Innovations for Automatic Detection of Explosives and Weapons

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Director, Nondestructive Characterization Institute

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Lawrence Livermore National Laboratory

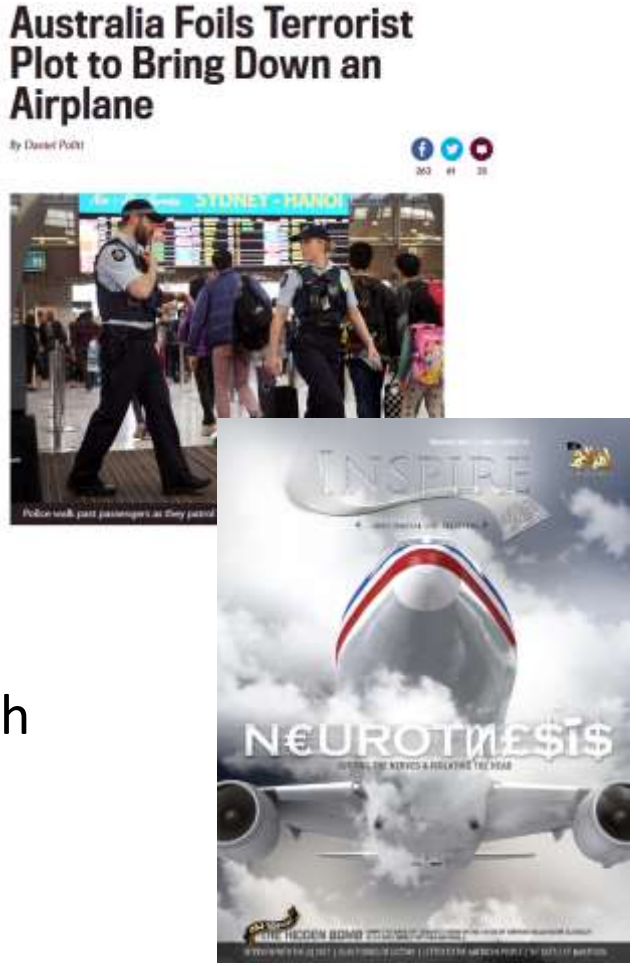
Lawrence Livermore National Laboratory is one of 17 Department of Energy National Labs

- Our mission is to strengthen the United States' security through the development and application of world-class science and technology to:
  - Enhance the nation's defense
  - Reduce the global threat from terrorism and weapons of mass destruction
  - Respond with vision, quality, integrity, and technical excellence to scientific issues of national importance
- History
  - Established in 1952
  - Approximately 6,500 employees
  - 1 square mile, 684 facilities
- Customers
  - DOE, DoD, DHS, NASA, etc.
- Collaborations
  - Academia, Industry, other National Labs

"Your mission is to make the nation safer."
— George P. Shultz

Summary

- A primary target for terrorists is aviation security because of economic impact
- Terrorists are smart and are changing
  - Threats they use
  - To take advantage of social norms, i.e., underwear bomber
  - By doing research to circumvent detection, e.g., Inspire 13
  - Venues they are attacking
- My talk will address innovations developed to deal with some of these situations
- Constant innovation is required to keep up with terrorists who adapt as needed



Global Aviation Security needs

- Better detection
  - Increase probability of detection (P_D)
  - Decrease probability of false alarm (P_{FA})
  - Detect more threats including wide-variation of home-made explosives (HMEs)
  - Reduced mass
- Reduced labor costs
  - Eliminate human in the loop if possible
- To protect soft targets, insider threats, etc.
- To speed deployment for new threat detection and to protect changing venues

Innovations include

- Checked and carry-on luggage
  - Digital Imaging and Communication for Security (DICOS)—NEMA
  - Open System Architecture: Open Threat Assessment Platform (OTAP)—Sandia National Labs
  - System simulation and modeling—Academia, National Labs, Triple Ring: PRISM
  - Simulants—DHS accreditation program—Transportation Security Laboratory (TSL)
  - (Adaptive) Automatic Threat Recognition (ATR) and reconstruction algorithms
    - Iterative image reconstruction for artifact removal
    - Deep learning
    - Compressive sensing
  - Dual- & multi-energy decomposition into a system independent ρ_e, Z_e space—LLNL & TSL, etc.
  - X-ray diffraction, phase contrast, dark field scatter, Compton scattering—Duke, PNNL, Tufts, etc.
- Passengers, etc.
  - Millimeter wave (MMW)
    - Dielectric imaging—TSL, Awareness and Localization of Explosives-Related Threats (ALERT)-NEU
    - High-spatial resolution—Pacific Northwest National Laboratory (PNNL)
    - Walk through airport—ALERT-North Eastern University (NEU)
  - X-ray backscatter and transmission-Tech84
- Cargo
  - Dual-energy 3D CT—Astro Physics & ALERT
  - X-ray Backscattering—Passport Systems Inc

Innovations I will discuss are highlighted in yellow

- Checked and carry-on luggage
  - Digital Imaging and Communication for Security (DICOS)—NEMA
  - Open System Architecture: Open Threat Assessment Platform (OTAP)—Sandia National Labs
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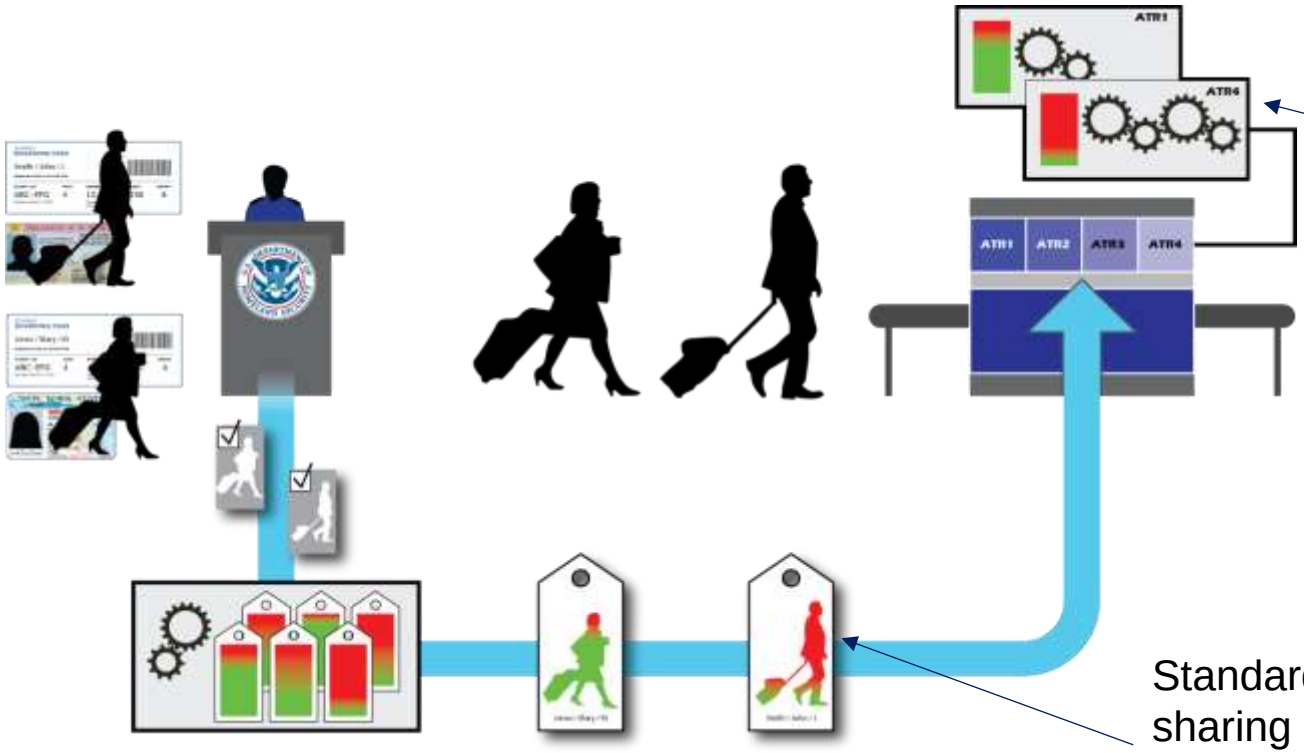
Open Architecture Enables More Flexible CONOPs

