UNIVERSITY OF Southampton

An introduction to full field deformation and strain measurement

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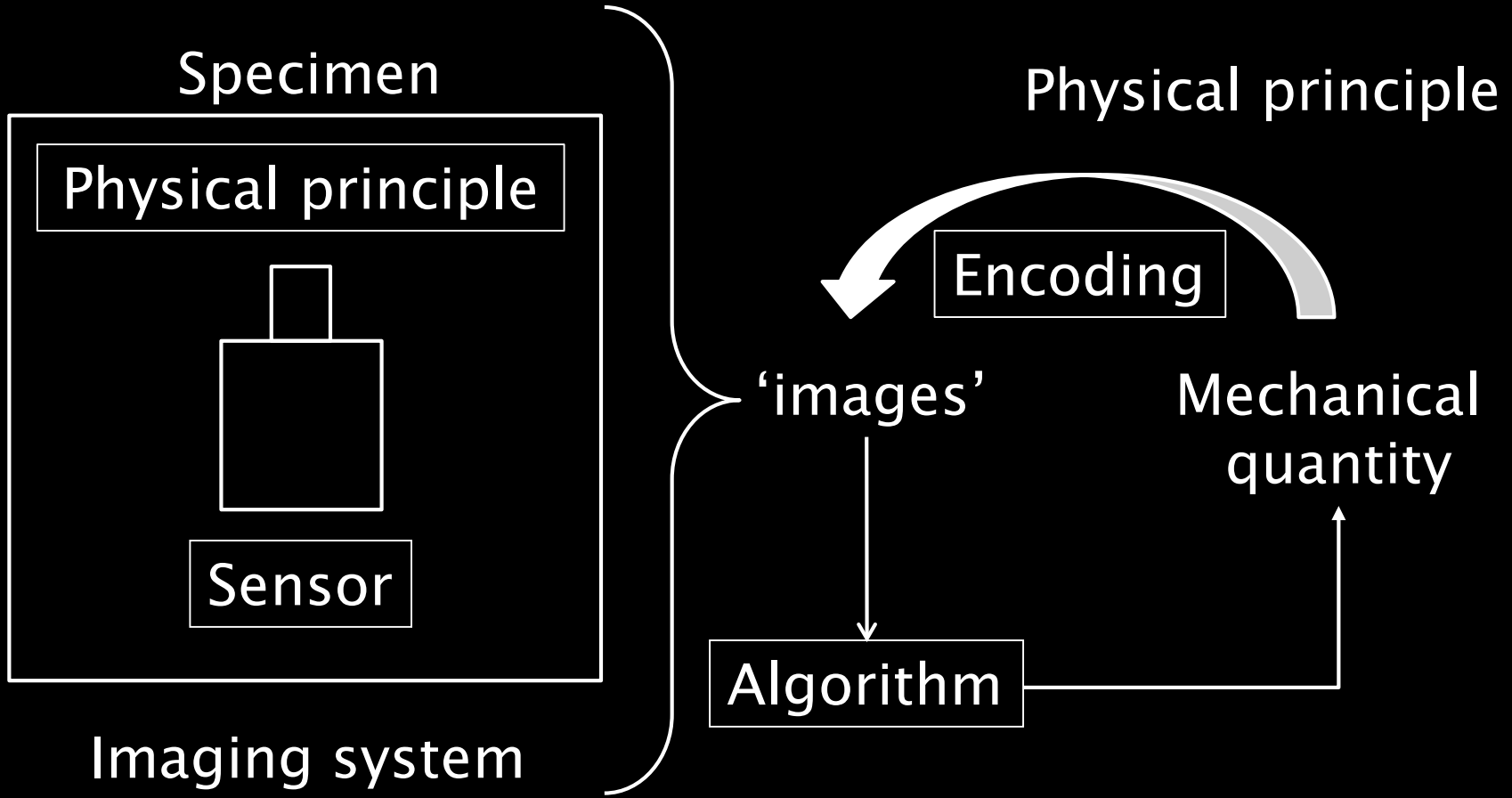
Summary

- Full-field measurements: A general view
- The important elements
  - Sensor
  - Physical principles
  - Encoding
  - Algorithm (decoding)
- A few applications
- Conclusion

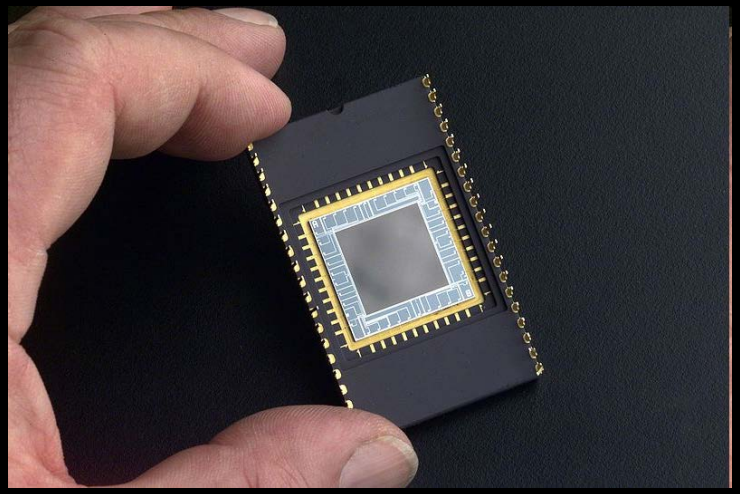
Full-field measurements

- General principle
  - Four important ‘boxes’

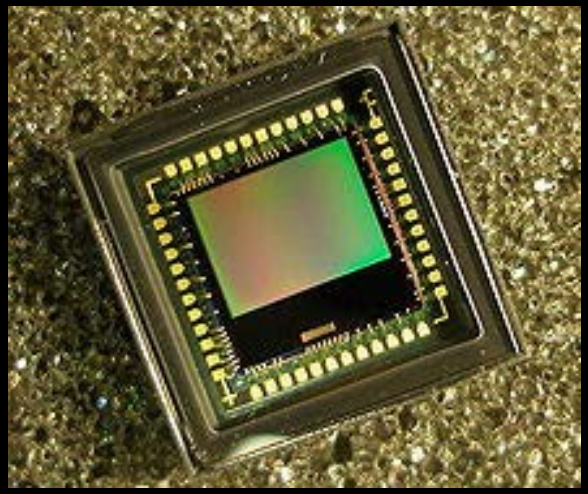


Sensors- 1/5

- CCD/CMOS
  - Charge-Coupled Device (1969)
  - Complementary Metal-Oxyde Semi-conductor
  - Principle: photons hitting the sensor generate electrons by photoelectric effect



CCD



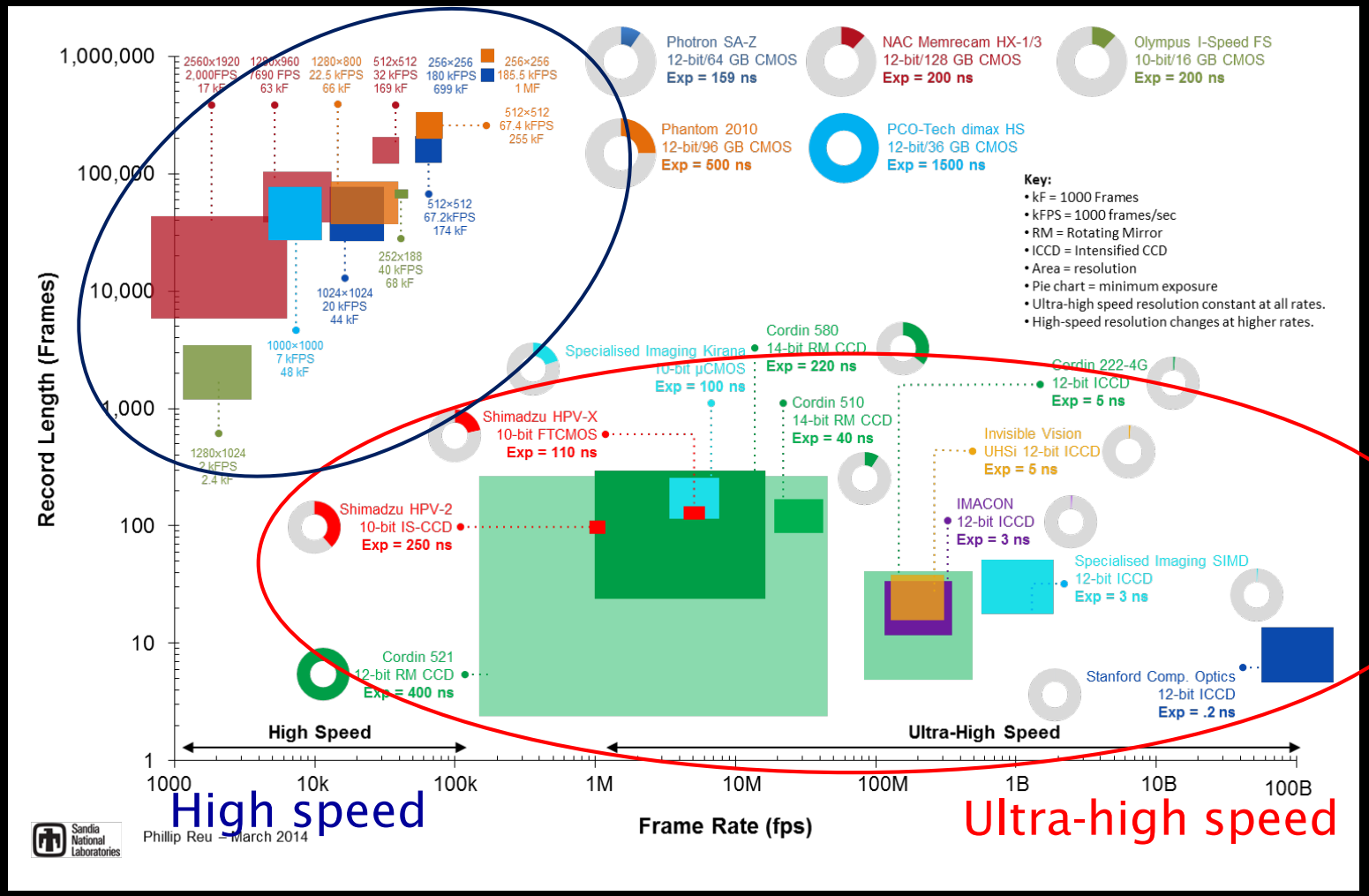
CMOS

source: wikipedia

Sensors – 2/5

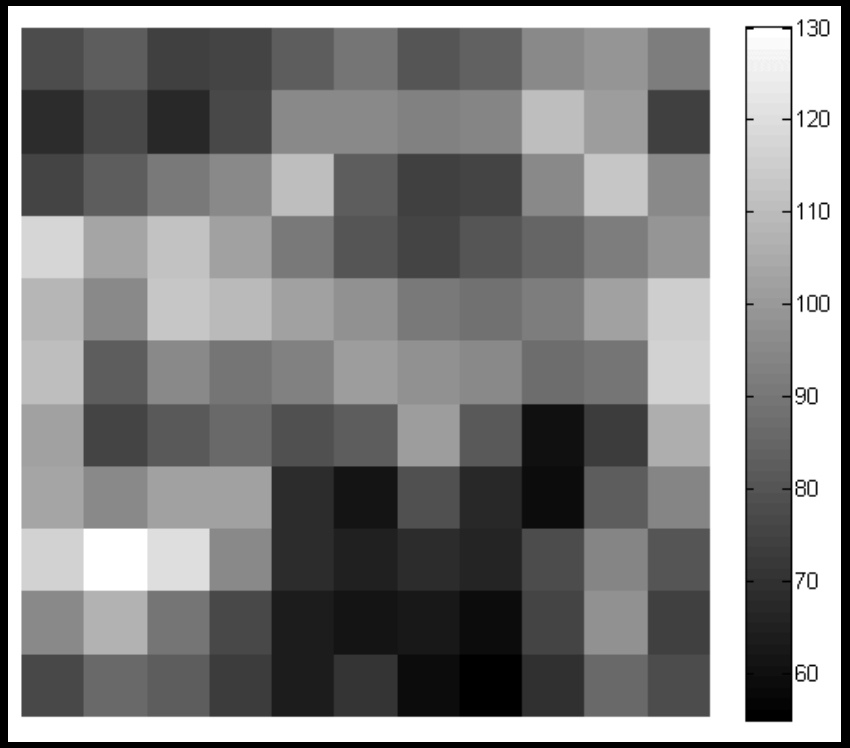
- High speed cameras

Reu, P. L., & Miller, T. J. (2008) *Journal of Strain Analysis for Engineering Design, 43(8), 673-688.*



Sensors – 3/5

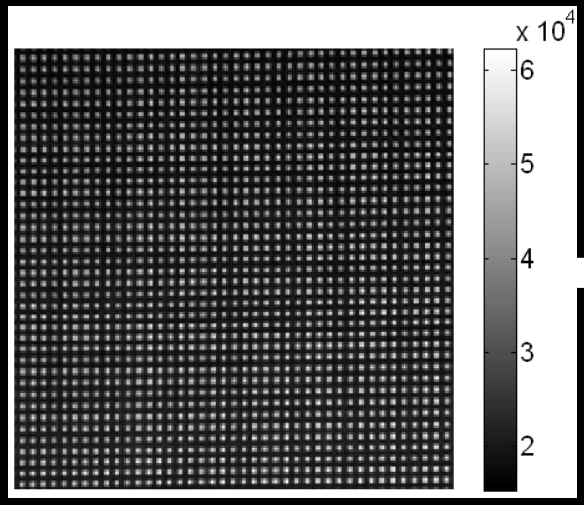
- Common features
  - Discrete information (from 10^5 to 10^7 pixels)
  - Electronic noise

