Emerging Explosives Detection Technologies for Luggage

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So What? Who Cares?

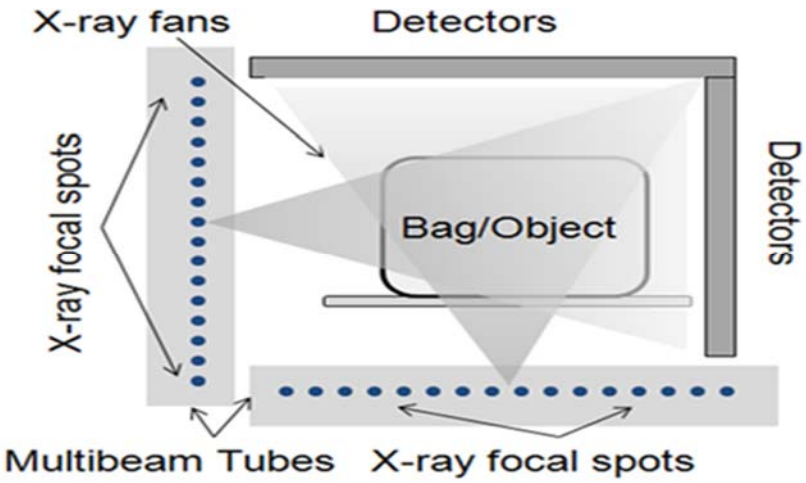
- Current systems have limitations for detecting emerging threats inside of luggage
  - Evolving explosive threats make them harder to distinguish from stream-of-commerce materials using signatures from current generation checked luggage scanners
  - Increased interest in automated CT explosives detection in other domains (hand-carried luggage, air cargo, …) bring new challenges
- Thus, looking for different solutions
  - Hardware/software systems: cheaper, smaller CT architectures suitable for large deployments in checkpoint, air cargo
  - Signatures: Extract more features concerning material properties to separate explosives from non-confusing threats.
- Some interesting ideas being pursued currently
  - But they have limitations
  - Can the limitations be overcome to produce robust, deployable systems?

Some Topics

- Limited Field of View Tomography
- Multi-Energy Tomography
- X-ray Diffraction Imaging and Tomography
- Compton Scatter Tomography
- Other X-ray Signatures: Phase-Contrast Imaging and Dark-field Imaging

Limited Field-of-View Architectures for X-ray CT

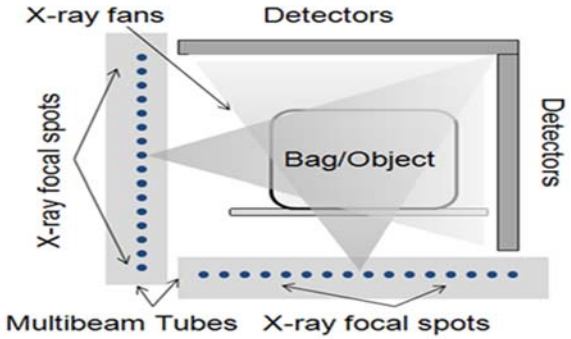
- Motivation
  - Fewer sources, detectors lower cost
  - Non-rotating scanning architectures reduce form factor, simplify mechanical structure
  - New sources enable flexible source placement
  - Designs with as few as 4 source locations
- Variations: slice-by-slice vs. volumetric imaging
  - Motion yields view diversity



XinRay, IEEE Access 2014 (V2)

