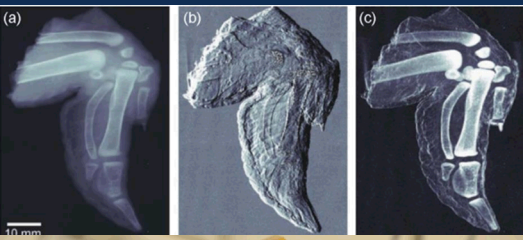

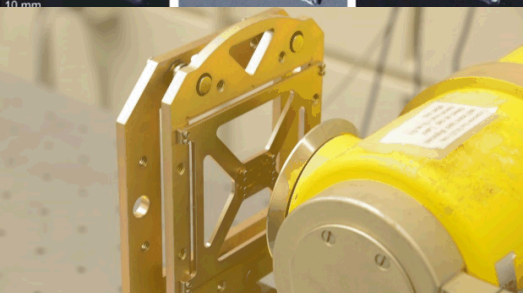

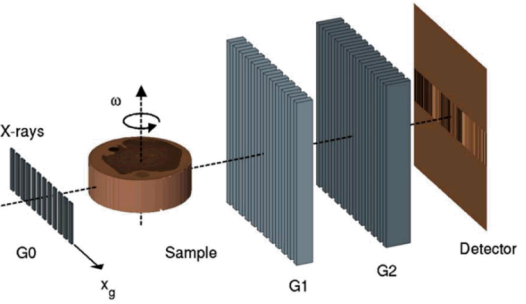

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Exceptional service in the national interest

SAND2016-3667C

Steep Phase Gradients and Challenges in Materials Science Applications of X-Ray Phase Contrast Imaging

Amber Lynn Dagel
aldagel@sandia.gov
Sandia National Laboratories
Albuquerque, NM

SPIE Defense + Commercial Sensing
Anomaly Detection and Imaging with X-Rays (ADIX)
Conference 9847, Session 2
Tuesday, April 19, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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X-RAY PHASE CONTRAST IMAGING

X-ray Phase Contrast Imaging

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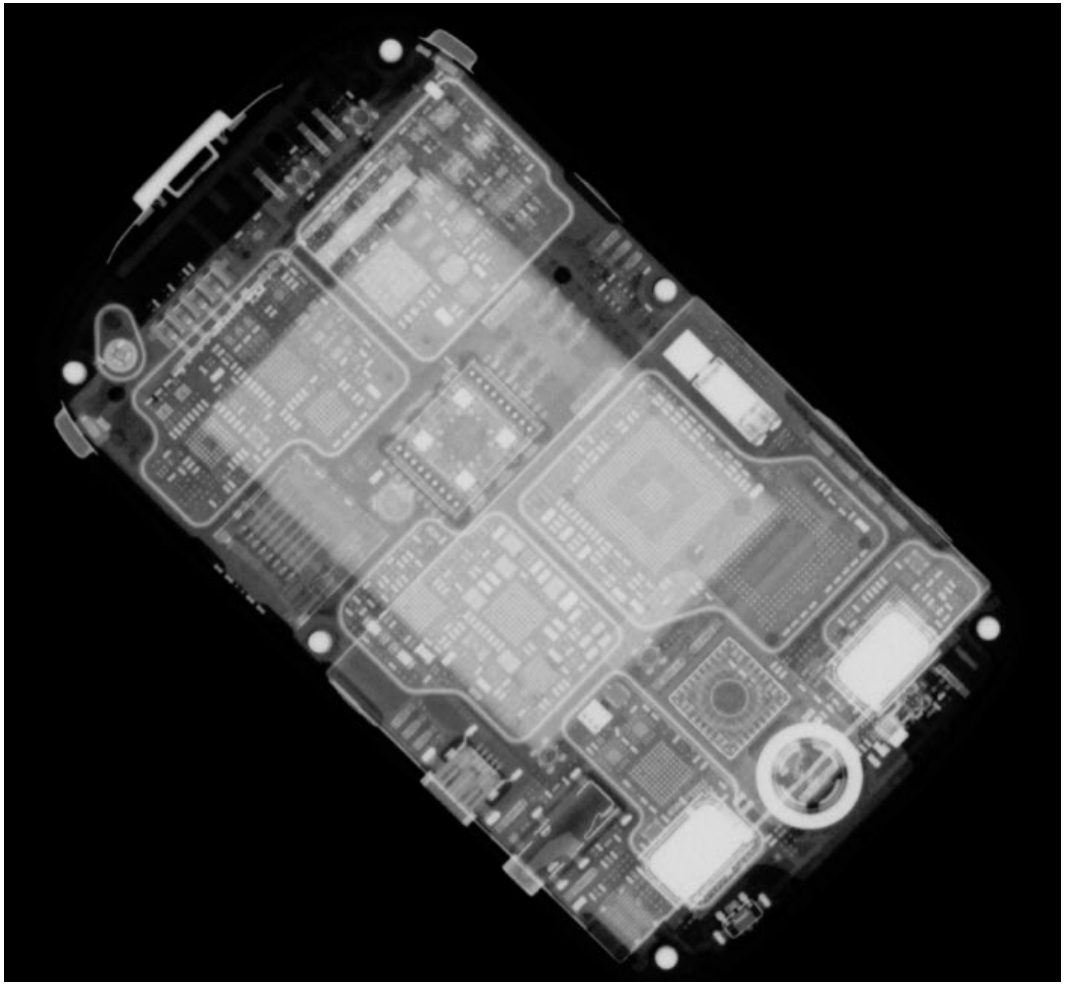


X-Ray Phase Contrast Imaging: Complementary Data

Absorption
Contrast between dense and less-dense (low-Z) regions. No material detail.

Phase Contrast
Fine structure within the low-Z regions.

Dark-Field
Sharp contrast at boundaries. Microstructures cause scattering.

To acquire only attenuation data leaves out significant information about the material properties

M. Bech, et. Al., Z. Med. Phys., **20,** 7, 2010.

Greater Sensitivity with Phase Contrast

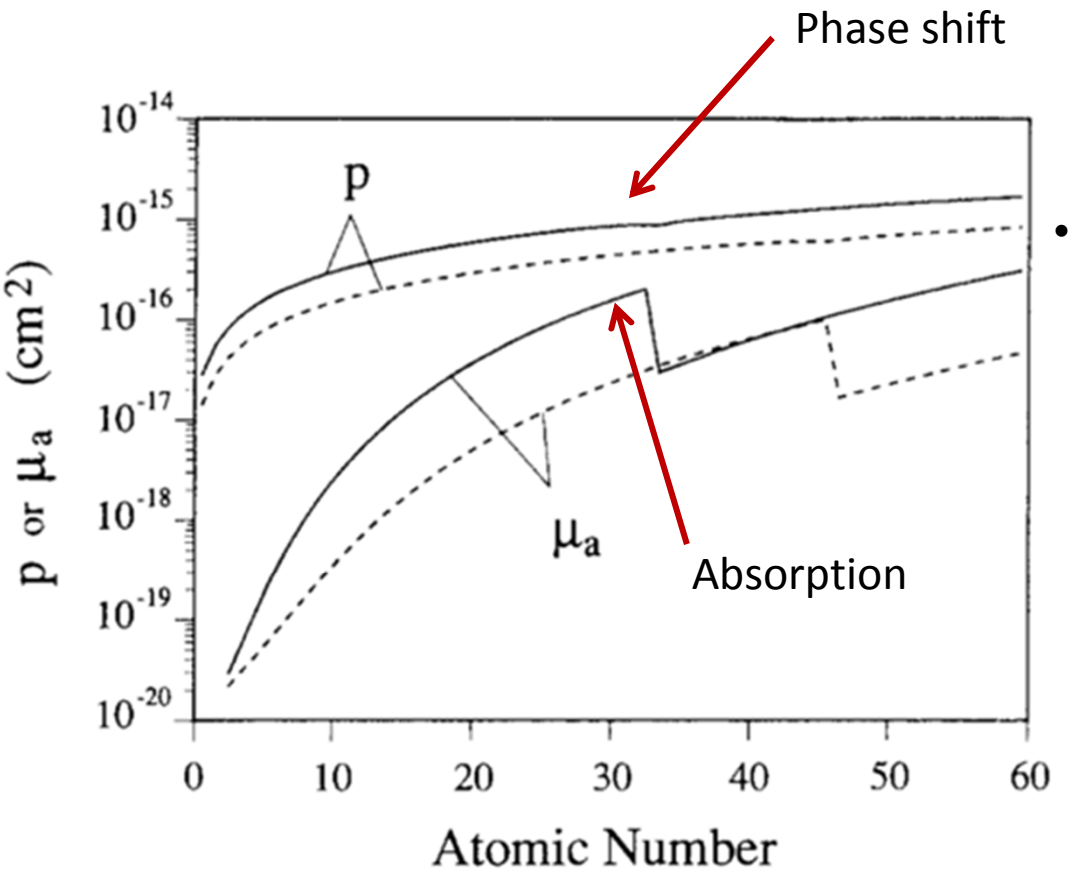


FIG. 1. Atomic x-ray phase shift p and absorption μ_a for 1 Å (solid line) and 0.5 Å (dashed line) x-rays are plotted versus the atomic number Z. The value of p is almost a thousand times larger than μ_a for light elements.

