Gratings-based phase contrast x-ray imaging for explosives detection

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October 23, 2013

What might gratings-based phase contrast have to offer?

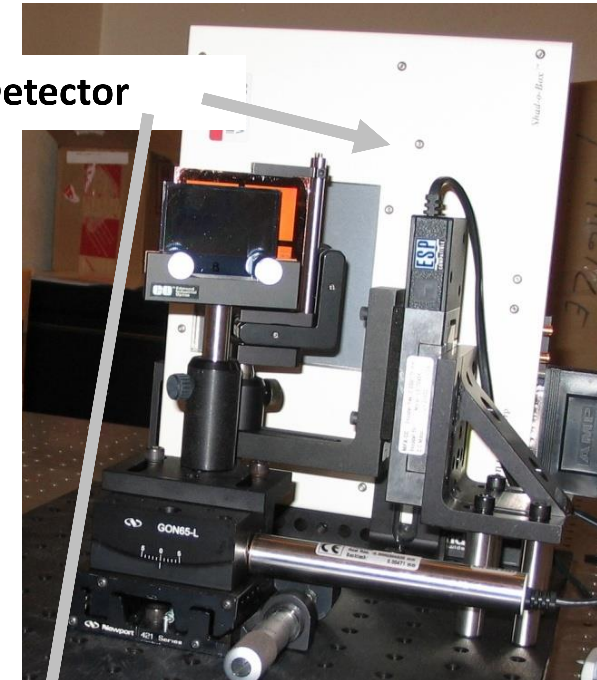
- Gratings-based phase contrast provides three physically distinct contrast mechanisms, which may improve material discrimination
  - Absorption contrast is strongly dependent on *effective Z*
  - Phase contrast is sensitive to variations in *electron density* and can give enhanced contrast for low-*Z* materials
  - Scatter contrast is sensitive to electron density variations (*texture*) on length scales smaller than the imaging resolution
- Multiple measurement approaches exist, spanning a wide range of complexity, energy scalability, and texture length scales
- Scatter contrast is based on ultra-small angle x-ray elastic scattering, and can provide texture information. This is a unique property which may be relevant for explosives.

PNNL Talbot-Lau System

X-ray source

- PNNL system has been used for investigations of:
  - sensitivity to texture
  - geochemistry, fish biology
  - explosives detection
  - synchrotron version has been used to investigate biofilm structure
- Multiple iterations on gratings fabrication

Detector



Example: powdered explosives simulants

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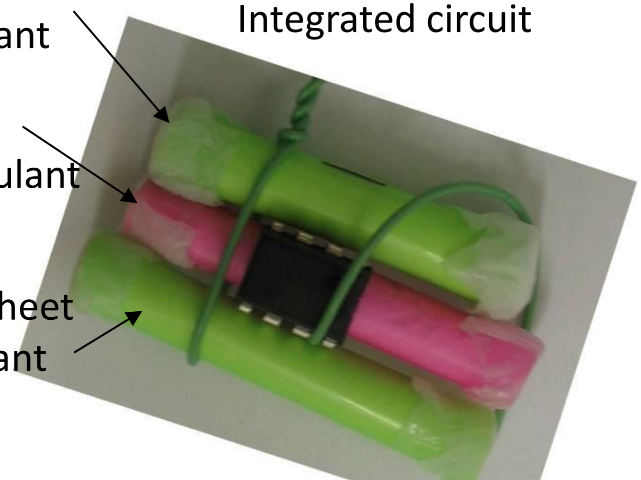
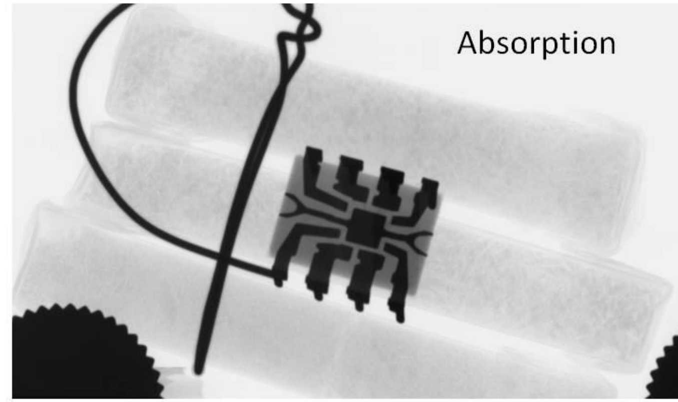
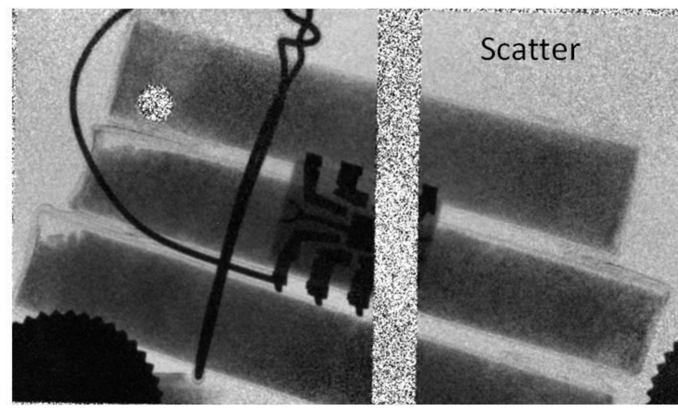
Sections 6mm in diameter







