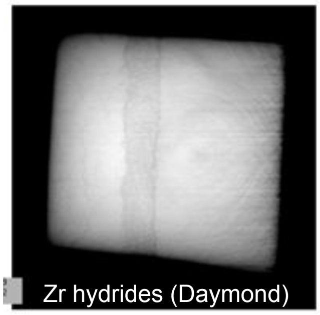
Tomography for studying strain, deformation and damage in materials science

MECASENS 2015 tutorial

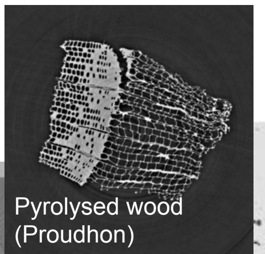
Andrew King

What is tomography?

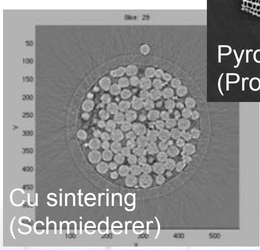
- 3D imaging with neutrons or x-rays
- Equivalent to medical CAT scan
- Many materials applications…



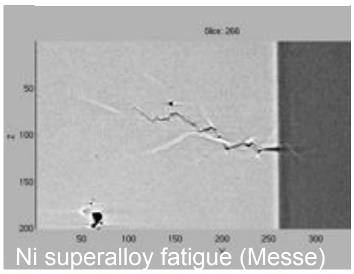
Zr hydrides (Daymond)



Pyrolysed wood (Proudhon)



Cu sintering (Schmiederer)



Ni superalloy fatigue (Messe)

Outline of this talk

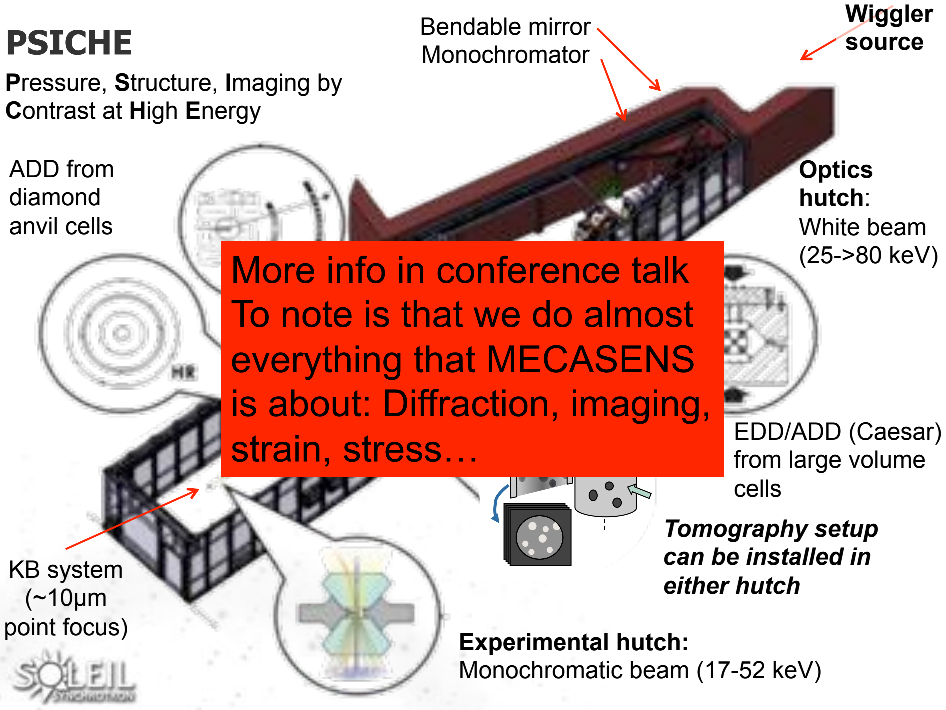
- Introduction
  - SOLEIL / PSICHE / Me
- Imaging and tomography
  - How the experiment works
- Analysis of 3D image data
  - Extract quantitative results
- Strain and deformation measurement
  - Digital image and volume correlation
- Other ideas and possibilities
  - Combining tomography and diffraction
  - Big data
- Conclusions

SOLEIL

- French national synchrotron source
  - 25 km outside Paris
  - Operational since ~2007

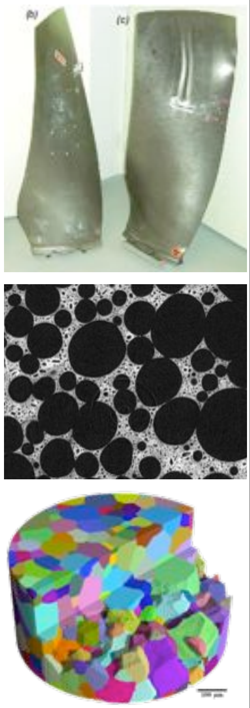
PSICHE

Pressure, **S**tructure, **I**maging by **C**ontrast at **H**igh **E**nergy



Myself

- Diffraction for strain, stress and damage characterisation
  - Manchester 2001-2005
- Tomography for 3D morphology of porous and granular materials
  - INSA de Lyon 2006
- Diffraction Contrast Tomography for mapping polycrystals and materials applications.
  - Manchester/ESRF/HZG 2009-2013
- At SOLEIL since 2013…