Ref: A. Momose and J. Fukuda, Med. Phys., **22**, 375, 1995.

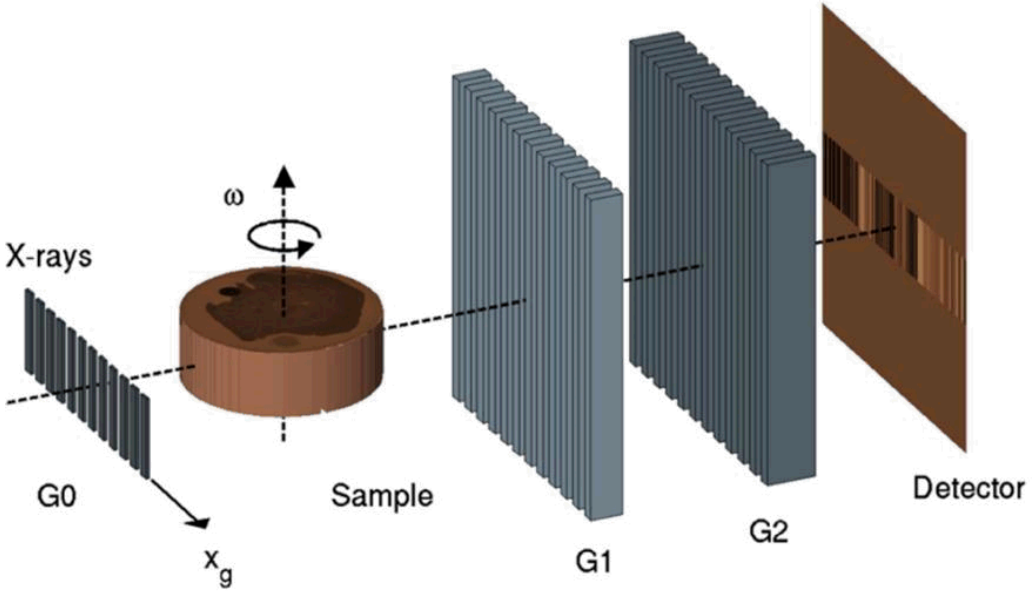
- X-ray absorption imaging is used for non-destructive imaging
  - Poor sensitivity to low absorbing (low-Z) materials

Phase contrast

1000x more sensitive

Grating-Based XPCI

Talbot-Lau Interferometer

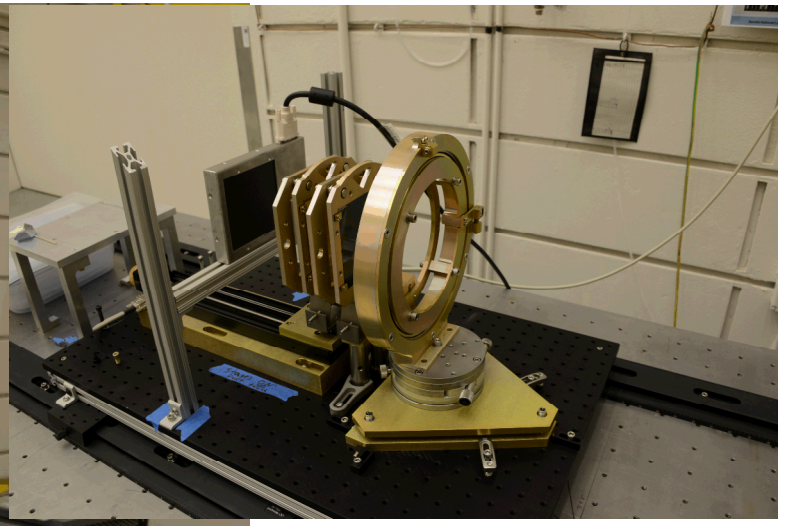


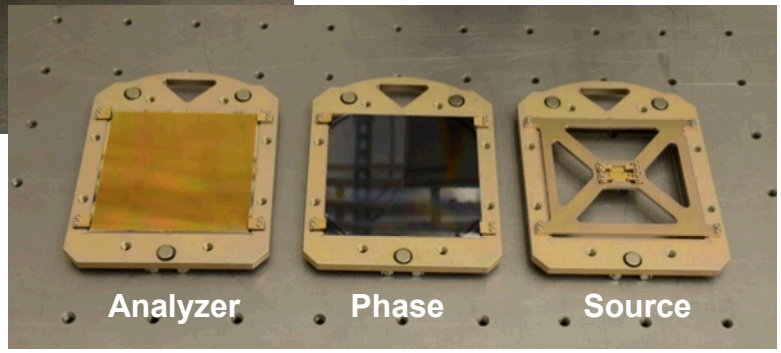
- Source grating: G0
  - Enables use of conventional x-ray tube
- Phase grating: G1
  - Imposes a modulated phase shift on wavefront
- Analyzer grating: G2
  - Converts narrow fringe pattern to intensity signal

Source grating enables lab-based XPCI

M. Nielsen, et. al., Phys Med Biol, **57**, 5971, 2012.

Laboratory Based System at Sandia





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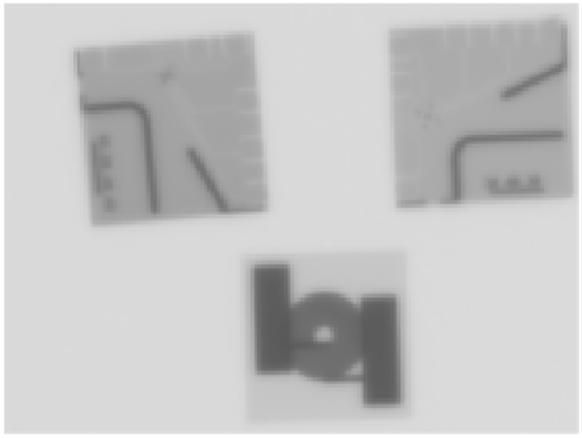
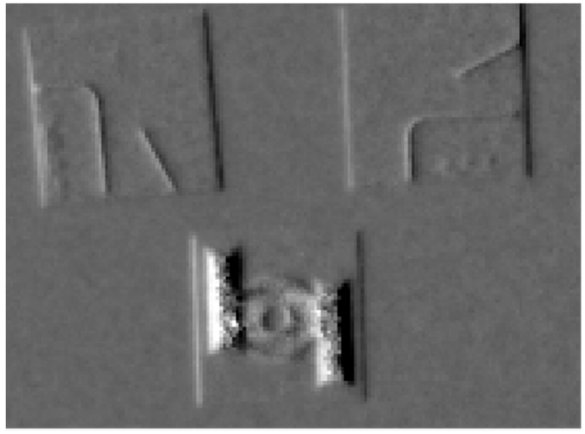
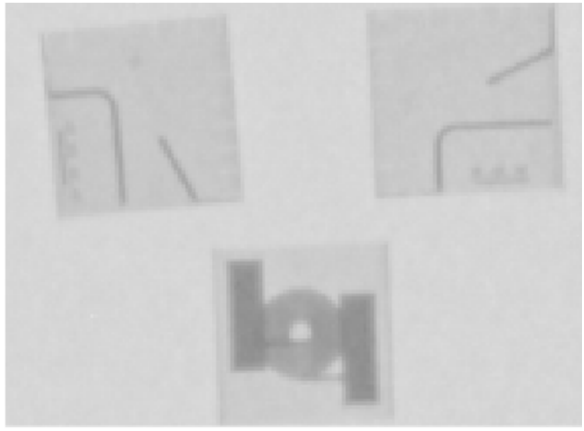
MATERIALS SCIENCE APPLICATIONS

Electroplated Gold and DRIE Etched Si MEMs

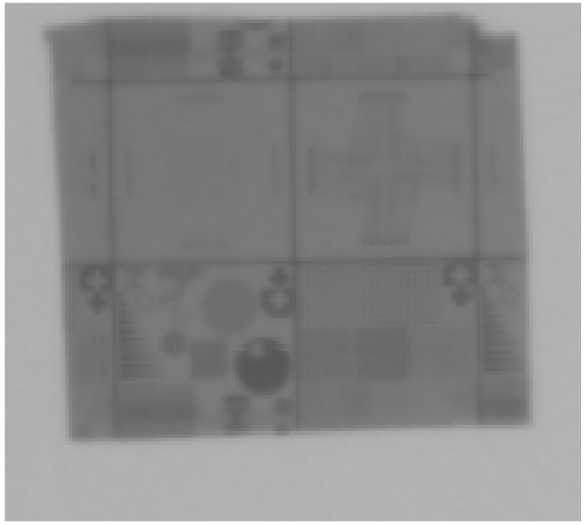
Gold electroplated magnetic coil and gold plated stylus ion trap



