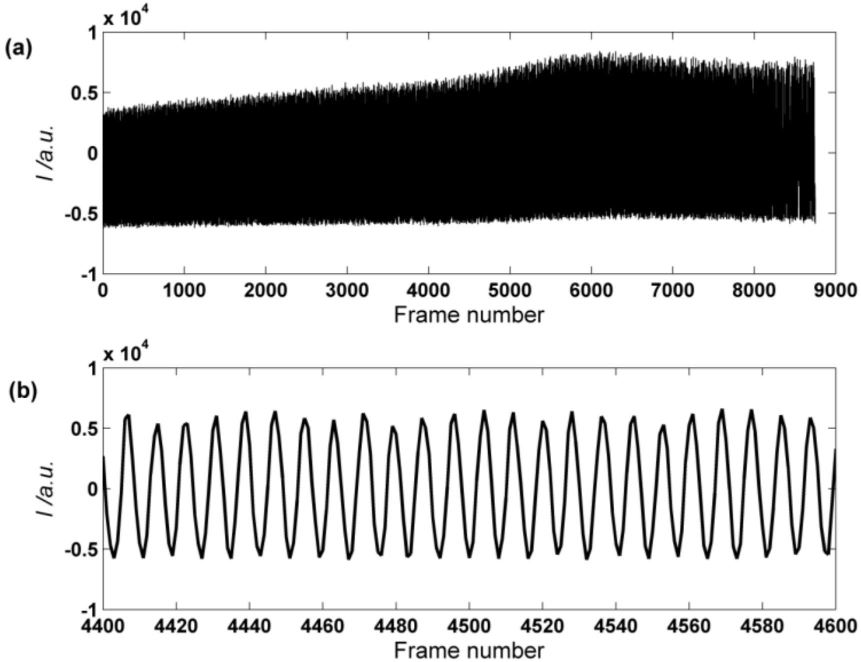
$$I(k) = I_0 + I_1 \cos[\phi(k)]$$

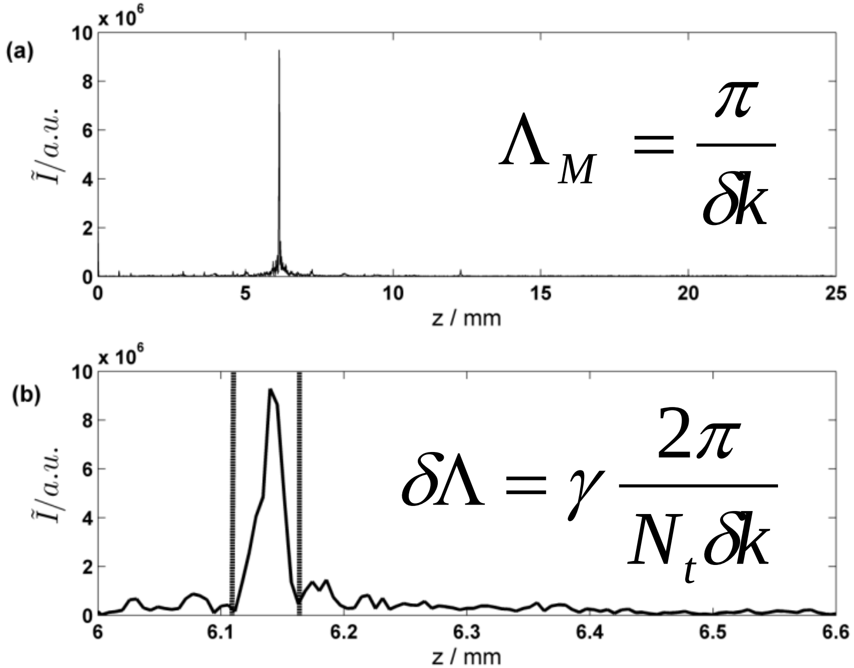
$$k(t) = k_c + \delta k t$$

$$\phi_j(t) = \phi_{sj} + k_c \Lambda_j + \delta k \Lambda_j t$$

$$f_j = \frac{N \delta k}{2\pi} \Lambda_j$$

Frequency encodes depth!