Issues with Limited FoV Architectures

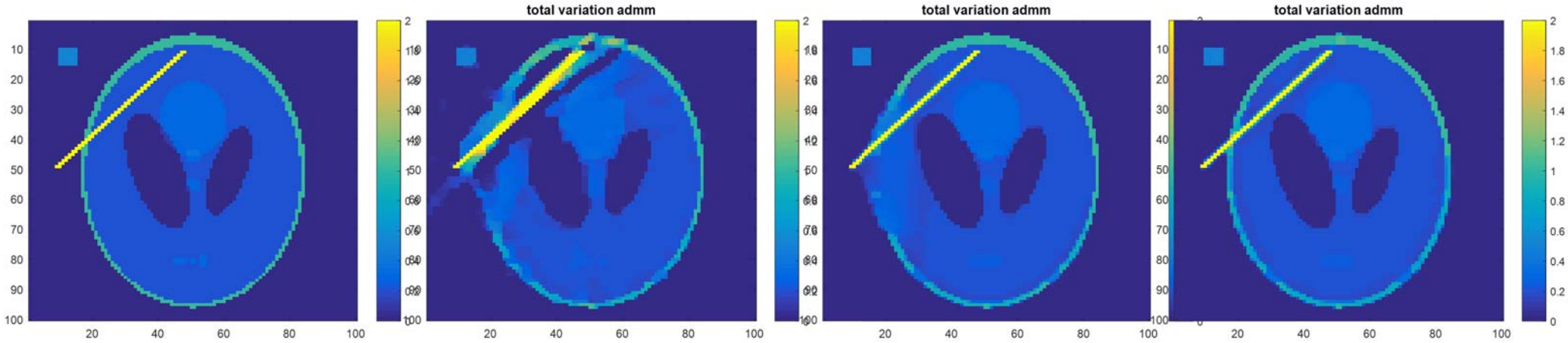
- Image formation requires complex iterative algorithms
  - Strong regularization used to add information that is not in the measured data
  - High-dimensional optimization: number of unknowns if full volumetric imaging
  - High computational cost: hours on CPUs: can be alleviated using GPUs: seconds



- Irregular sampling of geometry can lose observability in areas
  - Thin objects with wrong orientations hard to separate
  - High attenuating objects can create blind spots that are poorly illuminated
- Need enough sources…compressive sensing not a good answer

Illustration: Imaging with limited views

- K views, fan beam, ideal monoenergetic source, total variation reconstruction using ADMM
  - Need enough views and sufficient view diversity



Truth

15 Source Locations
180 degrees

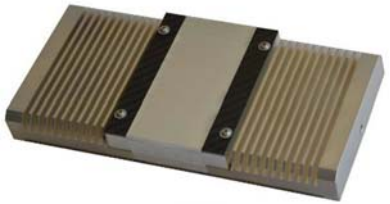
50 Source Locations
180 degrees

50 Source Locations
360 degrees

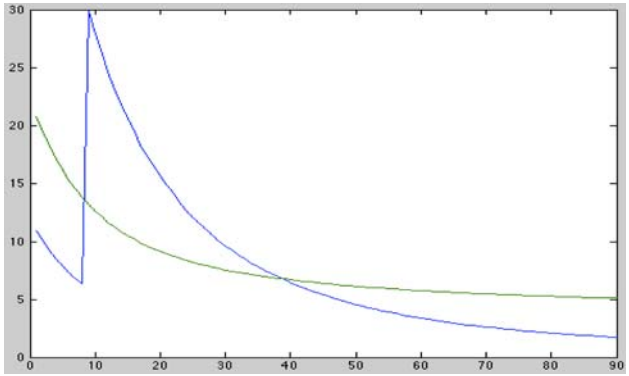
New Signatures: Multi-spectral CT

- Dual energy systems are available commercially
  - However, the RoR of some explosives and confusers are not well-separated in these features
  - Materials with k-edges in 30-120 KeV are poorly represented in dual energy imaging
- Can use of multi-spectral CT with many spectral bins help?
  - Multiple source spectra, photon-counting detectors, …
  - New features possible → greater separation

Reveal CT-80DR+ (from brochure)

