3D Phase Contrast Imaging

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From artefacts to 3D phase contrast imaging

Unpolished beryllium window

Rendering of a semi-solid
<table>
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<th>Tomography</th>
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<td><strong>Motivation</strong></td>
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<tr>
<td><strong>Compromise spatial resolution</strong></td>
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<td><strong>User Facility</strong></td>
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100 μm
Outline

Parallel beam imaging
- Absorption tomography
- Phase contrast tomography
  edge-detection
- Holo-tomography
  phase retrieval with images at different distances

Divergent beam imaging
- PCI with X-ray magnification
- Fluorescence imaging

Future needs
- \textit{Source}: more brilliance, more coherence?
- \textit{Optics}: mirror figuring
- \textit{Detectors}: speed and efficiency
- \textit{Methods}: universal phase retrieval
Parallel beam imaging

- Fresnel diffraction over a distance $D$ (few mm to meters)
- In-line Gabor holography
- Defocusing in electron microscopy
  Atom resolved EM (Van Dyck, EMAT, Antwerp)
Parallel beam imaging

Implemented on ID19 / ESRF

Dedicated microtomograph (P. Bernard)

Monochromator:
- double Si crystal ($\Delta\lambda/\lambda=10^{-4}$)
- or multilayer ($\Delta\lambda/\lambda=10^{-2}$)

Sample stage
- rotation stage (tomography)

Detector
- CCD-based (FReLoN)
  on translation (propagation)
  crucial for spatial resolution

Scan time
- $1024^2 * 900$ proj.: 7 minutes
- $2048^2 * 1500$ proj.: 20 minutes
Absorption Tomography

High flux, monochromatic beam yields:

- High spatial resolution
  - approx. 1 µm
  - $1024^3$ volume in 15 minutes
- Quantitative reconstruction
  - of linear absorption coefficient $\mu(x,y,z)$
  - composition (bone, teeth, …)
- Dynamic visualisation

![Diagram of absorption tomography setup]

**Parallel beam acquisition setup**
Spatial Coherence

- Wave is partially coherent when the source is small and far.

- Transverse coherence length

ESRF, ID19 Beamline:

- $L = 145$ m
- $s_v \approx 25$ μm
- $s_h \approx 125$ μm

\[
\alpha \approx 0.2 \mu\text{rad}
\]

\[
l_{\text{coh}} = \frac{\lambda}{2\alpha} \approx 250 \mu\text{m}
\]

and horizontally < 1 μrad
Spatial coherence

- *In principle*: complete object contributes to a point of the image
- *In practice*: only finite region: first Fresnel zone radius
  \[ r_F = \sqrt{\lambda D} \]
Edge Enhancement

- Essentially edge enhancement
  Weak defocusing (and weak contrast!)

\[ \sqrt{\lambda D} \ll a \]

- Radiography (2D)
  \[ I_D(x, y) \approx I_0(x, y) \]

- Tomography (3D)
  \[ o(x, y, z) \approx \mu(x, y, z) - D \Delta_{xyz} \delta(x, y, z) \]

- Detection of cracks
  holes
  reinforcing fibres, particles
Phase Contrast: Liquid Foams

Scientific Case:
Evolution (coarsening, drainage) of liquid foams in 3D

F. Graner (UJF), J. Lambert, P. Cloetens
Phase Contrast: Liquid Foams

Scientific Case:
Evolution (coarsening, drainage) of liquid foams in 3D

Phase enhancement to visualise liquid films separating bubbles:
Film thickness $\ll$ voxel size
thin films

$E = 15$ keV, Sample-detector distance: 0.15 m

F. Graner (UJF), P. Cloetens
Phase Contrast: Liquid Foams

Coarsening: pressure driven growth or disappearance of bubbles

\[ \Rightarrow 3D \text{ Growth Law} \]

volume individual bubbles in time
(cfr. grain growth, sintering)

2 minutes/scan (2GB data)

F. Graner (UJF), J. Lambert, P. Cloetens
Holotomography

1) phase retrieval with images at different distances

2) tomography: repeated for $\approx 1000$ angular positions

3D distribution of $\delta$ or the electron-density improved resolution straightforward interpretation processing

Holotomography

Breast Biopsy \( \varnothing \approx 15 \text{ mm} \); pixel size = 7.5 \( \mu \text{m} \)

\( \Rightarrow \) Huge distances: 0.03, 1, 4.3 and 8.8 m!