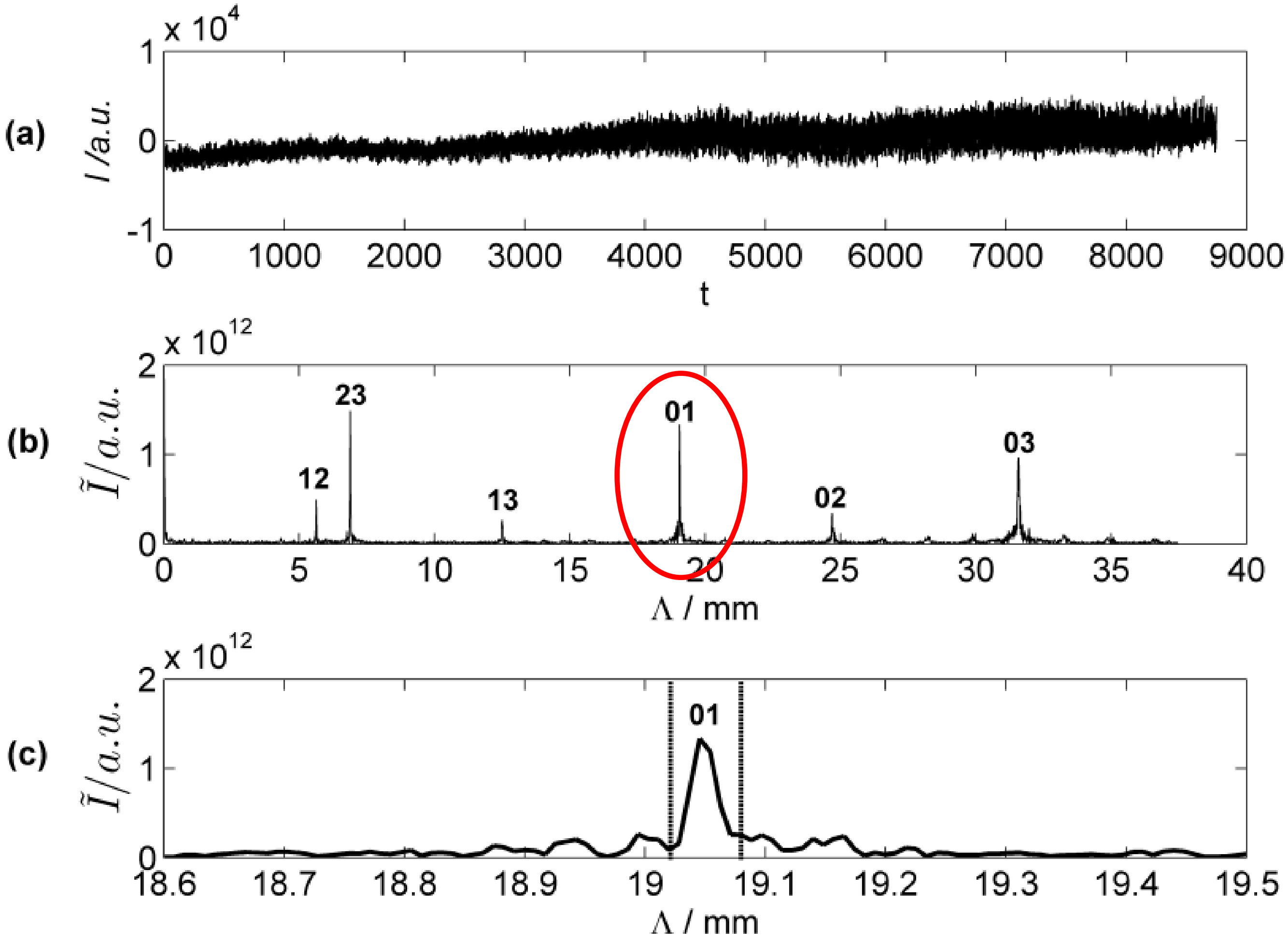


$$\Lambda_M = \frac{\pi}{\delta k}$$

$$\delta \Lambda = \gamma \frac{2\pi}{N_t \delta k}$$

WSI with multiple illumination directions

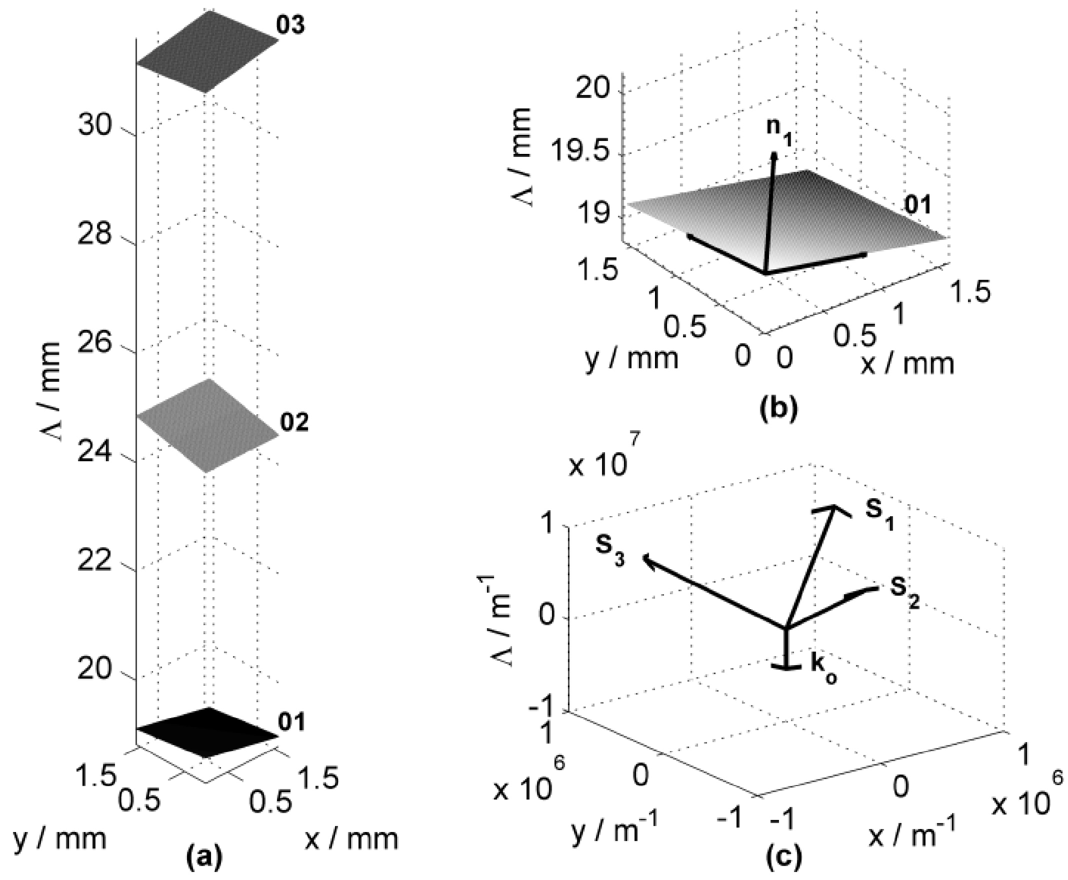
Signal for the case of an **opaque** surface



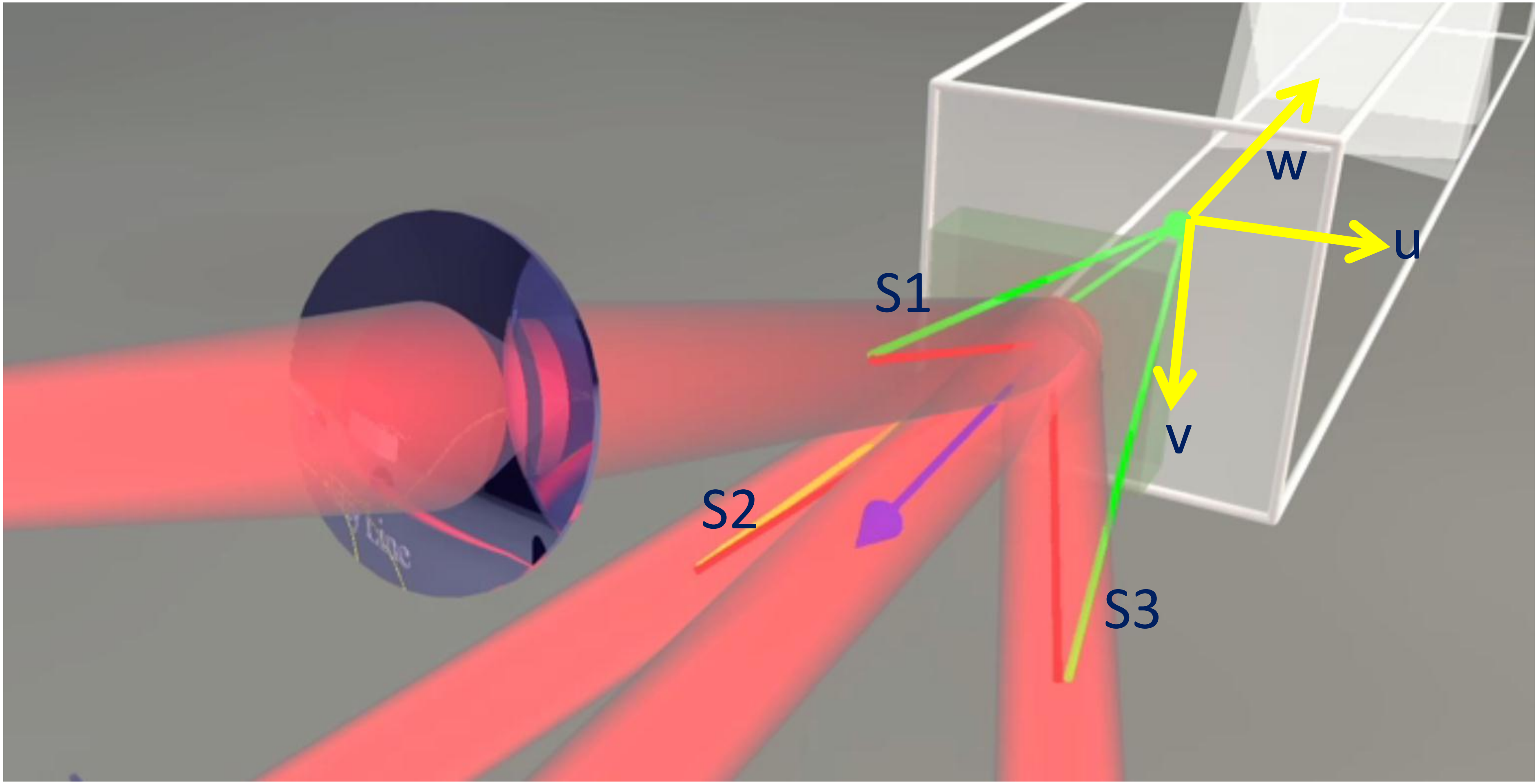
Theoretical $\delta\Lambda$=68 μm; measured $\delta\Lambda$ = 70 μm

Evaluation of the Sensitivity matrix

- Flat opaque scattering surface used as datum
- Record full scan and perform pixel-wise FFT
- Orientation of the reconstructed surfaces for each illumination is used to evaluate illumination and sensitivity vectors



Vector transformation to find u, v, w



2) phase unwrapping and displacements

$$\begin{pmatrix} \phi_1^U(x,y,\Lambda) \\ \phi_2^U(x,y,\Lambda) \\ \phi_3^U(x,y,\Lambda) \end{pmatrix} = \frac{2\pi}{\lambda_c} \begin{pmatrix} \sin\theta_1 \cos\xi_1 & \sin\theta_1 \sin\xi_1 & 1+\cos\theta_1 \\ \sin\theta_2 \cos\xi_2 & \sin\theta_2 \sin\xi_2 & 1+\cos\theta_2 \\ \sin\theta_3 \cos\xi_3 & \sin\theta_3 \sin\xi_3 & 1+\cos\theta_3 \end{pmatrix} \begin{pmatrix} u(x,y,\Lambda) \\ v(x,y,\Lambda) \\ w(x,y,\Lambda) \end{pmatrix}$$

measured | Known from calibration | calculated

$$\Phi = \mathrm{S} \cdot \Delta \mathrm{r}$$

u, *v* and *w* are obtained by inverting the sensitivity matrix

Unwrapping algorithm:

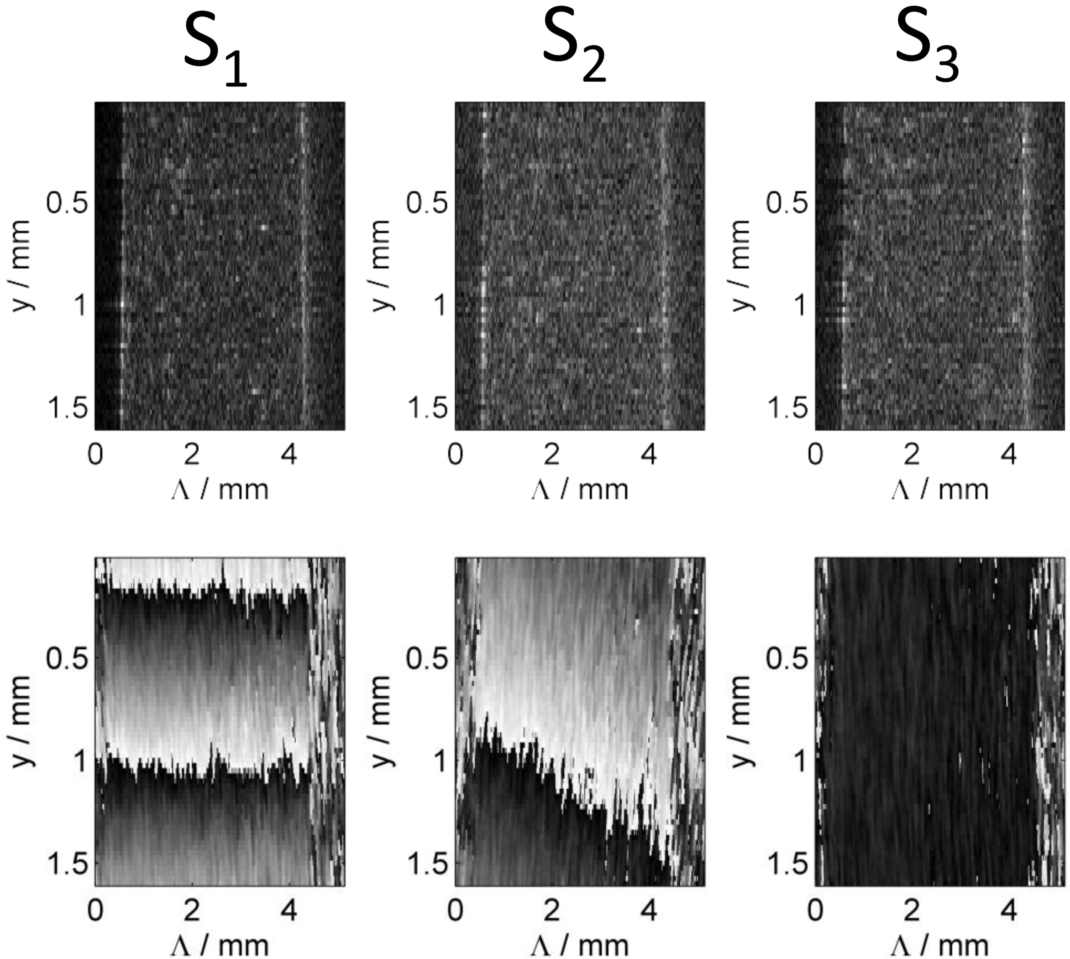
Salfity, M.F., et al., Applied Optics, 2006. **45**(12): p. 2711-2722.

Volume reconstruction: 1) Re-registration

- The complex volumes associated to all 3 sensitivity vectors are re-registered to a common coordinate system.

Magnitude (microstructure)

Phase (displacements)



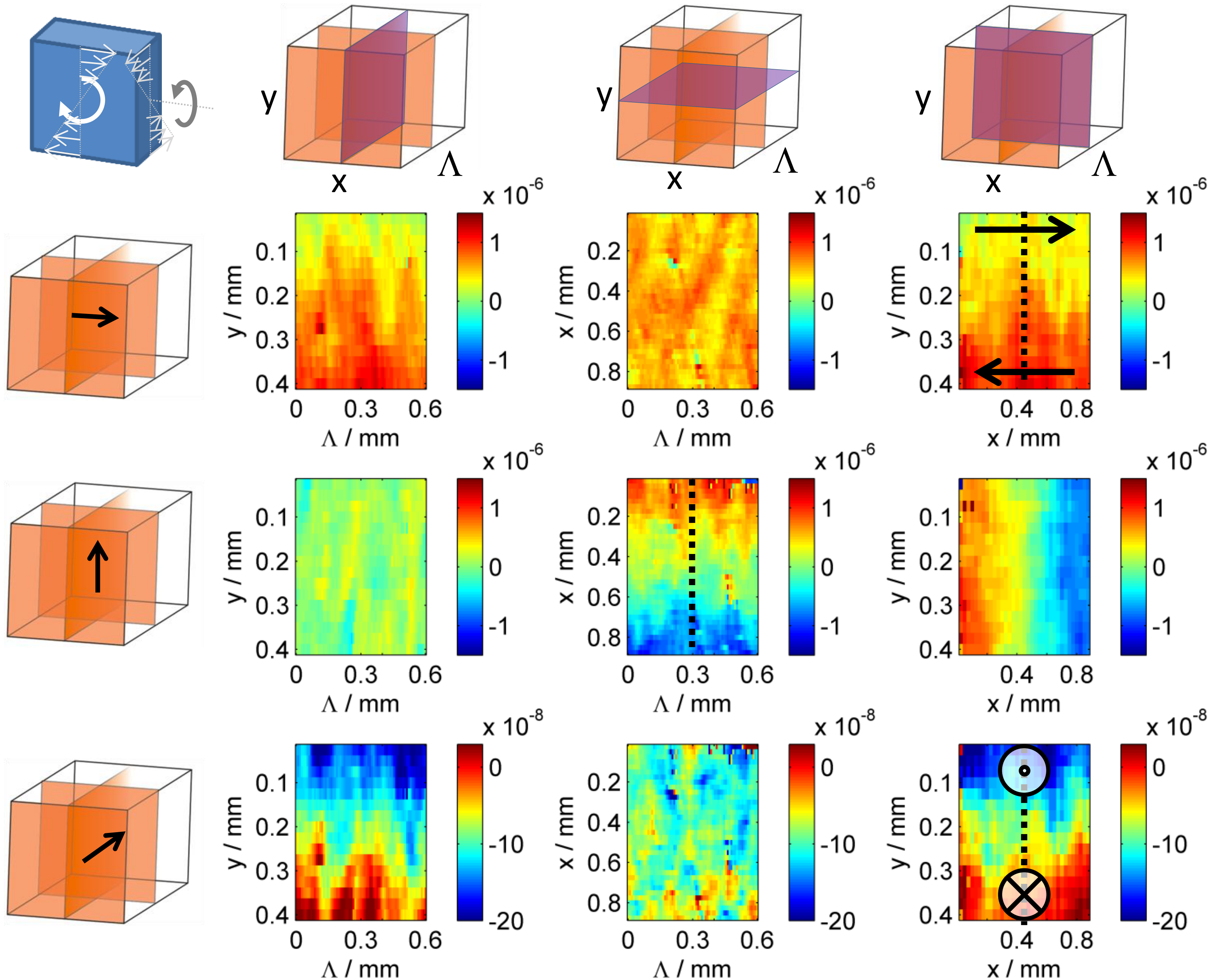
$\phi_1(x, y, \Lambda)$ $\phi_2(x, y, \Lambda)$ $\phi_3(x, y, \Lambda)$

Validation of *u*(*x*, *y*, *z*); *v*(*x*, *y*, *z*) and *w*(*x*, *y*, *z*)