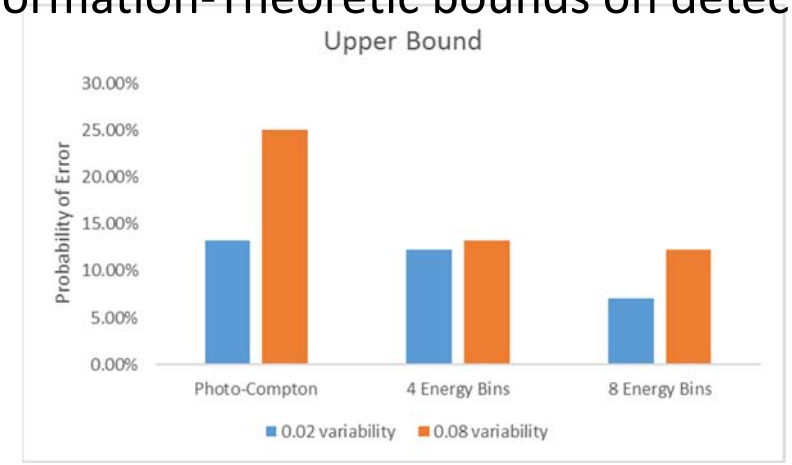

MultiX ME 100 www.multixdetection.com

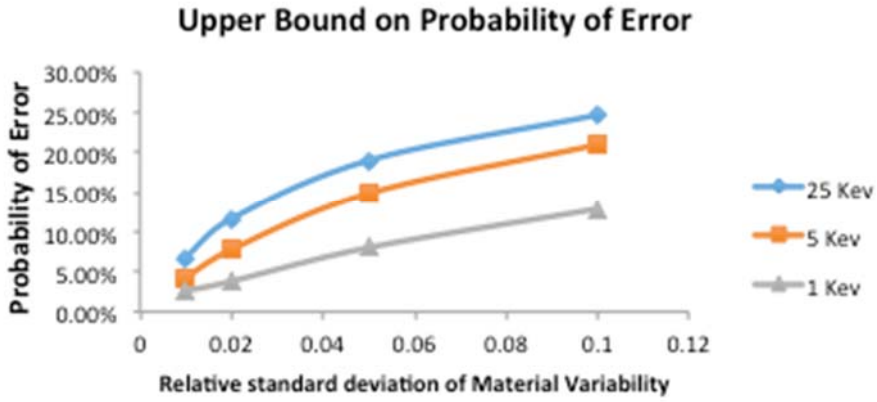
LAC of Baratol (TNT+Barium Nitrate) and best approximation using photoelectric and Compton basis



Which new features?

- May measure linear attenuation coefficients at various energy bins
  - But, is much of the information redundant? If so, what are the right features to obtain?
- Morpho (Smiths?) study (Skatter et al, 2014 ICCST): germanium detectors used to measure 38 materials, find that only two features are meaningful
  - But no materials in study with k edges in relevant energy region
  - Other studies with more materials suggests 3-4 or more
- Information-Theoretic bounds on detection (300 materials)

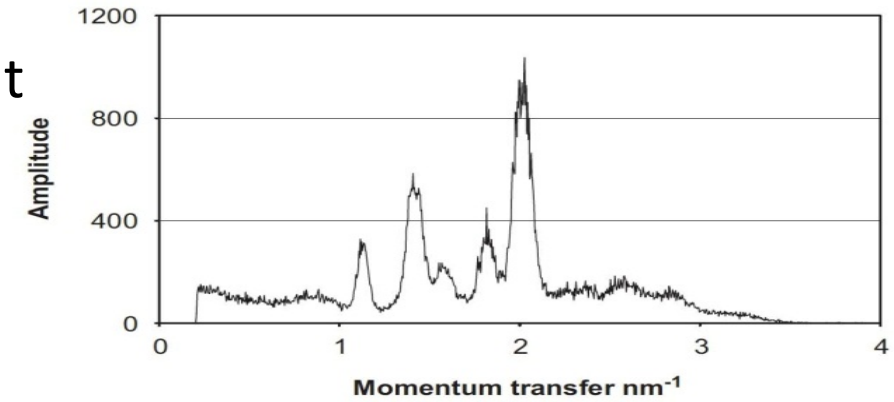




Non-Transmission X-ray Signatures: X-ray Diffraction

- Coherent scatter: momentum transfer to incoming photons from molecular electron cloud change of direction with no loss in energy
  - Primarily forward, at small angles
  - Not the primary interaction: approximately 5% of scatter events above 70 keV
  - Usually results in noise for transmission
- Goal: image the coherent scatter form factor – the distribution of photons that undergo specific momentum transfers