More flexible CONOPS and faster deployment



Plug-and-Play ATRs and other components

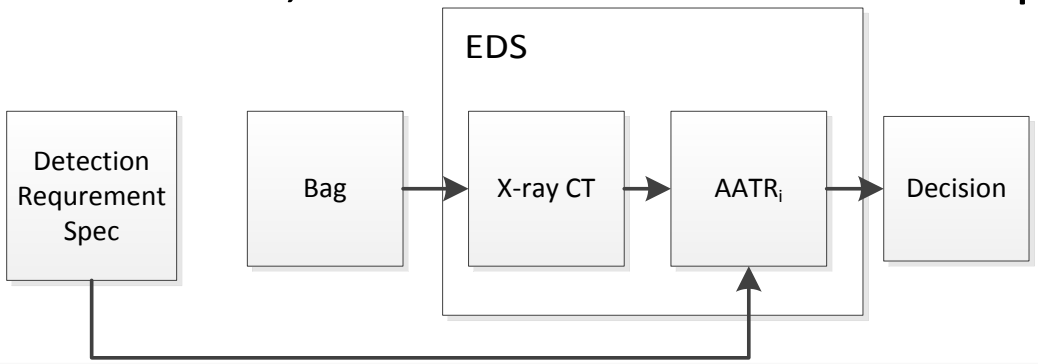
Standardized means of sharing screening information such as passenger risk and scan data

Data acquired by Tyndall Reactive Materials Group

Contact: Andrew Cox acox@sandia.gov by

Adaptive automated threat recognition to reduce time to field new detection capability

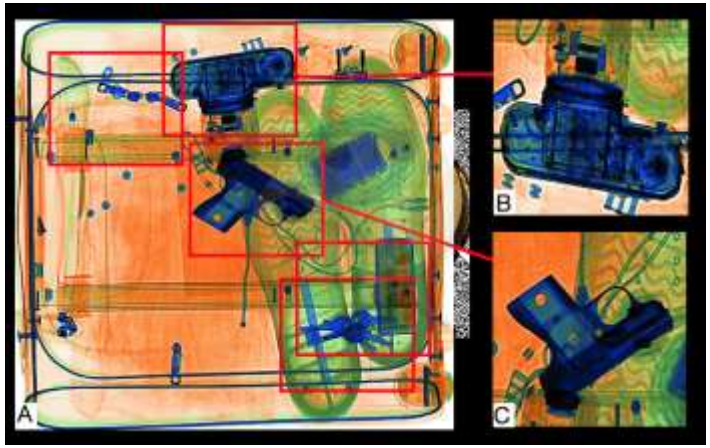
- Problem: Takes too long to field automated threat recognition based on emerging threats from adapting adversary (GAO 11-740)
- Part of the solution: Adaptive automated threat recognition (AATR); automatically adapt to computer-readable detection requirement specification.
- Status: ALERT & LLNL funded to understand requirements, algorithms and testing scenarios for AATRs.
- TSA benefit: Faster response to emerging threats, trade P_D/P_{FA}, change min mass, min sheet thickness. Also applicable to AT2, AIT.



ALERT
AWARENESS AND LOCALIZATION OF EXPLOSIVES-RELATED THREATS

Deep learning is being applied to ATR of weapons and image reconstruction

Transfer Learning using CNN for weapons detection*



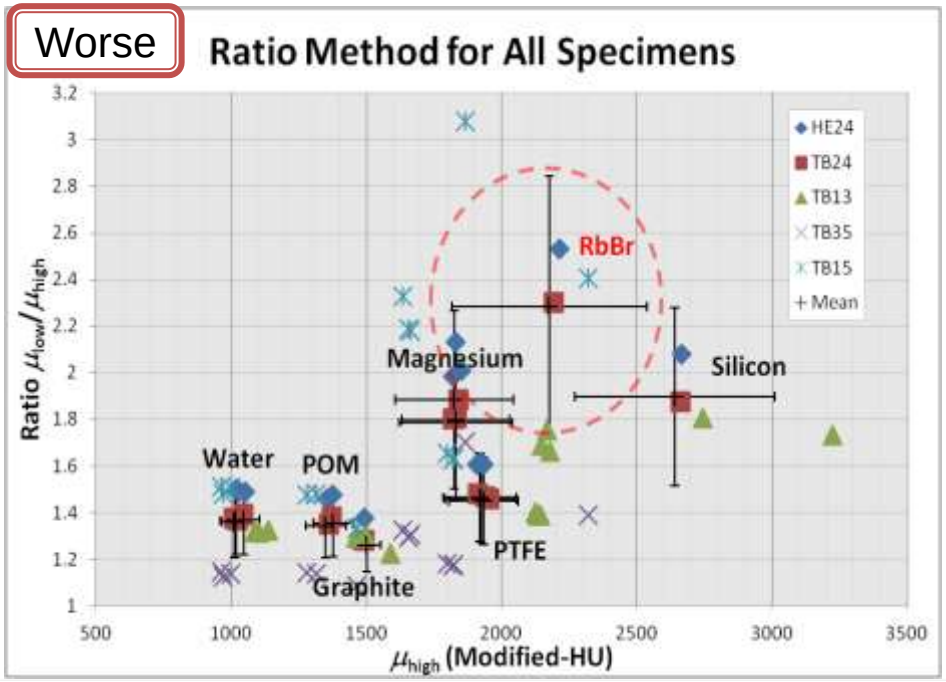
- Deep Learning refers to the latest generation of Artificial Neural Networks, e.g., convolutional neural networks (CNN)
- Deep Learning is characterized by networks with a large number of layers, typically > 5, hence "deep"
- Deep learning has enabled computers to beat human performance on tasks once thought impossible for machines, e.g.,
  - Speech recognition, object detection in imagery and machine translation
- Deep learning on CT images of bags would ideally be trained on massive amounts of labeled imagery
- However, new methods for reducing the need for massive amounts of labeled data, even for unlabeled data, are being developed

* S. Akcay, M. Kundegorski, M. Devereux, T. Breckon, "Transfer Learning using Convolutional Neural Networks for Object Classification within X-Ray Baggage Security Imagery", Proc. IEEE ICIP, September 25-28, 2016, pp.1057-1061.

