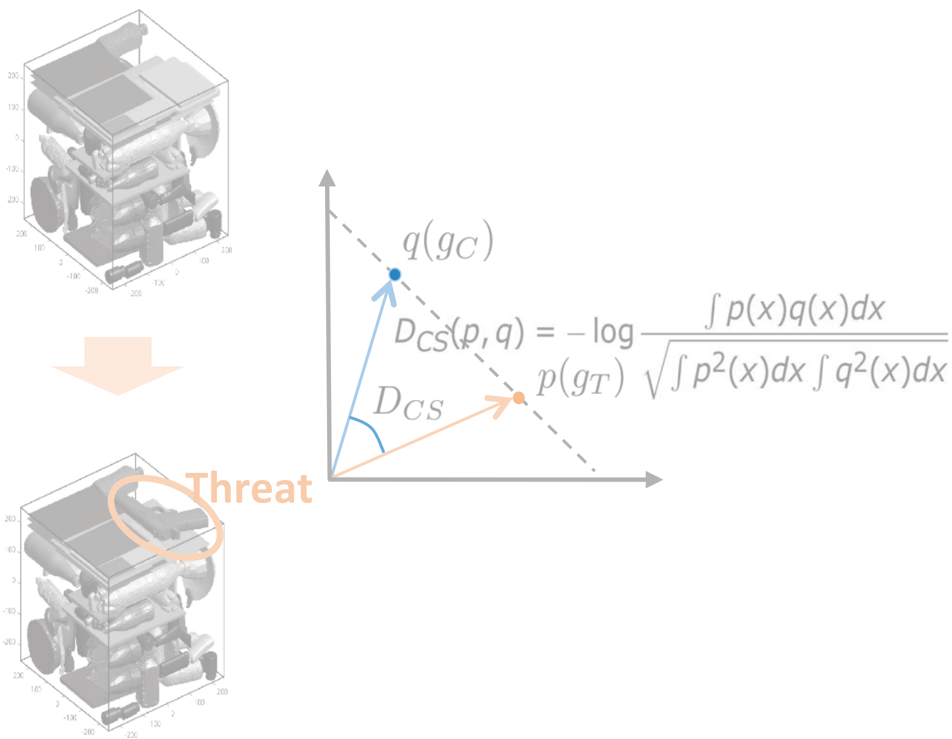
Task-Specific Information for Analysis and Design of Advanced X-ray Explosive Threat Detection

October 28, 2015
ADSA13 Workshop



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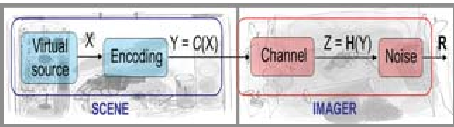
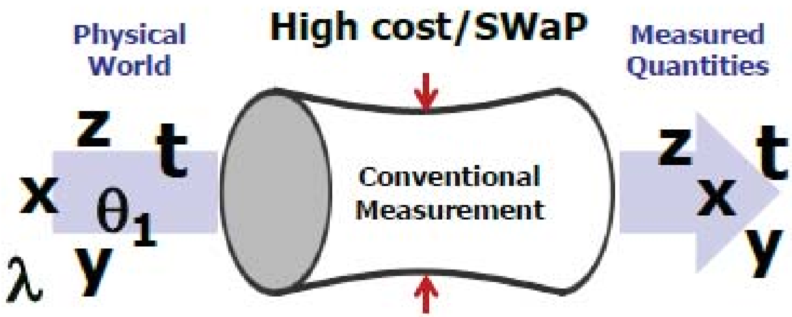
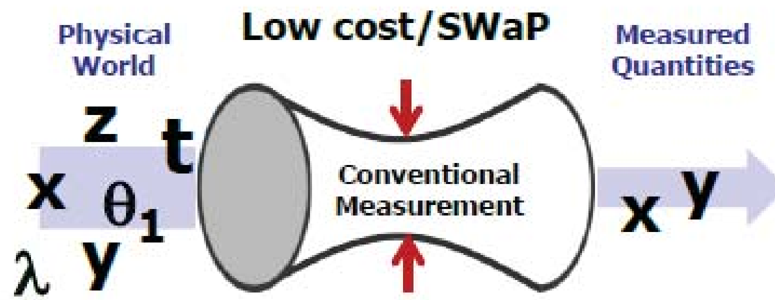


Task 2.1: *Task-Specific Information for Analysis and Design of Advanced X-ray Explosive Threat Detection*

Physical interaction encodes "information" about object(s) into the measurement.
Information embedded in the measurement determines the fundamental limit of threat detection.