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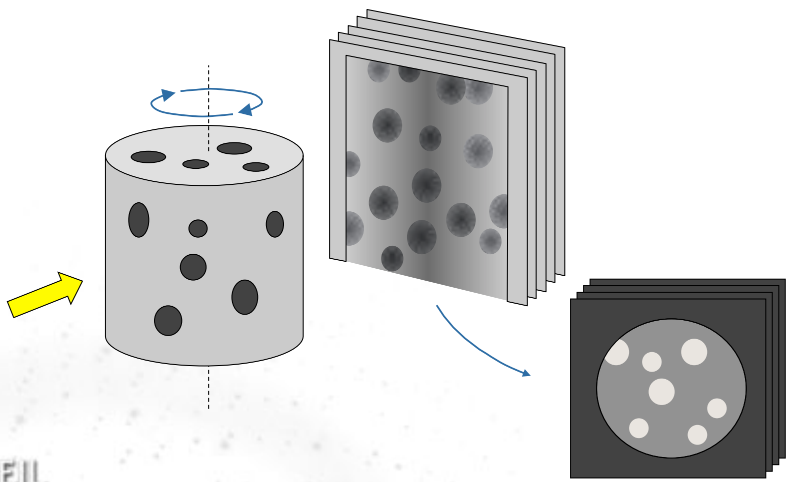
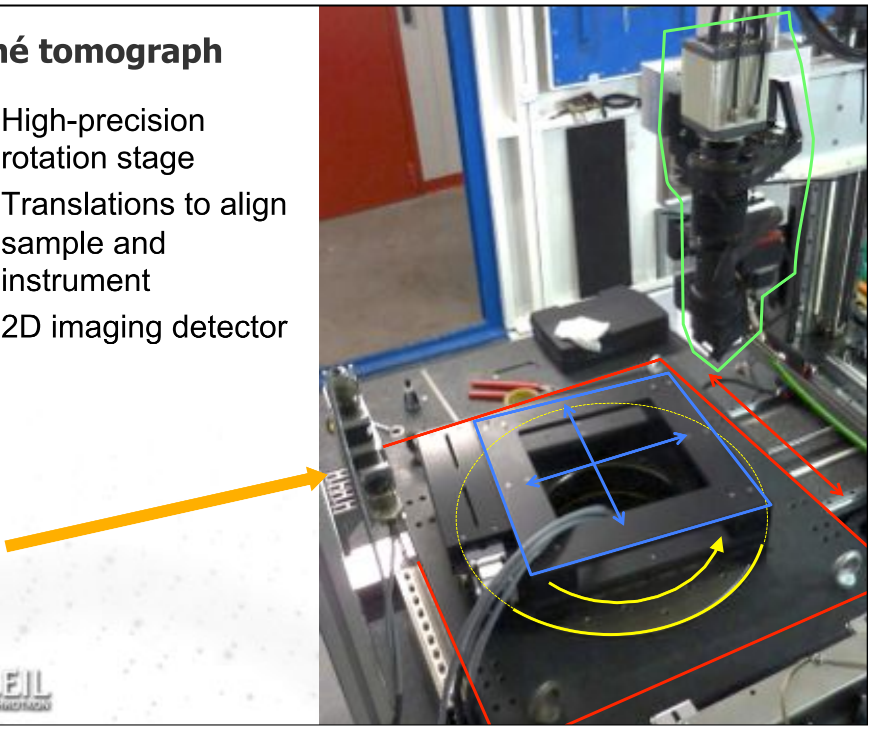
Tomography: Experimental setup

- Very simple!
- Almost same for lab or synchrotron X-rays or neutrons



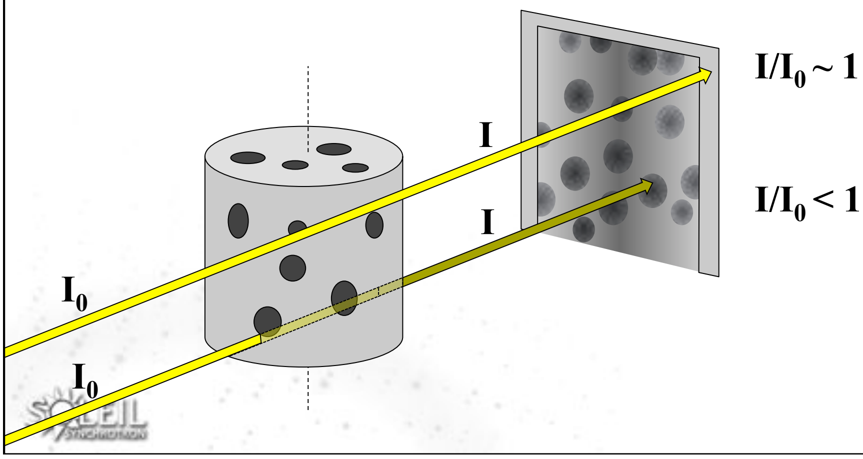
Psiché tomograph

- High-precision rotation stage
- Translations to align sample and instrument
- 2D imaging detector



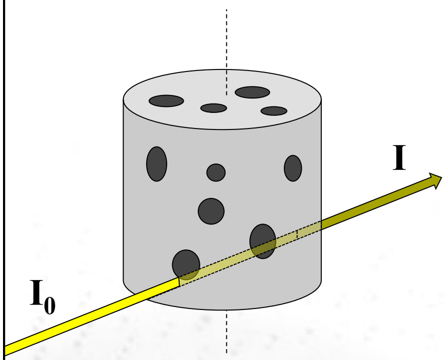
Radiography: Principle – measure attenuation

- Still pretty simple!
- Still almost same for lab or synchrotron X-rays or neutrons
- Measure intensity at each detector pixel



Radiography: Physical quantity

- Projection image of the sample
- Beer-Lambert law relates measured intensity to the integral of attenuation along the beam path:

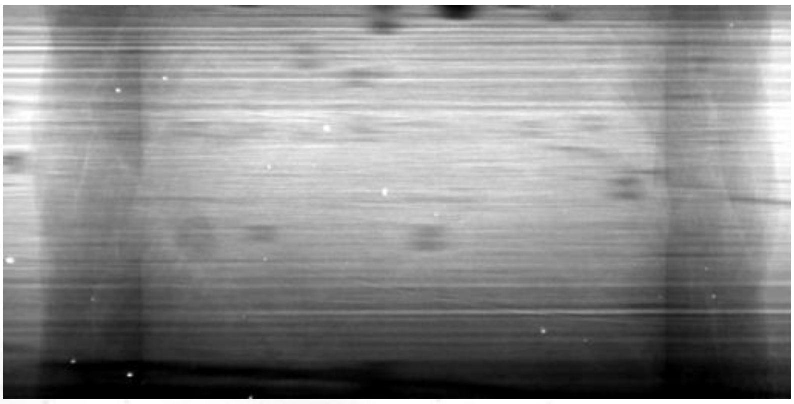


$$I = I_0 \exp\left(\int \mu\rho \, dx\right)$$

$$\int \mu\rho \, dx = -\log\left(\frac{I}{I_0}\right)$$

Tomography: Projections

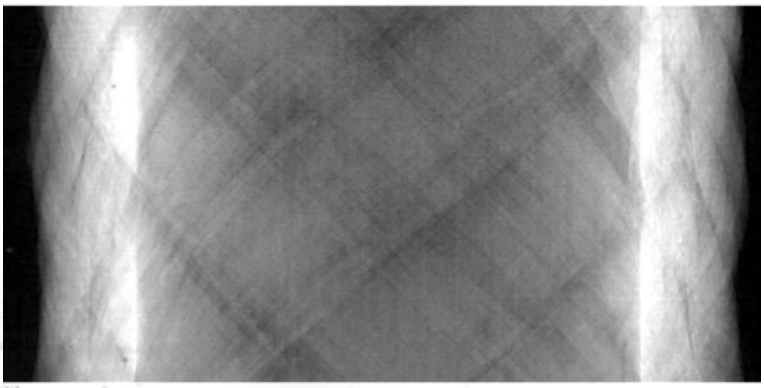
- Sample visible, but lots of defects
  - windows, beam optics, scintillator defects, camera defects…



SiC/SiC composite, Y. Chen / L. Gelebart CEA

Tomography: Correction of images

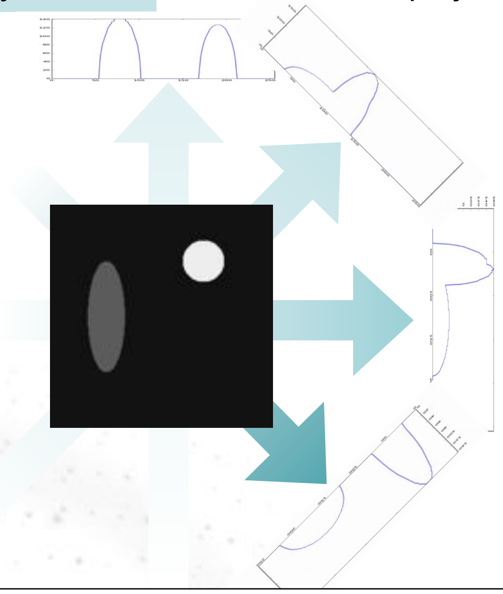
- Standard flat field correction
  flat = (image - dark) / (reference – dark)
- This gives I/I_0, and removes most artefacts
- **Beer-Lambert law: projected attenuation = $-\log(I/I_0)$**



SiC/SiC composite, Y. Chen / L. Gelebart CEA

Tomography: Experiment (phantom)

- Forward projection
- Back projection

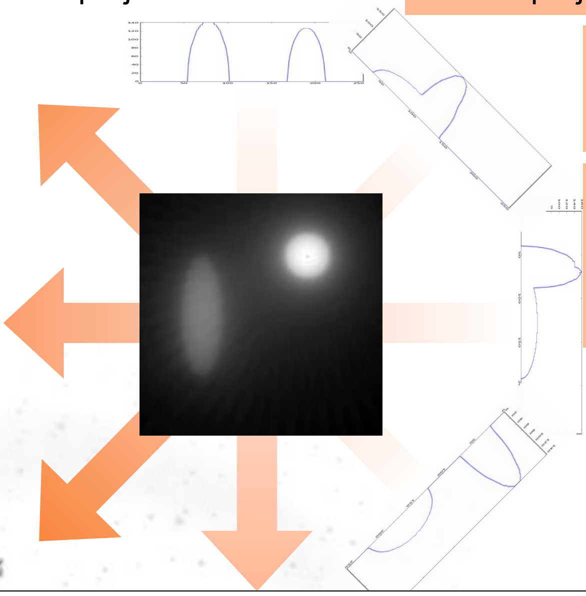


Tomography: Reconstruction (phantom)

- Forward projection
- Back projection

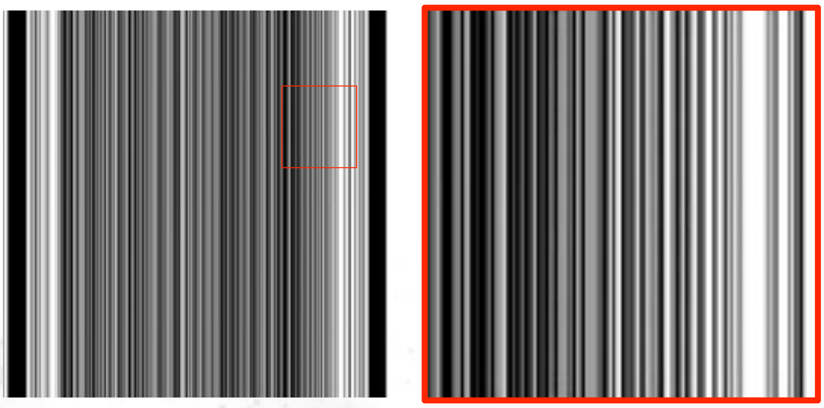
A filter in Fourier space removes the low frequency "glow" artefact

More sophisticated reconstruction techniques are available – better reconstruction from fewer projections



Tomography: Reconstruction (example 1)