- Images are simultaneously acquired
- **Absorption** emphasizes metal components; **phase** image (differential phase) highlights fine details of low Z materials such as the parafilm endcaps; **scatter** image is sensitive to powdered simulants.

Gratings Fabrication

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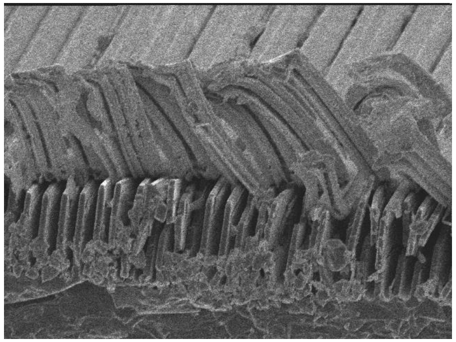
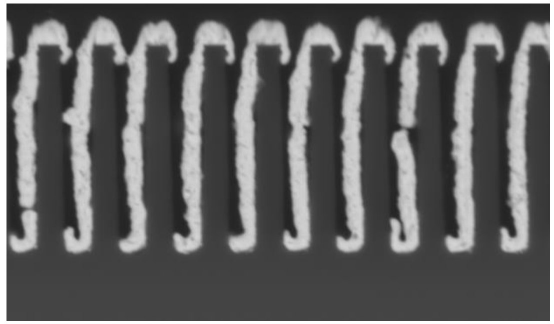
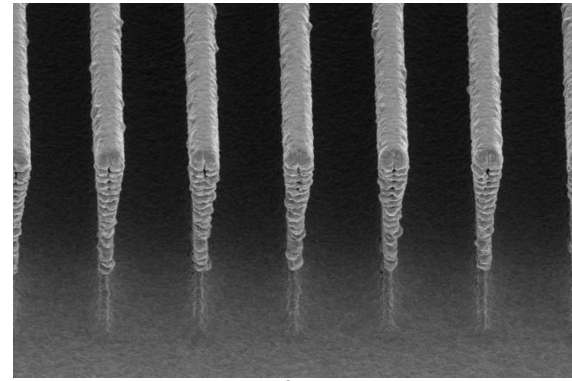