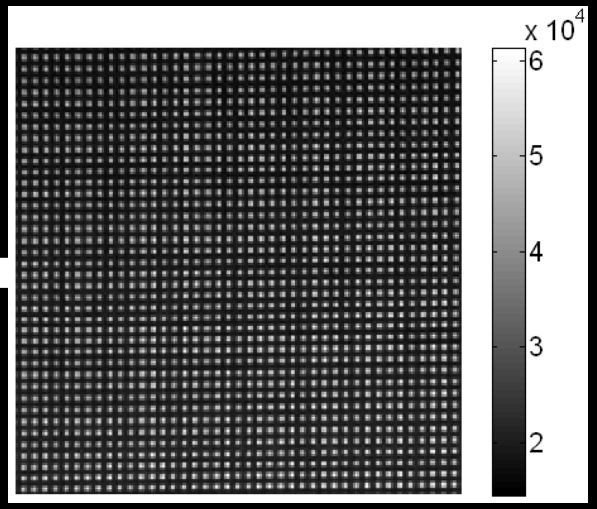


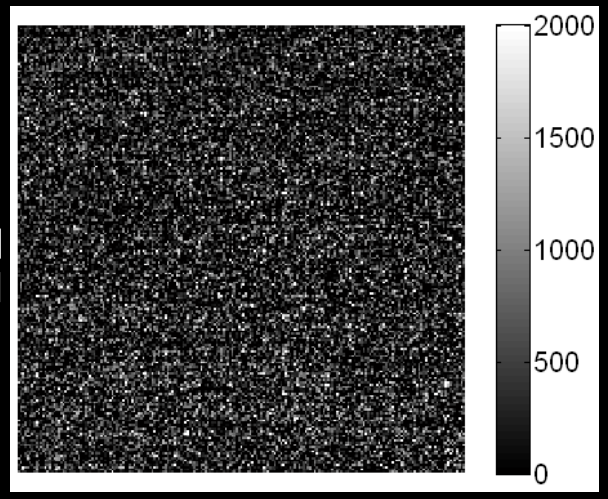
Sensors – 4/5

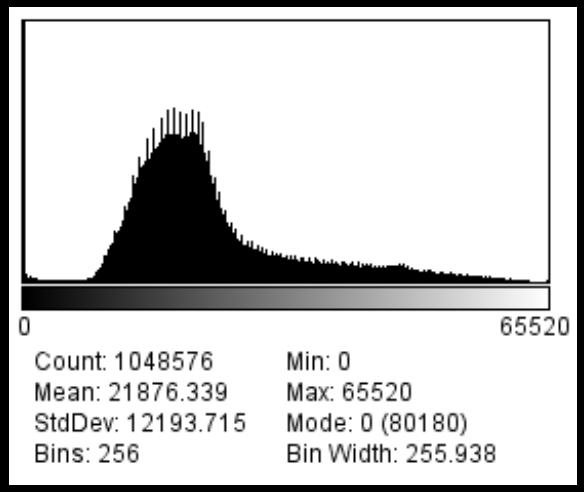
- Noise

Mean = 145 grey levels
Std = 637 grey levels



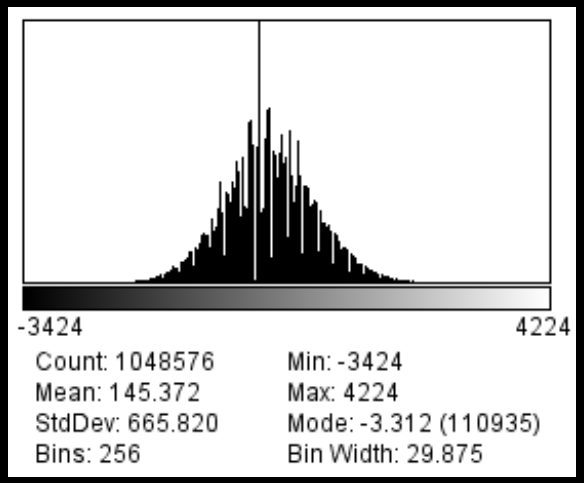






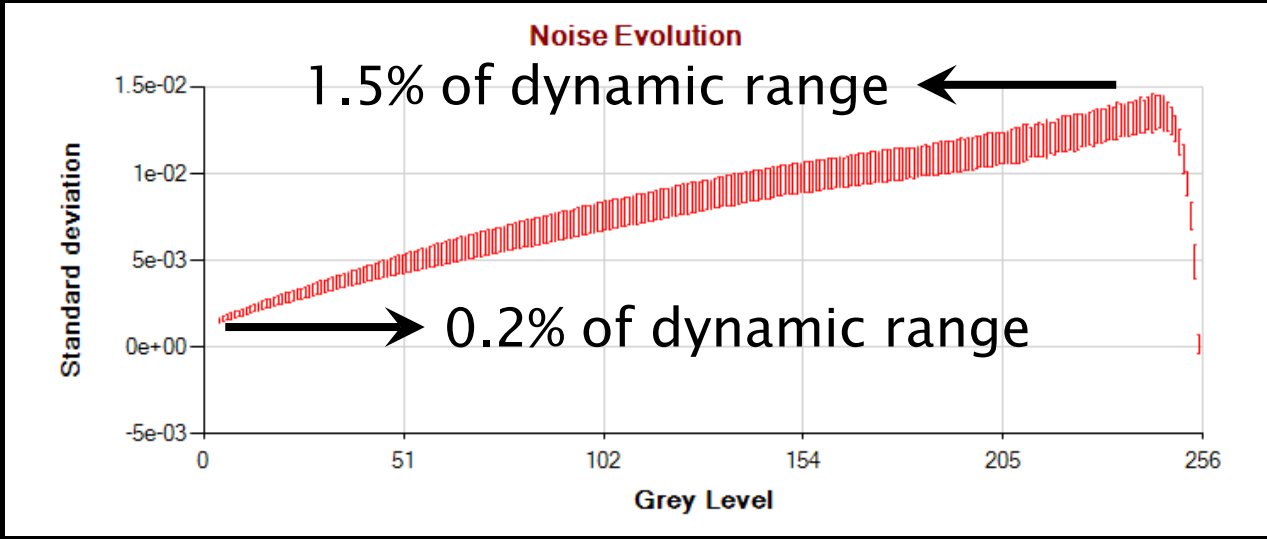
Noise: 637/65520

0.97% of dynamic range

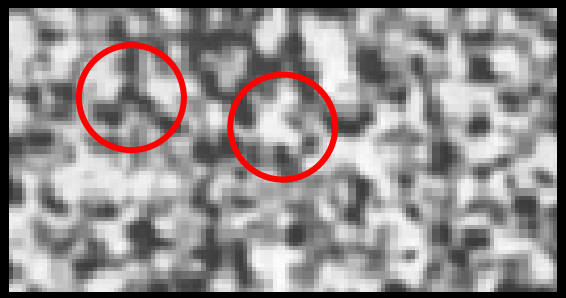


Sensors – 5/5

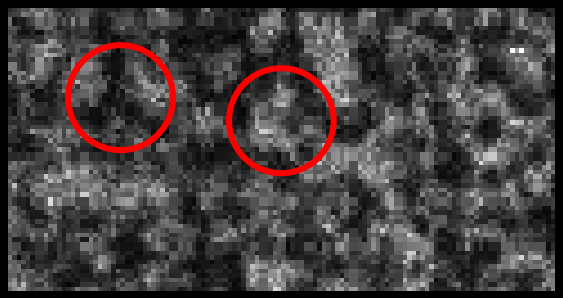
- Noise scales up with grey level
  - Take many images and work out mean and standard deviation