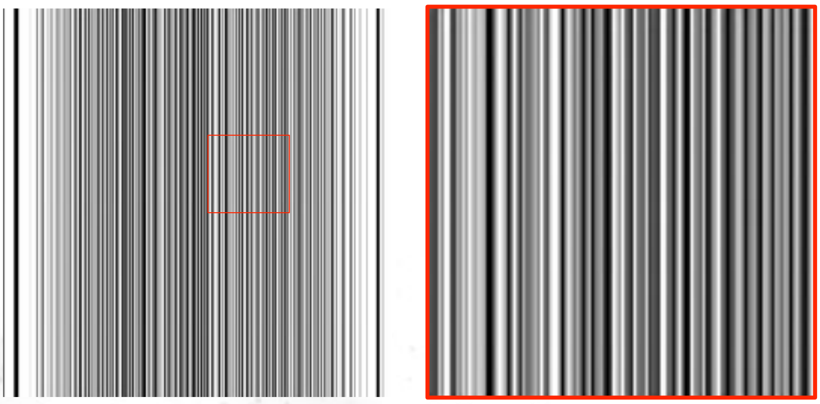
- Filtered back projection
  - most standard, basic reconstruction technique
- 1 / 2 / 4 / 8 / … / 1024 / 1800 projections



SiC/SiC composite, Y. Chen / L. Gelebart CEA

Tomography: Reconstruction (example 2)

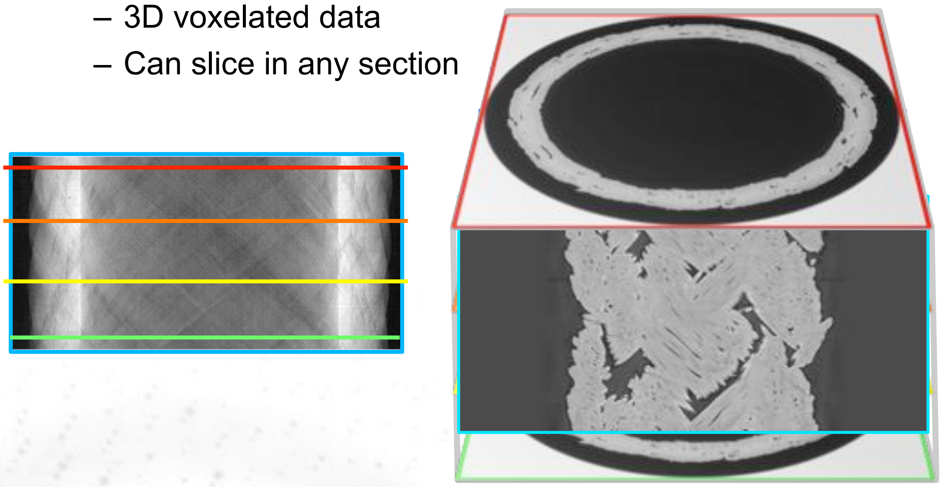
- Filtered back projection
  - most standard, basic reconstruction technique
- 1 / 2 / 4 / 8 / … / 1024 / 1800 projections



Aluminium alloy for DVC. M. Fregonese, MATEIS, INSA de Lyon

Tomography: Volume data

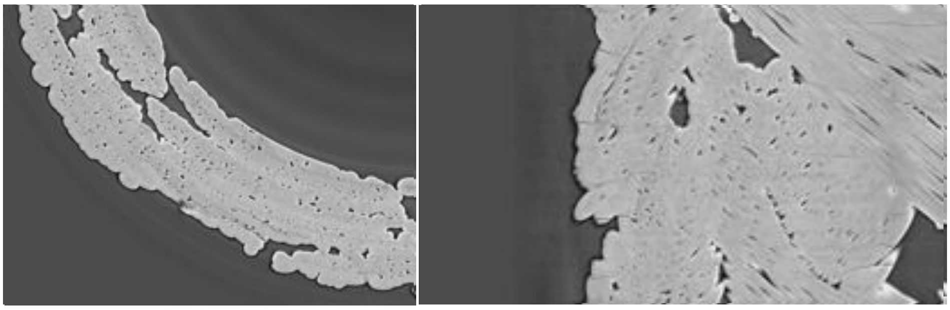
- Reconstruct a slice for every row of pixels
  - 3D voxelated data
  - Can slice in any section



SiC/SiC composite, Y. Chen / L. Gelebart CEA

Tomography: Time series

- Non-destructive: 3D to 4D



- Observe dynamic processes in-situ
- Fast tomography can be <<1 second *per volume*
- Fundamental to measurement of deformation by DVC

SiC/SiC composite, Y. Chen / L. Gelebart CEA

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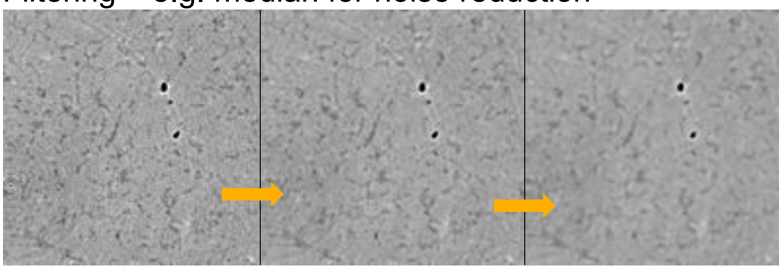
Analysis: What to do with these data?

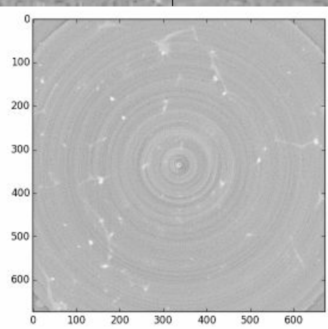
- How do we use images?
  - Morphological analysis – shapes or structures
  - Are we looking for a particular feature?
  - Do we need a statistical description of a microstructure?
  - Can we automate the process?