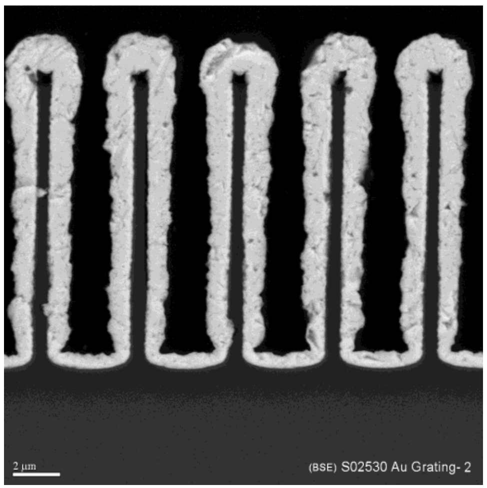
- April 07



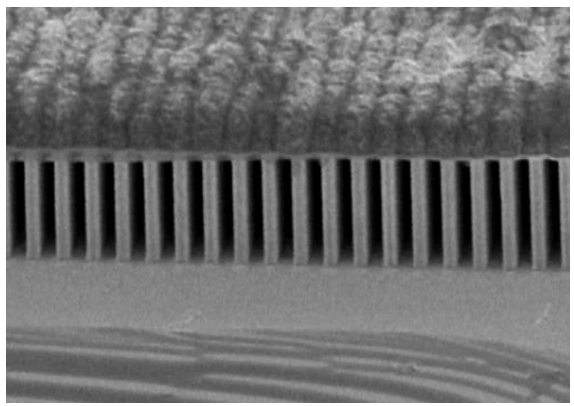
- August 07



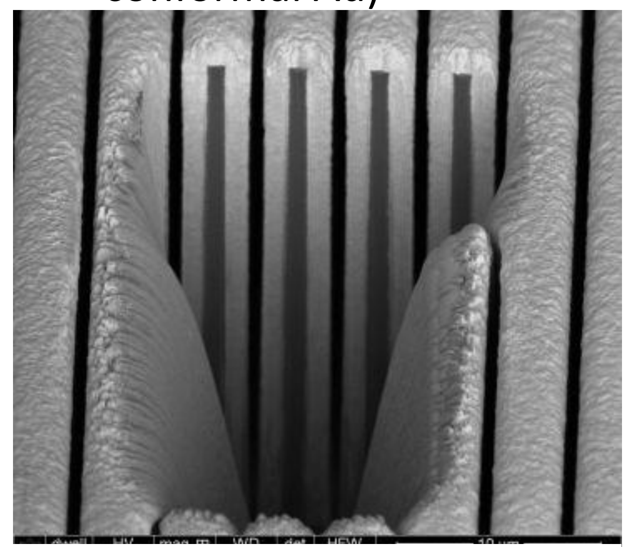
- March 08 (sputtering for conformal Au)



- September 08
  - deep reactive ion etch with conformal 1 µm electroplated Au



- March 09 (LIGA)
  - built-up PMMA and Au



- June 11
  - Deep RIE; ALD Pt; electroplate Au

Fringe Visibility	15.4 keV	22.5 keV	40 kVp	50 kVp
Lab			15%	10%
Synchrotron	80%	40%		

Many Phase Contrast Techniques Exist

Tradeoffs between phase sensitivity, complexity of setup and ease of energy scaling, and length scales for scattering

Number of Gratings	Grating Characteristics	Considerations
3 (Talbot-Lau)	High aspect ratio Limited to < 100kV(??)	High resolution, sensitive to small density variations. Sensitive to relatively large length scales for scatter
2 (Talbot/ Tsinghua)	(Phase or absorption) and absorption	Stronger constraint on either source size or grating period; easier alignment than 3-grating system.
1 (H. Wen)	Usually absorption; may be commercially available	Simple and inexpensive; grid pattern is imaged directly and processed image resolution is reduced to grid period. Scatter sensitive to smaller length scales.
0 (propagation based)	N/A	Simplest x-ray optics; requires very small source focal spot; works best for high resolution imaging of small objects. No scatter information.