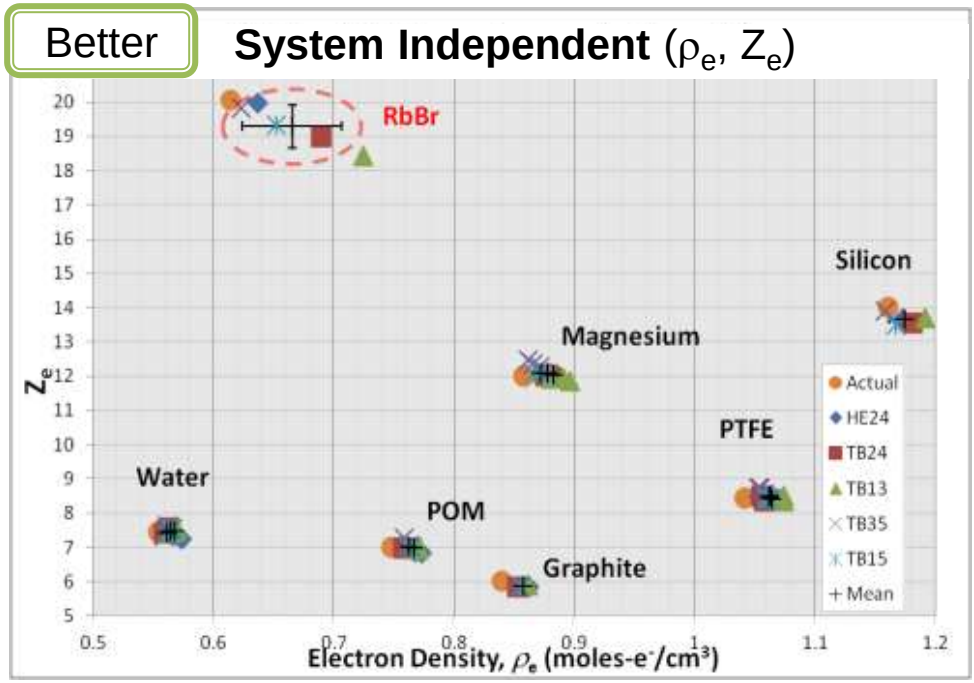
(ρ_e, Z_e)* is useful for precise and accurate material discrimination and system independence

- **Physical properties (ρ_e, Z_e) provide a system independent feature space**
- **Enables transfer of data between systems, e.g., R&D systems to EDS**
- **Different dual-energy methods are available to determine (ρ_e, Z_e)**
- **Reduced artifacts and errors may lead to increased P_D and lowered P_{FA}**

Worse



Better

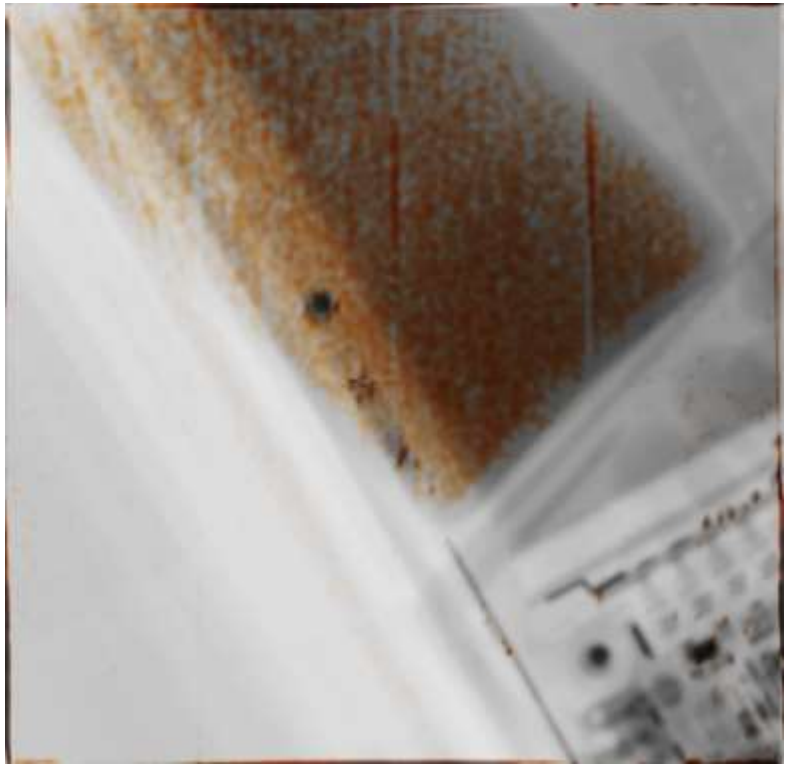


* ρ_e is electron density, Z_e is effective atomic number

Phase Contrast/Scattering or Gratings-Based X-rays for Explosives Detection

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- X-ray imaging is a mainstay of baggage screening, but has limited material discrimination
- Gratings-based (phase contrast) x-ray imaging provides 3 distinct contrast mechanisms: can this improve detection? or material discrimination?
  - Phase contrast has been seen to improve contrast for small biological samples
  - Scatter provides a signature unlike any currently used for explosives detection
- New materials signatures may distinguish threat/benign pairs which are otherwise ambiguous: Fewer bags opened, reducing time and labor for screening

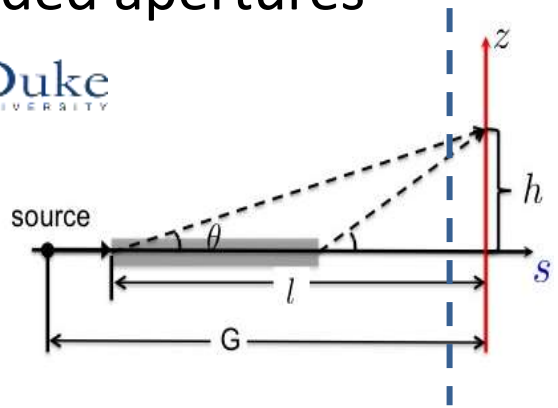


Gratings based imaging reveals additional information about a sample (2" FOV, 160 kV, single exposure)
Bag containing wallet, phone, etc., and a vial of plaster-of-paris
Black: absorption Orange: scatter

Contact: Erin Miller, PNNL / erin.miller@pnnl.gov / (509)375-1878

X-ray Diffraction Imaging – Direct and CT

- Current: X-ray diffraction imaging provides material-specific signatures for enhanced threat detection
  - Existing systems (Morpho XRD 3500) use collimated excitation/ observation to localized areas – useful for confirmation of small areas
  - New designs increase flux, throughput, but still are limited by collimation
- New: X-ray diffraction tomography using coded apertures
  - Developed by Duke U. * past 7 years
  - Prototype under implementation (Rapiscan)
  - Approach: slice-by-slice reconstruction using dual-energy transmission detectors, together with off-plane photon-counting scatter detectors using coded apertures instead of collimation



Coded aperture mixes scatter radiation heterogeneously, allowing localization through inverse processing