Mean

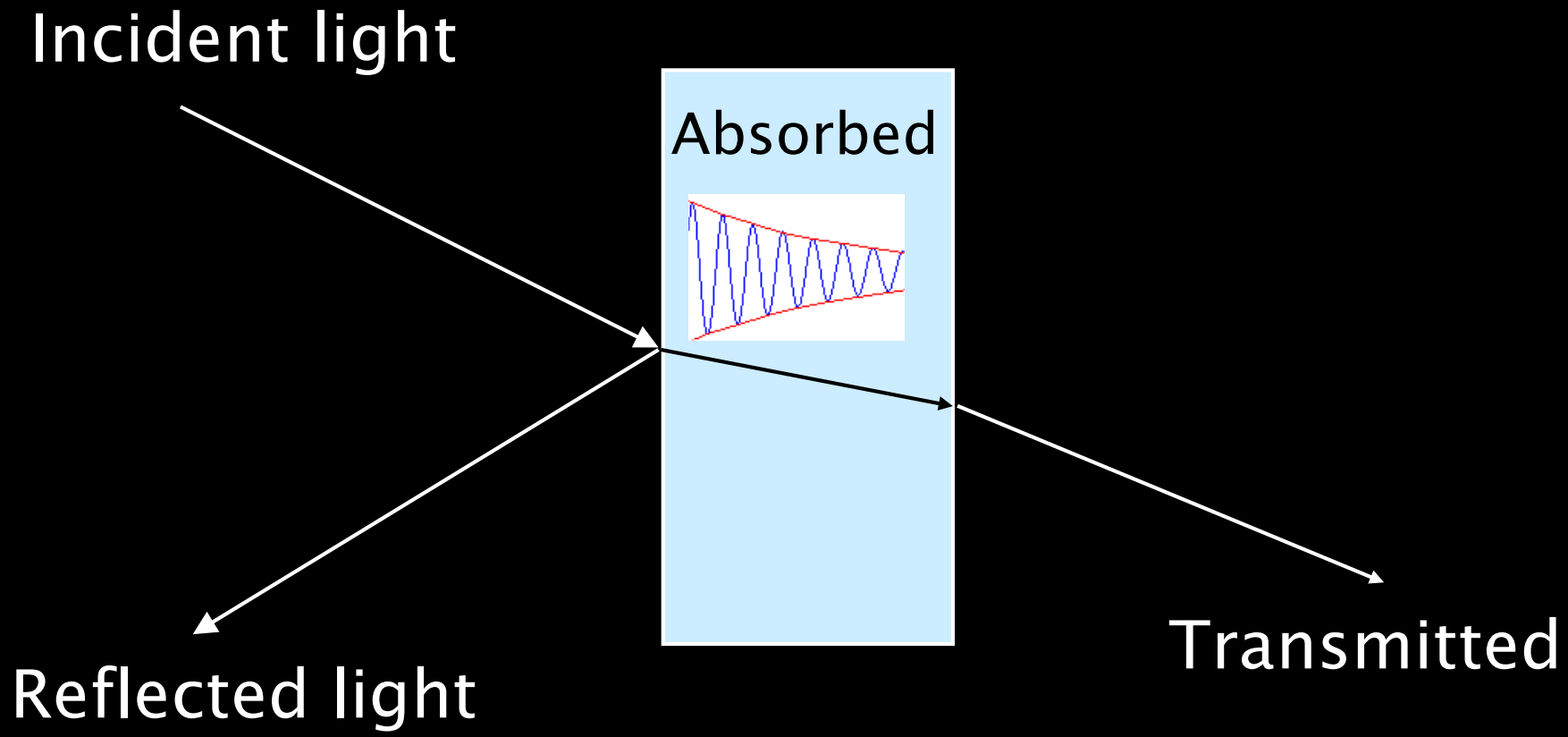


Standard deviation



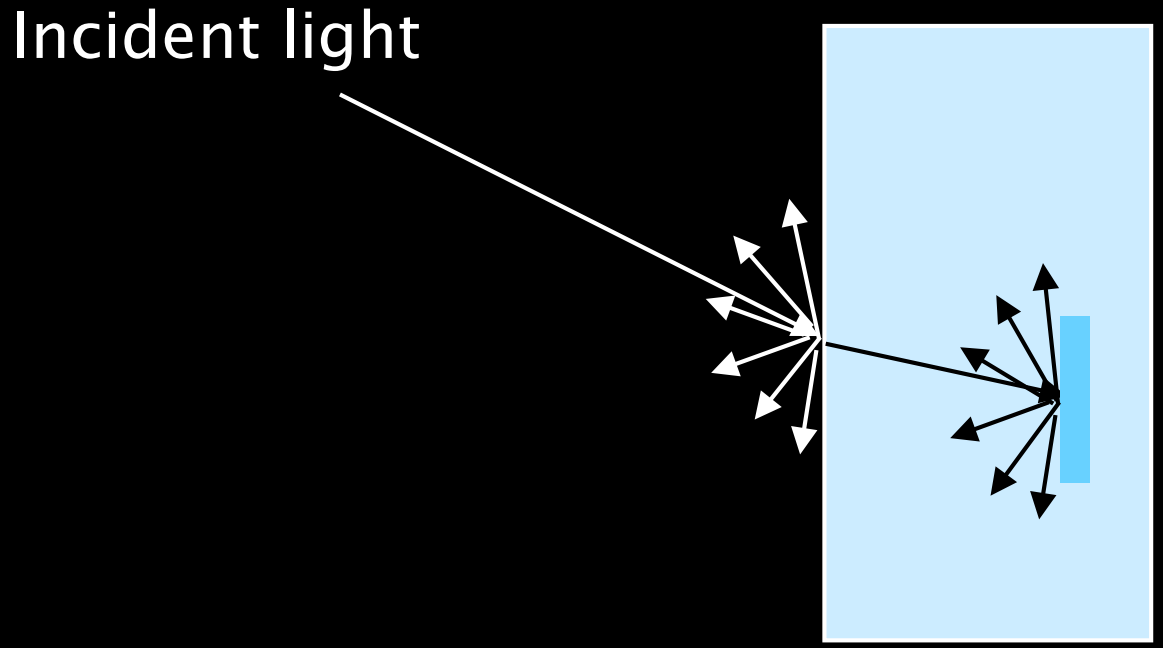
Physical principles – 1/5

- Reflected light
  - Different types of light/solid interactions



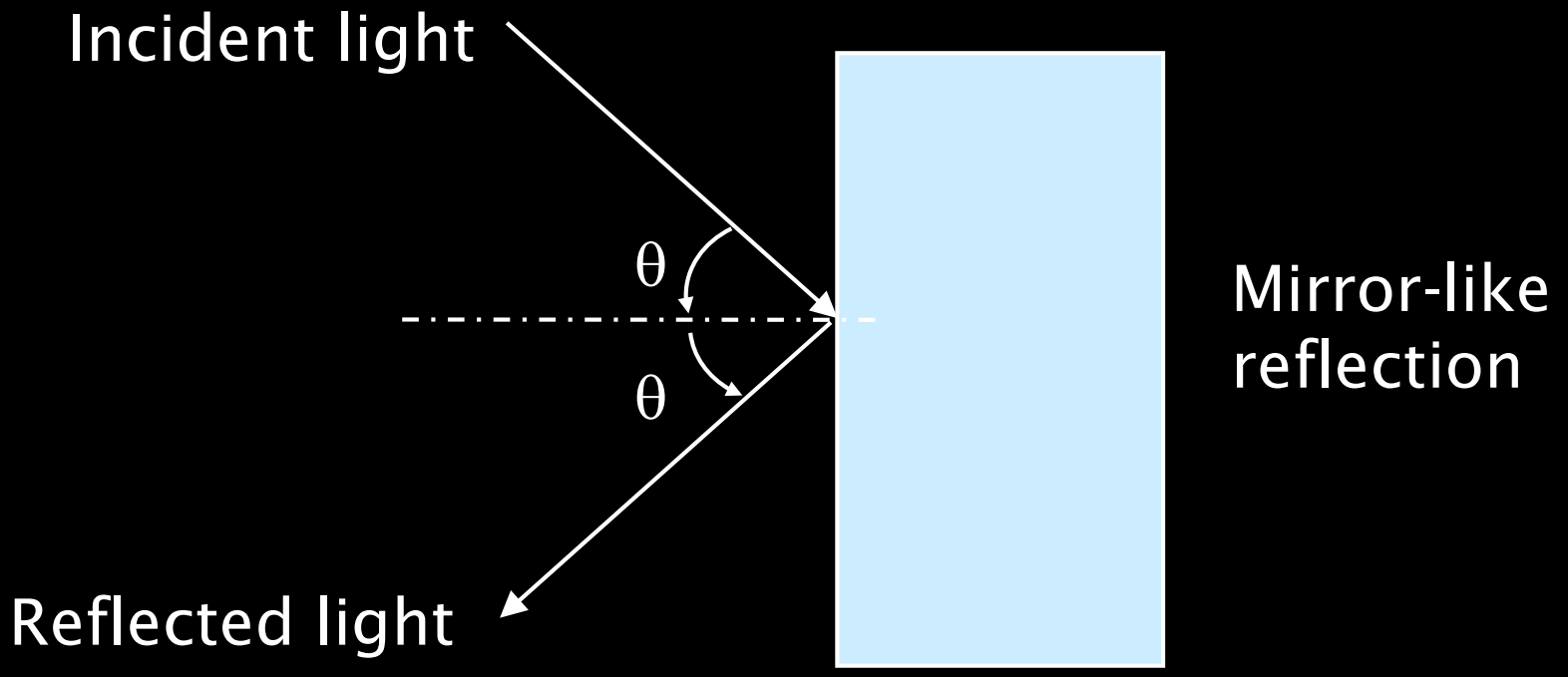
Light / solid interaction - 1/3

- Diffusive reflection
  - Light scattered in all space directions when seeing change of index
  - Also known as ‘scattering’



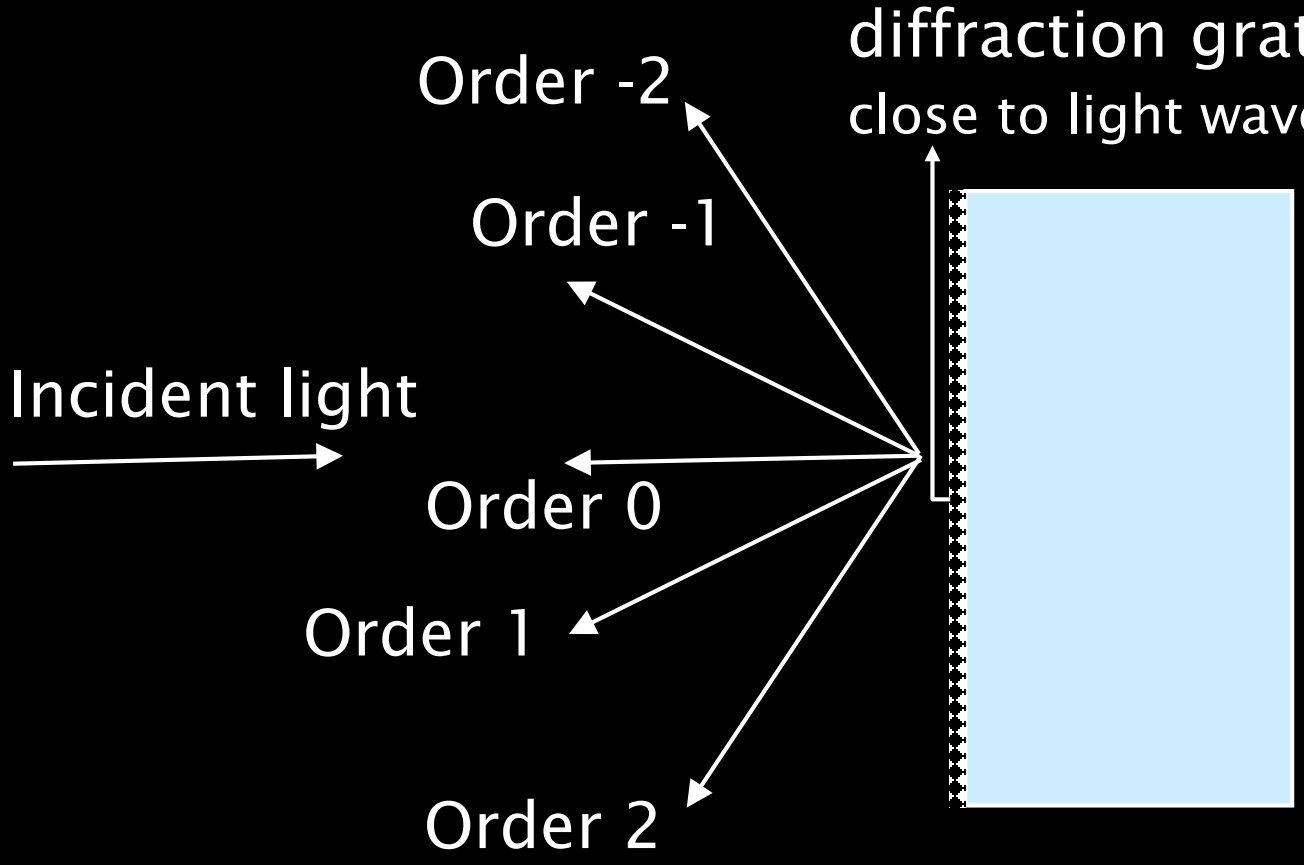
Light / solid interaction - 2/3

- Specular reflection
  - Light scattered in a particular space direction



Light / solid interaction - 3/3

- Diffractive reflection
  - Light scattered in particular space directions



Physical principles – 2/5

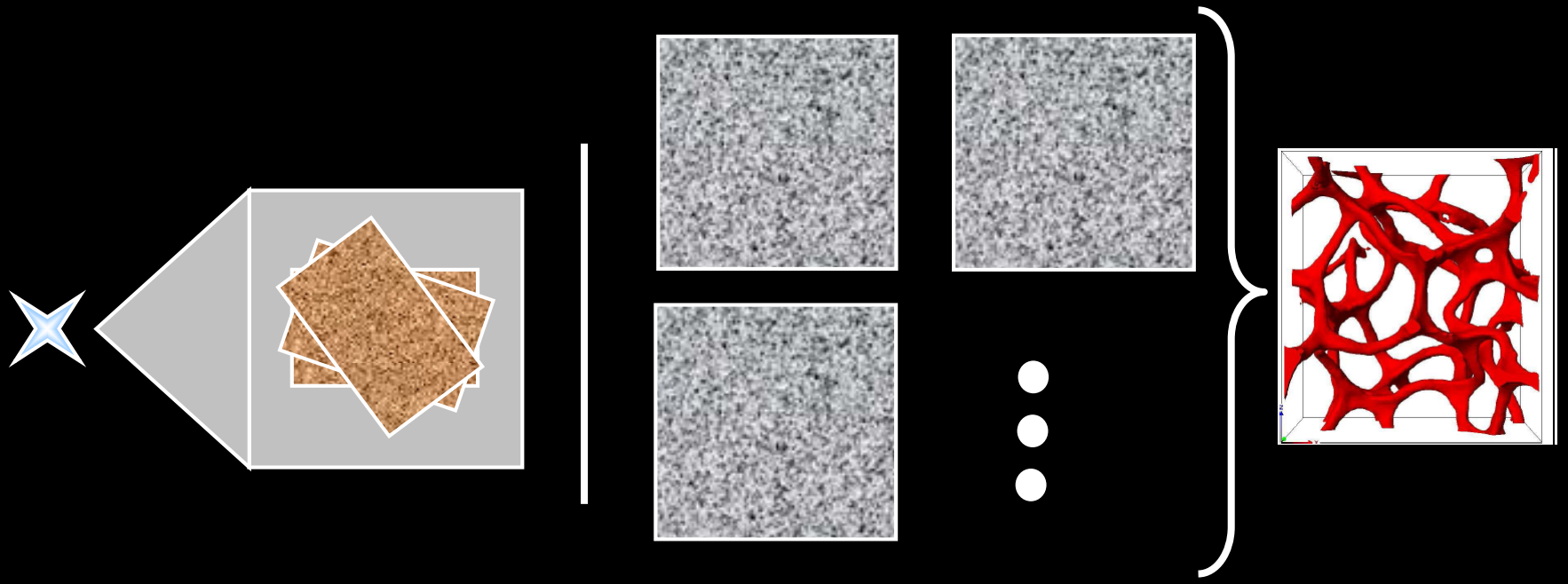
- Intensity or phase of reflected light
  - Diffusive, grating or specular reflection
  - Random or periodical pattern
  - Sensor: CCD/CMOS
  - Encoded information: displacements (in-plane, out-of-plane), displacement gradients
- Interaction of an electron beam with a conductive material
  - Scanning Electron Microscope (complex image forming, image distortion, beam drift)
  - Transmission electron Microscope (TEM)

Physical principles – 3/5

- Mechanical probing for surface profiles
  - Atomic Force Microscope (AFM)
  - Mechanical profilometers
- Short coherence of white light
  - White light interferometer (surface profiles)
- Nuclear Magnetic Resonance
  - Contrast in water contents
  - Many variants of MRI
  - Magnetic Resonance Elastography: direct encoding of displacements

Physical principles – 4/5

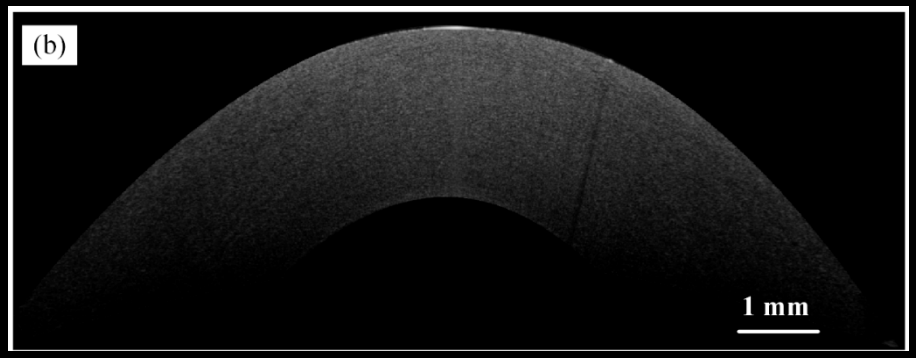
- X-ray absorption
  - X-ray photography
  - X-ray tomography



  - Bone, foam, cast iron, syntactic foams…

Physical principles – 5/5

- Contrast in light index
  - Optical Coherence Tomography (OCT)



Eye cornea

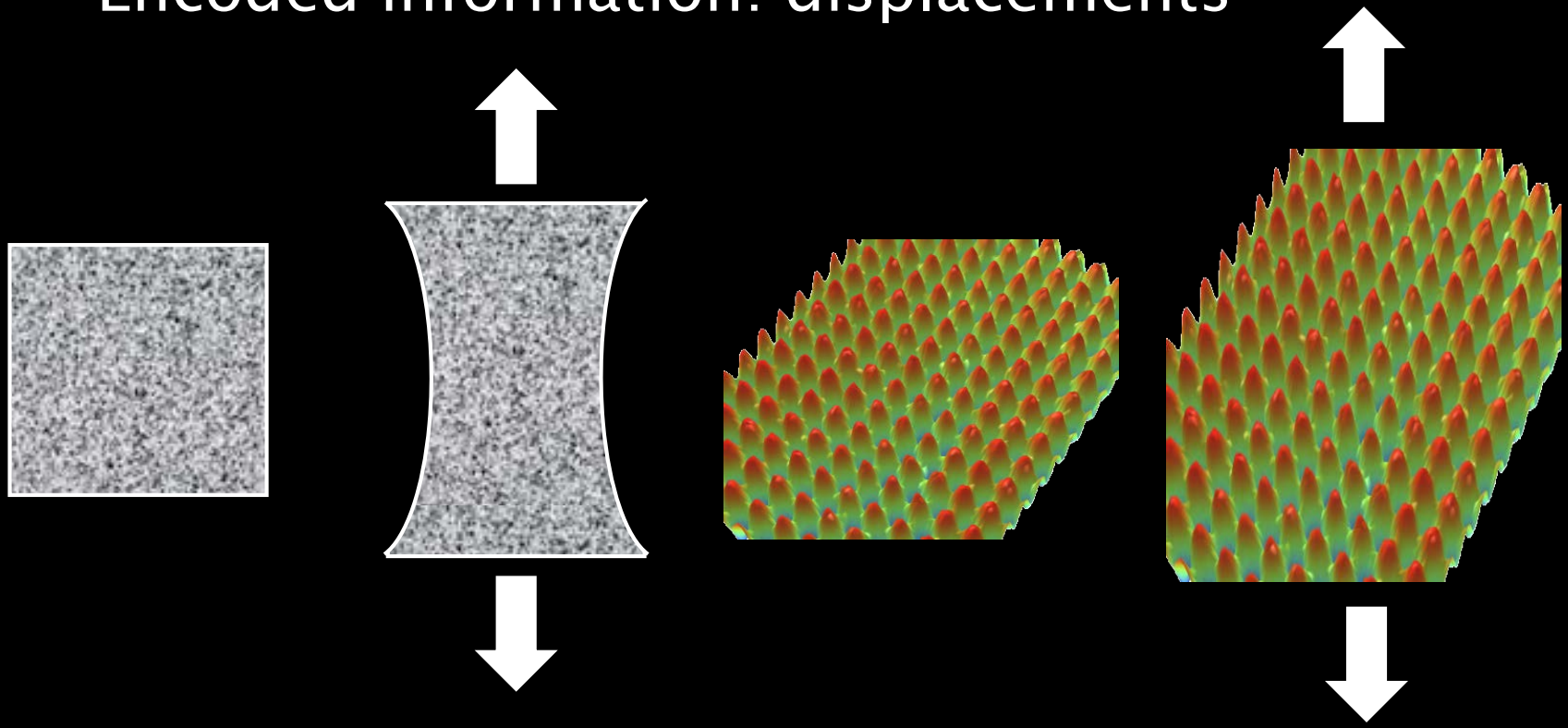
Fu, J., Pierron, F., & Ruiz, P. D. (2015). *Journal of the Mechan,ical Behaviour of Biomedical Materials, submitted*