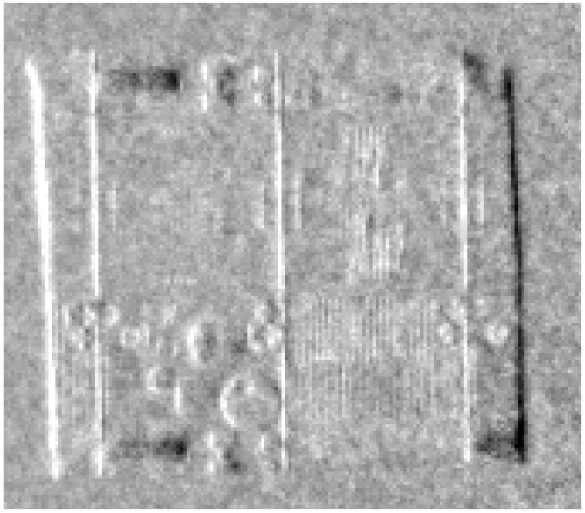




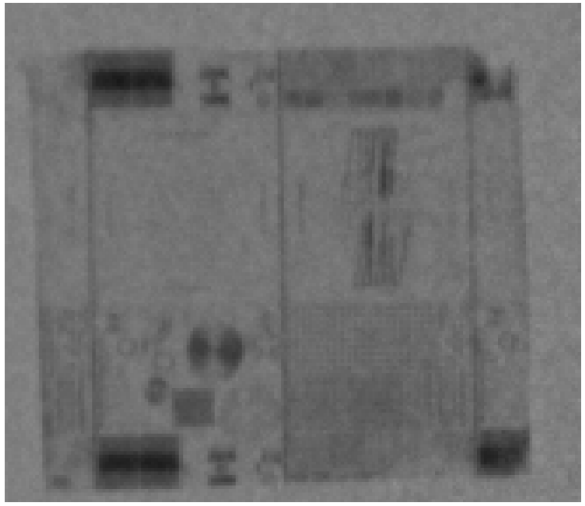
Deep reactive ion etched silicon MEMs



Absorption



Phase Contrast



Dark Field

Microfabricated Ion Trap (not packaged)

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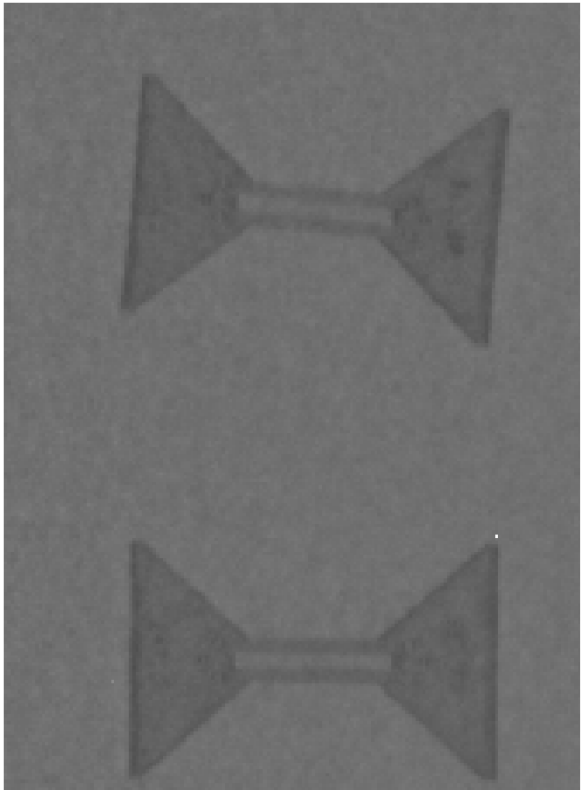
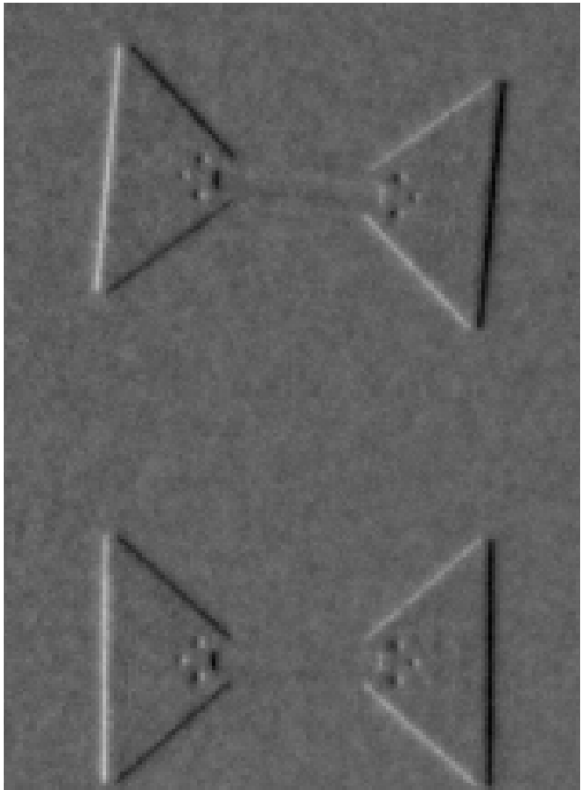
Transmission

Dark Field



Differential Phase



Detection of Hidden Flaws in Aircraft Solid Laminate Composite Structure

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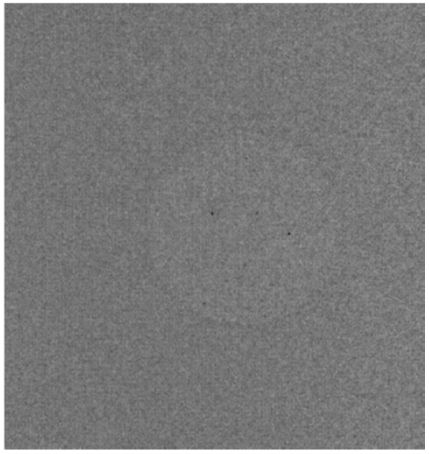
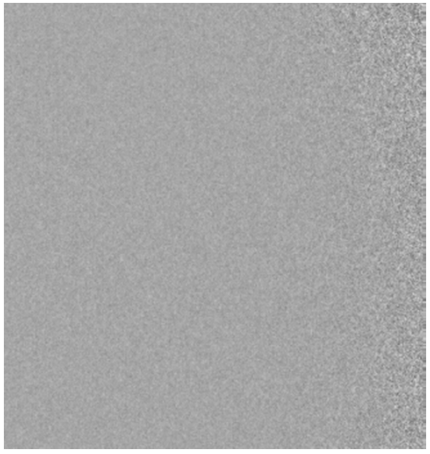
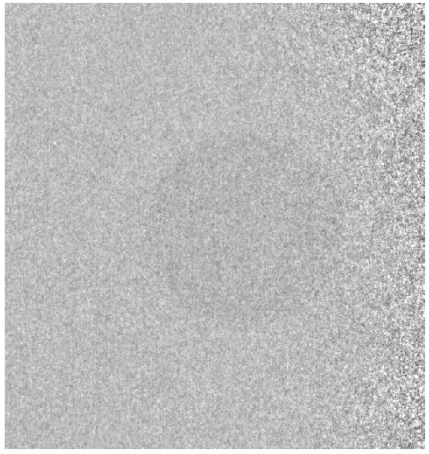
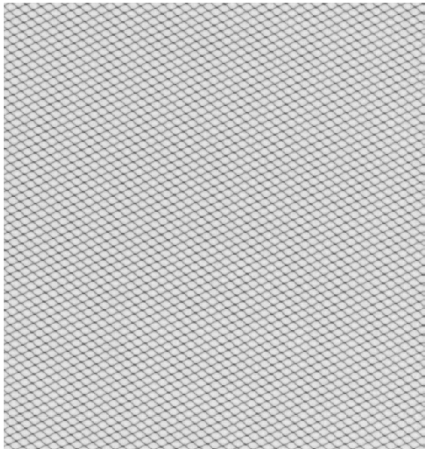
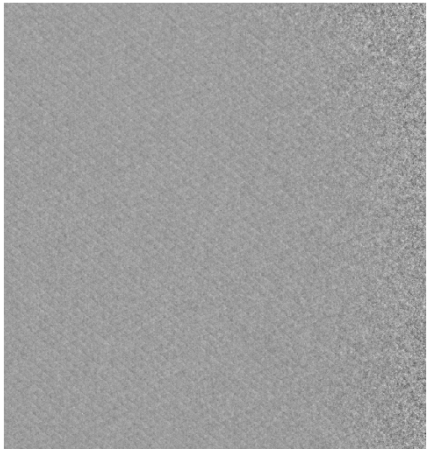
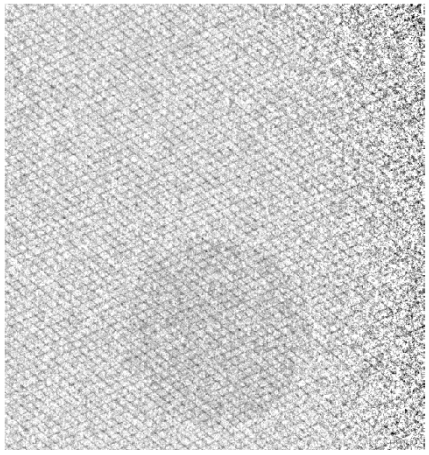