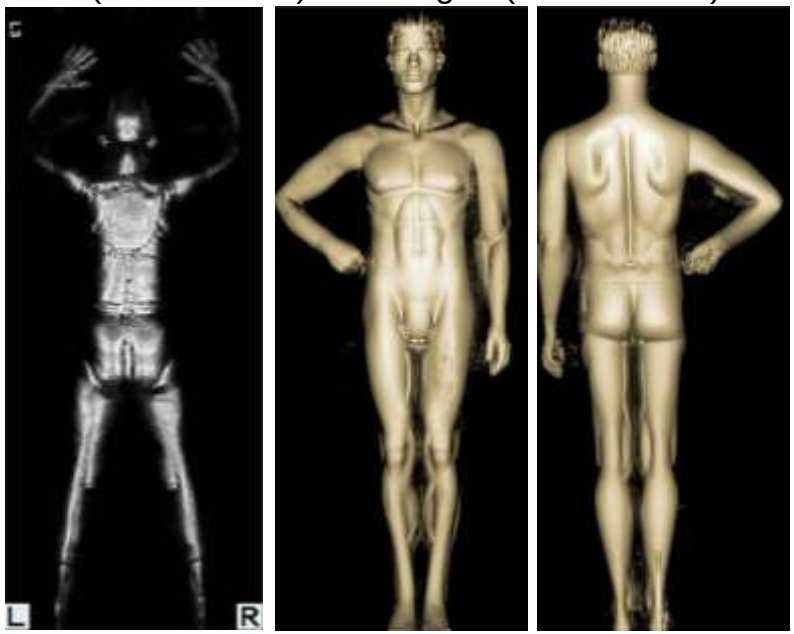
* Hassan M, Greenberg, J, Odinaka I, and Brady D, "Snapshot fan beam coded aperture coherent scatter tomography," Opt. Express 24, 18277-18289 (2016).

PNNL Radar Imaging Research

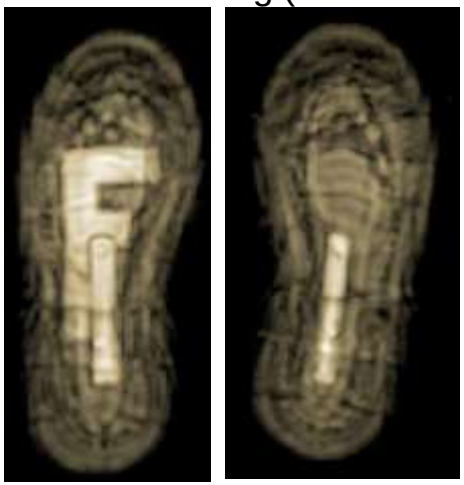
- PNNL is actively researching microwave, millimeter-wave, and sub-millimeter-wave imaging for a wide variety of applications including:
  - Weapon detection imaging (personnel screening)
  - In-wall and through-wall imaging
  - Ground penetrating radar (GPR) imaging
  - Radar cross-section (RCS) imaging
  - Non-destructive evaluation of dielectric materials
  - Body measurement
- Aviation security applications
  - Next-generation mm-wave security portals
  - Millimeter-wave shoe scanning
  - Standoff detection at sub-millimeter wavelengths

Portal Screening Imaging

Current (24 – 30 GHz) Next-gen (10 – 40 GHz)



Shoe scanning (10 – 40 GHz)



Standoff imaging (340 – 360 GHz)

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Contact: Sheen, David M
David.Sheen@pnnl.gov

LLNL-PRES-738165

Dielectric imaging of Explosives using Active MMW

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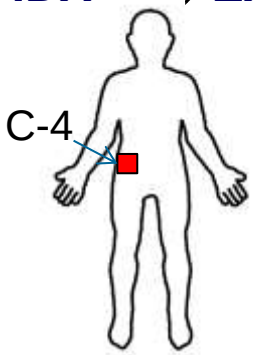
Science and Technology

MMW AIT ➡ Anomaly

United States Patent
Smith et al.

(12) Patent No.: US 8,946,641 B2
(45) Date of Patent: Feb. 3, 2015

MMW IDX ➡ EXPLOSIVE



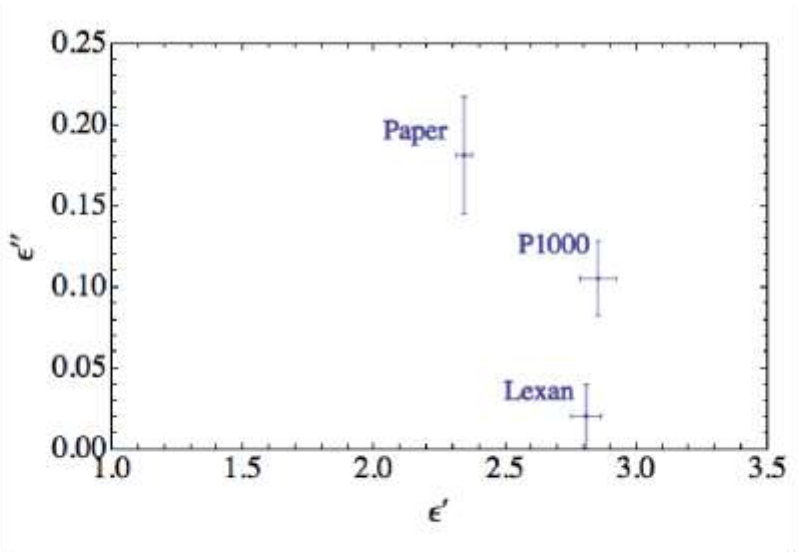


Figure 1 Detected materials in dielectric space.

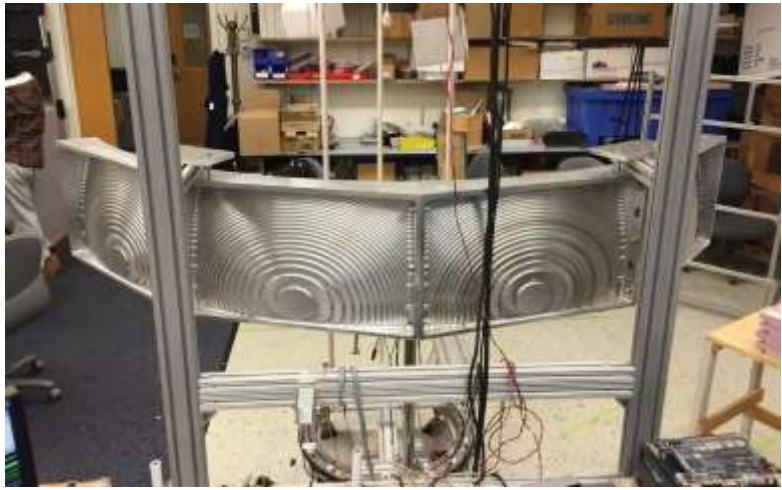
Contact: BT Smith, TSL

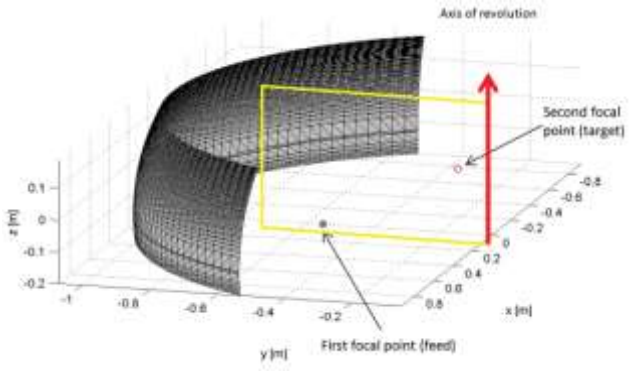
Radar Imaging at Speed

- New techniques for multistatic millimeter wave dynamic imaging:
  - Work done at Northeastern University under DHS ALERT Center of Excellence for Explosives Detection
  - Transmitter/Receivers on both sides of passengers to achieve observability of all surfaces
  - Integration of picture over time as passengers walk through inspection area
  - No need for still pose or fixed observation geometry

https://web.northeastern.edu/jmartinez/?page_id=31

- New concepts for multistatic millimeter wave imaging of objects on persons
  - Multi-receiver toroidal antenna
  - Higher-resolution images
  - Capable of imaging material dielectric properties of materials on body
  - Inexpensive