Analysis: Pretreatment

- Filtering – e.g. median for noise reduction

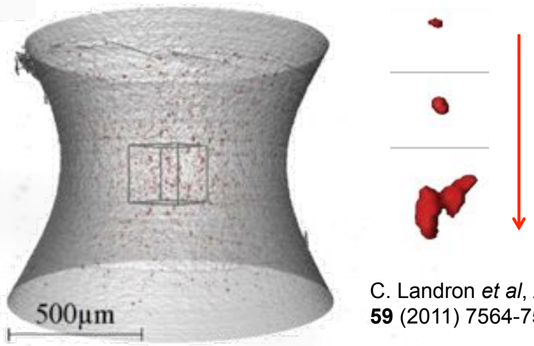


- Corrections – e.g. ring correction



Analysis: Simple quantitative analysis

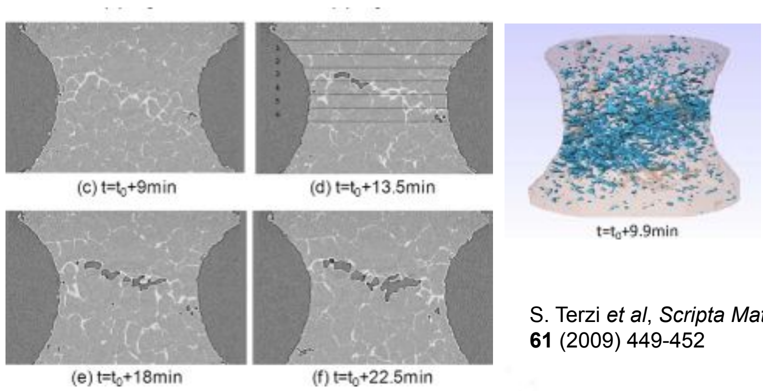
- Example: porosity development during plasticity
  - Segmentation -> fraction of porosity
  - Labeling -> volume, shape, position of each pore, percolation
  - Time series -> evolution of parameters
  - Statistical description or individual behavior



C. Landron *et al*, *Acta Mat.* **59** (2011) 7564-7573

Analysis: Other information

- Crack propagation
- Tortuosity of a **connected** network
- Identifying individual cells in a **connected** network



S. Terzi *et al*, *Scripta Mat.* **61** (2009) 449-452

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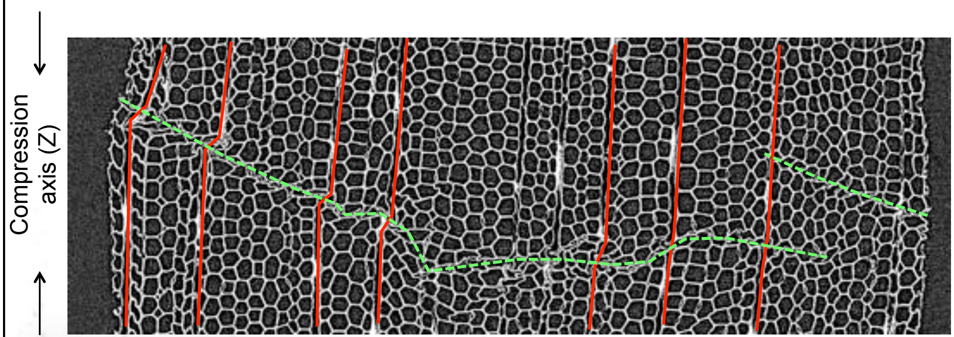
DIC/DVC: What is it?

- Digital Image Correlation / Digital Volume Correlation
- Measure deformation or movement of a sample
- Use all the information in a sequence of images



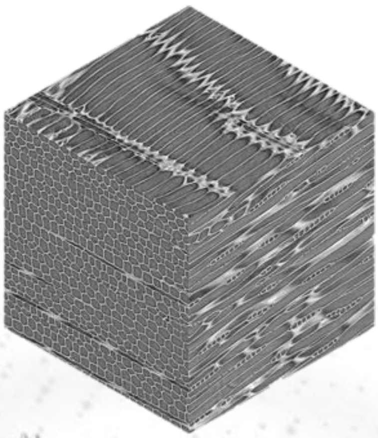
Wood in compression, M. Bonnet, ENPC

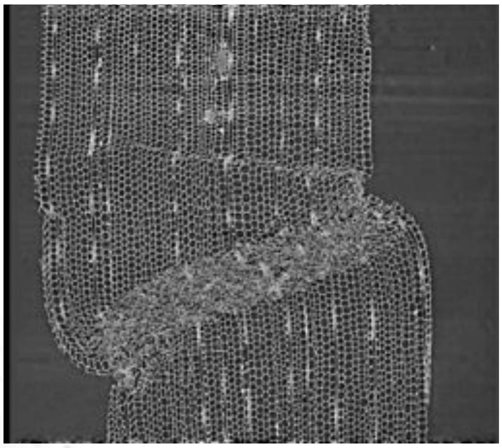
DIC/DVC

- *Drawn from Michel Bornert's lecture*
  - *Mistakes and misunderstandings added by me*
- What is involved, and how does it work?
  - simple example
- What does this mean?
  - characteristics of the measurement
  - advantages
  - requirements / limitations
- Some more details on the method
- *Examples are mostly 2D (or 1D) but everything is applicable to 3D tomography data*

DIC/DVC: Simple example

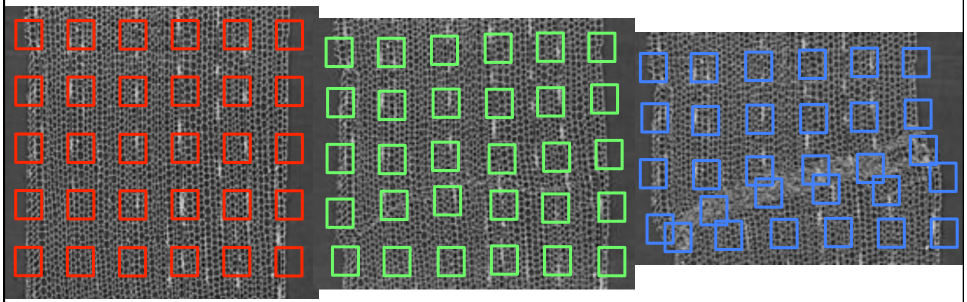
- Wood: Important engineering material
  - cellular microstructure, deformed in compression