Without copper mesh

With copper mesh

Absorption

Phase Contrast

Dark Field

Flaw: GRAFOIL

Additively Manufactured Plastic in Metal Mount

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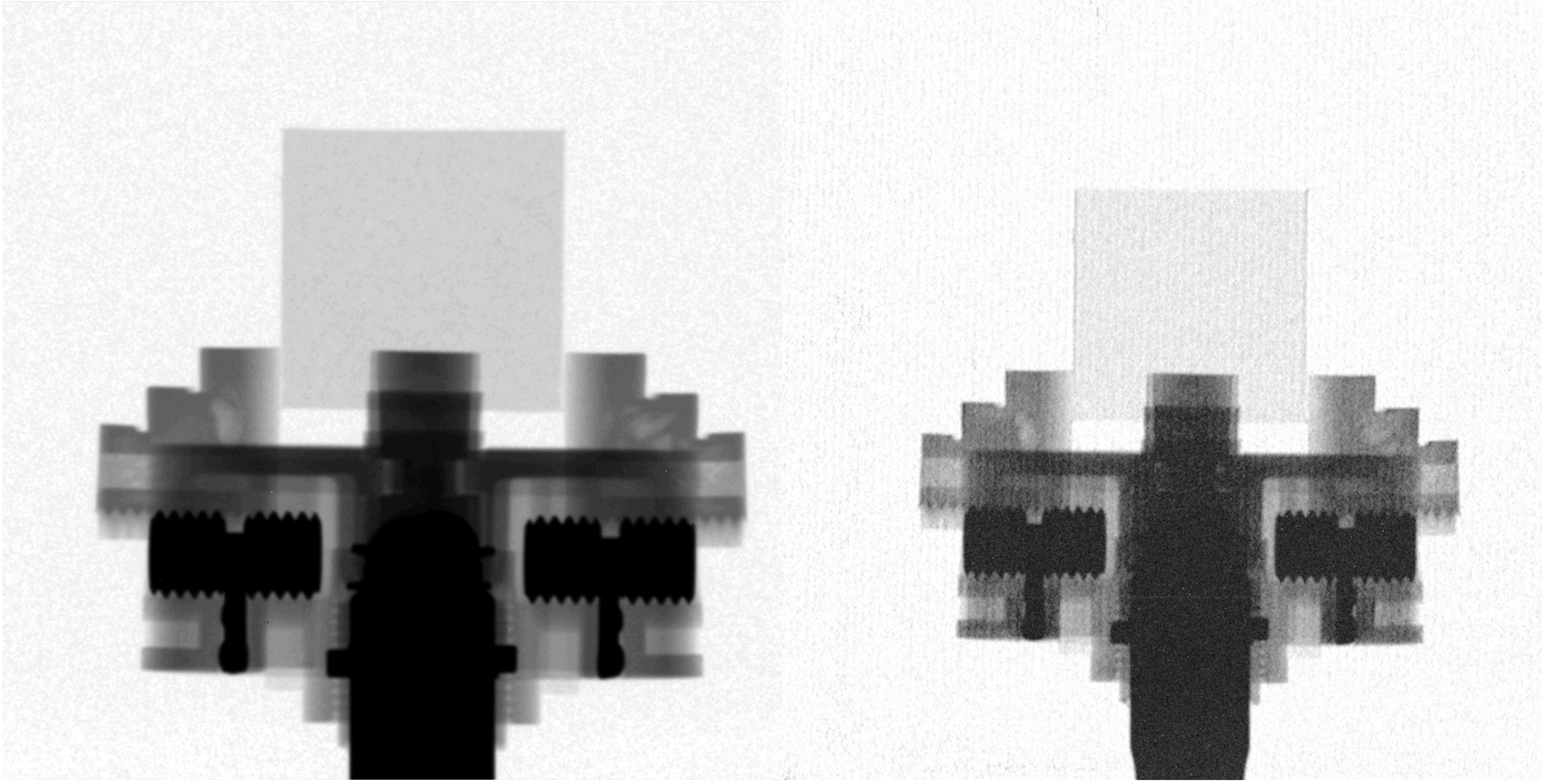
Transmission