Energy = 25 keV

Phase Map

13 mm

E. Pagot, P. Cloetens
Larger field of view

Breast Biopsy Ø ≈ 15 mm; pixel size = 7.5 µm

Absorption Holotomography

Lobular tissue

E. Pagot, P. Cloetens
Density Resolution

Semi-solid Al / Al+Si

Absorption

Phase contrast

β-map

E = 18 keV

δ-map

\[ \Delta \delta \approx 3.5 \times 10^{-8} \Rightarrow \Delta \rho \approx 0.05 \text{ g/cm}^3 \]

15 % of Si

L. Salvo (GPM2, Grenoble)
Density Resolution

Semi-solid Al / Al+Si

Results:
Interdendritic liquid 15 (±1) wt% Si
Trapped liquid 23 (±2) wt% Si

⇒ Out of equilibrium solidification

L. Salvo (GPM2, Grenoble)
Divergent beam imaging

- Improve the spatial resolution

\[ \lambda < 1 \, \text{Å} \]

resolution \( \approx 0.5 \, \mu\text{m} \) with scintillator based detectors

X-ray magnification using
- diffractive optics (FZP)
- refractive optics (CRL)
- reflective optics (KB)

Gabor’s Microscopic principle (Nature, 1948)

*The object is illuminated with by an electron beam brought to a fine focus...*

*The object is a small distance behind (or in front) of the point focus, followed by a photographic plate at a large multiple of this distance...*
Kirkpatrick-Baez focusing

< 300 mm

150 m

Source size
Mirror quality
Diffraction

O. Hignette, G. Rostaing
Focusing results at 20.5 keV

Measurement:
Direct line scan, no derivation
Fluorescence of Au slit

X-rays

Au thickness < 70 nm

<table>
<thead>
<tr>
<th>Aperture V*H (µm)</th>
<th>Spot fwhm V*H (nm)</th>
<th>Flux (ΔE/E=10^{-2}) ph/s @ 80 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 x 50</td>
<td>118 x 109</td>
<td>5 x 10^{10}</td>
</tr>
<tr>
<td>400 x 100</td>
<td>86 x 83</td>
<td>2 x 10^{11}</td>
</tr>
<tr>
<td>600 x 160</td>
<td>116 x 90</td>
<td>4.5 x 10^{11}</td>
</tr>
</tbody>
</table>

Gain > 3 x 10^6 !!

O. Hignette, P. Cloetens
Applications: Projection Microscopy

Object

$z_1$

$z_2$

Detector

Equivalent to

$D = \frac{z_1 \cdot z_2}{z_1 + z_2}$

Limit cases

$z_1 >> z_2$

$D = z_2 ; M = 1$

$z_1 << z_2$

$D = z_1 ; M = \frac{z_2}{z_1}$

Plane wave illumination

Magnification
Projection Microscopy

2 μm pitch grating (Si)

C. David, PSI

D = -20 mm  
M = 115

D = -10 mm  
M = 230

D = 10 mm  
M = 230

D = 20 mm  
M = 115

Exposure time = 0.4 s ! (16-bunch, saturation CCD)  
P. Cloetens, O. Hignette
Projection Microscopy

Optical microscope view

X ray microscope view

Cu fiber

25 µm

Group of cells

Cellular imaging Cancerous cells
S. Bohic
Projection Microscopy

Cancerous cells
S. Bohic

Towards focus

10 µm

D = 50 mm
M = 45

D = 30 mm
M = 75

D = 10 mm
M = 230

E = 20.5 keV
Exposure time = 0.3 s ! (16-bunch)

No X-ray optics behind the sample ⇒ dose efficient

P. Cloetens, W. Ludwig
Applications: Fluorescence

Cancerous cells treated with anti-cancer drug (Cisplatin)