Fu, J., Pierron, F., & Ruiz, P. D. (2013). *Journal of Biomedical Optics, 18(12), 121512*

Silicone gel seeded with copper particles

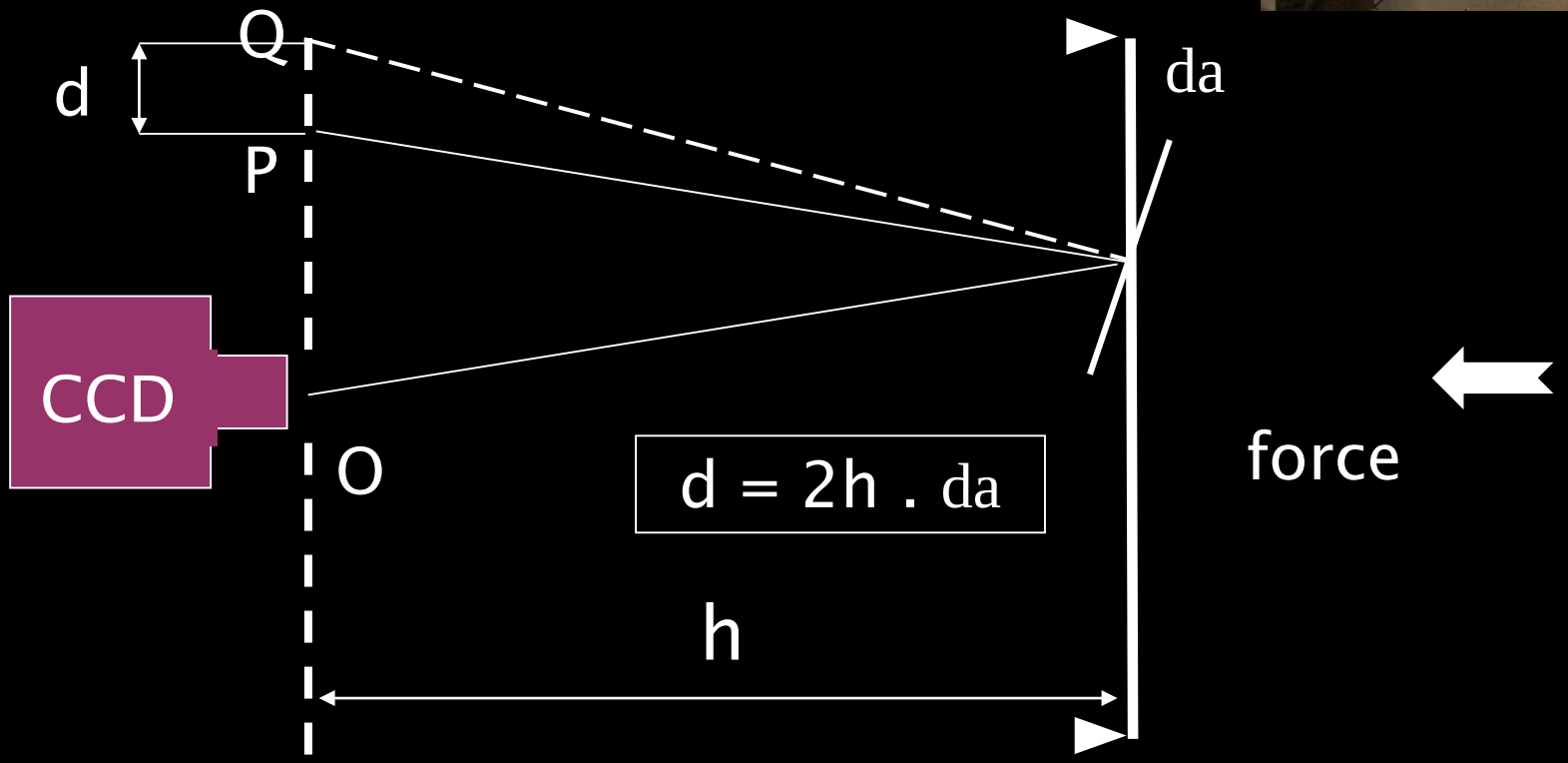
Encoding – 1/6

- Surface or internal pattern deforms as material
  - Easiest phenomenon, intuitive
  - Encoded information: displacements



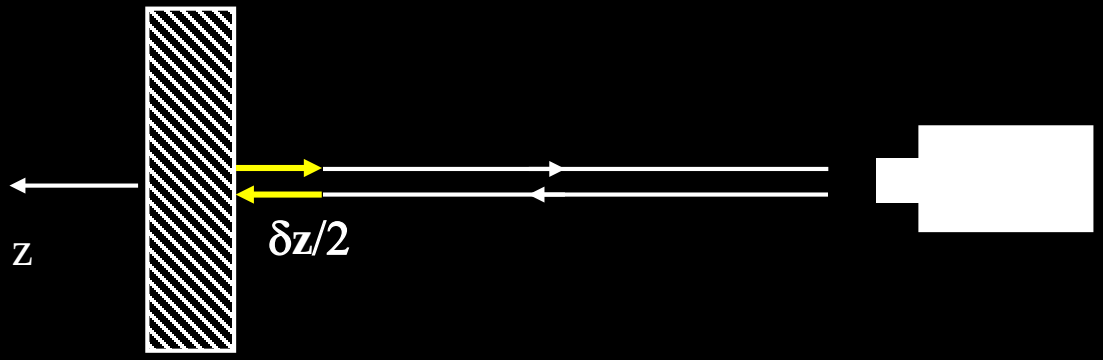
Encoding – 2/6

- Reflected image deforms
  - Specular reflection
  - Encoded information: slope



Encoding – 3/6

- Interferences of light waves
  - Diffusive or diffractive reflection
  - Encoded information: displacements



$$E_x^1 = E_x^0 \cos(\frac{2\pi}{\lambda} z - \omega t) \qquad E_x^2 = E_x^0 \cos(\frac{2\pi}{\lambda}(z + \delta z) - \omega t)$$

$$\overline{(E_x^1(t) + E_x^2(t))^2} = (E_x^0)^2 (1 + \cos\frac{2\pi}{\lambda}\delta z)$$

Fringe pattern

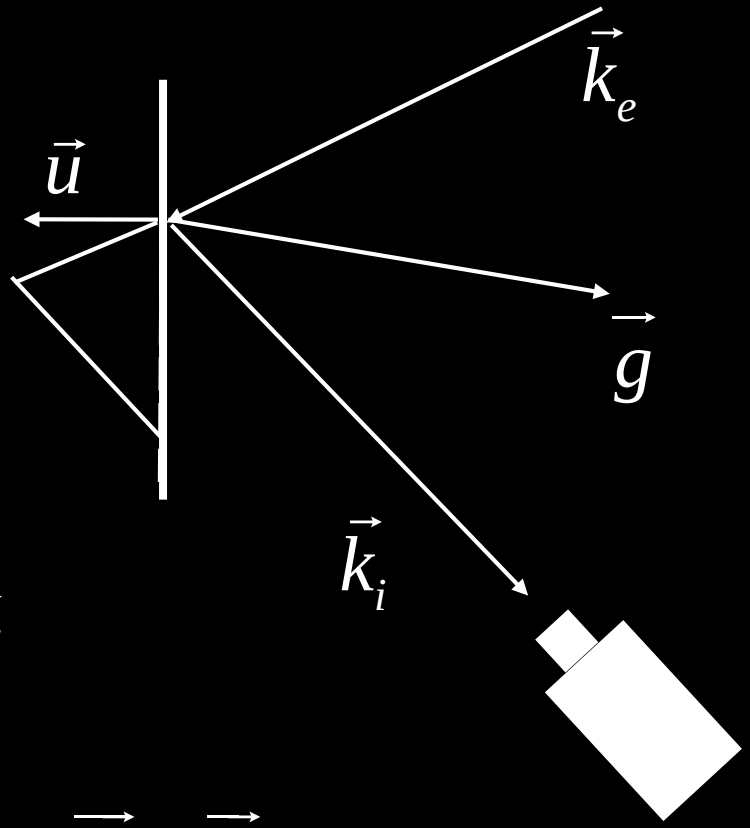
Encoding – 4/6

- Notion of sensitivity vector

$$\Delta\phi_1 = -\frac{2\pi}{\lambda}\vec{k_e}.\vec{u}$$

$$\Delta\phi_2 = \frac{2\pi}{\lambda}\vec{k_i}.\vec{u}$$

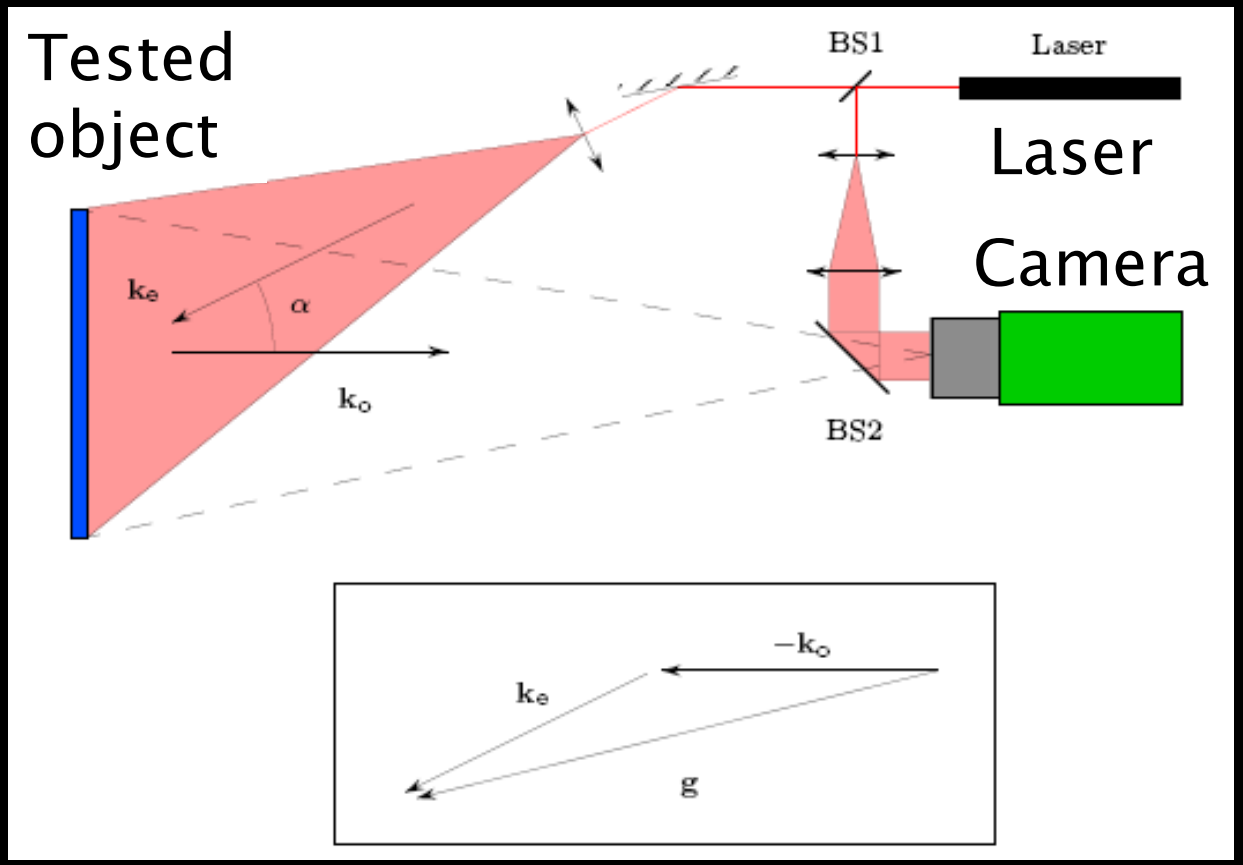
$$\Delta\phi_t = -\frac{2\pi}{\lambda}(\vec{k_e} - \vec{k_i}).\vec{u}$$



Sensitivity vector $\vec{g} = \vec{k_e} - \vec{k_i}$

Encoding – 5/6

- Out-of-plane measurements



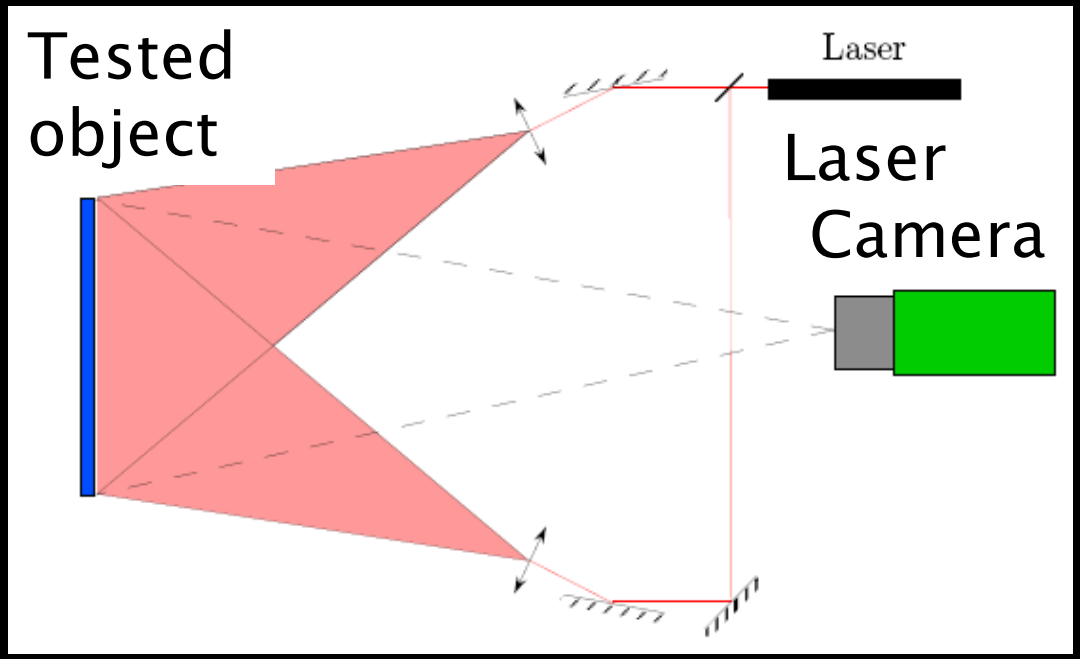
Sensitivity: one fringe (2π phase) corresponds to

$$\frac{\lambda}{2\cos(\alpha/2)}$$

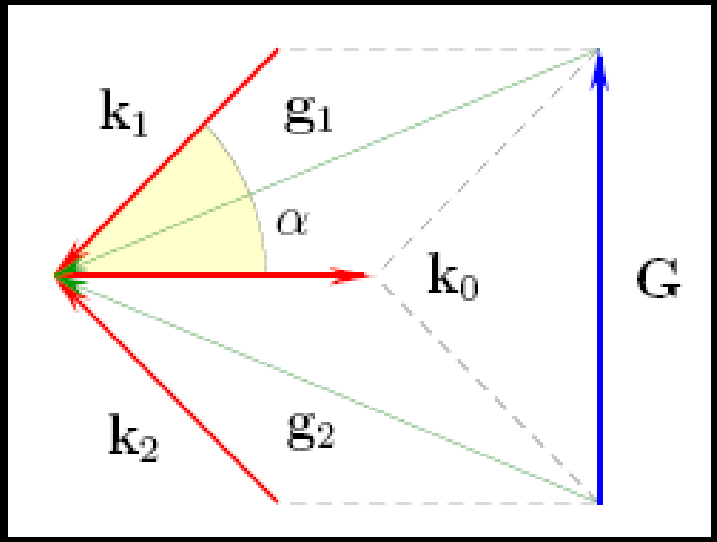
$\alpha = 0$
$\lambda = 500$ nm
→ 250 nm