Dark Field



Additively Manufactured Plastic in Metal Mount

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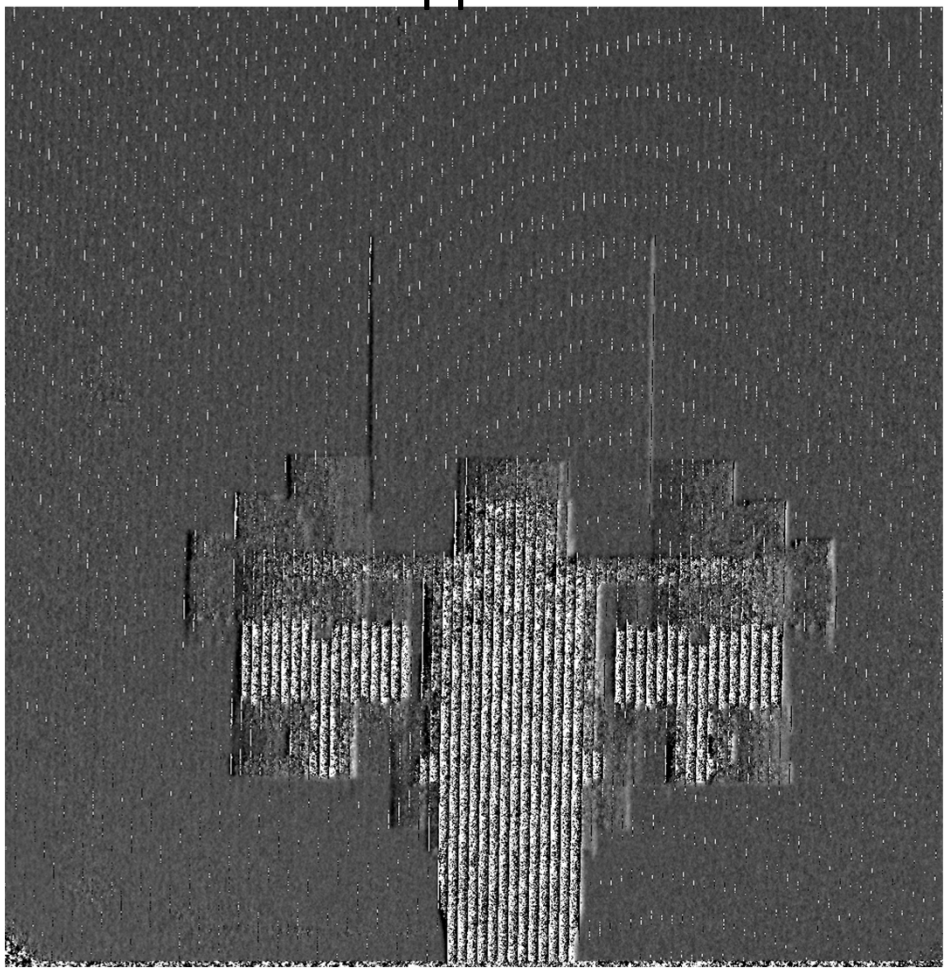
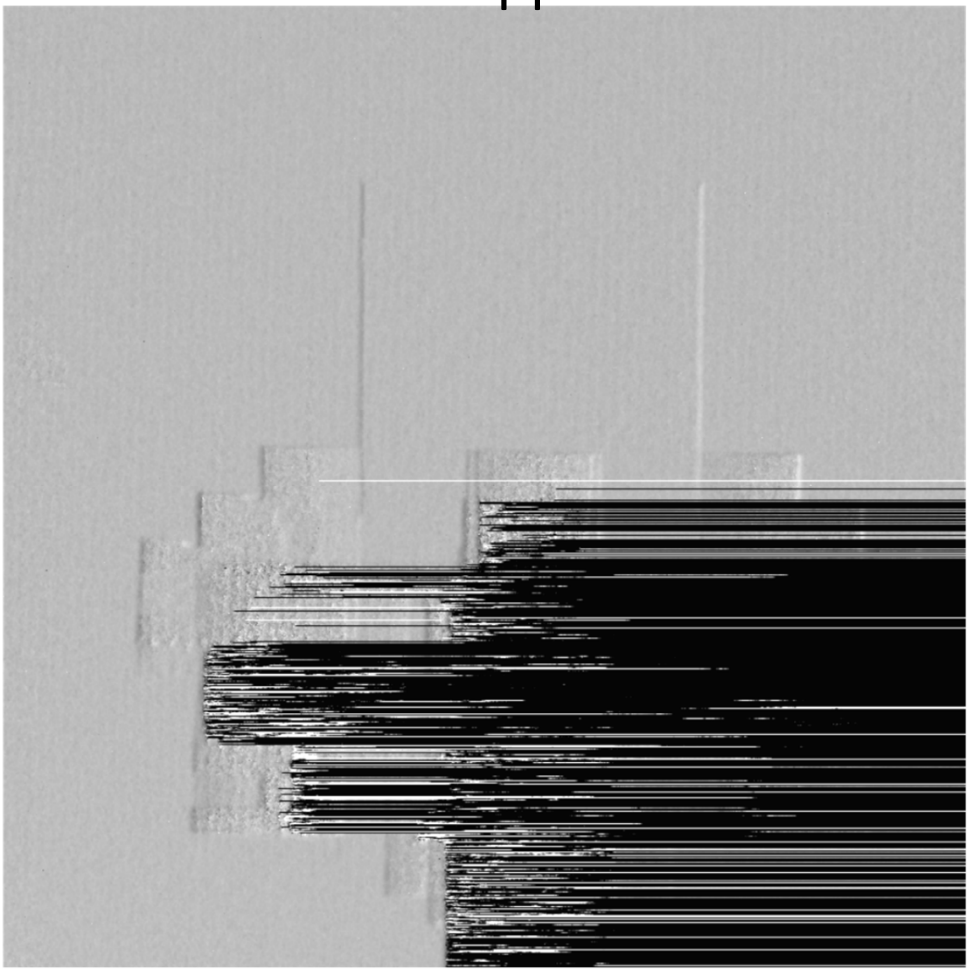
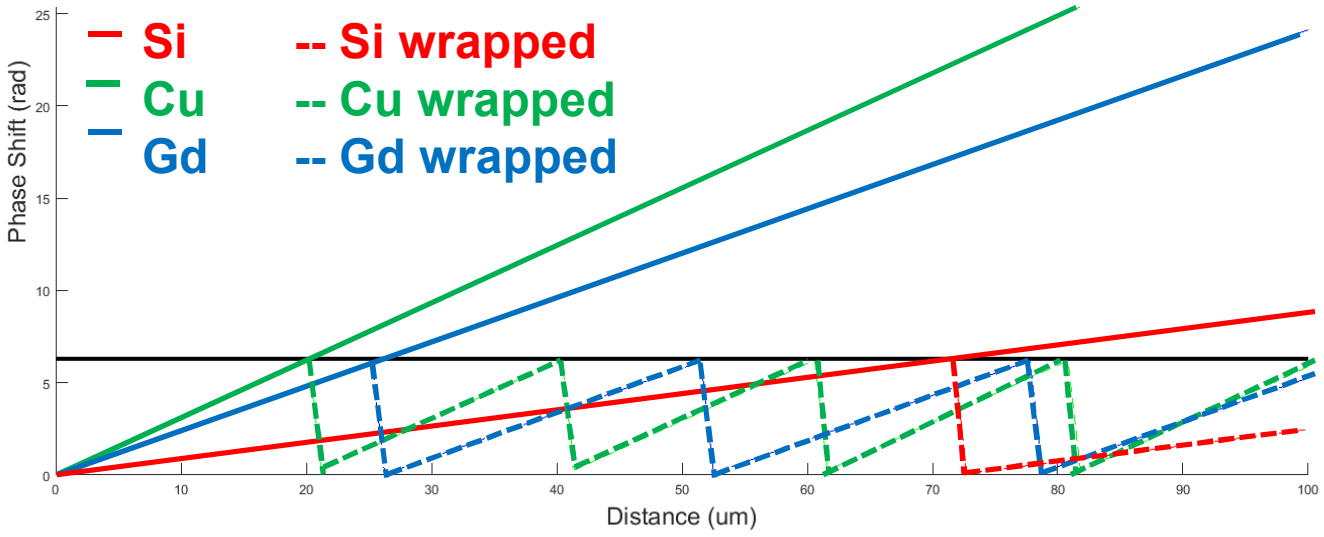
Wrapped Phase



Unwrapped Phase



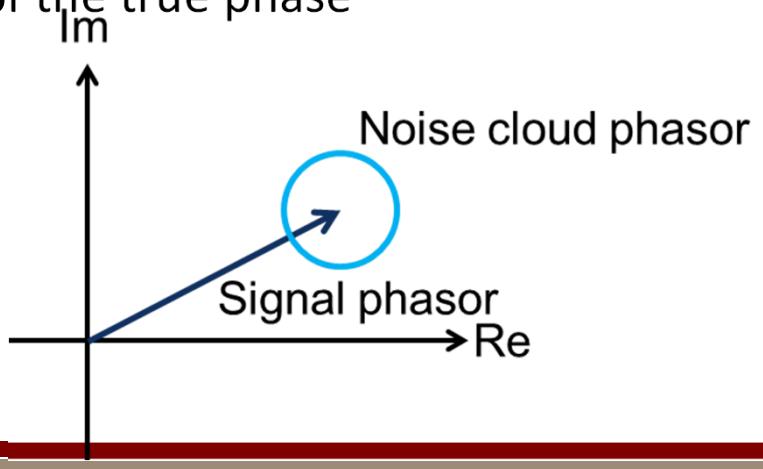
Phase Wrapping



- Phase wrapping process is nonlinear
  - $\psi(x) = \varphi(x) + 2\pi k(x)$
    - k is an integer; $-\pi < \psi \leq \pi$
    - $\varphi(x)$ relates to some physical quantity
      - SAR: surface topography
      - XPCI: electron density/index of refraction
- Phase unwrapping problem: estimate $\phi(x)$ for $\varphi(x)$ from wrapped function $\psi(x)$

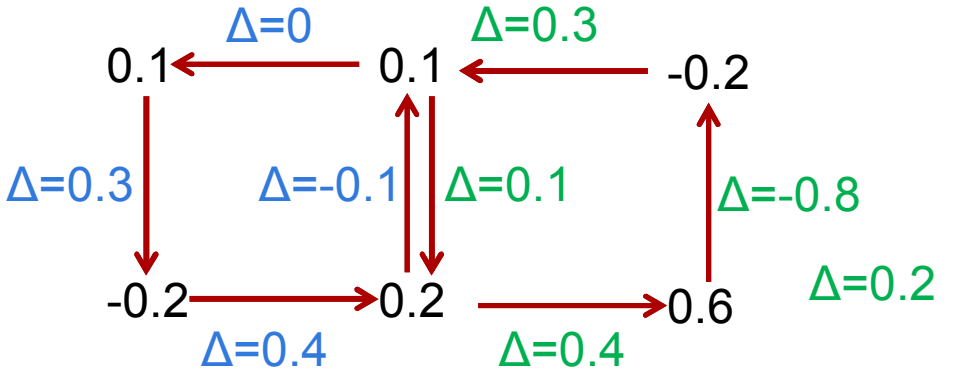
Phase Data

- Continuous phase stored digitally: incomplete representation
  - Measure continuous function at discrete points
  - Samples span a limited extent of total signal
  - Insufficient sample spacing may preclude reconstruction to a satisfying level of fidelity
  - Wrapped phase extracted from sampled signal may not allow unwrapping to any level of fidelity
- Noise can cause phase unwrapping failure
  - Unwrapping captures a noisy estimate of the true phase
  - Causes an effect analogous to aliasing



Identifying Residues

- Unwrapped phases can be obtained by integrating (summing) wrapped phase differences
  - Inconsistencies detected by summing wrapped phase differences (gradients) around every 2x2
  - Nyquist sampling: phase change constrained to π rads/sample
  - Helps localize source of each phase inconsistency
- Sources of residues
  - Zero magnitudes
  - Phase discontinuities
  - Noise
  - inconsistent phase gradients
  - Aliasing
- The existence of residues → path-dependence in 2-D phase unwrapping



$$q = \sum_{i=1}^{4} \Delta_i = 0 \qquad q = \sum_{i=1}^{4} \Delta_i = 1$$

Path Dependence

- If the phase or its gradient $\nabla\varphi$satisfy conditions for path independence, phase unwrapping is path independent and task is trivial
  - Evaluate $\varphi(\vec{r}) = \int_C \nabla\varphi \cdot d\vec{r} + \varphi(\overrightarrow{r_0})$ sequentially along a path that covers domain D.
- In real data, usually violate path independence
  - Need to choose a path that covers domain D and satisfies certain properties, OR
  - Use minimization criteria to get unwrapped phase estimates with explicitly satisfying an integration path
- Aliasing, singularities or noise can make phase unwrapping path dependent
  - All 2-D path following phase unwrapping algorithms are concerned with choosing a path