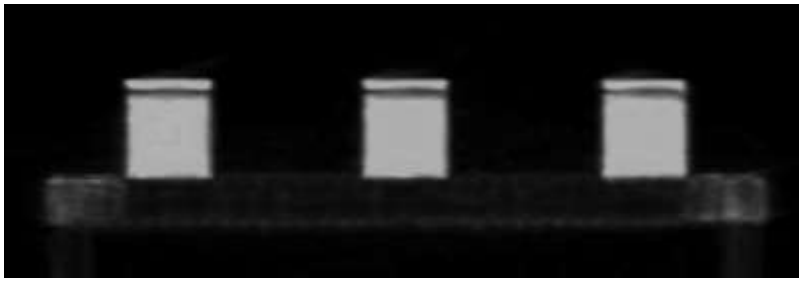


NEU ALERT Contacts:
Prof. Jose Martinez-Lorenzo
Prof. Carey Rappaport

Cargo CT Imaging (ALERT & Astrophysics)

- Limited angle CT for Air Cargo pallets
  - Multi-View CT Capable (MVCTC) air cargo pallet inspection system
  - 3-D reconstruction: angle diversity from motion
  - Penetrating energies
  - Full range of multi-view and CT image manipulation tools
  - Advanced algorithms for real-time reconstruction and rendering using advanced computing architectures

- Allows for non-destructive inspection of internal contents of pallets



Paint cans (Slice of 3-D)

Case of Water Bottles (slice-by-slice)

Conclusion

- Dealing with Terrorists is a difficult problem
- Innovation/smart people are required
- New ideas are being transformed into future system concepts
- If you have ideas please talk to me

- Venues to get and share ideas
  - ALERT Advanced Development for Security Applications (ADSA) workshops http://www.northeastern.edu/alert/transitioning-technology/adsa/
  - Concealed Explosive Detection (CED) https://www.concealedexplosives.org/
  - IEEE International Symposium on Technologies for Homeland Security https://spie.org/SID/conferencedetails/anomaly-detection-imaging-x-rays?SSO=1
  - SPIE Anomaly Detection and Imaging with X-Rays (ADIX) https://spie.org/SID/conferencedetails/anomaly-detection-imaging-x-rays?SSO=1
  - Trace Explosives Detection (TED) http://traceexplosivesdetection.wildapricot.org/event-1772840

Innovations show promise for increased performance, P_D, P_{FA} and throughput

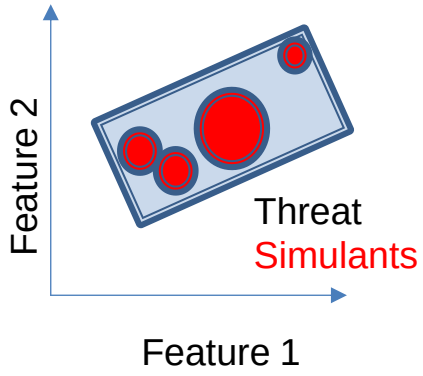
I want to thank the Science & Technology Directorate of the U.S. Department of Homeland Security for supporting these innovations

Any Questions ?

Simulant Validation Program

- Explosive simulants are used for detection system development, performance testing, operational screener training and testing, and other applications.
- The increasing proliferation of HMEs has further driven the need for explosive simulants.
- The government has not yet adopted a uniform approach to simulant verification and validation (V&V).
- This project will develop and implement a program for the verification, validation, and accreditation of explosive simulant materials.
- Technical approach will be based on robust and defensible threat feature measurements and statistical analysis
- First pilot project will be for X-ray CT technology, 1QFY18
- Sponsored by S&T HSARPA Explosives Division (EXD)
  - Awarded to Battelle
  - Task order ongoing

Sample Explosive Simulants



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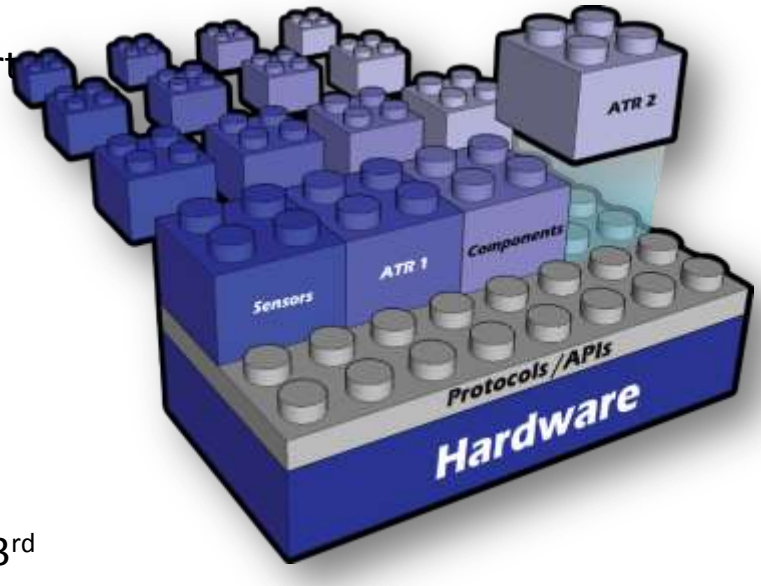
OTAP Enables Industry Solutions

The OTAP project enables new solutions developed by industry (OEM *and* 3rd parties) by creating the tools to implement an *open system architecture*.

OTAP delivers the following:

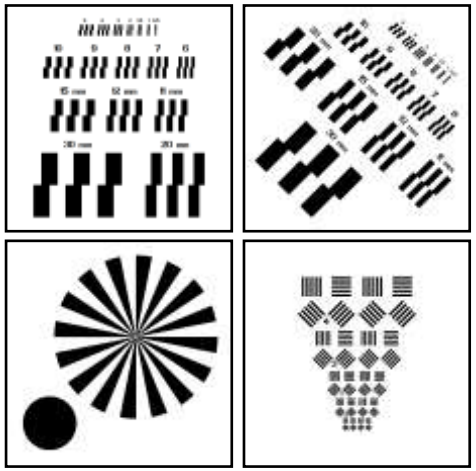
- **Open Platform Software Library (OPSL)**: A set of open, commonly available, and standardized data interfaces, exchanges, and formats to enable engineering of 3rd-part components for seamless integration into TSE.
- **Mature Requirements for Open Architecture TSE**
- **Prototypes and Demonstrations:** The open architecture approach must be validated through implementation to ensure it is operationally robust.
- **Passenger Baggage Object Database (PBOD):** A non-proprietary database of threat and SOC scans to enable 3rd parties and TSE OEMs to develop certifiable third-party ATRs and ATRs with improved detection capabilities. (PBOD transitioning to TSL).