Encoding – 6/6

- In-plane measurements



Synthetic sensitivity vector

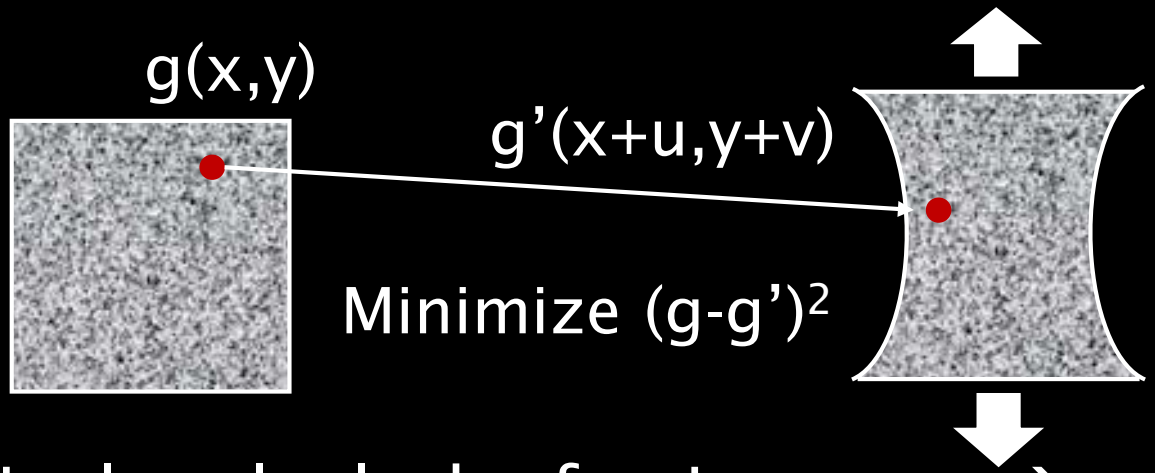


Sensitivity: one fringe (2p phase) corresponds to

$$\frac{\lambda}{2\sin\alpha}$$

Algorithms – 1/4

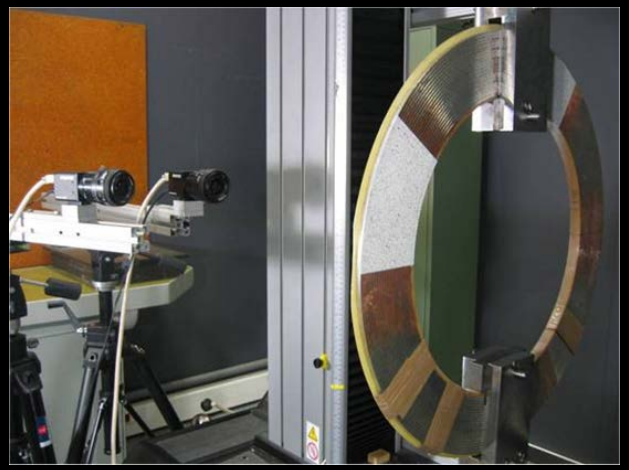
- Pattern correlation ('image registration')
  - Conservation of optical flow (grey level values conserved through deformation)

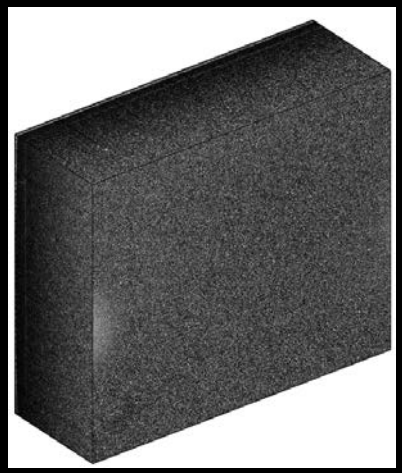


  - Pixel scale: lack of uniqueness → subset
  - Parameterize u and v: shape functions
  - Matching criterion
  - Interpolation (subpixel accuracy)

Algorithms – 2/4

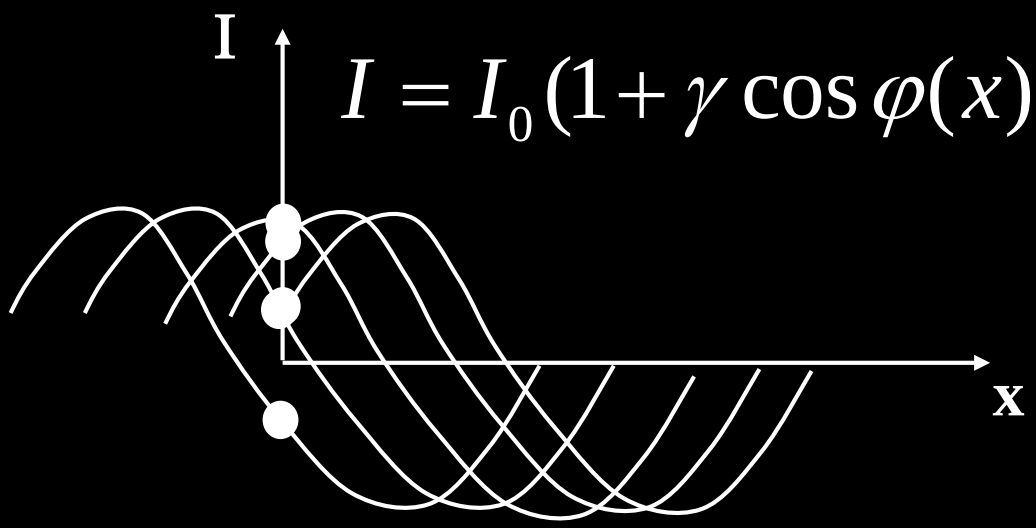
- Pattern correlation
  - Extends to stereo-vision: 2 cameras with different view (Stereo-DIC)
  - Extends to volume images: DVC
  - Very general: works on random and not so random patterns
  - No a priori knowledge: limits performances



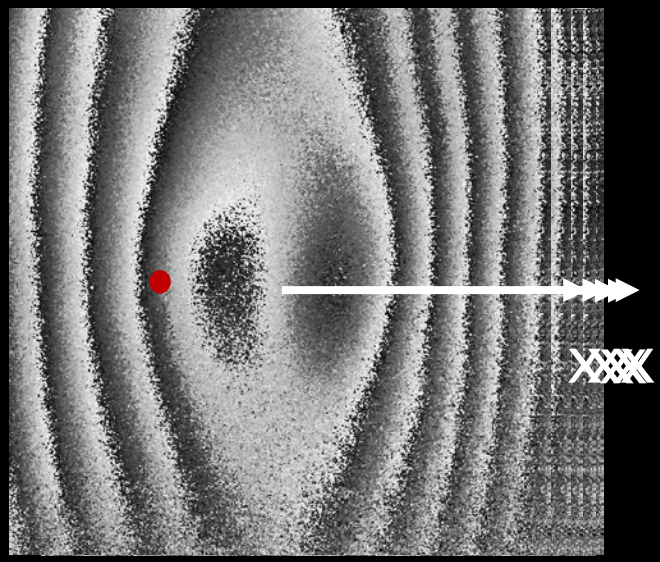


Algorithms – 3/4

- Phase detection
  - Temporal phase shifting

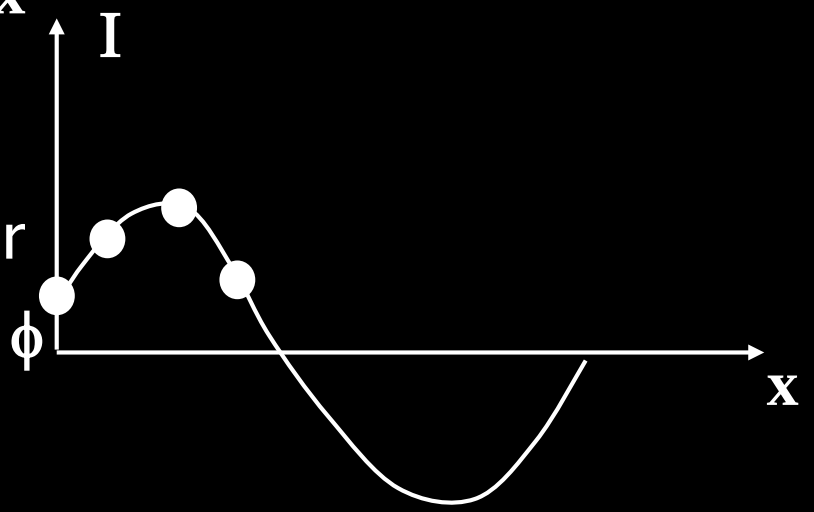


$$I = I_0(1+\gamma\cos\varphi(x))$$



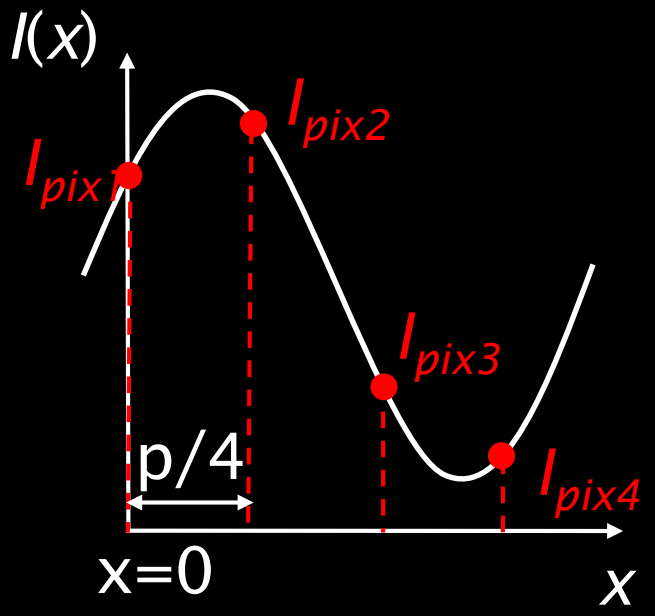
Mirror with piezoelectric actuator

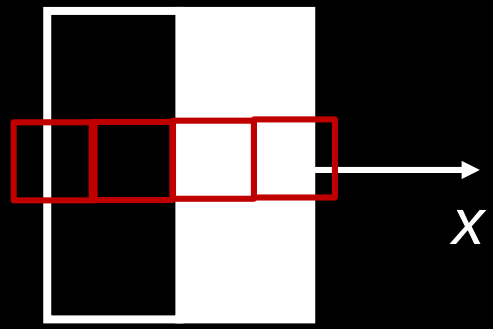
$$I = I_0(1+\gamma\cos[\varphi(x)+\Delta\varphi])$$