Methods of 2-D Phase Unwrapping

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- Find a function whose unwrapped phase gradients are close to the measured wrapped phase gradients

Global	Local

• Unwrap all simultaneously
• Minimum norm methods
  • Case: L2 norm: least squares
  • Transform (FFT,DCT)
  • Matrix (weighting, nonlinear)
• Fast
• Sensitive to residues
• Corruption spreads throughout image
• Doesn't work well with
	• Solve along a path
	• Branch cuts connect residues of opposite polarity; path doesn't cross
	• Fast
	• Efficient if low phase noise
	• Optimization spatially incomplete in noisy regions

- Network Flow
  - Local path to calculate residues = node; node connected by arcs; look for optimal flow that minimizes sum for all arc flows
  - Intensive memory usage and computational complexity

1-D Unwrapping is Insufficient

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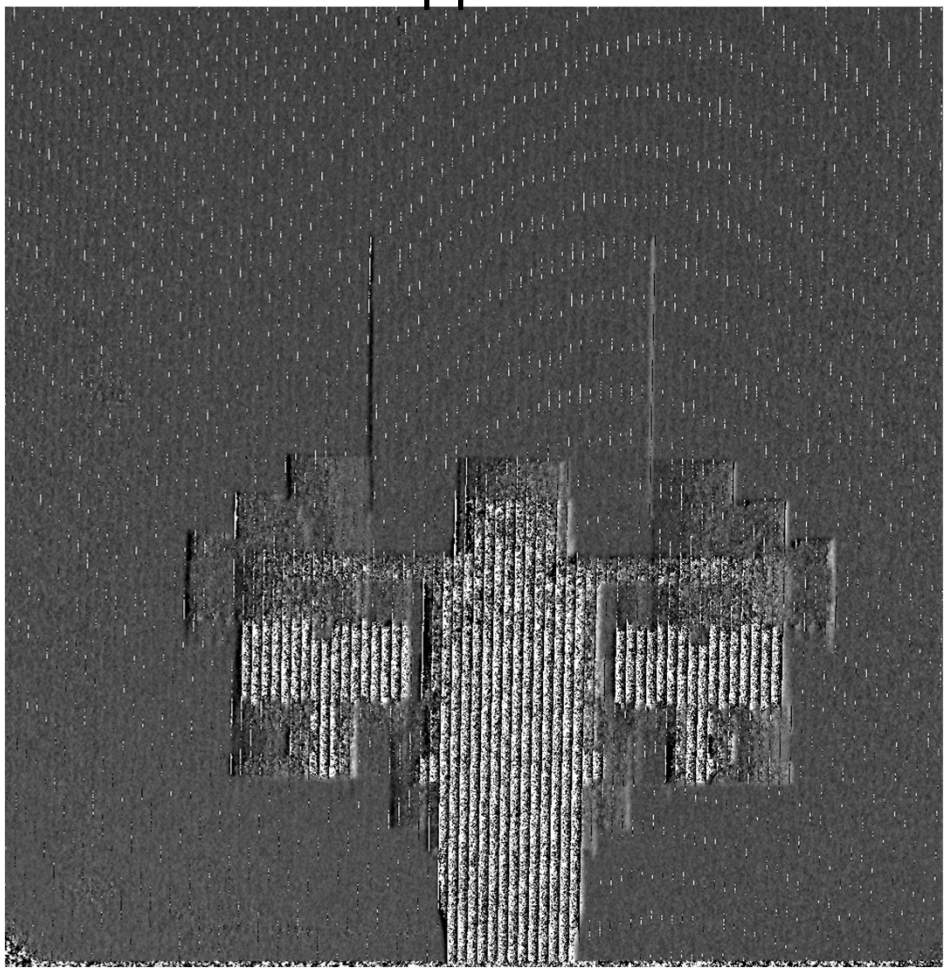
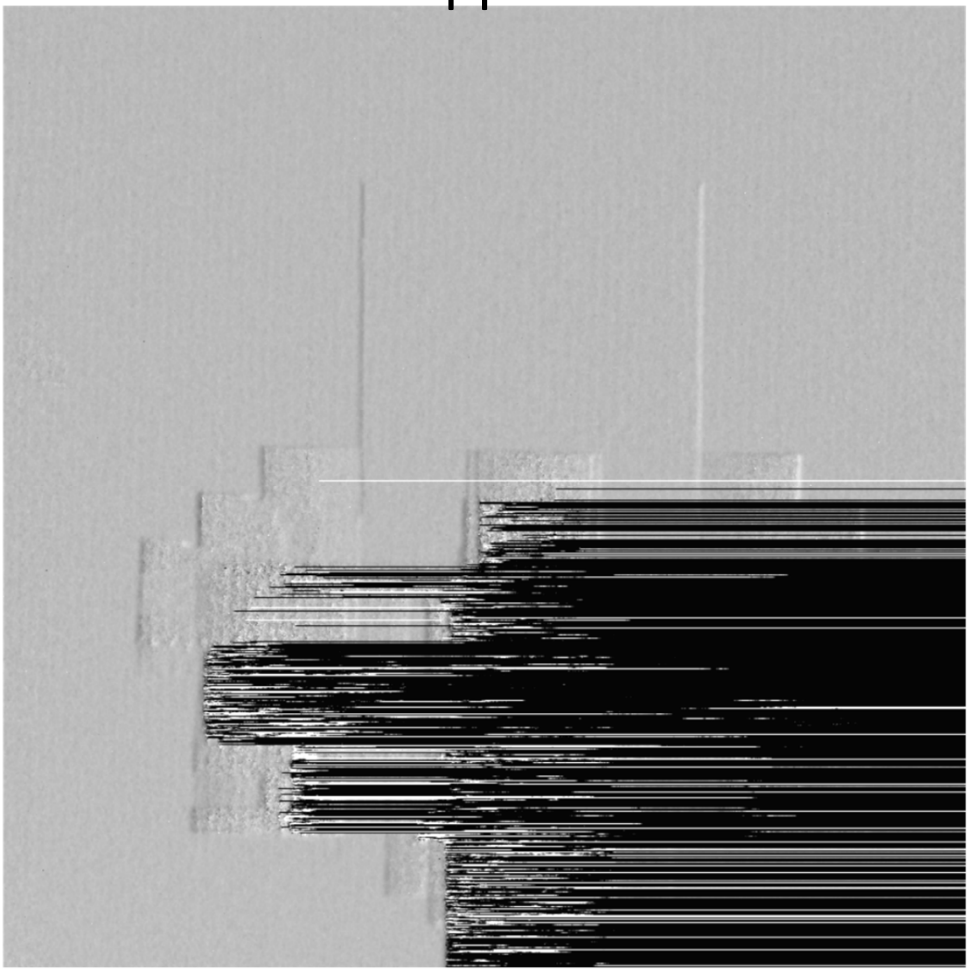
Wrapped Phase



Unwrapped Phase



Advanced Phase Unwrapping Challenges

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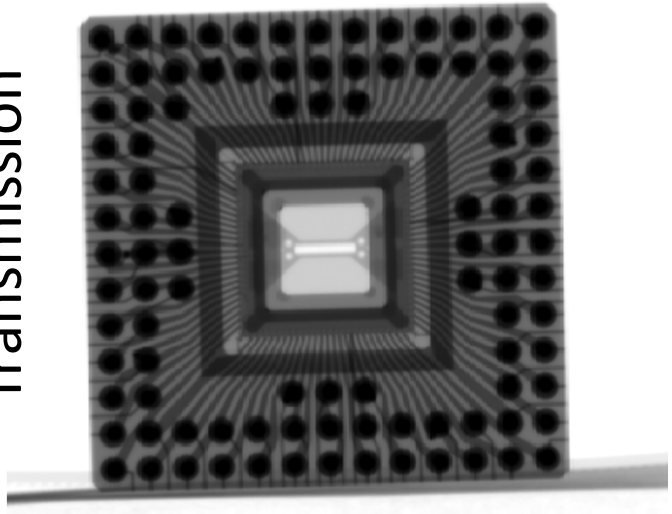
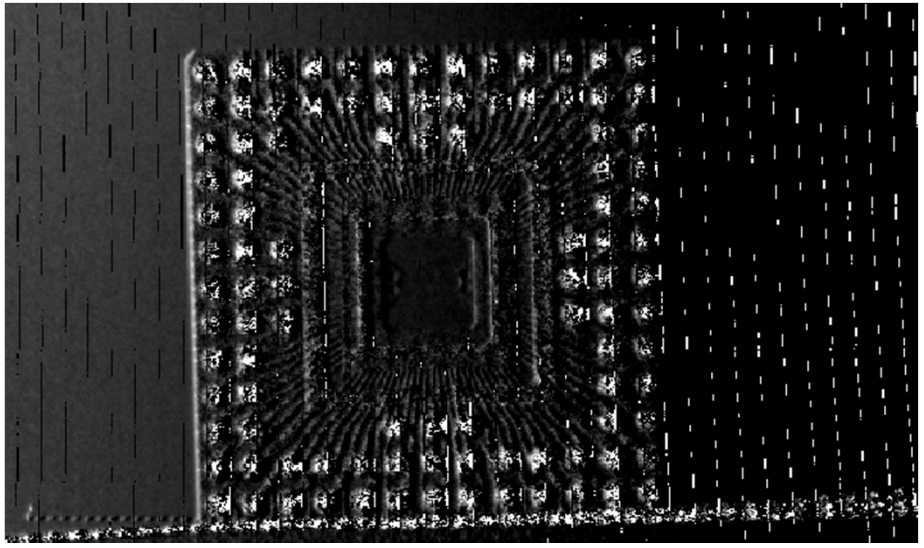
Packaged microfabricated surface electrode ion trap