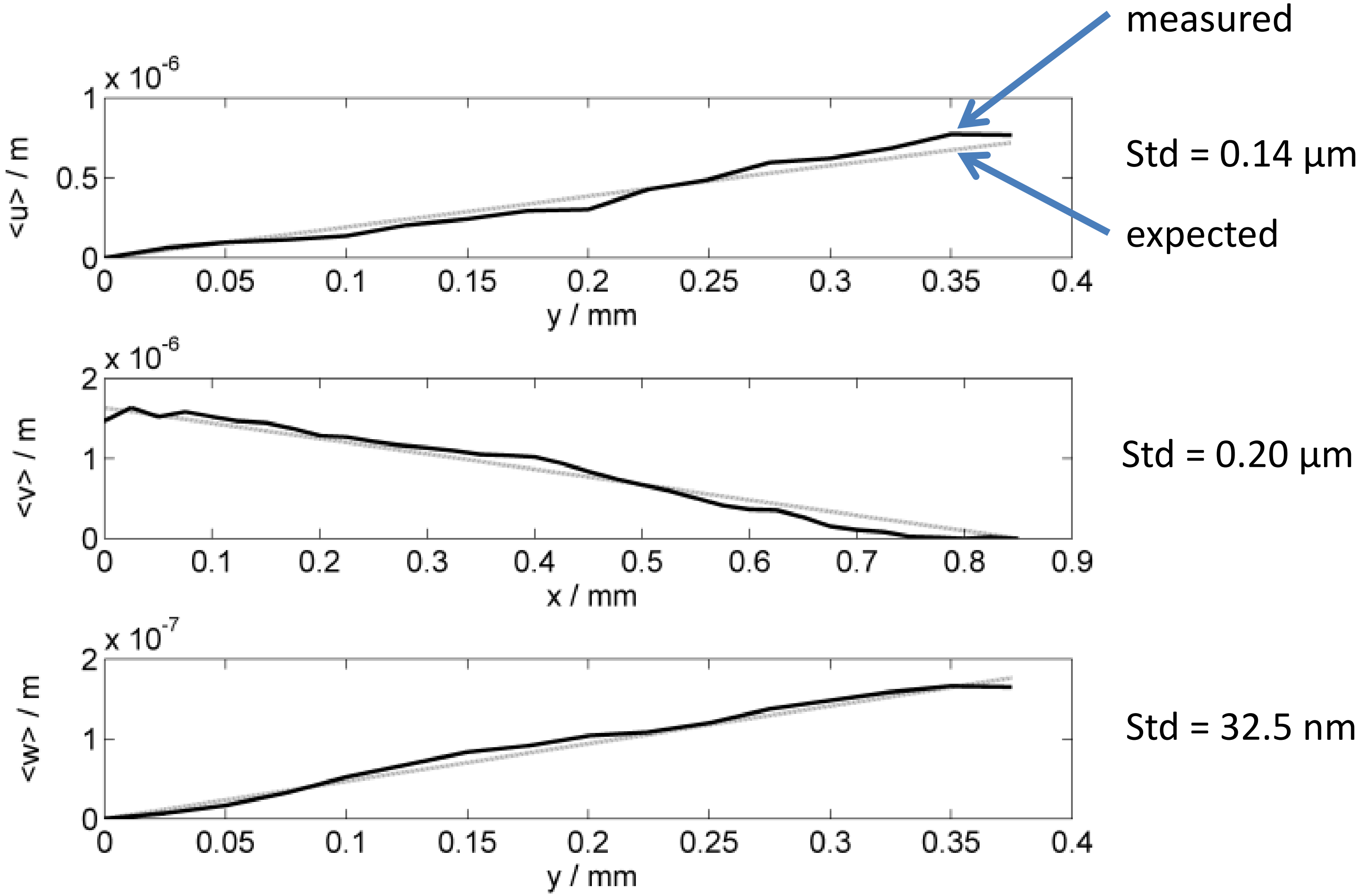
In-plane rotation +

Out-of-plane tilt

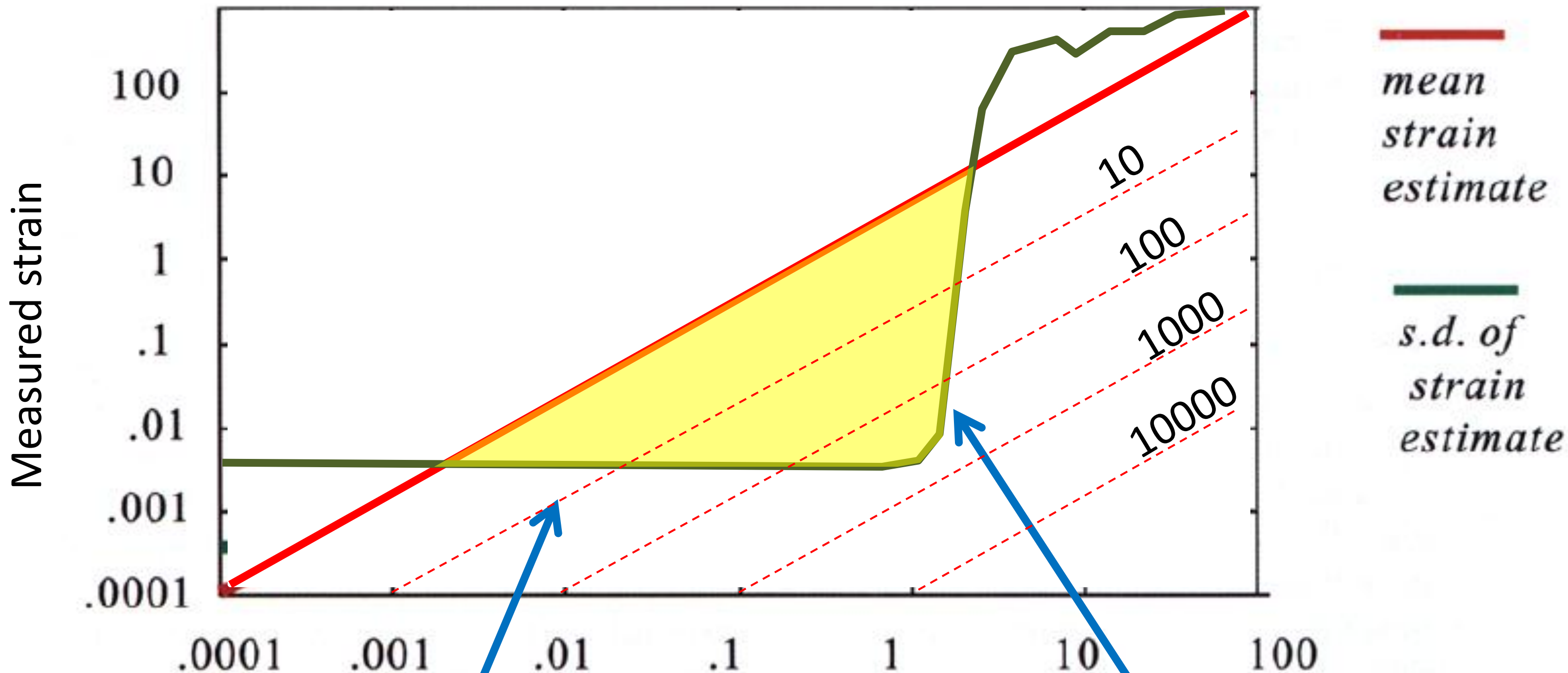
Volume shown ~0.2 mm^3



Validation results



OCT & DVC noise study



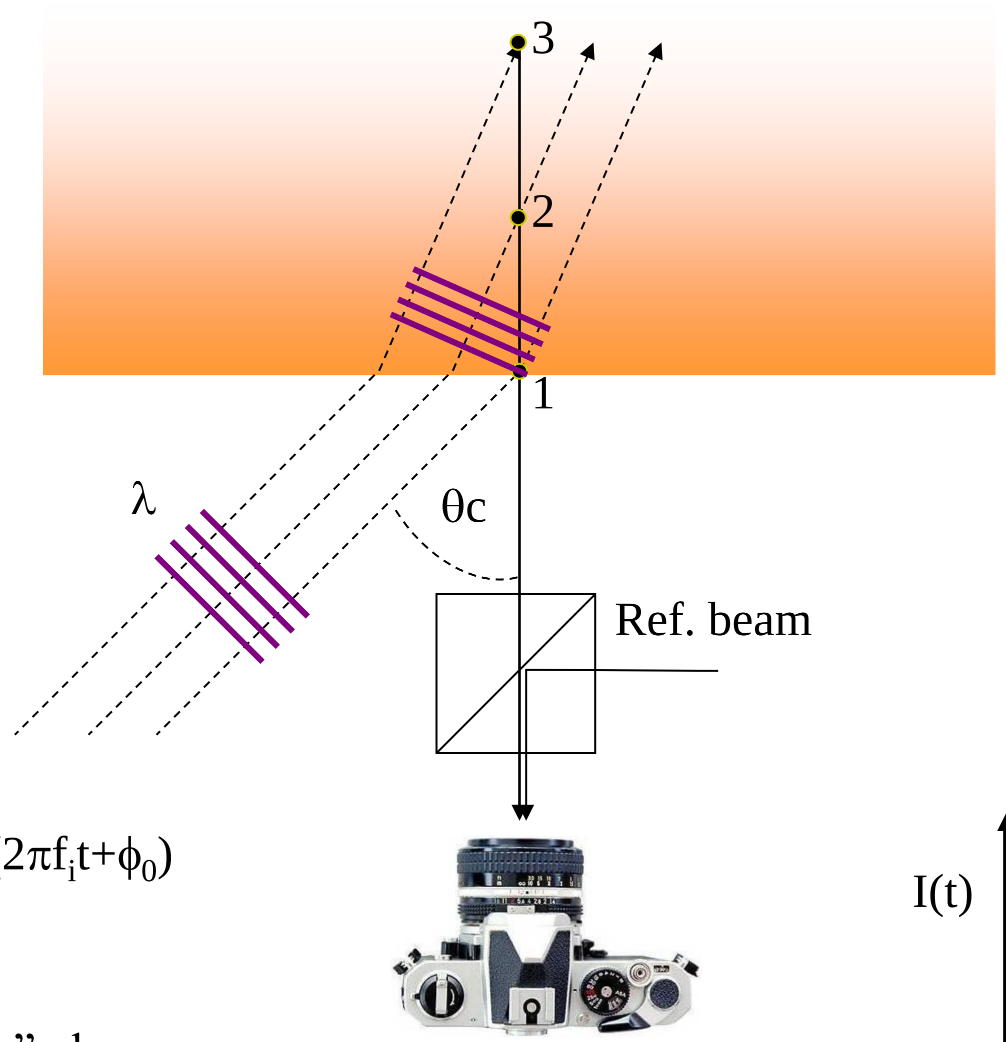
Applied strain

Systematic noise
(intensity, electronic, phase jitter)
strain~0.0005

Speckle decorrelation
Strain sd~0.015

Tilt Scanning Interferometry
(phase detection)