Algorithms – 4/4

- Phase detection for regular ‘grids’
  - Spatial phase shifting





$$I_{pix2}: +\frac{\pi}{4}$$

$$I_{pix3}: +\frac{\pi}{2}$$

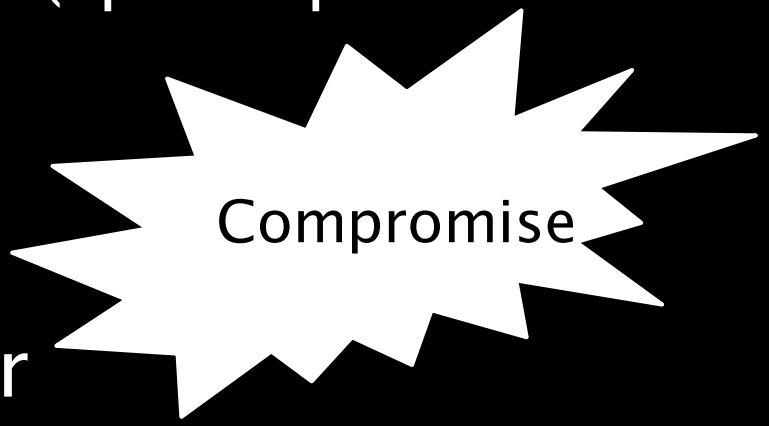
$$I_{pix3}: +\frac{3\pi}{4}$$

$$I(x) = I_0(0)\left[1+\gamma(0)\sin\left(\frac{2\pi x}{p}+\phi(0)\right)\right]$$

$$\phi = Arc\tan\left(\frac{I_{pix1}-I_{pix3}}{I_{pix4}-I_{pix2}}\right)$$

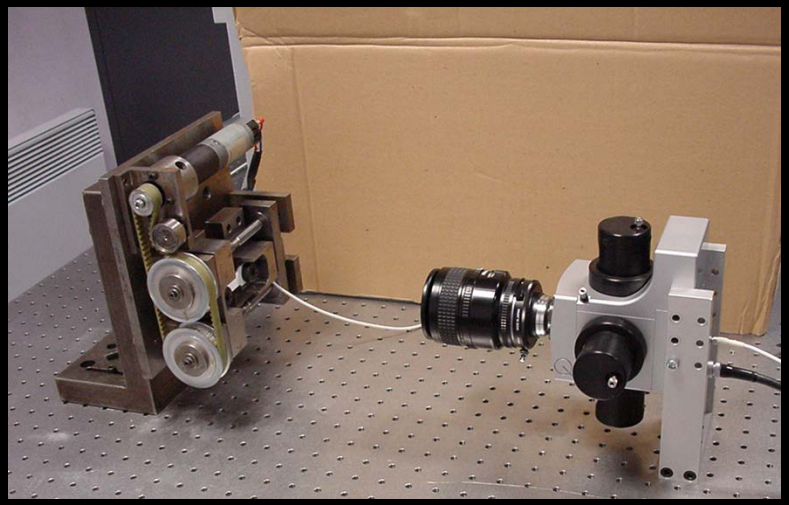
An important remark

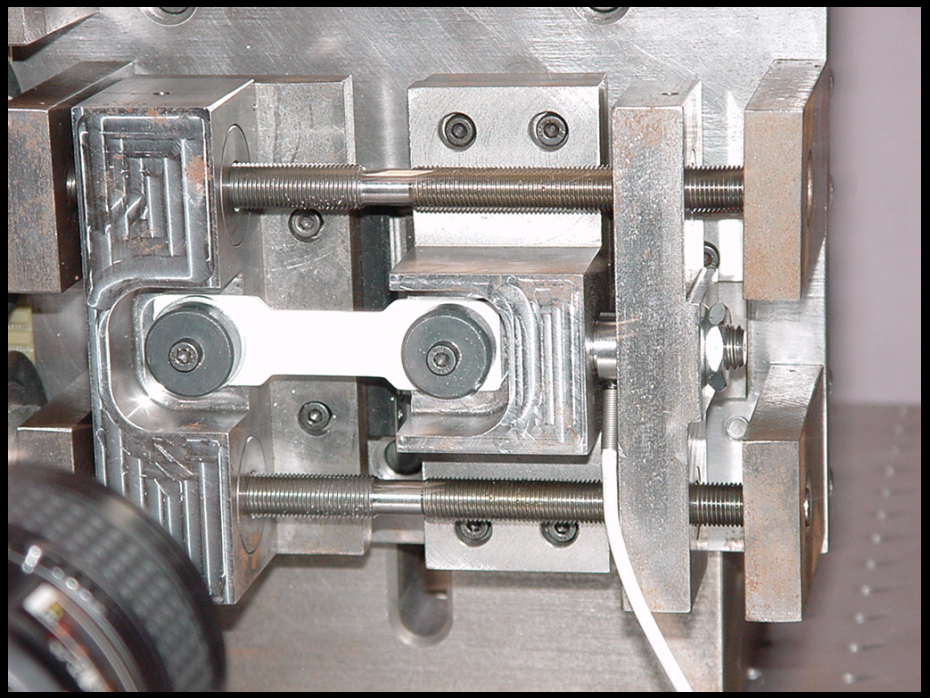
- Measurement acts as a spatial filter
- Smallest sampling size: pixel
  - Temporal phase shifting
- Effective sampling size
  - Subset (correlation), typically 25 x 25
  - Number of sampling pixels (spatial phase shifting), typically 5 x 5
- Noise: random error
- Sampling: systematic error



A few examples – 1/12

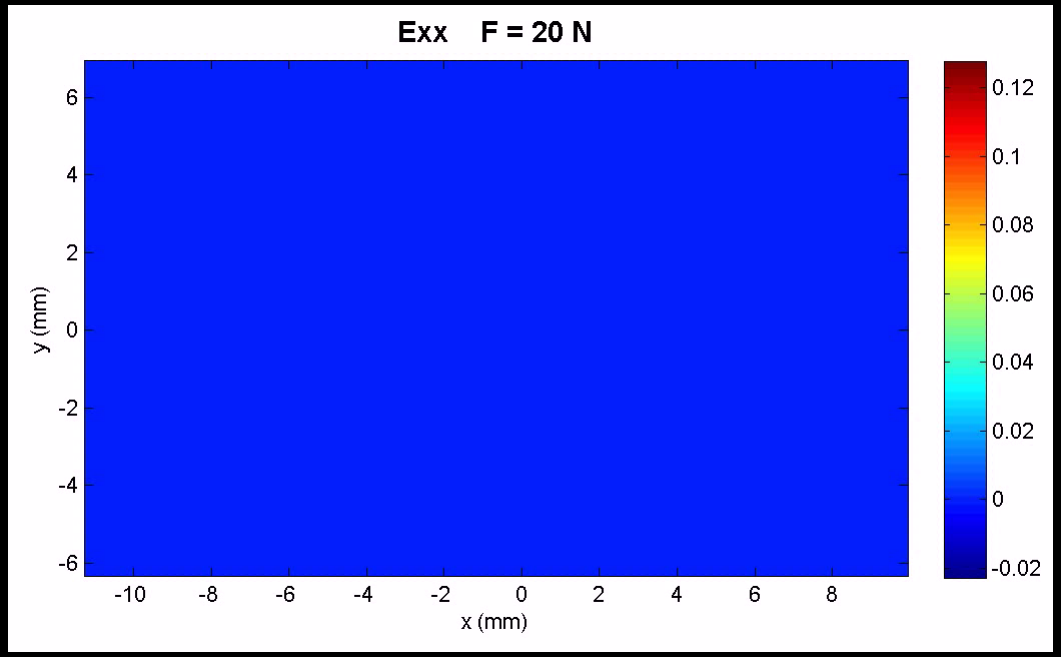
- Speckle interferometry (also called 'ESPI')
  - Interferences, diffusive reflection, temporal phase shifting
- Tensile test on a magnesium friction stir weld



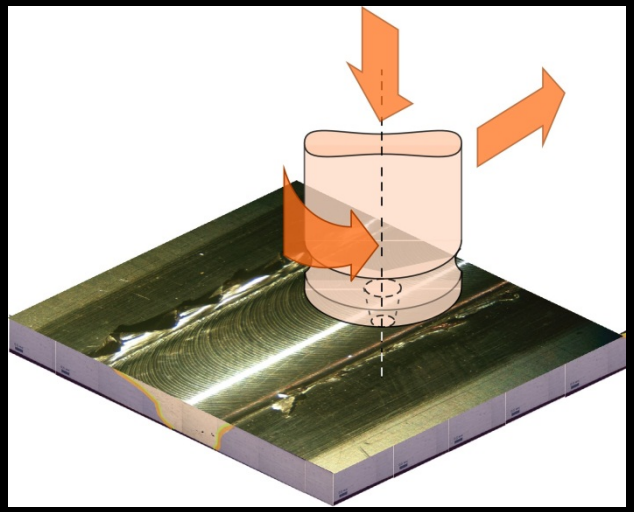


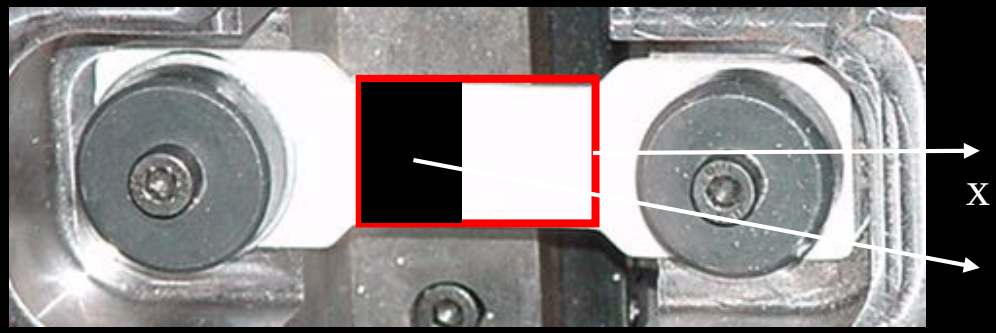
A few examples – 2/12

- Longitudinal strain component



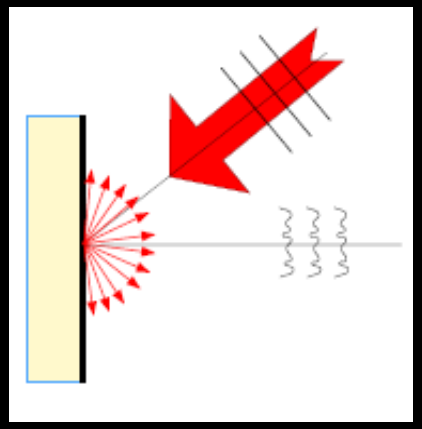
Top surface (polished)

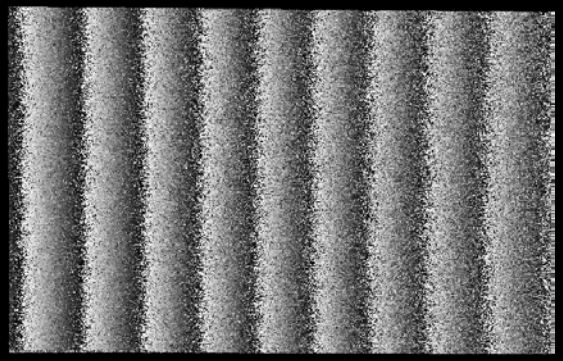




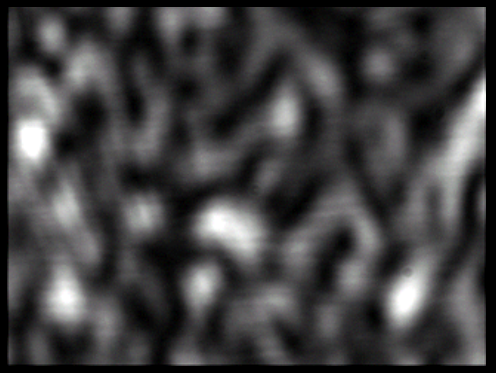
A few examples – 3/12

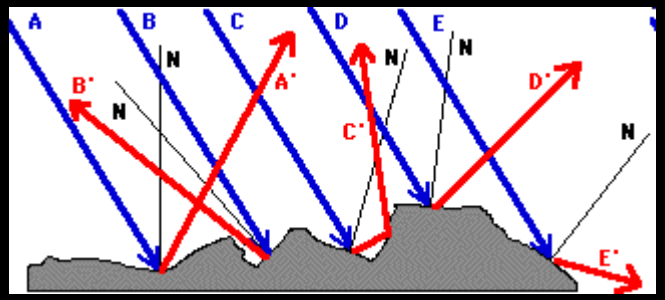
- Speckle interferometry
  - By the way, speckles are not necessary, they are a nuisance (and source of decorrelation)

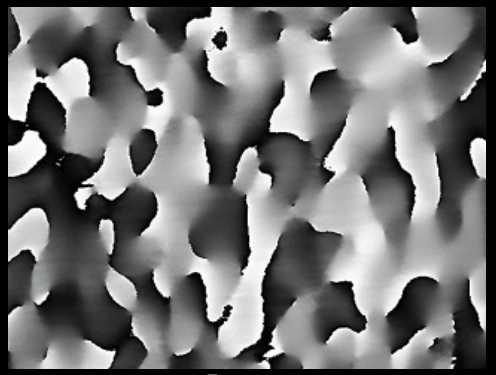




Intensity



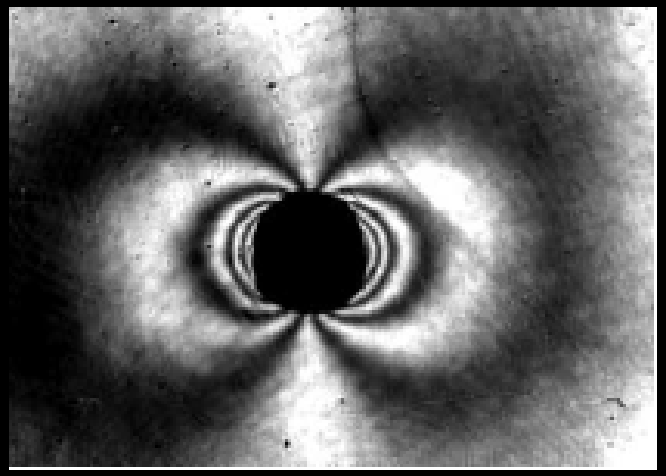




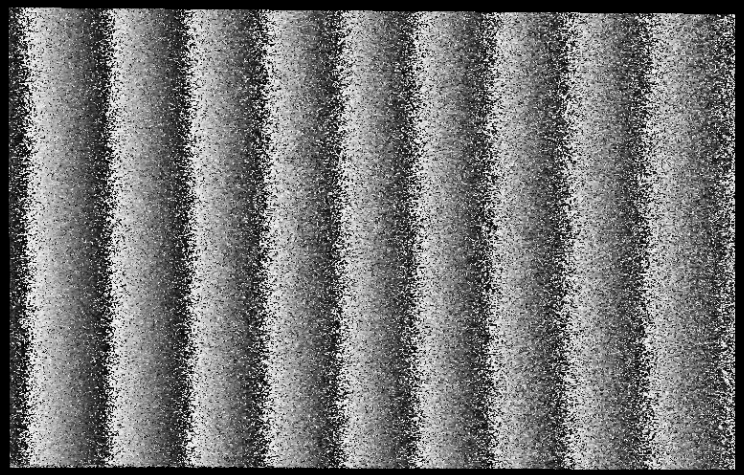
Phase

A few examples – 4/12

- Moiré interferometry
  - Interferences, grating reflection, temporal phase shifting