Complexity ↑

Single Grid Setup

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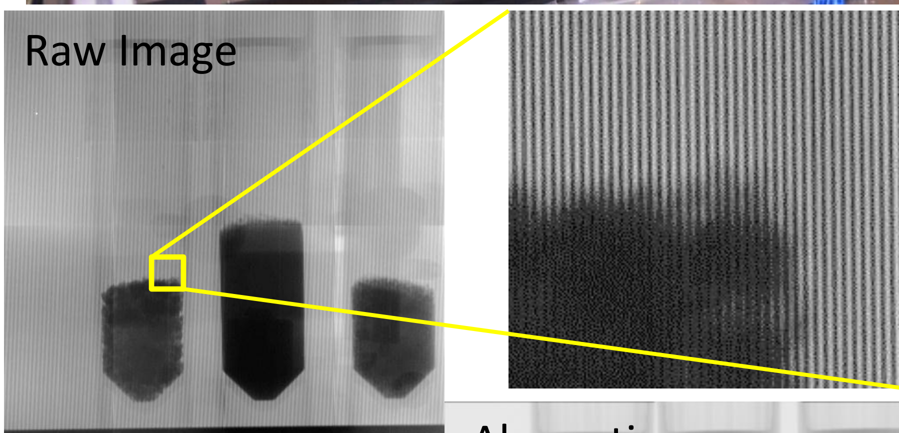
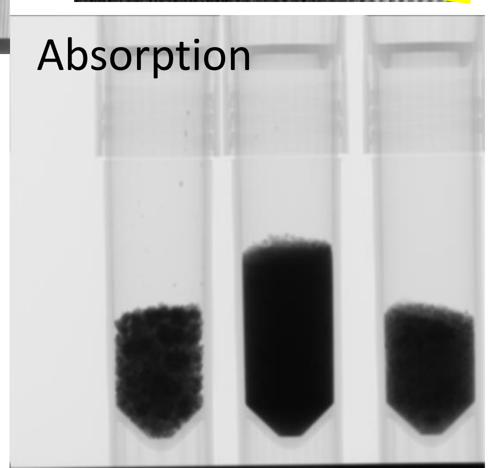
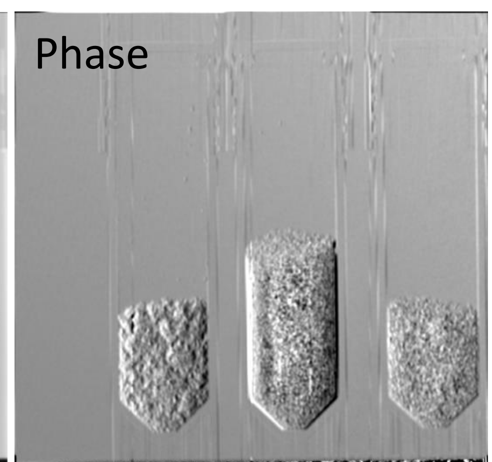
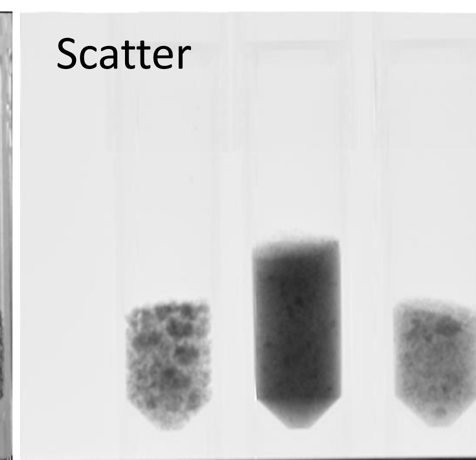


1000 nm 30 nm 8 nm
Dry iron oxide nanoparticles

- Single exposure is processed to recover all 3 images
- Significant loss of spatial resolution
- Relatively easy to scale energy







What about scatter?

- Sensitive to texture (variations in electron density such as powders, paper, wood, bone, etc…) below the imaging resolution
- Length scale which is most visible depends on the measurement method (10’s of microns down to 10’s of nm)
- Some explosives have texture within this range (e.g., Lee et al., “A study on the thermal decompositions behaviors of PETN, RDX, HNS, and HMX,” Thermochimica Acta v392-393, 2002). X-ray microtomography studies have been performed to characterize microstructure of explosives

PETN (particle size 100% ≤40 μm, average particle size 15 μm), RDX (particle size 100–800 μm), HMX (100% ≤60 μm, average particle size 19.8 μm), HNS (particle size 74–100 μm) and silicone rubber (Slygard 182) are the raw materials used in this work. PETN, RDX, HNS and HMX composed of silicone rubber with a weight ratio of 4:1, respectively, are also studied.