TSI

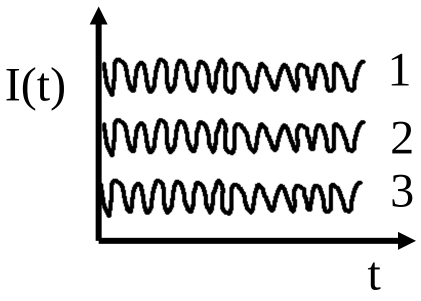
Tilt Scanning Interferometry: Principle



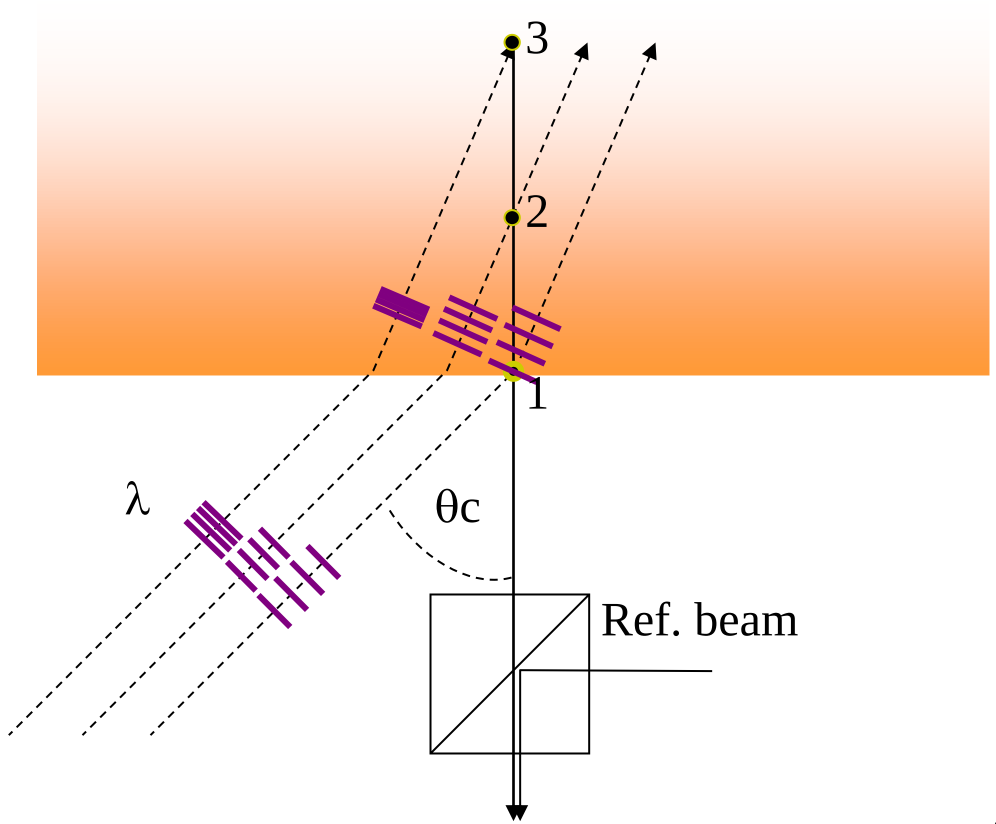
$$I_i(t) = I_0 + I_M \cos(2\pi f_i t + \phi_0)$$

$$f_1 = f_2 = f_3$$

Effect of a "piston" phase



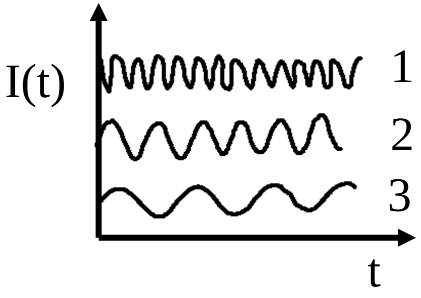
Tilt Scanning Interferometry: Principle



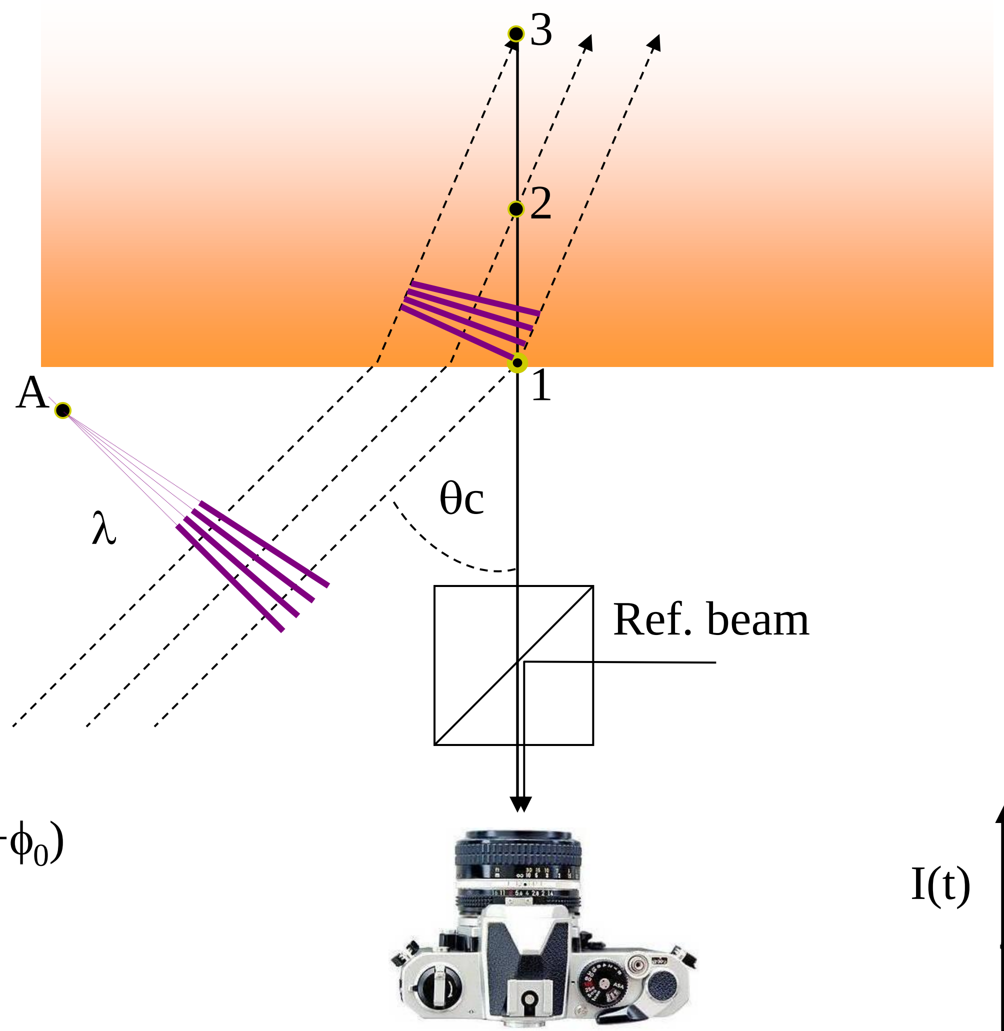
$I_i = I_0 + I_M \cos(2\pi f_i t + \phi_0)$