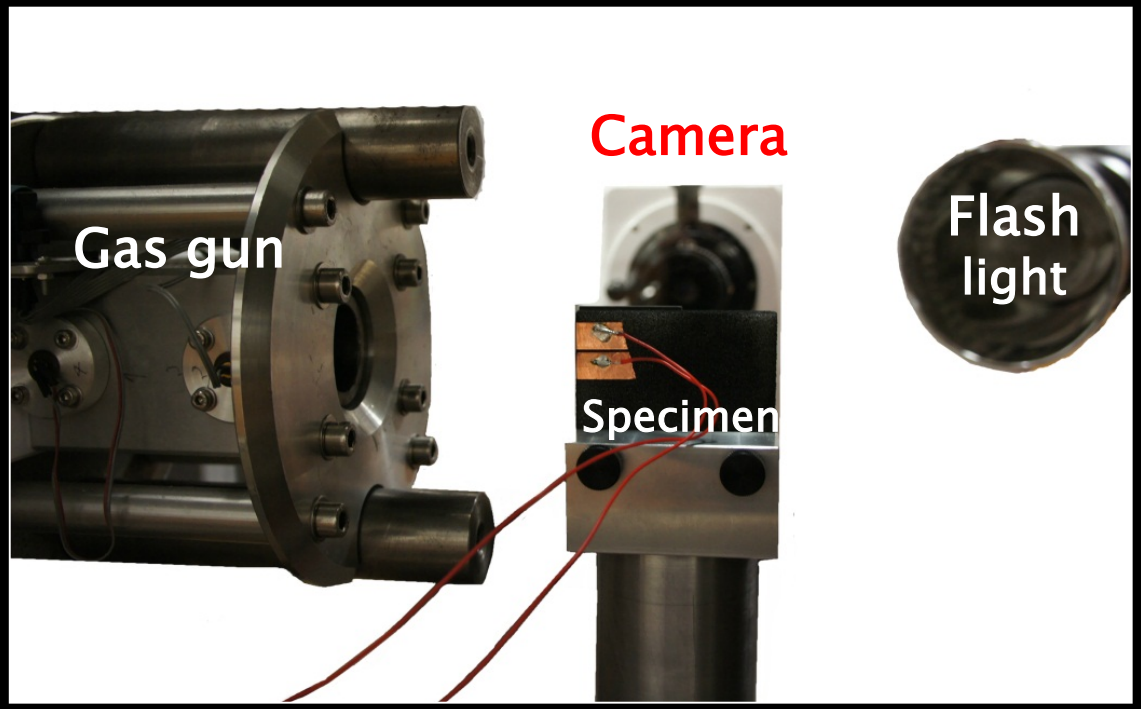
Wu et al, CRAS, 2001
Hole diameter: 2 mm



Speckle interferometry

A few examples – 5/12

- Grid method
  - Intensity, diffusive reflection, spatial phase shifting



Projectile: steel,
30 mm diameter,
40 mm long,
30 $m.s^{-1}$

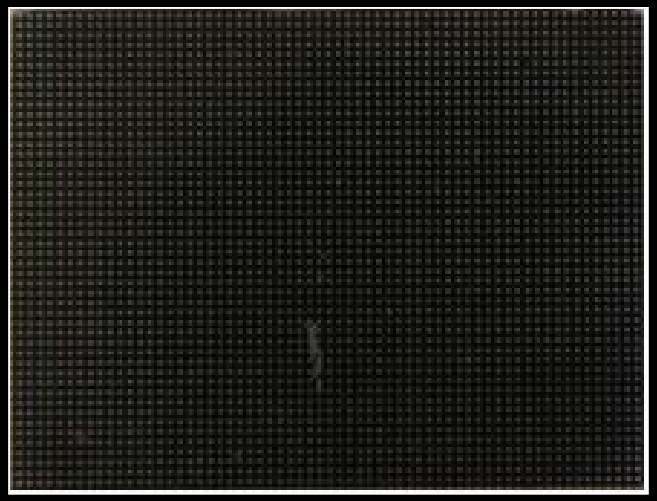
Pierron, F., Zhu, H., & Siviour, C. (2014). Beyond Hopkinson's bar. Phil. Trans. A, 372(2023), 20130195.

A few examples – 6/12

- Camera

  SHIMADZU HPV-X
  Inter-frame time: 0.2 μs
  Spatial resolution: 400 by 250
  Recorded images: 128

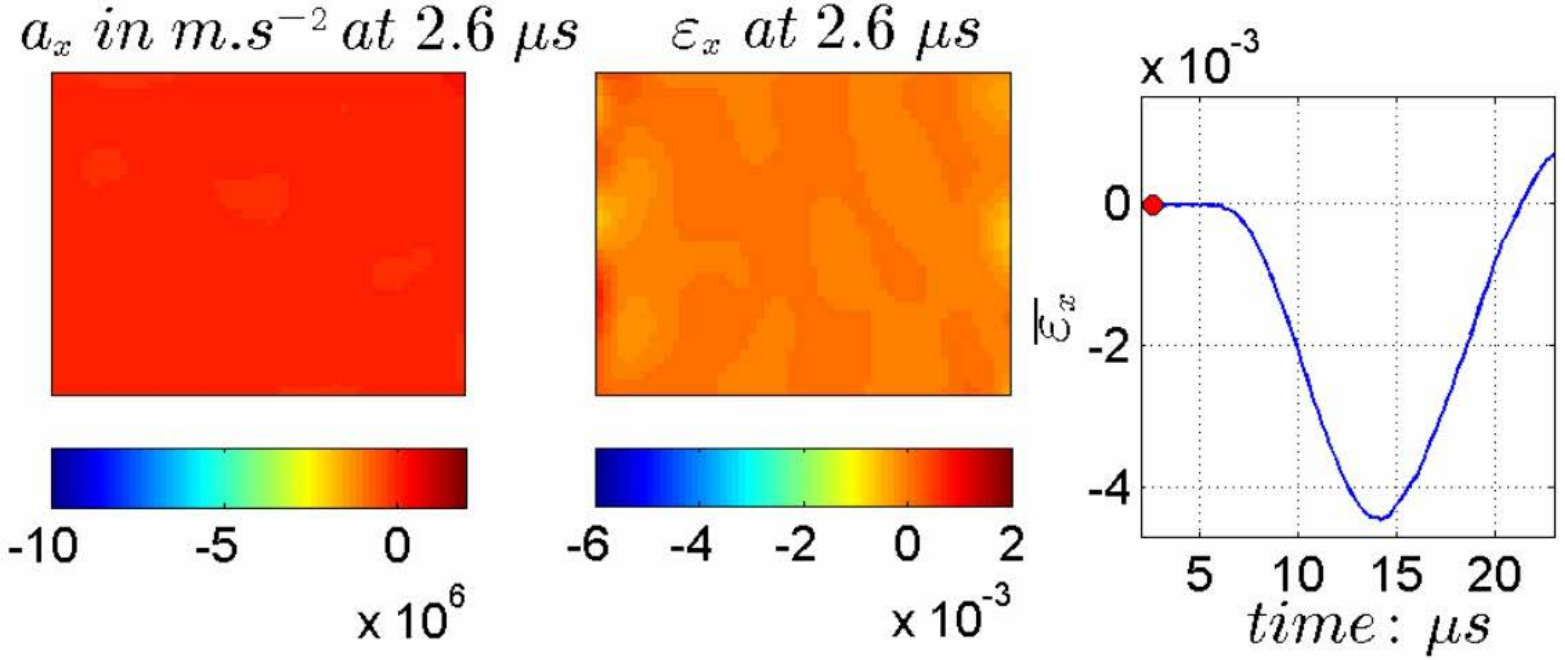
- Grid
  - Grid pitch : 0.6 mm
  - 5 sampling pixels per period



40 x 30 x 3.6 mm

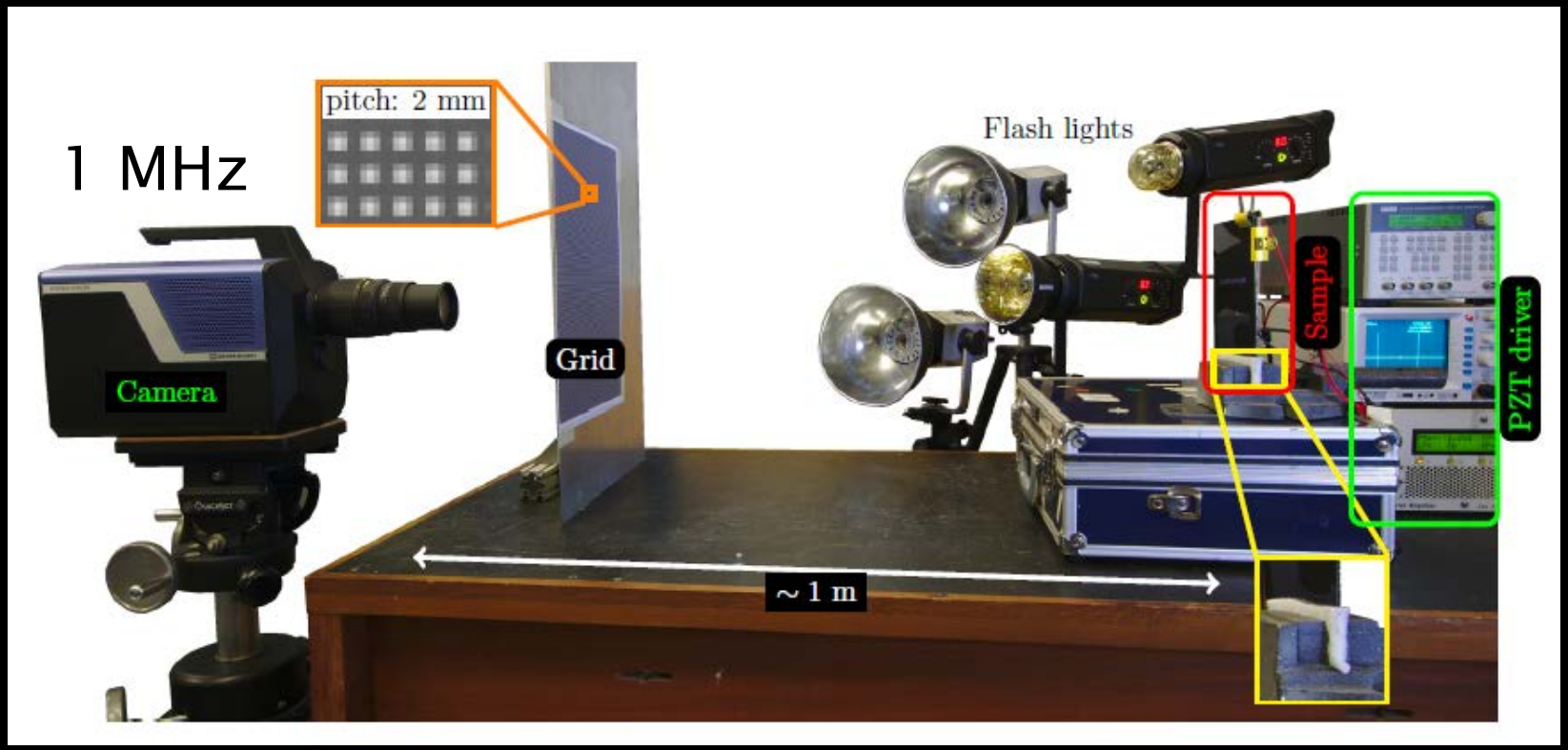
- Material
  - Carbon/epoxy QI $[0/\pm 45/90]_s$

A few examples – 7/12



A few examples – 8/12

- Deflectometry
  - Intensity, specular reflection, spatial phase shifting

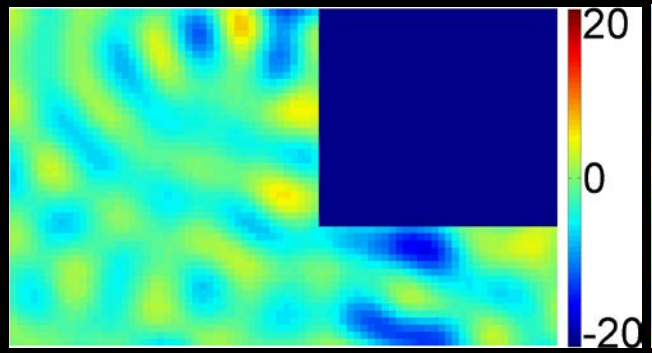


Devivier C., Pierron F., Glynne-Jones P., Hill M., Experimental Mechanics, in revision, 2015

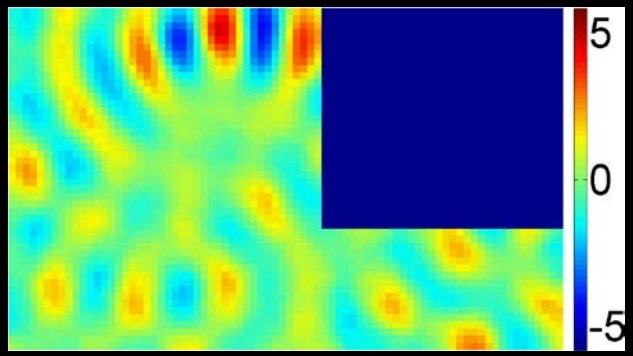
A few examples – 9/12

- Carbon/epoxy plate excited at 99.8 kHz

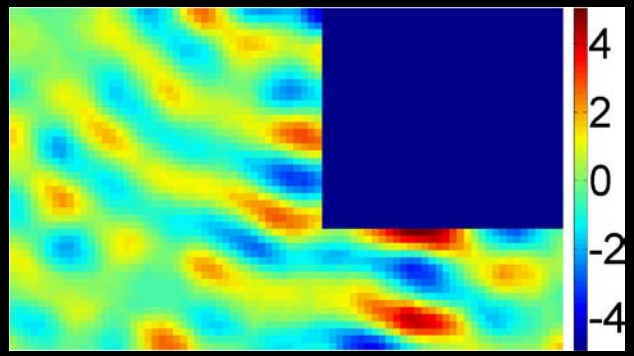
deflection (nm)



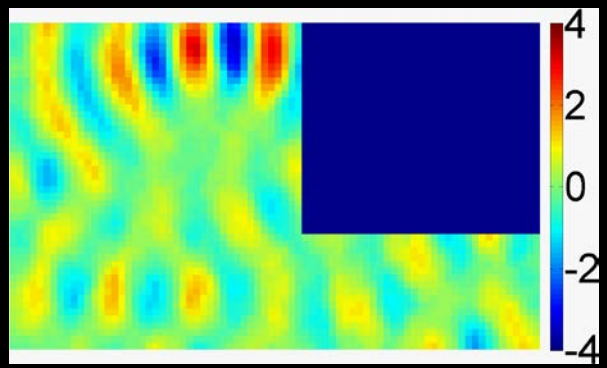
slope x (mm/km)