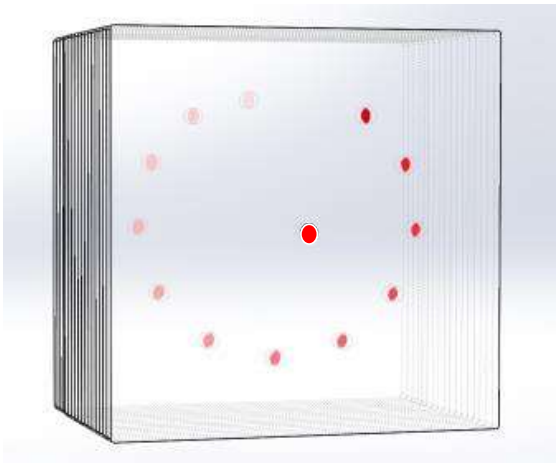


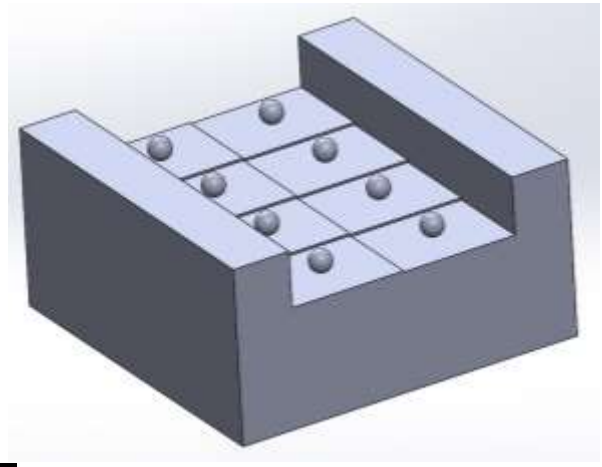
Sandia National Laboratories

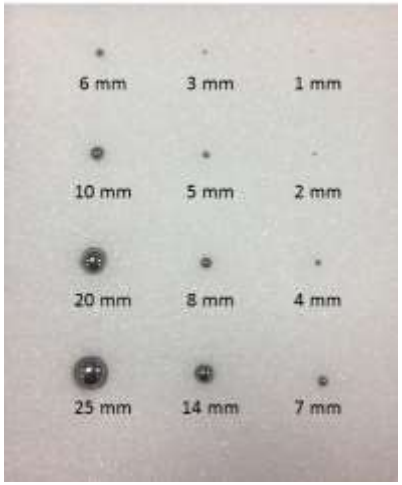
Contact: Cox, Andrew <acox@sandia.gov>

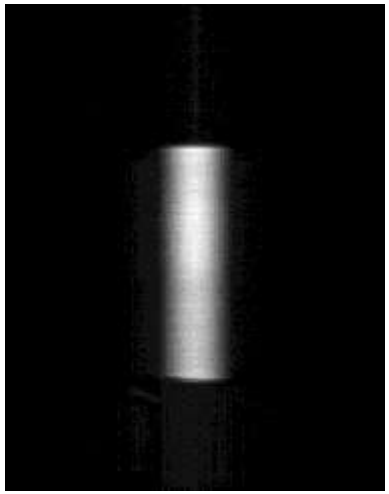
Image Quality Tools: ANSI 42.59











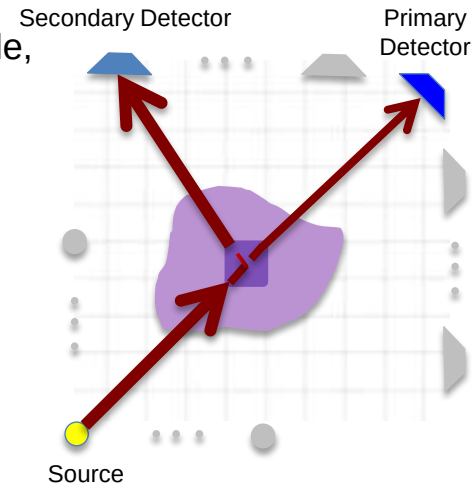
Homeland Security
Science and Technology

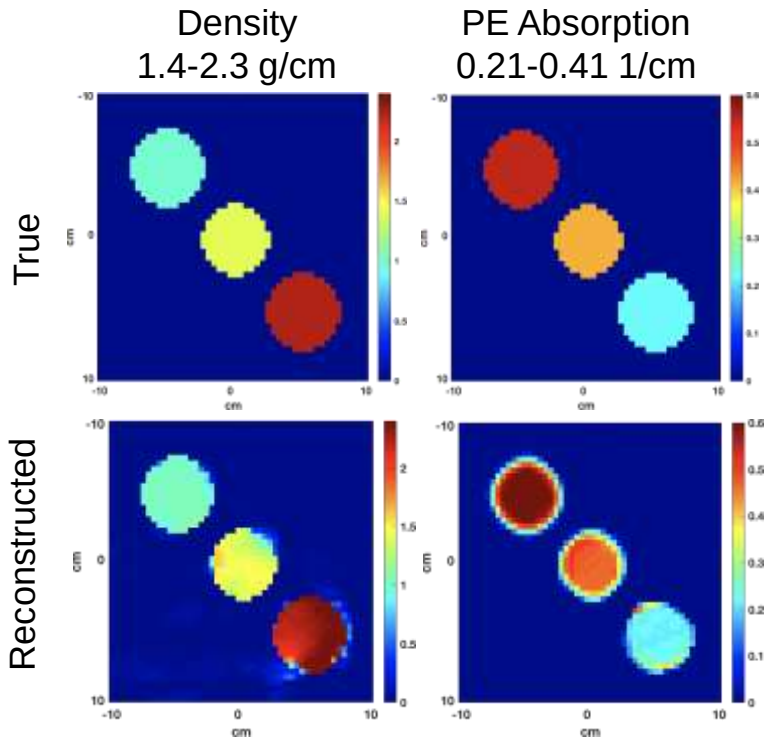
POC: BT Smith, TSL

Model-Based Fusion of Energy Resolved Compton Scatter and Transmission Tomography

Hamideh Rezaee[1], Abdulla Desmal[1], Misha Kilmer[2], Eric L. Miller[1], Brian Tracey[1]
[1]Department of Electrical and Computer Engineering, Tufts University
[2]Department of Mathematics, Tufts University