$f_1 > f_2 > f_3$

Piecewise "piston" phase



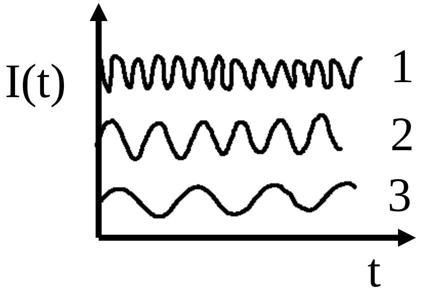
Tilt Scanning Interferometry: Principle



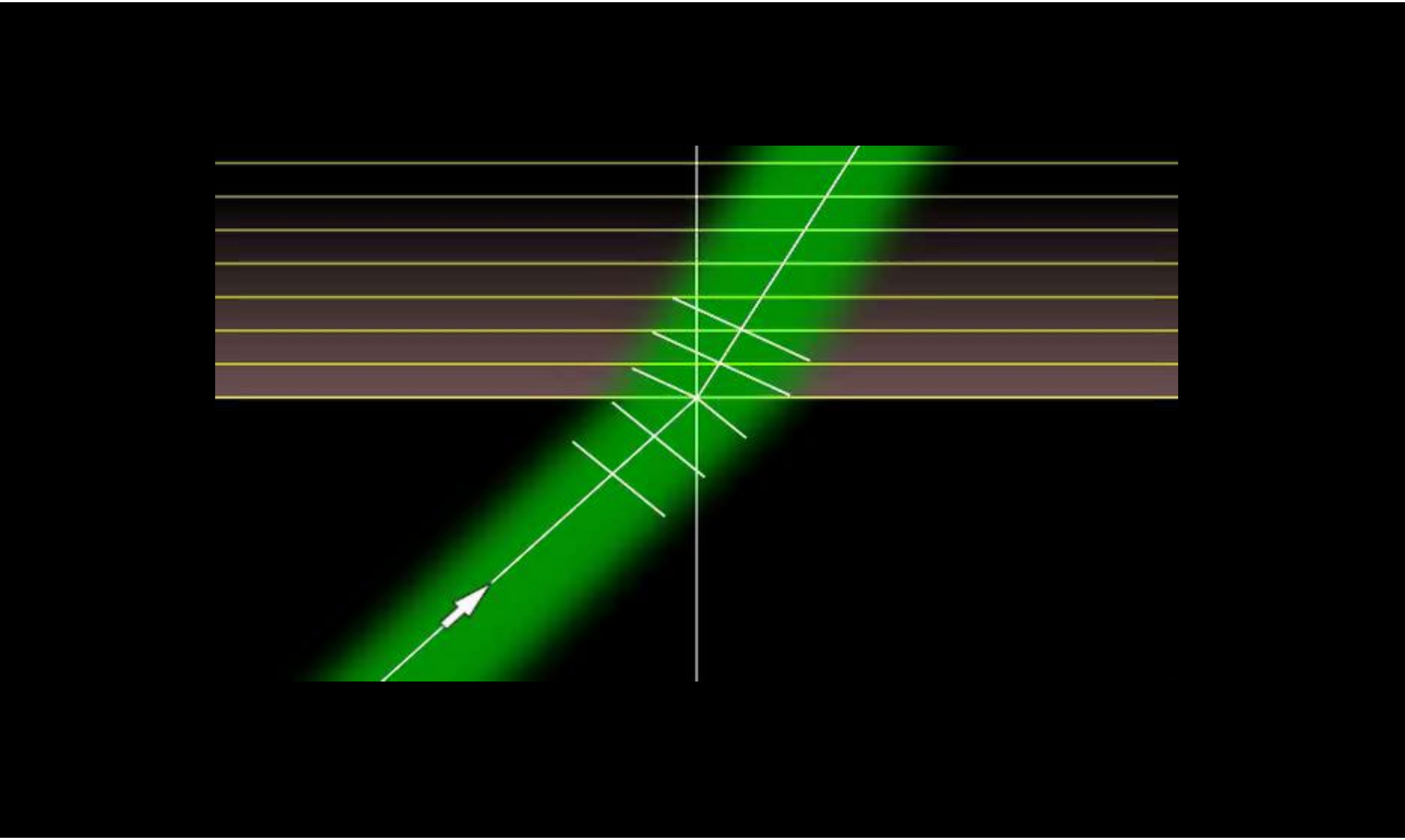
$I_i = I_0 + I_M \cos(2\pi f_i t + \phi_0)$