Scatter and Length Scales (1)

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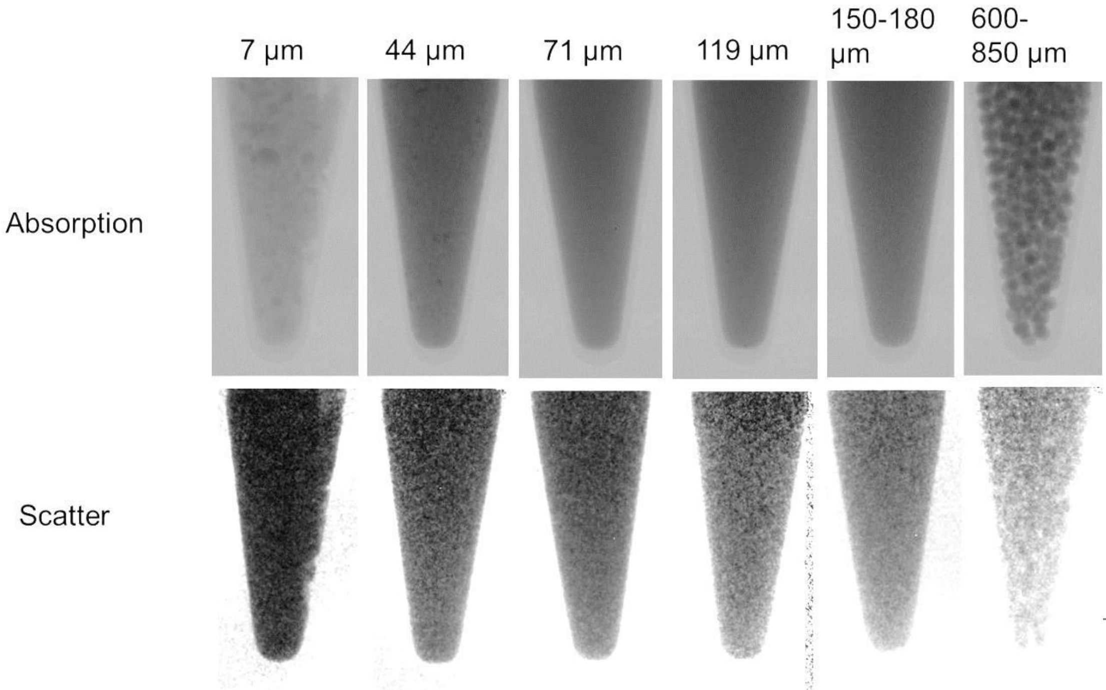

- 3-grating system; glass beads 7-850 µm (dry and wet); 40 kVp
- Scatter intensity changes with sample length scale
    - Packing fraction also varies
- Miller et al., IEEE Trans Nuc Sci 2013

- Absorption is uncorrelated with particle size
- Scatter intensity increases as particle size is reduced