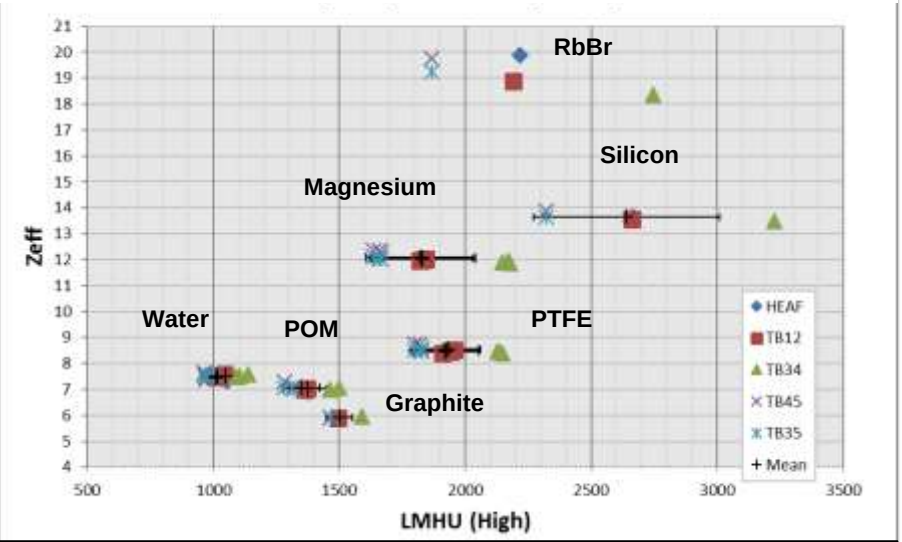
- Motivating application: Luggage screening
  - Limited view, non-rotating sources/detectors
- Goal: Materials characterization
  - Recover mass density and photoelectric scattering coefficient
- Solution
  - Compton scatter (= additional raypaths) + energy resolved data compensated for limited view
  - Iterative, physics-based image formation
- Example to the right
  - Three sources (bottom middle, bottom corner, left middle)
  - 41 detectors along top and right edge
  - 50 dB SNR





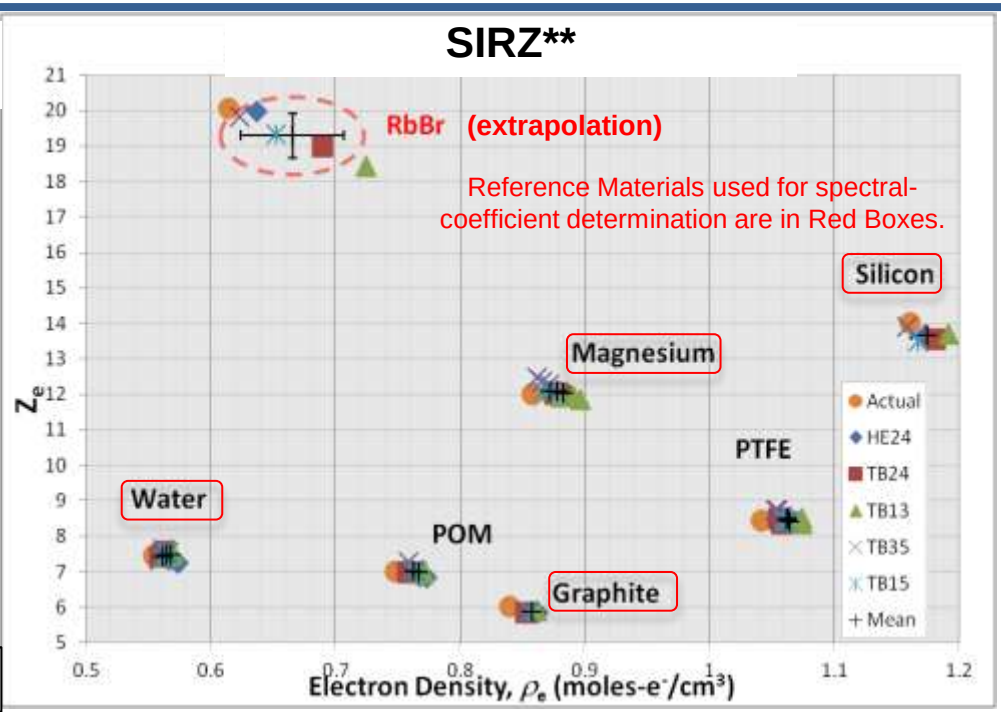
R&D, applied to MicroCT showed better precision and accuracy over other methods

YNC*



Legend: HE24=(100,160kV); TB24=(100, 160kV); TB13=(80, 125kV), TB35=(125, 200kV), TB15=(80, 200kv)

SIRZ**



- Seven known materials were scanned on LLNL MicroCT systems and processed using SIRZ.
- SIRZ estimate quality degrades in the extrapolation regime, e.g., rubidium bromide (RbBr).
- Using six reference materials generates similar results to using only the four highlighted.
- "Actual" values on the SIRZ plot were estimated with ZeCalc.

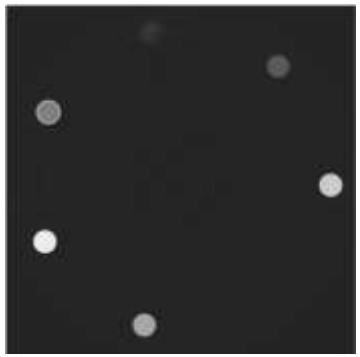
*Z. Ying, R. Naidu, C. R. Crawford, *Dual Energy Computed Tomography for Explosive Detection*, J. of X-Ray Science and Tech., no. 14, 235-256 (2006)
**S. Azevedo, et. al., *System-Independent Characterization of Materials Using Dual-Energy Computed Tomography,* IEEE TNS., vol. 63, 341-350 (2016)

SIRZ is system-independent and outperforms Ratio, Z_{eff}-interpolation and YNC.

Basis Material Decomposition

- TSL MicroCT X-ray systems support material characterization studies
- Basis Material Decomposition (BMD) is being developed as a method to reduce system-dependent factors and provide consistent MicroCT measurements across different platforms at various labs (TSL, TRMG, and LLNL).
- Sponsored by S&T HSARPA Explosives Division (EXD)
  - Awarded to Battelle
  - Phase 1 Complete
  - Phase 2 Ongoing

PE Image



Al Image

Summary of Phase 1 Results

- Electron Density (ρ_e)
  - inaccuracy < 1.1% for all materials expect 1" Al (3.1%)
  - Standard deviation < 1%
- Effective Atomic Number (Z_e)
  - inaccuracy was under 2% for all materials
  - Standard deviation < 1%
- Materials characterization results were system–independent comparable to LLNL SIRZ (photoelectric/Compton decomp)
- Satisfactory results were obtained without the need for beam-hardening compensation