Wood in compression, M. Bonnet, ENPC

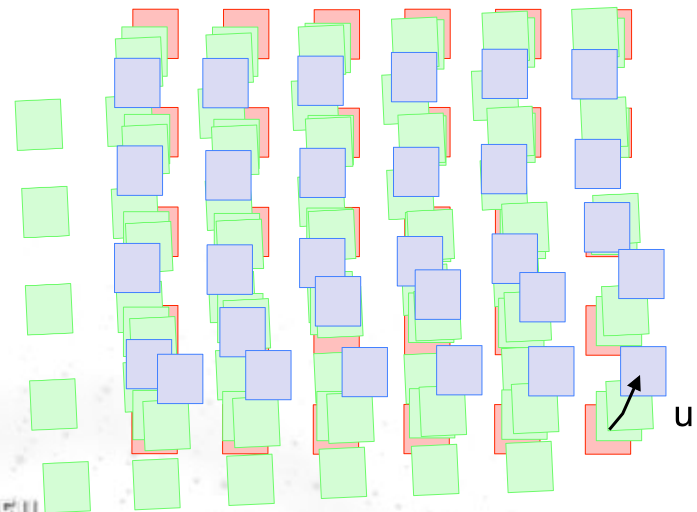
Identify the same regions in each step



- Measure local displacements with respect to a reference state
  - Simple example - 2D displacement (x,z)
  - In 3D (x,y,z)
  - Can also search for more deformation components

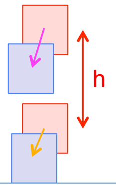
Extract deformation

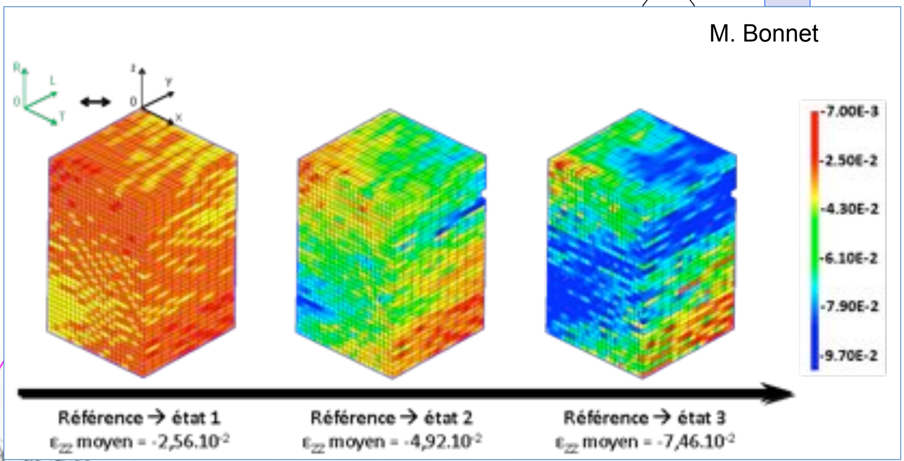
- Remove rigid body motion (displacement and rotation)



Strain is gradient of deformation

- Look at the vertical component
- Strain is $F_{zz}(z) - 1 = \lim_{h \to 0} \frac{u_z(z+h) - u_z(z)}{h}$





DIC/DVC: Characteristics

- Work from a series of images
  - Measure changes
  - No absolute measurement
- Measure a displacement field across the image
  - Full field technique
- Determine strain (solids) or flow (fluids)
- $\varepsilon_{Total} = \varepsilon_{Elastic} + \varepsilon_{Plastic}$

  ε_{Total}: DIC/DVC; $\varepsilon_{Elastic}$: Diffraction
- Strain from gradient of displacement *versus* change in lattice plane spacing

DIC/DVC: Advantages

- Measure the whole of the deformation field
  - measure total deformation (not just elastic strain)
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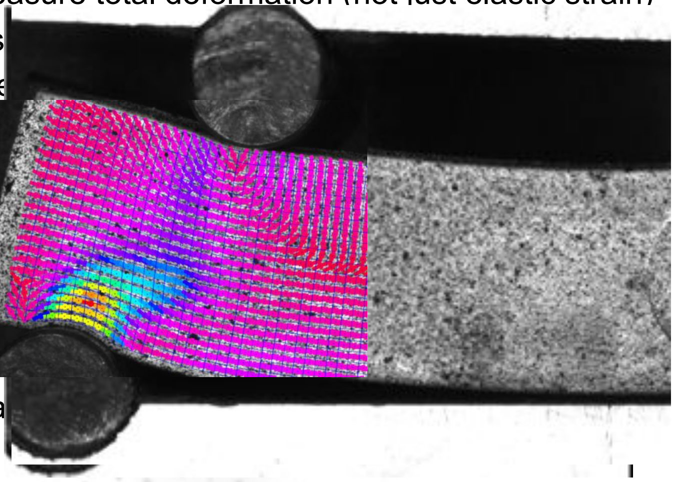
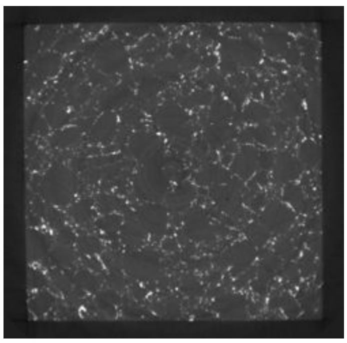


Bornert (lecture course)

DIC/DVC: Requirements

- Contrast (on surface or in bulk)
  - Some structure that allows us to recognise points in the sample
  - Contrast at the right scale
- Natural contrast
  - Scratches, precipitates, grain boundaries
- Artificial contrast
  - Paint or etch surface
  - 2nd phase in microstructure in volume
- Good signal to noise and minimal distortion in images



NaCl + Cu particles (Bornert)