TNT form factor measured with diffractometer



X-ray Diffraction Systems

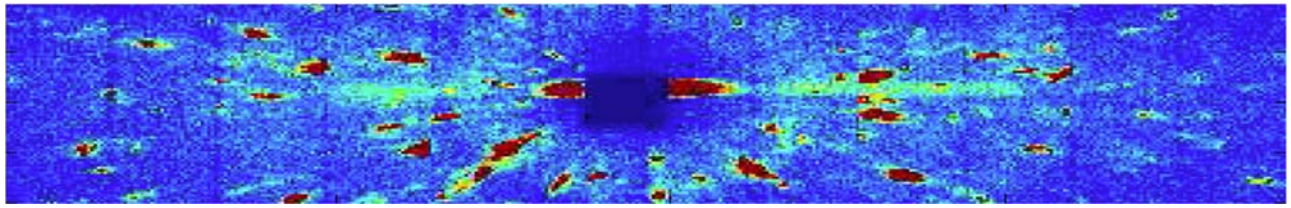
- Commercial System: ???? XRD 3500^{TM}
  - Deployed, uses XRD in secondary mode in combo with transmission image
  - Upgrades in progress to deliver stronger signals
  - Collects scatter at fixed angle, resolves in frequency photon counting detectors
  - Limited viewing geometry susceptible to loss of observability
- Alternative approaches under investigation: XRD tomographic systems using less collimation to capture more photons (based on Duke concepts)
  - Coded aperture collimation, small number of sources
  - Same detector measures photons from different angles, need to solve inverse problem to localize
- Question: used as secondary, or primary imaging?

Issues with XRD - CT

- Advantage: Stronger signals – 1-2 orders of magnitude increase in scattered photons measured vs. collimation architecture

- Disadvantages
  - Energy sensitive attenuation distorts form factors, requires 3-D energy-sensitive attenuation correction – Must fuse with dual-energy transmission imaging
  - Lack of collimation increases noise from Compton scatter, secondary scatter
  - Limited illumination directions can lead to lack of observability
  - High-dimensional inverse problem – 3 space plus spectral dimensions
  - For many materials, form-factor signatures may not be isotropic – and may depend strongly on other factors

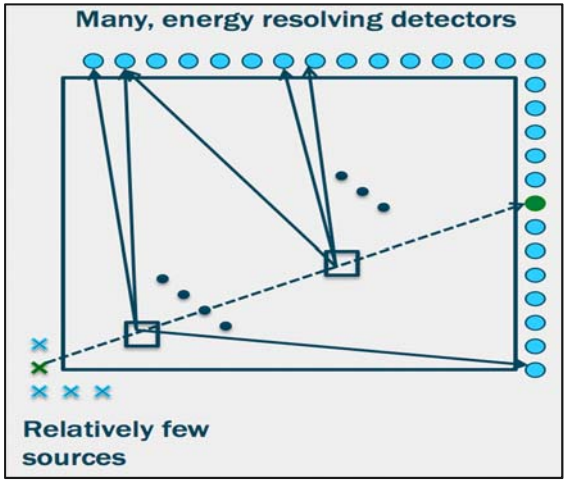
2-D coherent scatter intensity from NaCl
(J. Greenberg, Duke)



X-ray signatures: Compton scatter

- Concept explored by Tufts, AS&E
  - Much stronger scatter cross section than coherent scatter, at higher energies
  - Strong scatter signature from low Z materials – complement of transmission

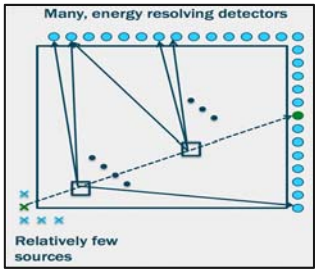
- Concept
  - Line scan illumination, with lines scanned from a few source locations, plus wide array of photon counting detectors
  - Energy of scattered photon indicates momentum transfer, identifying direction of scatter and allowing localization
  - Scatter provide "virtual sources" with different orientation directions illuminating volume – fuller angle from limited source points
  - Must compensate for transmission and scatter loss – Requires good knowledge of energy-dependent attenuation

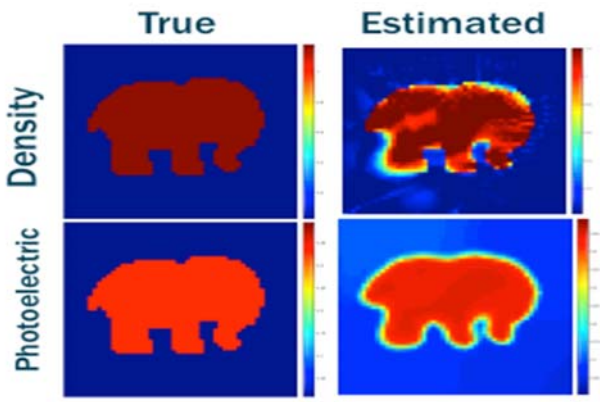


E. Miller (ALERT)

X-ray signatures: Compton scatter - 2

- Research prototype implemented by AS&E
  - Collaboration with Tufts University under DHS BAA 13-05
- Challenges
  - Transmission detector technology different because of signal strength dynamic range
  - Line scan illumination required for well-posed inverse problem, leads to slower coverage
  - Complex inverse problem requires model of energy-dependent Compton scatter cross-section
  - Initial 2D prototypes tested in both simulation nd in hardware by AS&E, Tufts team
- Advantages
  - Better estimation of electron density, effective atomic number with limited angle illumination