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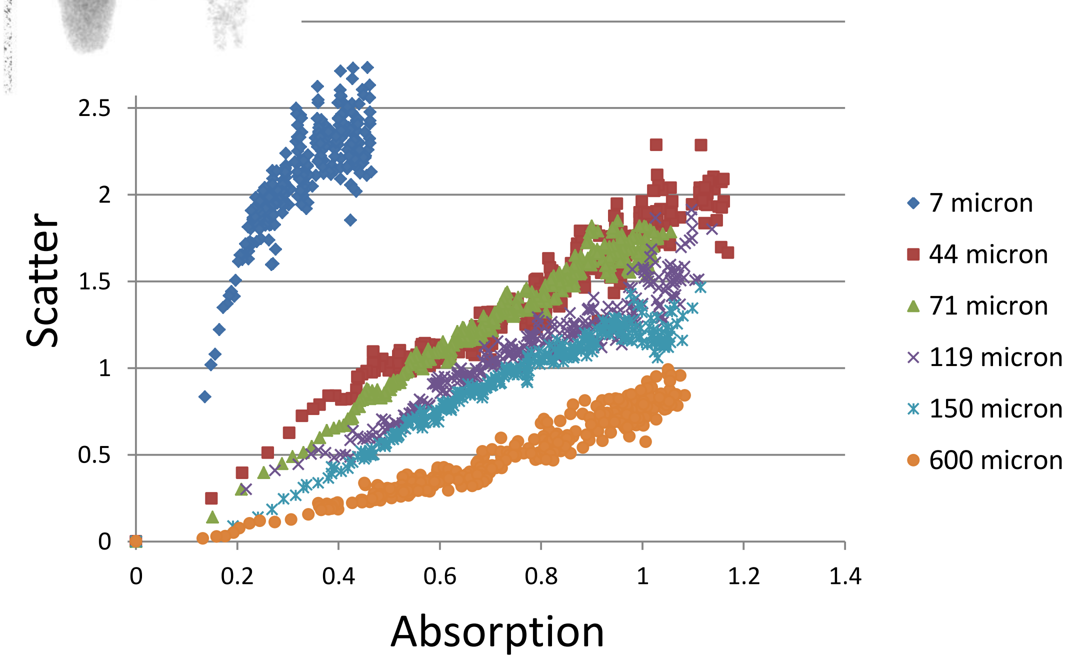
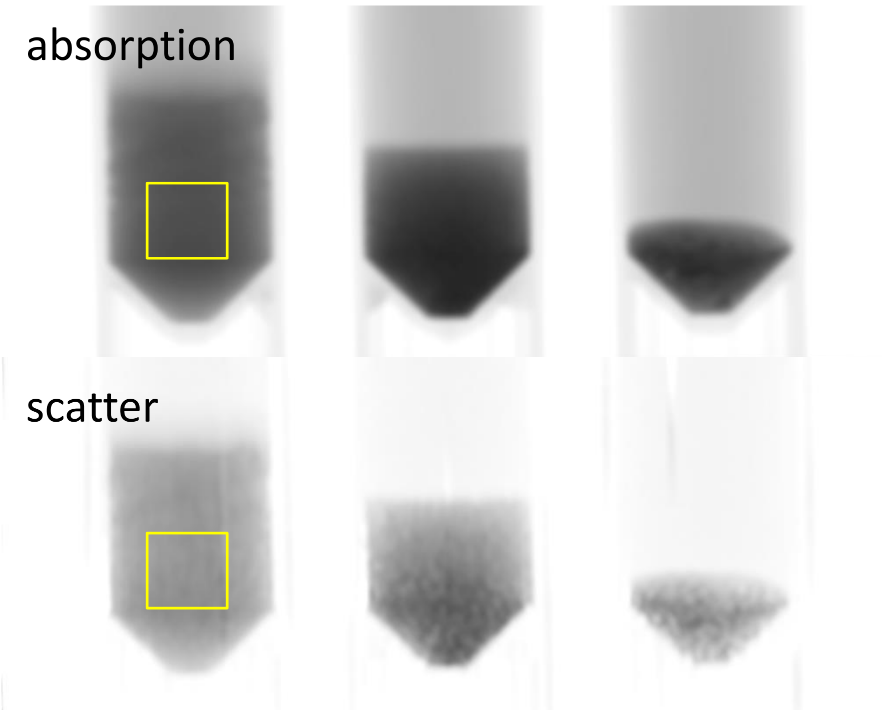
Phase Contrast X-Ray Imaging Signatures for Security Applications

Erin A. Miller, Timothy A. White, Benjamin S. McDonald, and Allen Seifert



Scatter and Length Scales (2)