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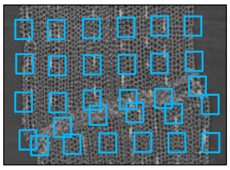
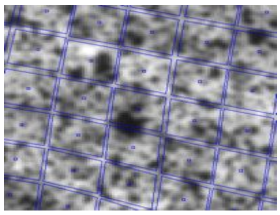
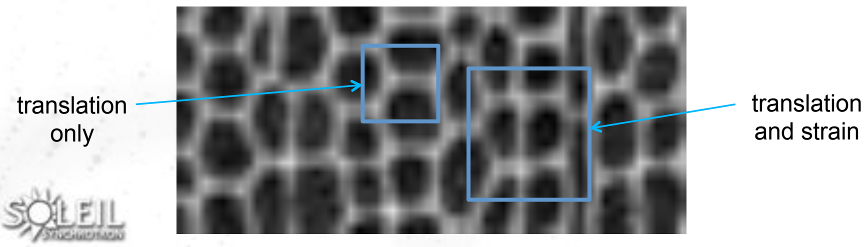
DIC/DVC: Details





- What do we try to measure?
  - just translations? (3)
  - translations plus rotations? (6)
  - … plus homogenous transform? (12)
  - … plus 2^{nd} order transform? (39)
- More parameters
  - potentially better fit, more information
  - more calculation, need a bigger window



DIC/DVC: Length scale

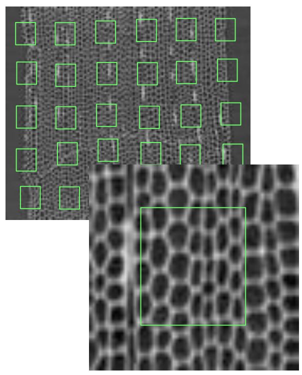
- Measure strain associated with a characteristic length
  - window size (h)

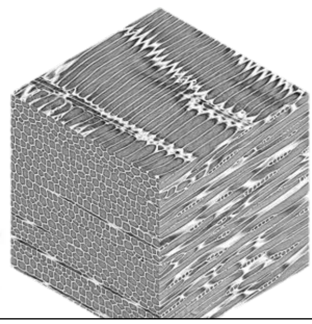
$$F_{zz}(z)-1=\lim_{h\to 0}\frac{u_z(z+h)-u_z(z)}{h} \Rightarrow F_{zz}^{h}(z)-1=\frac{u_z(z+h/2)-u_z(z-h/2)}{h}$$

- Spatial resolution of strains is limited to the window size
  - Somewhat like the gauge volume in diffraction
  - Strain gradients smaller than the window/gauge are not resolved directly
  - Weaker correlation ~ analogous to diffraction (microstrains increase peak width)

DIC/DVC: Length scale

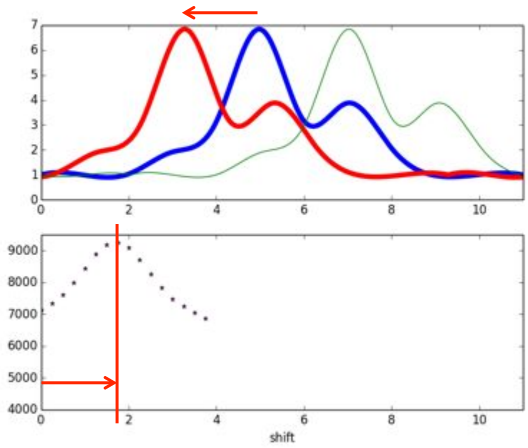
- Choice of window size.
- Smaller window:
  - better spatial resolution
  - more influence of noise
  - might not have enough structure
- Bigger window
  - more sensitivity
  - large distortions have more effect on correlation





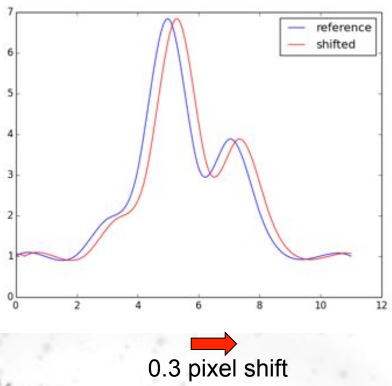
DIC/DVC: Correlation

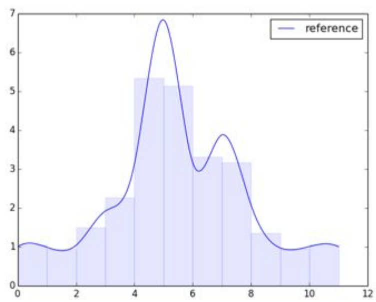
- Example: 1D, translation only, no noise, perfect signal
  - the maximum gives us the shift