Step = 0.3 μm, 0.9 sec/pt

40 μm

K

Pt

Fe

Phase Contrast

P. Cloetens,
W. Ludwig,
S. Bohic
Applications: Fluorescence

Cancerous cells (Coll. S. Bohic- ID22)

K

Pt

50 µm

Step = 0.5 µm
1 sec/pt

Traces of Pt-based drug can be imaged
New opens in elemental cellular chemistry
Adapted length scale for
- sub-cellular structures (cell organelles)
- unicellular organisms (bacteria, algae and fungi)

P. Cloetens, W. Ludwig, S. Bohic
Source: more photons?

Increase $N \Rightarrow$ number of photons $N_{\text{phot}}$ needed increases as $N^4$
(Flannery 87)

U. Wegst, Max-Planck-Institute, Stuttgart
More coherence?

Distance to be most sensitive to lengthscale $a$:

\[ D_{\text{opt}} = \frac{a^2}{2\lambda} \]

For example at $\lambda = 0.5\,\text{Å}$ (25 keV):

- $a = 1 \, \mu\text{m} \implies D = 10 \, \text{mm}$
- $a = 10 \, \mu\text{m} \implies D = 1 \, \text{m}$
- $a = 40 \, \mu\text{m} \implies D = 16 \, \text{m}$
- $a = 0.3 \, \text{mm} \implies D \approx 1 \, \text{km}$

\[ D = \frac{z_1 \cdot z_2}{z_1 + z_2} \]
Optics

Everything in the beam can act as a phase object

- Stringent requirements on beamline optics:
  Polished windows,
  Monochromator surface, …
  Dust!

- Unpolished Beryllium

- Scratches

- Dust
No Optics

If source provides spatial and *temporal coherence*

\[ \frac{\Delta E}{E} = 10^{-2} \text{ or } 10^{-4} \]

Single line undulators

**NO OPTICS** (source - sample - detector)

*Spurious contrast remains major limitation of sensitivity of PCI*

Improved signal-to-noise ratio
More coherence and better optics

Critical focusing

Present source size limit with KB:
90 nm x 50 nm

(Source size)
(Mirror quality: ion beam figuring)
Diffraction

ultimate focus: 20 nm (h) x 12 nm (v)

Much more efficient:
0.2 mm x 1.2 mm of a 20 mm x 3 mm beam
High Resolution Detector

Crucial for parallel beam imaging
X-ray $\rightarrow$ visible light conversion
Down to 0.5 $\mu$m spatial resolution

Efficiency drops at higher energies with resolution

In-situ tomography:
  goal: 3D images in $\sim$ 1 second (1 ms / image)
  CCD technology
  afterglow of scintillator

Alternatives needed to classical scheme
X-ray $\rightarrow$ visible light $\rightarrow$ CCD
Detector for holotomography

Scintillator is semi transparent

→ use several detectors in parallel
Methods: universal phase retrieval

Cases that work well:
- slowly varying phase (and slow absorption)
- weak phase (and weak absorption)

General case:
- distance with optimum contrast can often not be used
- limitation to smaller distances due to algorithms

Poor sensitivity to low spatial frequencies
- support helps, but method becomes iterative
Methods: universal phase retrieval

Combination with ‘diffraction’ imaging (cf. Fienup)
not limited to small objects
support given by edge enhancement
‘low’ resolution image from near and intermediate field
high spatial frequencies from weak non-linear interference terms

Oversampling in real space
Destroying the interference pattern

Spinning inhomogeneous material: wood, ...

Alternative

Random holographic grating (O. Hignette)

nylon fibre

Applications: homogeneous beam incoherent illumination in X-ray microscopy

Chr. David (PSI - CH)

P. Cloetens, T. Bigault (ESRF)
Conclusions

• Tomography more powerful than ever: absorption, phase contrast, holotomography, ...

• Quantitative mapping in 2D and 3D

• Projection microscopy by KB focusing:
  (90 nm)$^2$ focusing made ‘easy’
  High flux ($10^{12}$ph/s)

• Micro-structure: fast nano-radiography, nano-tomography

• Fluorescence: for sub-micron element mapping (2D - 3D)

• Improvements in brilliance are important
  but also optics, detectors and methods
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