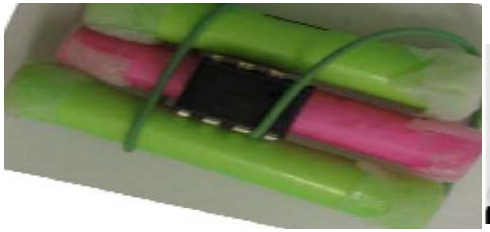




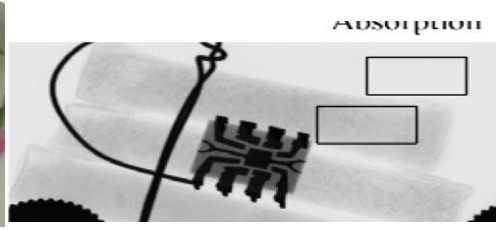
Other X-Ray Signatures

- Phase contrast imaging
  - New developments using gratings and interferometry to avoid use of coherent x-ray sources (e.g. synchrotrons)
  - Enhances contrast when attenuation is similar
  - Demonstrated at low energies (40 keV)

Miller et al., PNNL
Analyzer grating is stepped to collect information that leads to phase contrast imaging



picture



absorption

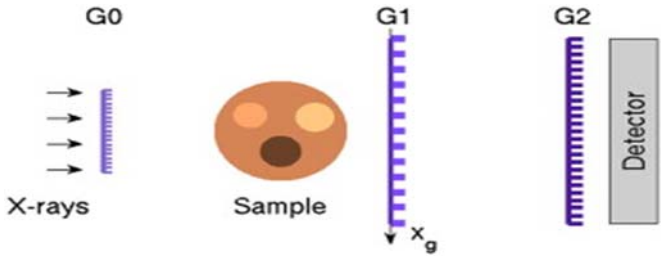
Phase contrast

Miller et al., PNNL

- Issues
  - Higher energies? Clutter effects? Penetration in luggage? Localization in 3-D? Value of signature?
  - May be better suited for separate liquid detection

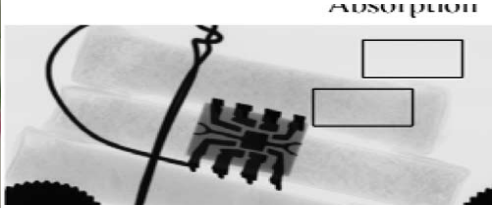
Other X-Ray Signatures

- Dark-field imaging
  - Again using gratings as in phase contrast
  - Objective: measure total amount of coherent scatter (not energy-resolved)
  - Provides measure of texture below detector resolution

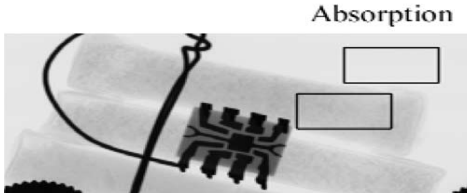


Miller et al., PNNL

picture



absorption



Dark-field image

Miller et al., PNNL

- Issues
  - Higher energies? Clutter effects? Penetration in luggage? Localization in 3-D?

Summary

- Discussed some on-going work aimed at enhancing current EDS and AT luggage inspection systems
  - Limited Field of View Tomography, Multi-Energy Tomography, X-ray Diffraction Imaging and Tomography, Compton Scatter Tomography
  - Other X-ray Signatures: Phase-Contrast Imaging and Dark-field Imaging
- Plenty of questions remain as to whether these approaches will be effective at improving performance
  - Must demonstrate ability to generate signal strength in attenuation environments
  - Reliability of signatures to nuisances: clutter, environmental variations
  - Define appropriate regions of responsibility in terms of new features
  - Establish value of signatures for separation of objects of interest from background