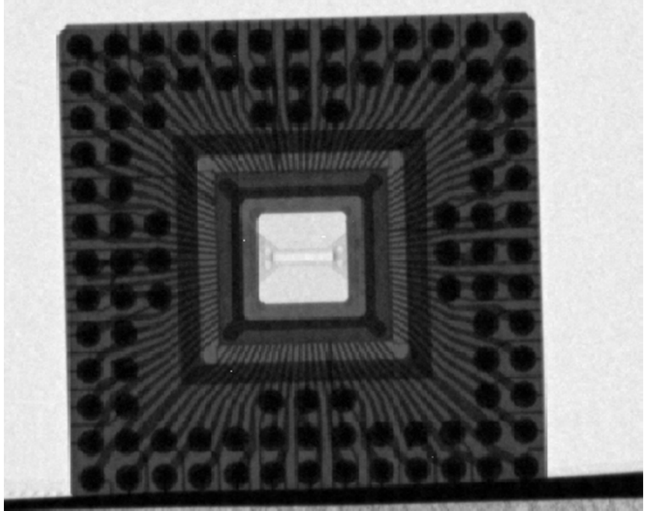
Transmission



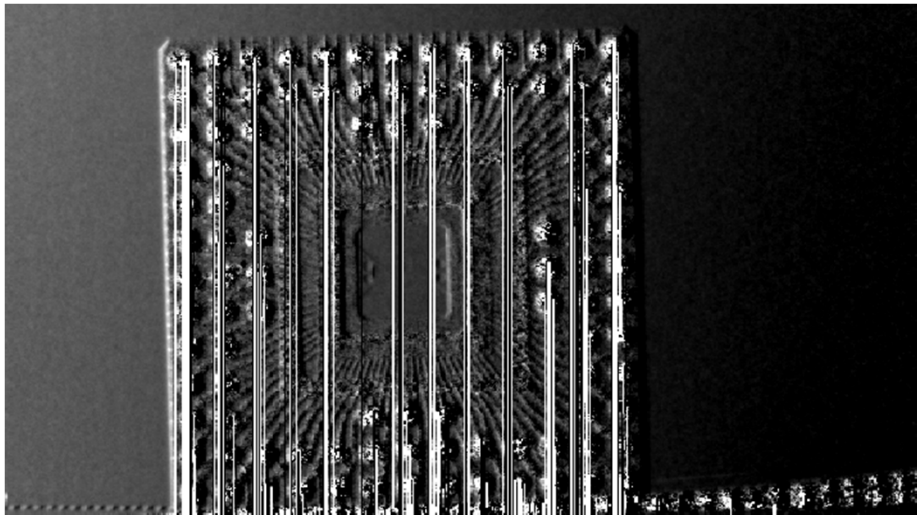
Wrapped Phase



Dark Field



Unwrapped Phase



XPCI in Materials Science

- Inspection is critical to assuring functionality and security
  - "Slice and dice" inspection
  - Randomly selected samples
  - Labor intensive
  - Limited imaging depth
  - Complicated sample preparation
  - Limited in materials that can be inspected
- X-ray phase contrast imaging (XPCI)
  - Non-destructive
  - Three orders of magnitude greater sensitivity to phase over absorption imaging
  - Complementary imaging modalities (absorption, phase, dark-field)
  - Visualization of internal structure
    - Compare part topography to CAD design
    - Look for cracks, voids
    - Identify unfused powder
- Need advanced phase unwrapping algorithms

XPCI in Materials Science

Sandia National Laboratories

- Non-destructive
- Three orders of magnitude greater sensitivity to phase over absorption imaging
- Complementary imaging modalities (absorption, phase, dark-field)
- Visualization of internal structure
  - Compare part topography to CAD design
  - Look for cracks, voids, delaminations
- Need advanced phase unwrapping algorithms

Acknowledgements

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Project Manager: Brad Gabel

Funding: Laboratory Directed Research and Development (LDRD)

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505-844-7285

Sandia National Laboratories

BACK-UP SLIDES

Phase Unwrapping: Analogies to SAR

Cone beam geometry? aka flat earth

flat-earth phase is the phase present in the interferometric signal due to the curvature of the reference surface

Flat Earth Phase

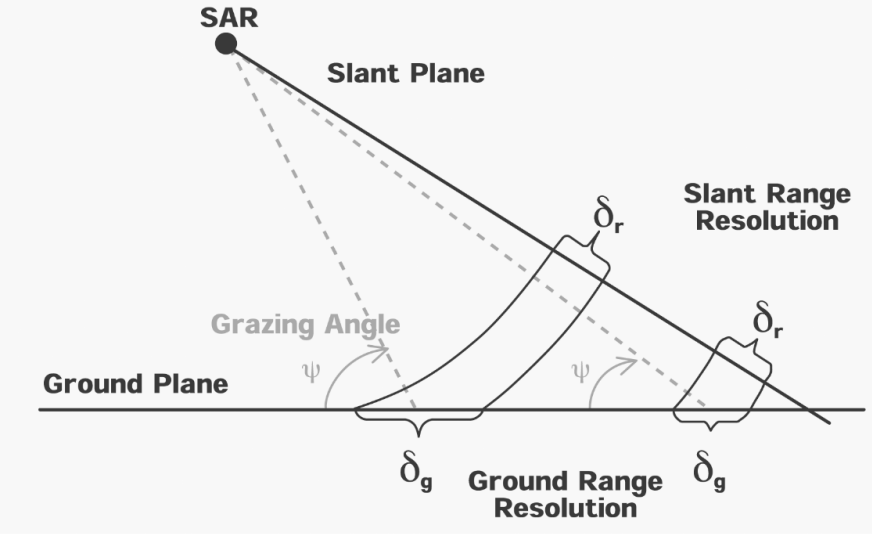
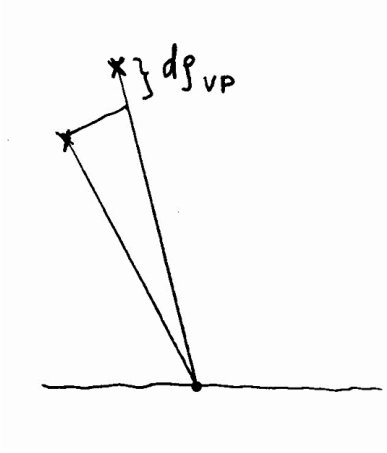
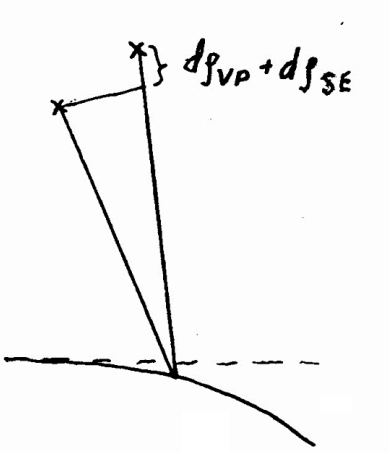


Figure 1.6. Slant plane and ground plane imaging geometry (flat earth).