$f_1 > f_2 > f_3$

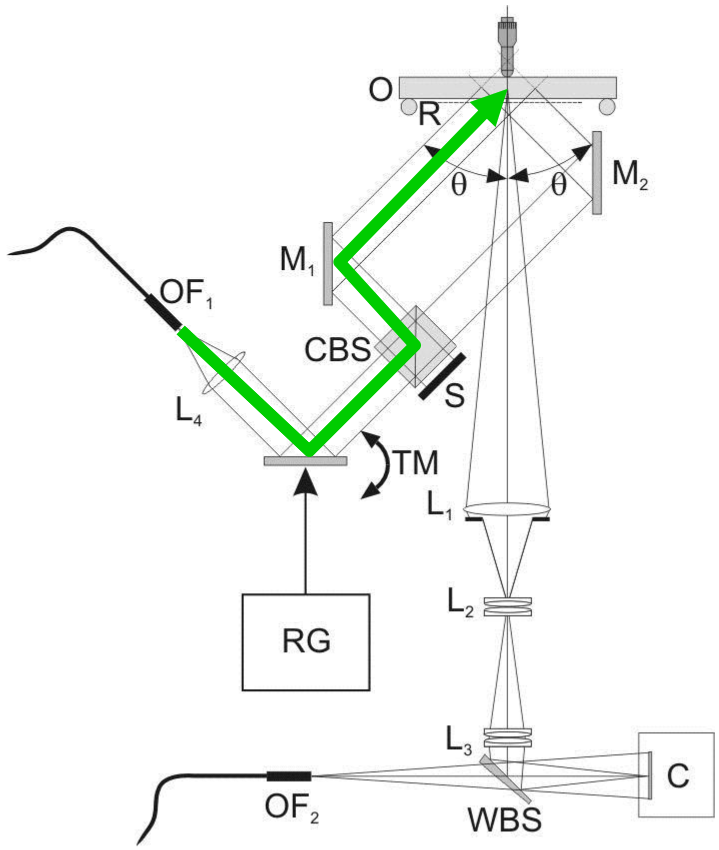
Wavefront tilt about A



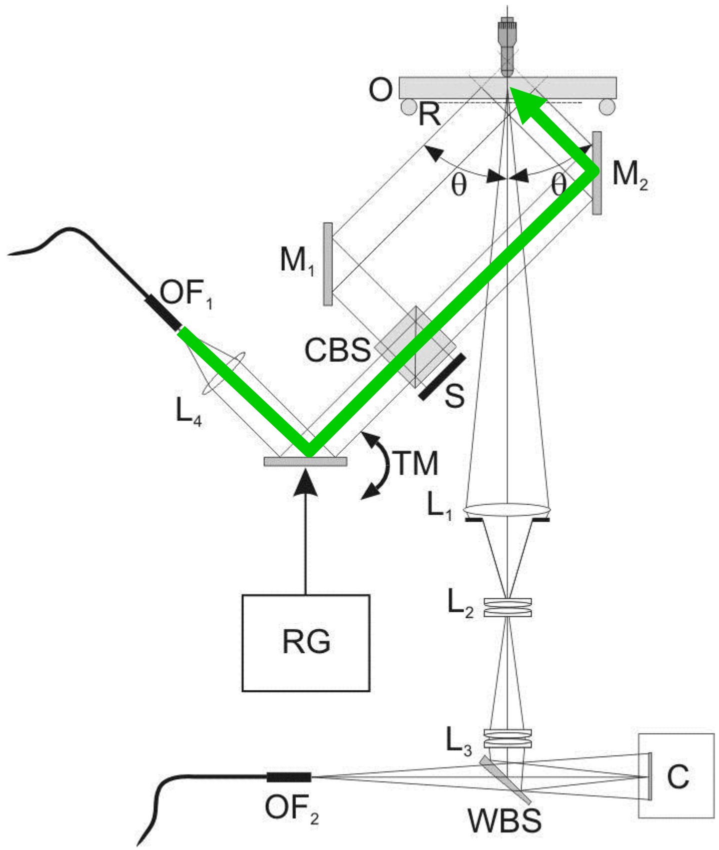
Tilt Scanning Interferometry: Principle

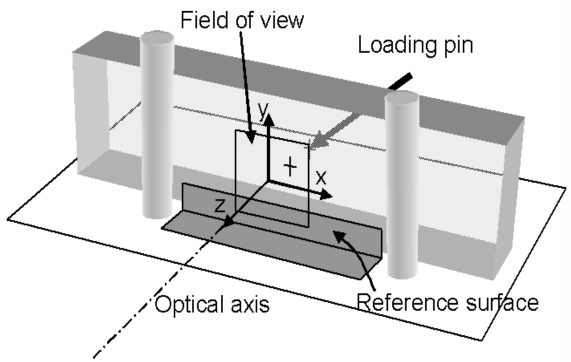


Tilt scanning interferometry: Setup

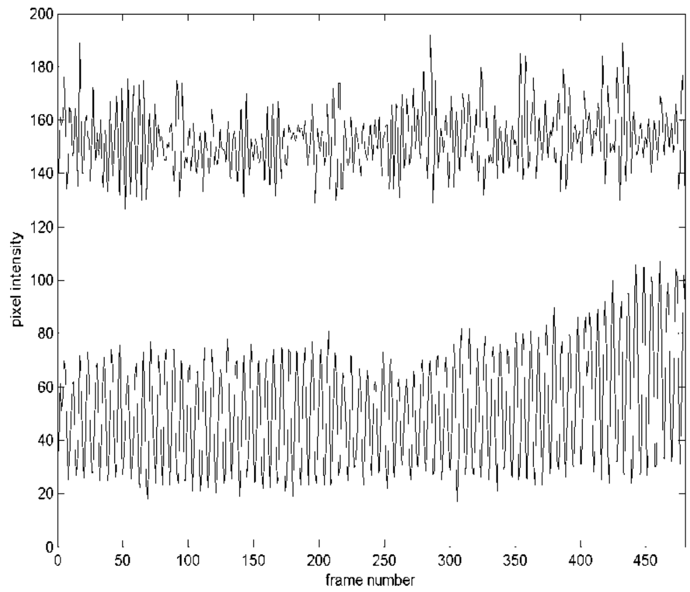


Tilt scanning interferometry: Setup

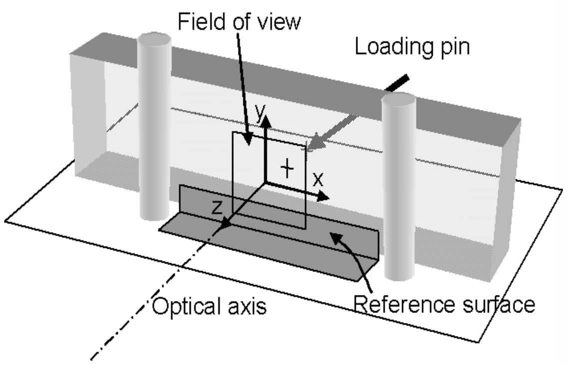




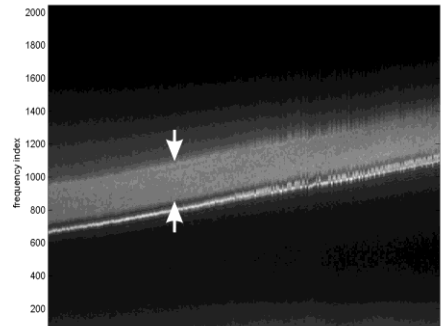
Time-varying intensity at two pixels



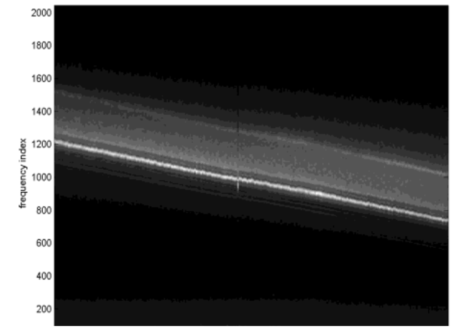
Wrapped phase maps



Left illumination

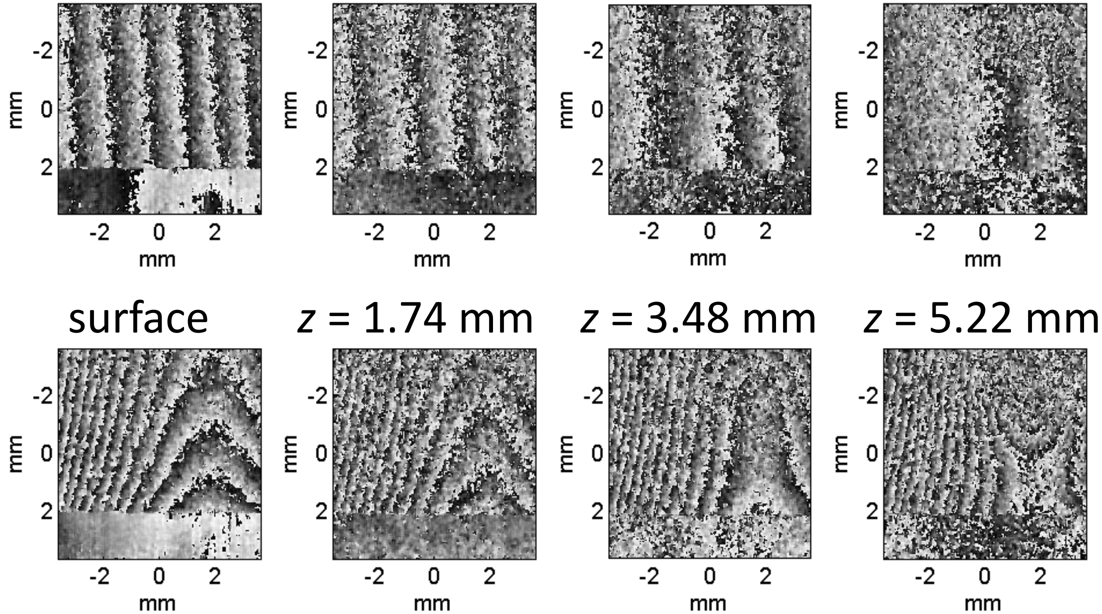


Right illumination



Horizontal in-plane displacement component

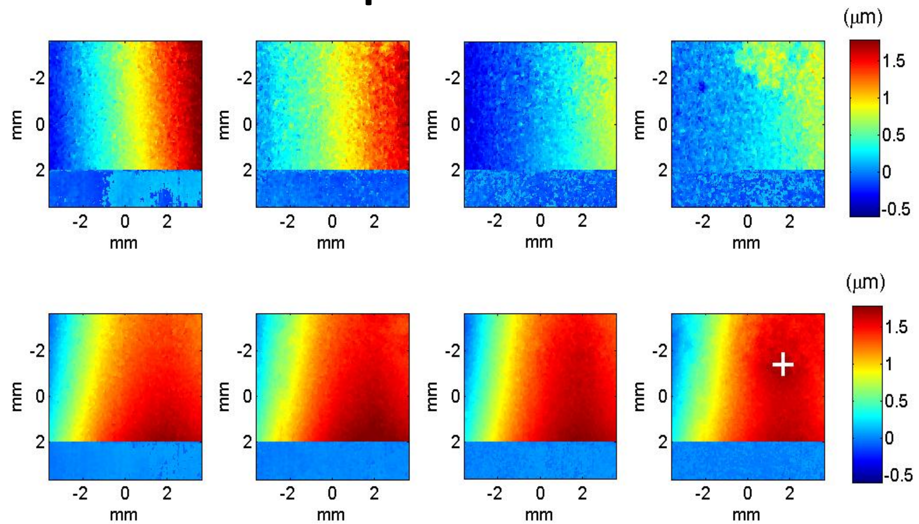
Out-of-plane displacement component



P. D. Ruiz et al (2006) *Proc. Roy. Soc. A* , 462, (2072):2481-2502

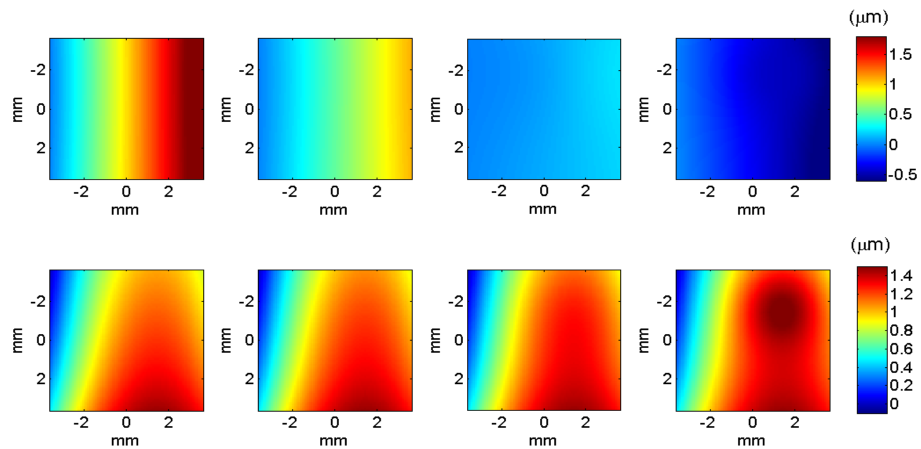
Displacement fields – experimental vs FEA

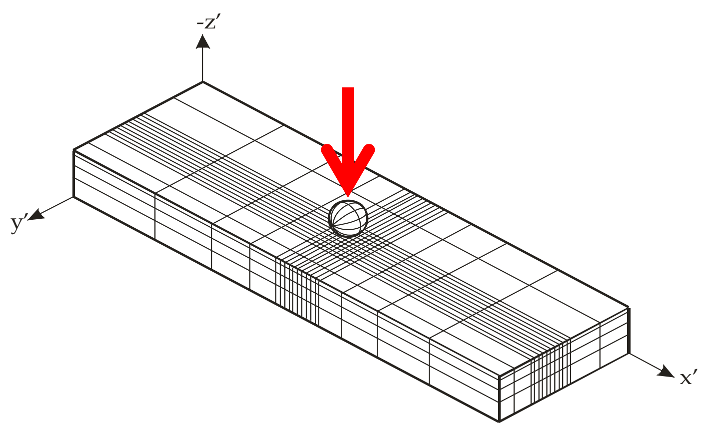
Experiment



Horizontal in-plane displacement component

Out-of-plane displacement component