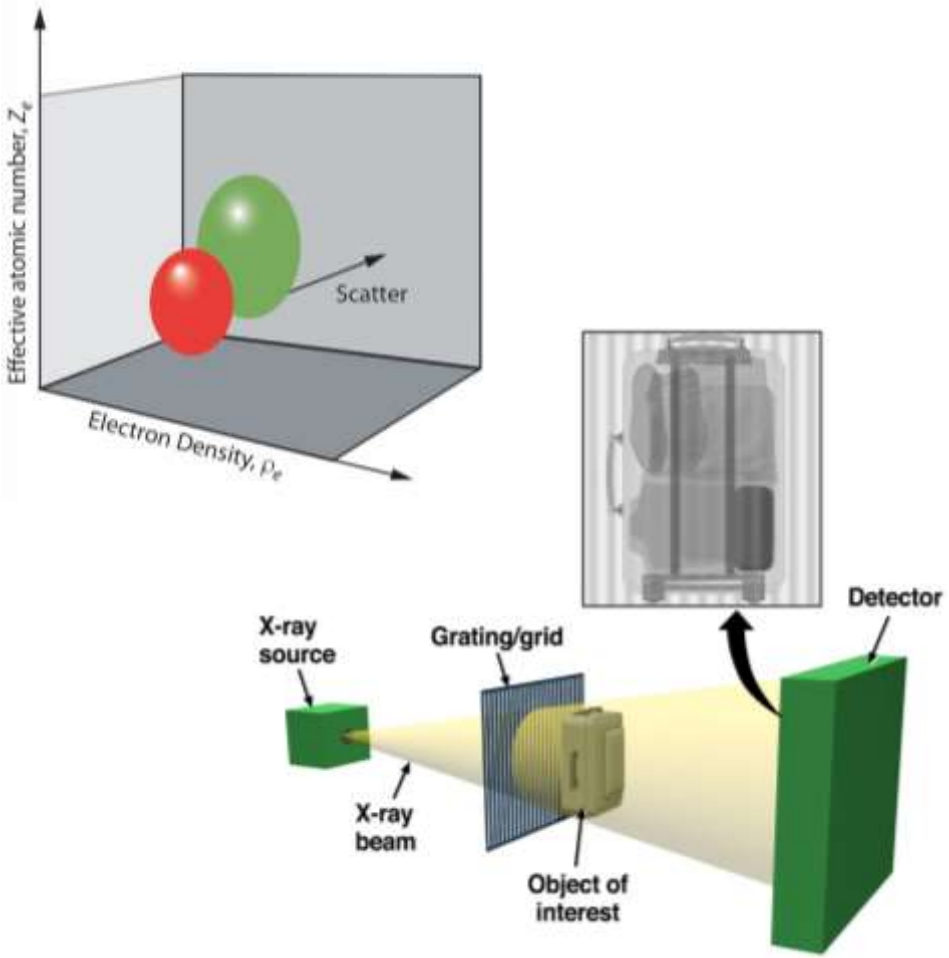
POC: Ron Krauss, TSL

Homeland Security
Science and Technology

Gratings-based x-ray imaging for explosives detection

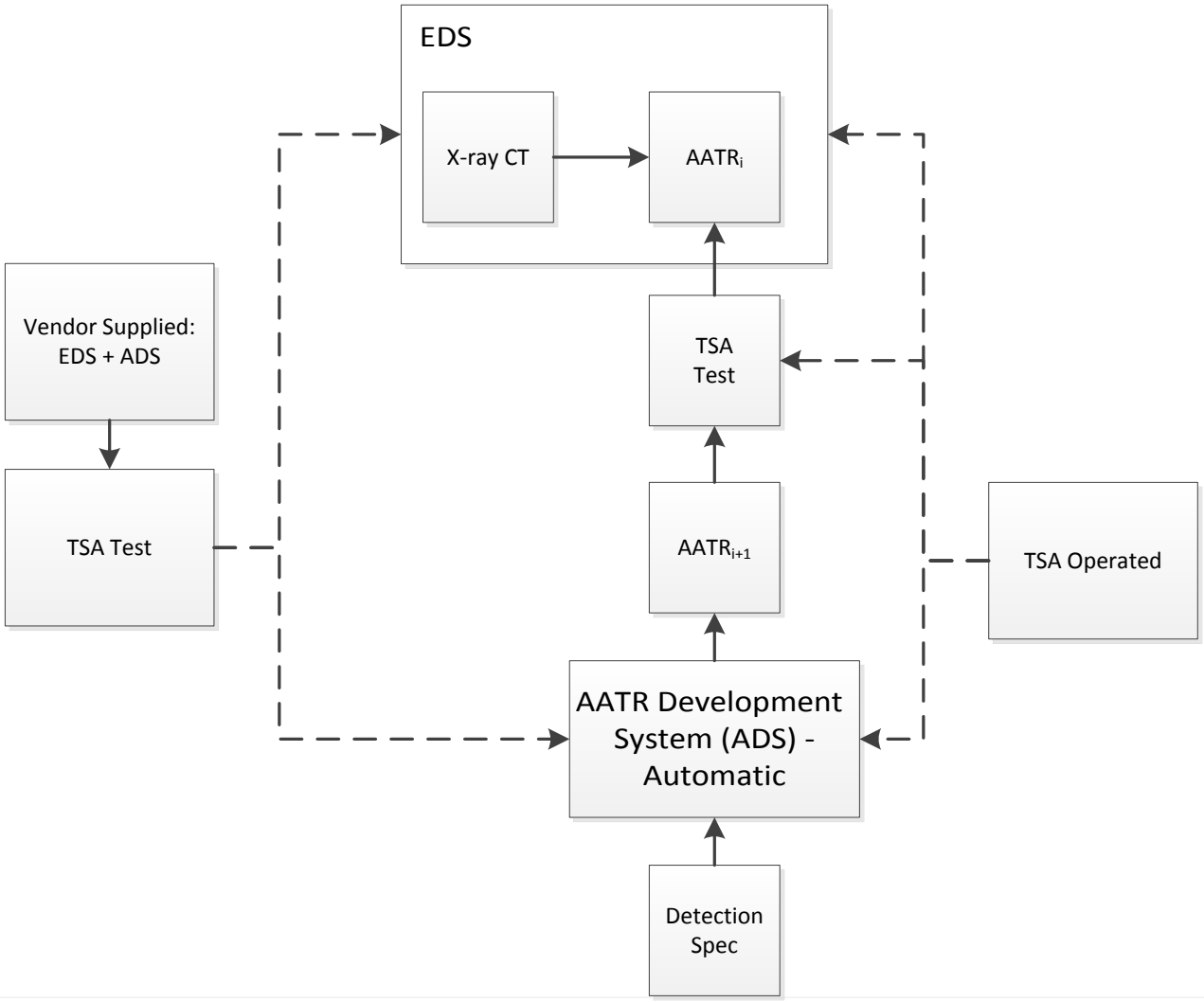
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Technique can operate at energies high enough to penetrate bags (160 kV)
- New signatures of threat materials and common interferents in scatter are being explored
- Candidate for secondary screening to avoid opening bags
  - Similar equipment, hazards, and footprint as conventional x-ray imaging



Contact: Erin Miller, PNNL / erin.miller@pnnl.gov / (509)375-1878

Initial adaptive ATR flow diagram



Current TSA R&D CONOPS not sustainable

- Vendors want data for training ATRs
  - Boxes containing all explosives that will be on tests
  - Vendors pack and scan on their own systems
  - Test feedback
- Cannot give the vendors what they want
  - Some explosives are dangerous to formulate and handle
  - Expensive to provide all explosives to all vendors

- Proposed solutions
  - Provide limited or no explosives to vendors
  - Scan other explosives on none vendor systems, e.g., sm. samples on MicroCT
  - Use simulants or theoretical data
  - Provide boundaries of features (e.g., density and atomic number) – denoted as regions of responsibility (RORs)
  - System-to-system transfer functions