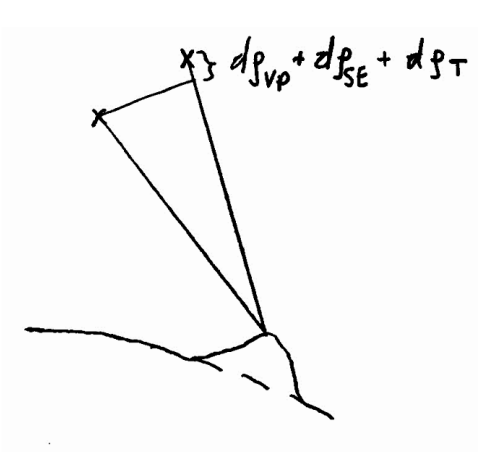
Viewing Position



Spherical Earth



Topography



Ref: Jackson, C.R., Chapter 1: Principles of Sythentic Aperture Radar from Radar Imaging Resources, Denver, CO

SAR interferogram

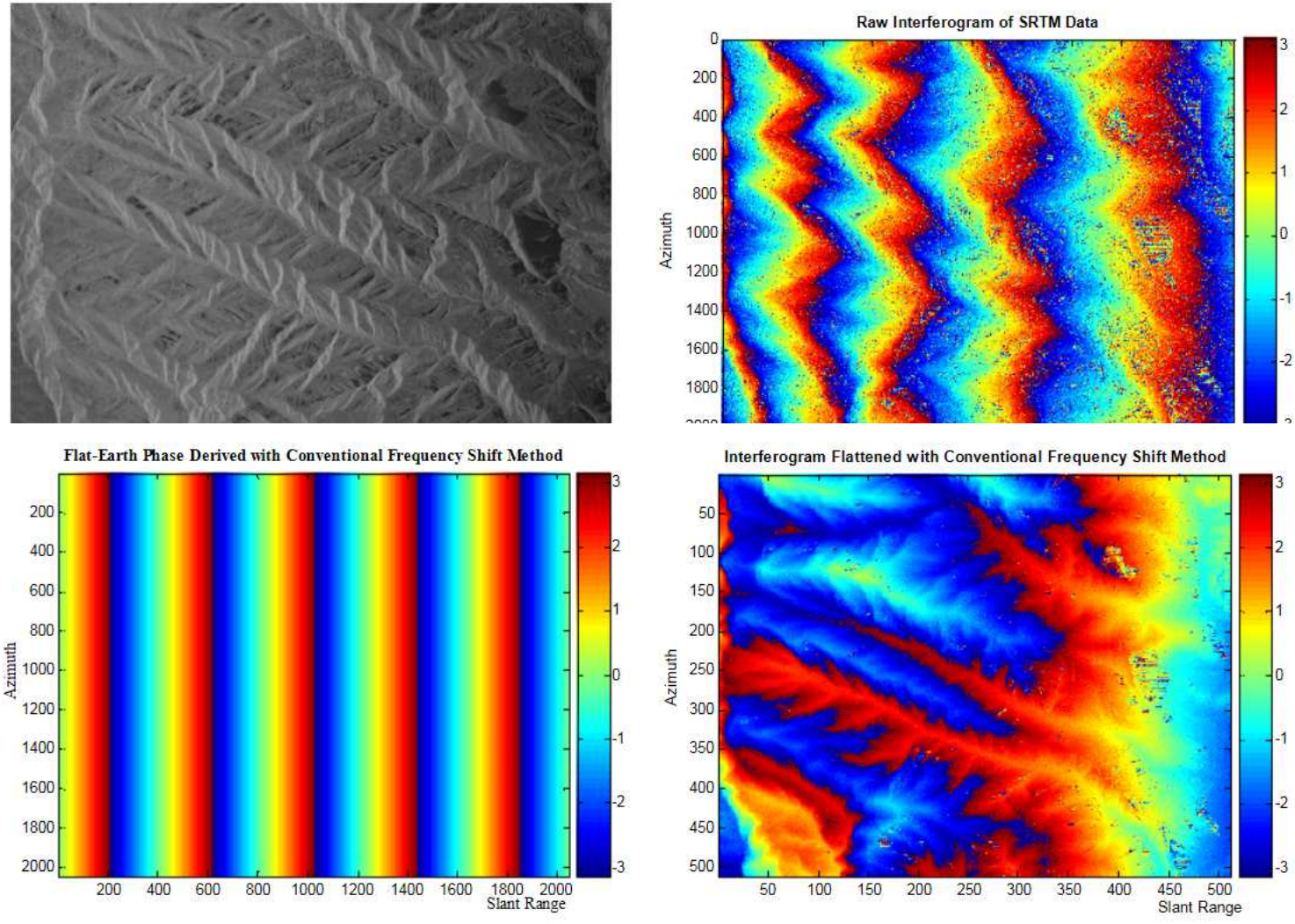
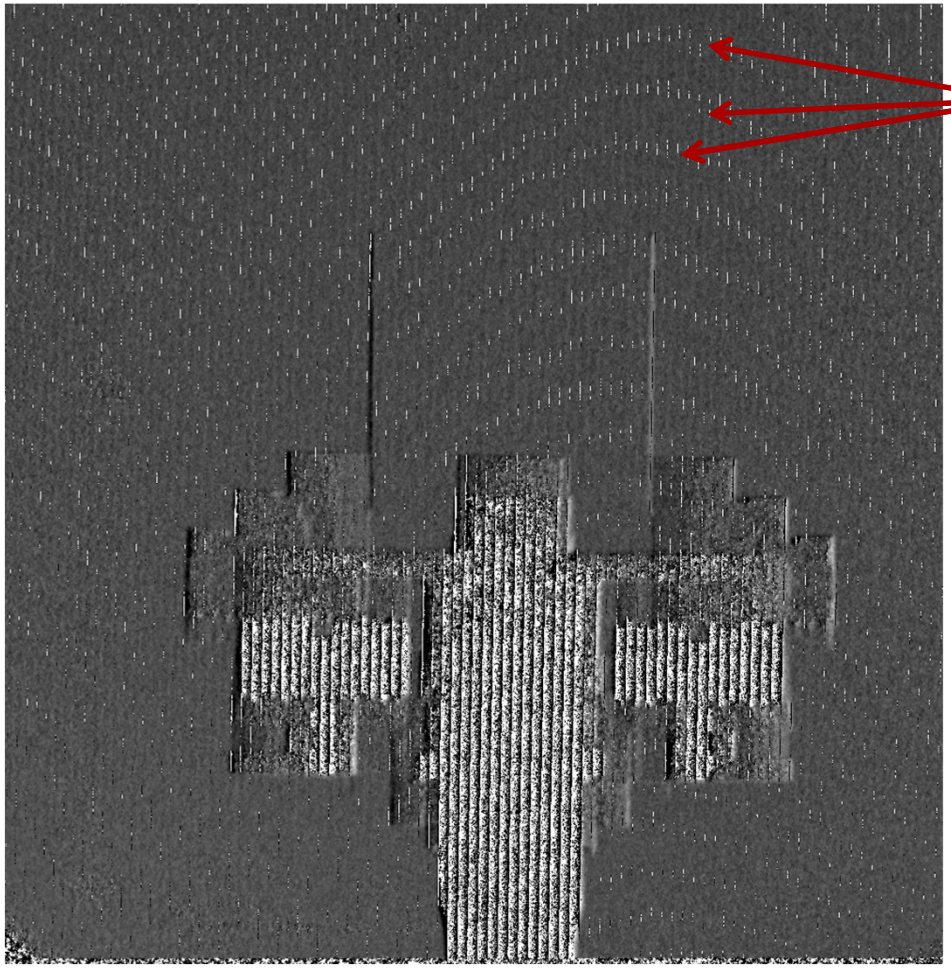


Fig.4 (a) Flat-earth phase Derived with Common Method Fig.4 (b) Interferogram Flattened with Common Method

Ai, B., Liu, K., Li, X. & Li, D. H. Flat-earth phase removal algorithm improved with frequency information of interferogram. in *Proc. SPIE 7147, Geoinformatics 2008 and Joint Conference on GIS and Built Environment: Classification of Remote Sensing Images* **7147,** 71471A–71471A–10 (2008).

Phase Unwrapping: Analogies to SAR



Cone beam geometry? aka flat earth

flat-earth phase:

the phase present in the interferometric signal due to the curvature of the reference surface

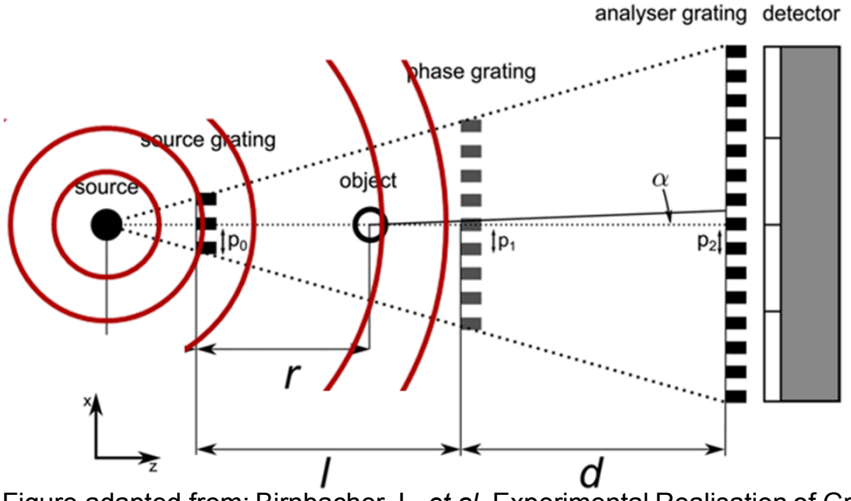


Figure adapted from: Birnbacher, L. *et al.* Experimental Realisation of Grating-based Phase-contrast Computed Tomography. *Sci. Rep.* **6,** 24022 (2016).