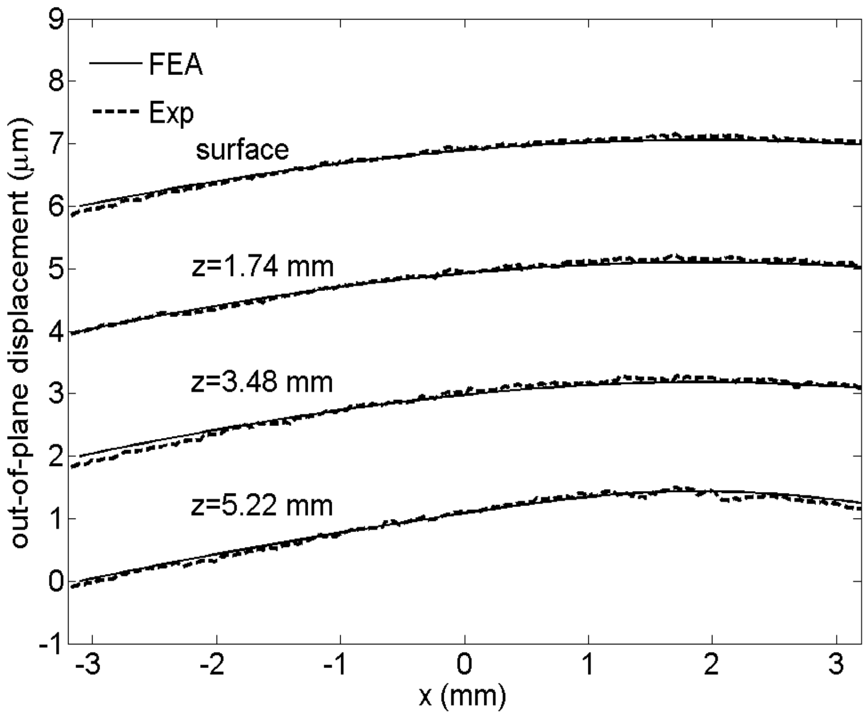




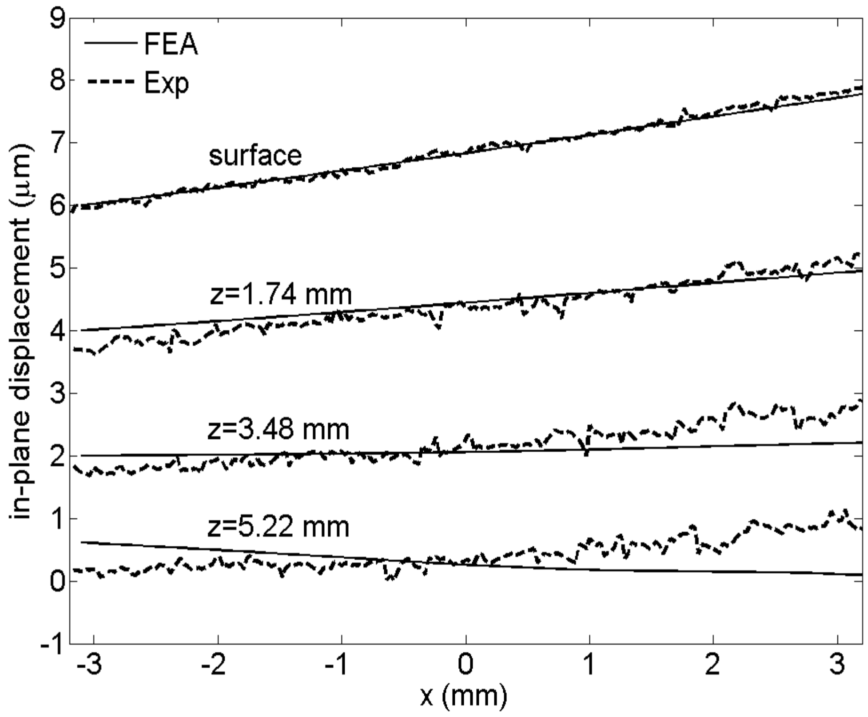
Finite Element Analysis

Horizontal cross-sections through contact point

Out-of-plane displacement



In-plane displacement



Summary of measurement techniques

Technique	Materials	Minimum size of gauge volume	Displacement/strain sensitivity	Acquisition time
3D strain gauge	polymer model	> 1 mm^3	~10e-06	~1 μs (1 point)
Ultrasound	Tissues, metals, composites	~ 1 mm^3	~ 10e-03	~ and below 1 s 3-D US
MRE	Proton rich water-fat carbon possible?	$(250\ \mu m)^3$	< 1 μm	4 ms/slice (spin tagging) Few minutes/slice (phase contrast)
Xray CT+DVC	foams, ceramics, granular materials, composites, bone	$(1\text{-}10\ \mu m)^3$ (structure) $(10\text{-}100\ \mu m)^3$ (displacement) $(30\text{-}300\ \mu m)^3$ (strain)	~10e-04 - 10e-06	tens of minutes
OCT Phase contrast	optically translucent	$<(10\ \mu m)^3$	< 1 μm	10 μs A-scan (Spectral domain)
OCT + DVC	optically translucent	$\sim(50\ \mu m)^3$	~10e-04	~10 minutes per scan (full volume)

Thank you for your attention!