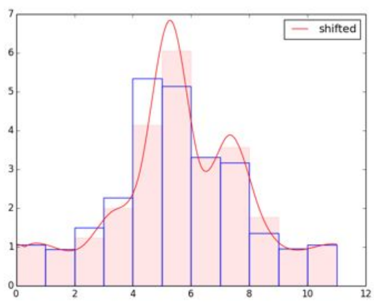


DIC/DVC: Discrete data

- Pixelated (voxelated) data
  - small (sub-pixel) shift changes gray levels

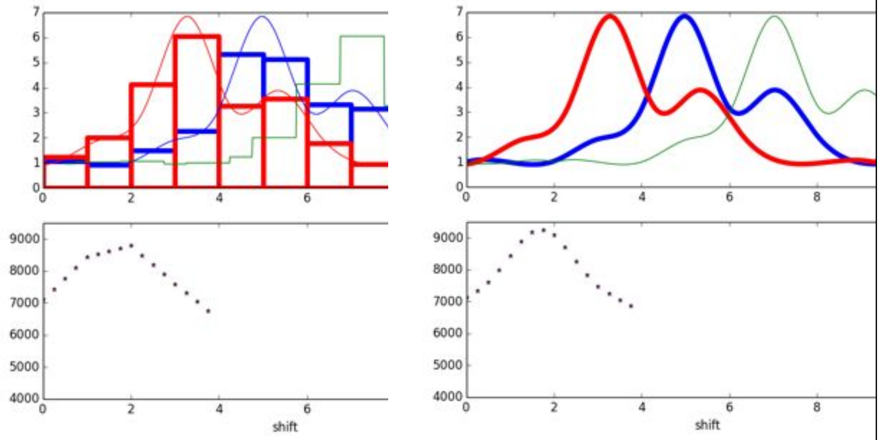






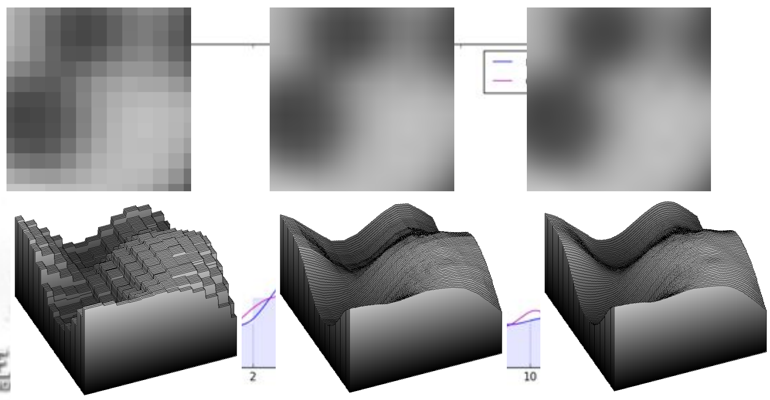
DIC/DVC: Correlation with pixels

- Some information/resolution is lost



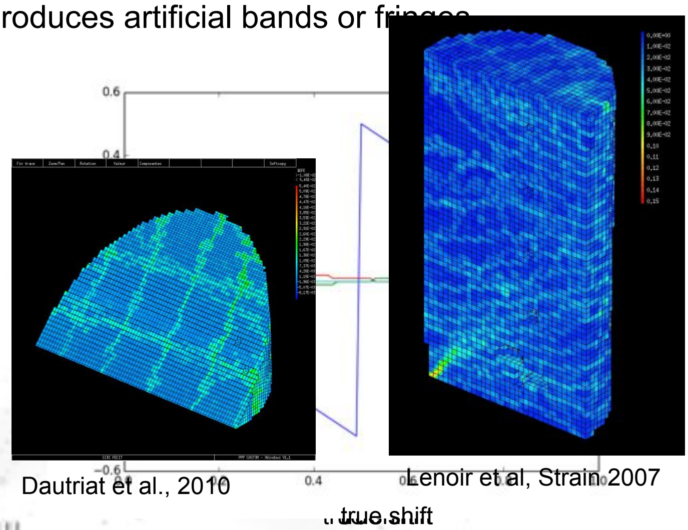
DIC/DVC: Sub-pixel resolution

- Essential for good strain resolution
- Use interpolation of the gray levels in the image data
  – try to recover the lost information
- Can introduce systematic errors



DIC/DVC: Systematic error from interpolation

- Characteristic “S-shaped” curve
- Produces artificial bands or fringes



Dautriat et al., 2010

Lenoir et al, Strain 2007

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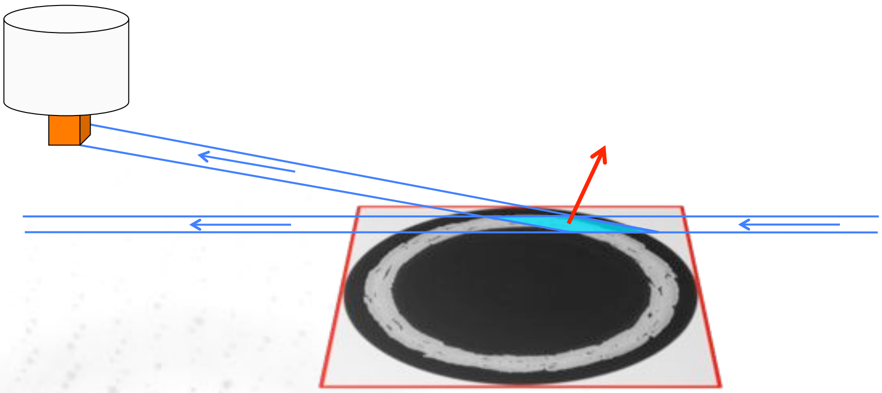
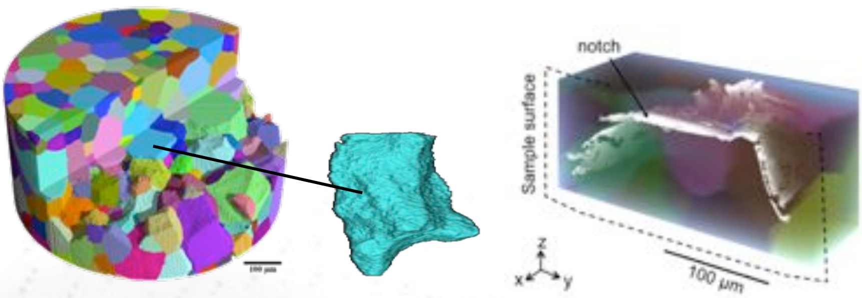
DVC + diffraction?

- Plan to develop this
  - complementary information
  - global deformation + elastic strain or phase transitions



Diffraction contrast tomography (3DXRD)

- Use the diffraction signal from grains in a polycrystal to build a grain map
- Each grain reconstructed tomographically
- Available at ID11, near future at Psiché.



Big data and correlative tomography

- Tomography *is* big data
  - 2k^3, 32bit = 32GB x n time steps
- *"Big data"* is an approach to working with such large datasets
  - Automation is essential
  - Choose tools or packages that allow automation of your analysis
  - Efficient optimisation of parameters
- Correlative tomography
  - combine multiple datasets for more information
  - timesteps, tomo+diffraction, tomo +fluorescence,multiple energies,tomo+SEM…

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Conclusions

- Image based deformation measurement
  - strain, plasticity, flow…
  - full field results
- Applicable to all imaging techniques
  - tomography (lab / synchrotron X-rays, neutrons), radiography, optical microscopy, electron microscopy…
- Highly complementary to diffraction
  - Total strain rather than elastic strain
  - Should combine techniques