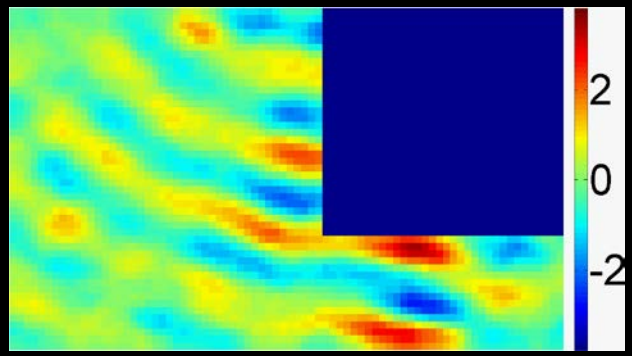
slope y (mm/km)



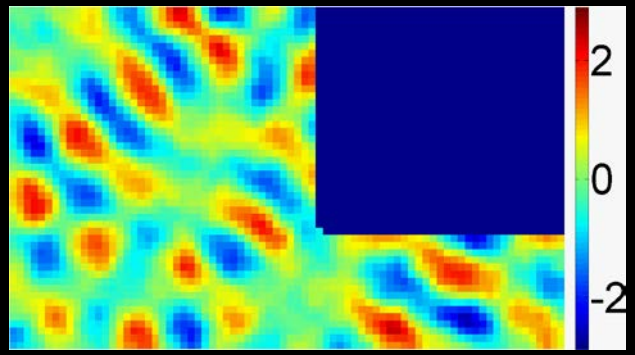
strain x (μm/m)



strain y (μm/m)



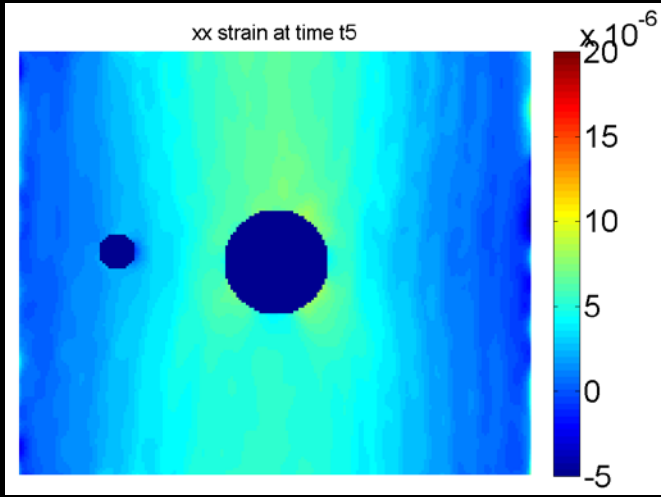
strain s (μm/m)

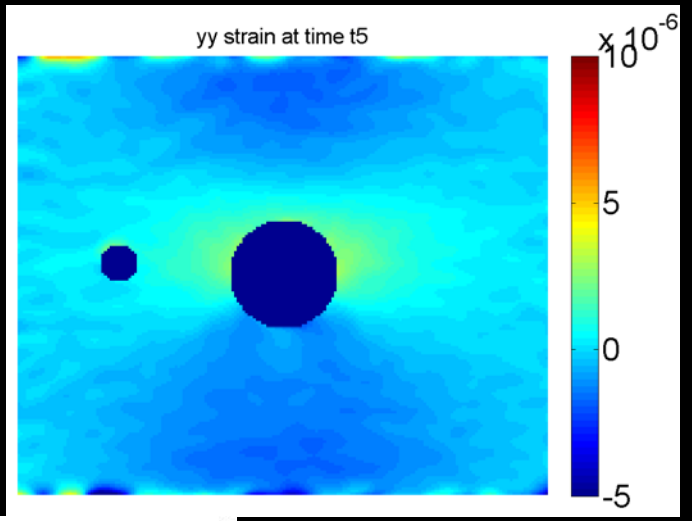


A few examples – 10/12

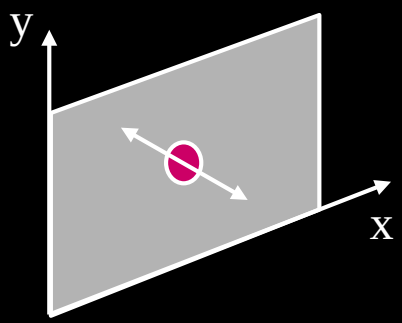
- PMMA plate excited at 100 kHz

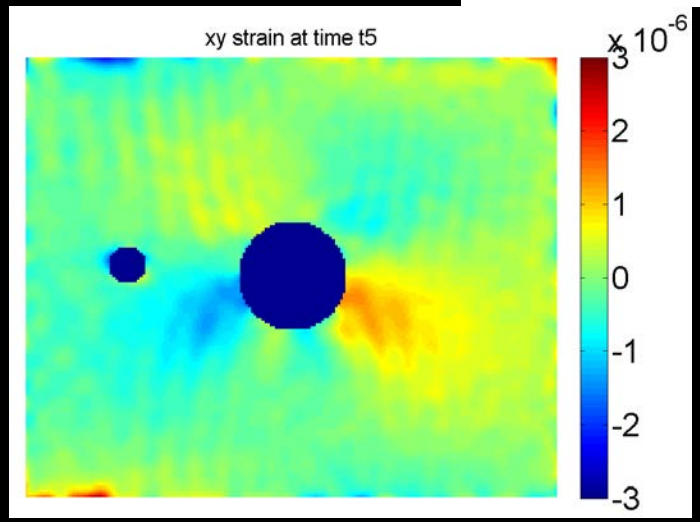
ε_{xx}



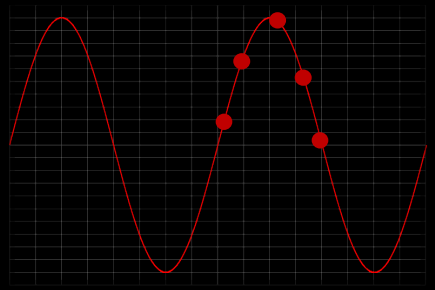


ε_{yy}



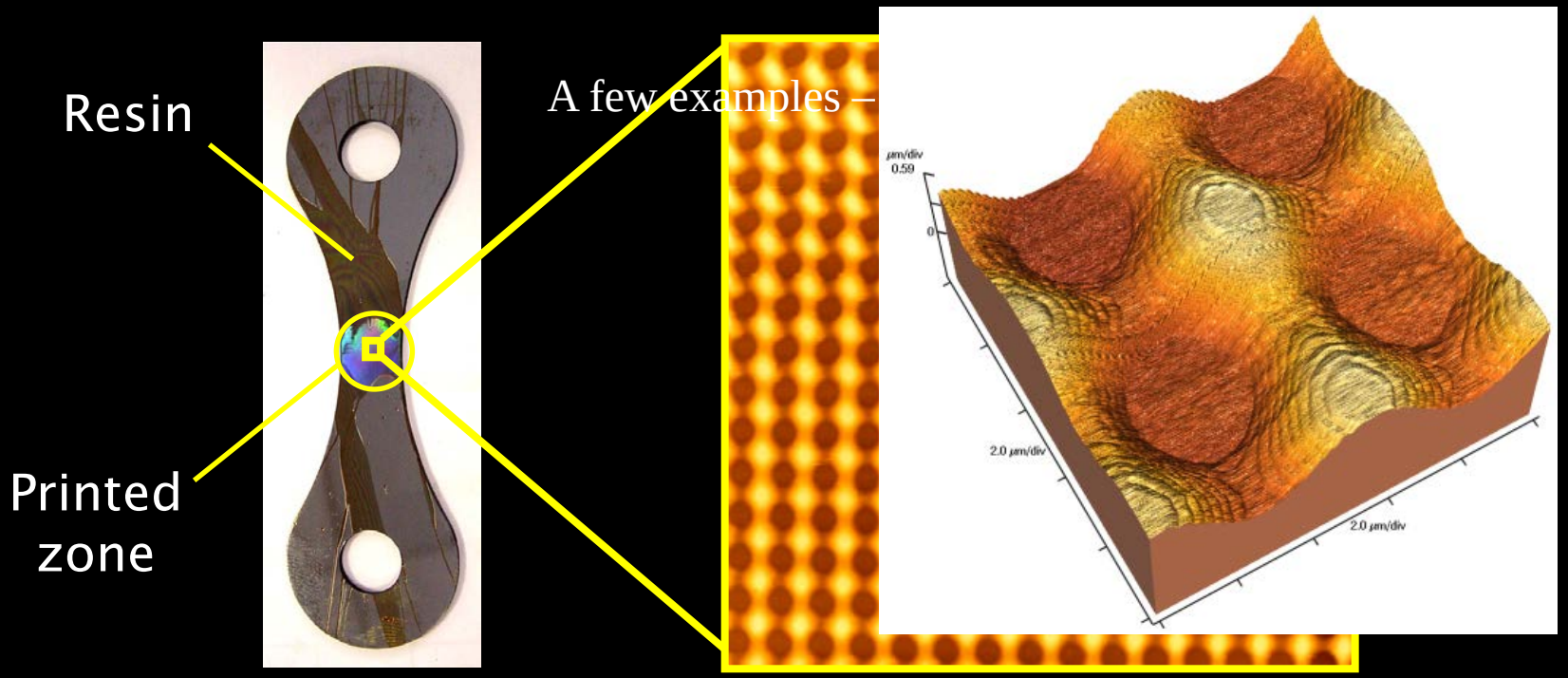


ε_{xy}



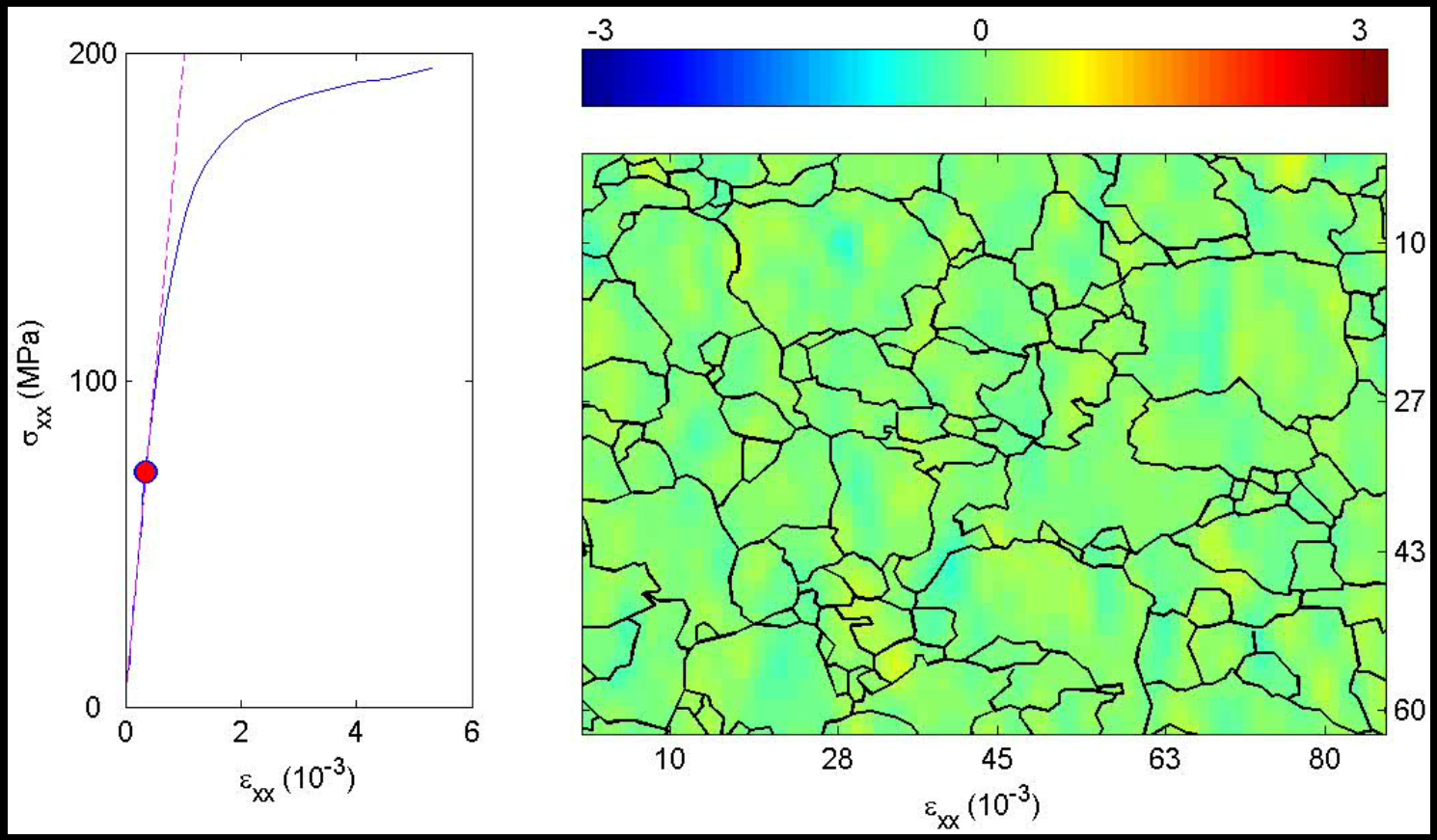
A few examples – 11/12

- Grid method
  - Surface profile (WLI), spatial phase shifting
  - Grid pitch: 5.3 μm (interferometric lithography)
  - Field of view: about 275 by 200 mm²



A few examples – 12/12

- Result (mild steel, 300 x 200 μm^2)



Moulart, R., Rotinat, R., & Pierron, F. (2009). Full-field evaluation of the onset of microplasticity in a steel specimen. Mechanics of Materials, 41(11), 1207-1222.

Conclusion – 1/2

- Overview of main techniques
  - Image pixel size of 10 μm
  - 1000 by 1000 CCD camera

	DIC	GM	SI
Spatial resolution			
in pixel	32	9	1
indep. data points	960	12100	10^6
Displacement resolution			
in pixel	0.01	0.01	0.001
in μm	0.1	0.1	0.01

Conclusion – 2/2

- Overview of possibilities
- Important issue: uncertainty quantification
  - Need for more metrological concepts
  - Critical: low pass filtering effect of DIC
- DIC is not a synonym of FFM (‘toolbox’)
- Need for more training
- Future: integration with data processing
  - MatchID platform, www.matchIDmbc.com

More?

- 5 days DIC course: diccourse.matchid.org
  - 11-15 January 2016 in Ghent, Belgium

Dr Philip Reu
Sandia National Laboratories, USA

Prof. Pascal Lava
KU Leuven, Belgium

Yours truly

- BSSM Experimental Mechanics workshop
  - 11 – 15 April 2016 at the University of Southampton, www.bssm.org (Prof. J. Barton)