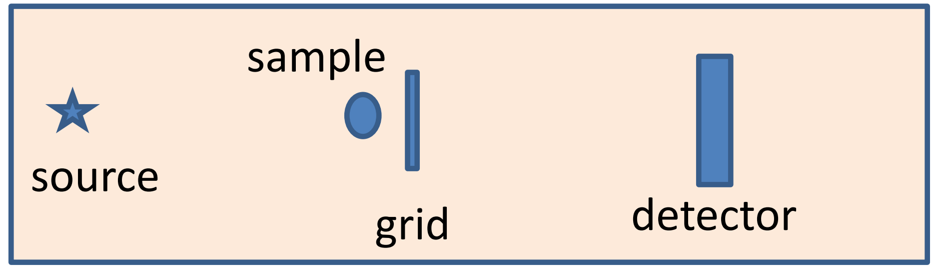
1000 nm 30 nm 8 nm

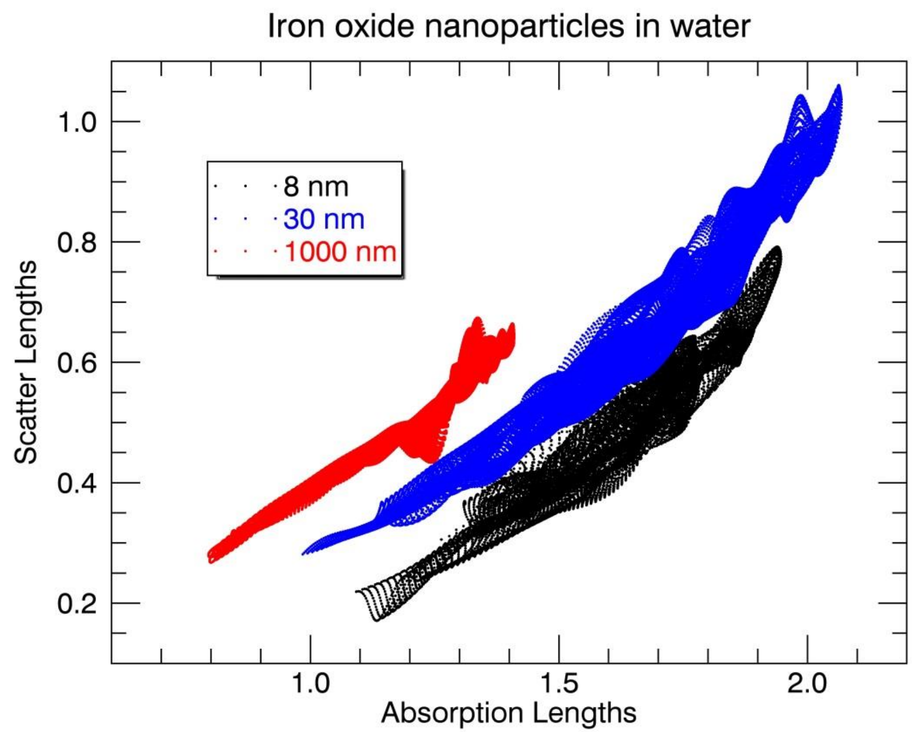
Iron oxide nanoparticles in water

Same three contrast modes, but different length scale sensitivity

Single grating: 2m working distance, grid and sample near center; 40 kVp

d=76 nm





Conclusions

- Gratings-based phase contrast provides three physically distinct contrast mechanisms, which may improve material discrimination
- Multiple measurement approaches exist, spanning a wide range of complexity, energy scalability, and texture length scales
- Scatter contrast is based on ultra-small angle x-ray elastic scattering, and can provide texture information. This is a unique property which may be relevant for explosives.

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Additional Information

Practical considerations for explosives detection

- **Scale-up to high energies**
  - Talbot-Lau has been achieved with design energy as high as 82 keV (Willner et al, TUM)
  - Easier with alternative (non Talbot-Lau) system design!
    - This will change the phase sensitivity AND scatter length scale sensitivity
- **System stability**
  - Preclinical Talbot CT with rotating gantry is being commissioned by Bruker MicroCT and may be commercially available in <5 years
- **Footprint**
  - Many setups (including ours) use about 2m src-det
  - A compact setup (32 cm) has been demonstrated, with a 6 cm field of view, using cylindrically bent gratings (Thuring, Swiss Light Source)
- **Measurement time**
  - Attenuation by gratings multiple frames for phase stepping will increase measurement time
- **Clutter**
  - The usual effects of clutter (difficulty in identifying features; reduced dynamic range) still apply
  - The 3 signals are interrelated: reduced counts due to attenuation will also affect phase and scatter; high scatter makes phase signal more difficult to extract

Gratings?

- Current set
  - source grating, 127 μm pd, electroplated through photoresist
  - phase grating, 3.94 μm pd, deep reactive ion etch
  - analyzer grating, 2 μm pd (up to 50 μm high), deep reactive ion etch (period doubled) followed by ALD platinum seed layer and electroplated 1 μm thick conformal gold layer
- Previous analyzer gratings
  - conformal gold with evaporated seed layer (period doubled etched substrate)
  - etched Si backfilled with Au
  - LIGA pattern, built up through photoresisit
    - This can do very high aspect ratio and works well; we moved away from it due to high cost and limited field of view
- Single grating parameters
  - Can be anything that you have the resolution to see; we've used a 2μm period grid at a synchrotron, and a 299μm grid with a lab source and a 50 μm/pixel detector