Information Bottleneck





Key Observations:

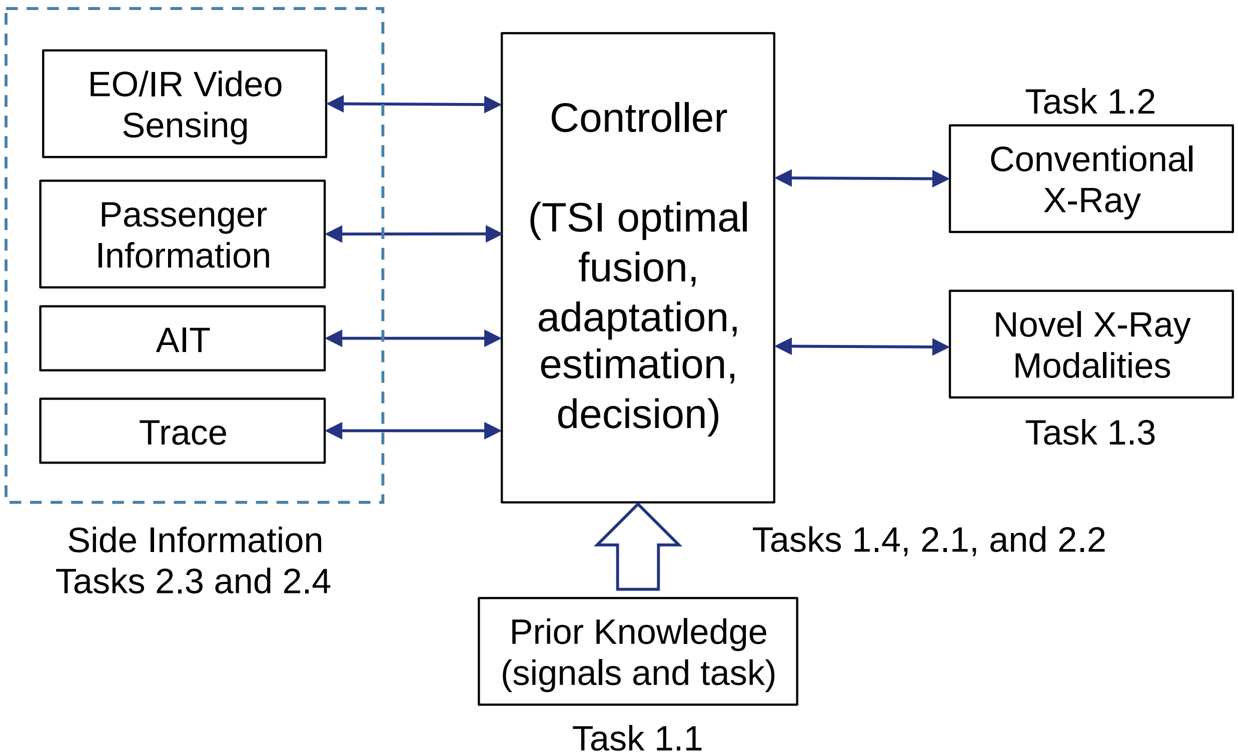
- Measurements have cost (size, weight, power, latency, …).
- Physical world represents more variables than we can *afford* to measure.
- Bottleneck demands judicious selection of measurements that convey most useful information relevant to task at hand.

Q: What is fundamental limit of a X-ray measurement (system) for threat detection ?
A: Our information-theoretic system analysis framework quantifies this fundamental limit.

Q: What are the optimal measurements for X-ray threat detection ?
A: Our analysis framework allows rigorous "comparison" of competing measurement (system) designs and enables measurement (system) optimization.

Project structure

Our work products will be theory and related analysis/design so the "system concept" presented below is notional and intended to provide structure/context to our explorations.



Thrust 1 – Application of Current TSI Tools
Task 1.1 - Signal and Task Priors
Task 1.2 - TSI Analysis and Design for Current Systems
Task 1.3 - Application of TSI to new Modalities
Task 1.4 - Exploration of Adaptive TSI Strategies

Thrust 2 – Extension of Current TSI Tools
Task 2.1 - Game Theoretic Approaches
Task 2.2 - Joint Detection and Estimation
Task 2.3 - TSI Optimal Fusion from Heterogeneous Data
Task 2.4 - TSI Optimal Measurements on Graphical Models

Staffing & Org Chart

Program Lead

Mark Neifeld–U. Arizona

Thrust 1 – Application of Current TSI Tools (*Gehm*)

Task 1.1
Signal and Task Priors
Amit Ashok–U. Arizona

Task 1.2
TSI Analysis and Design for Current Systems
Michael Gehm–Duke U.

Task 1.3
Application of TSI to new Modalities
Michael Gehm–Duke U.

Task 1.4
Exploration of Adaptive TSI Strategies
Mark Neifeld–U. Arizona

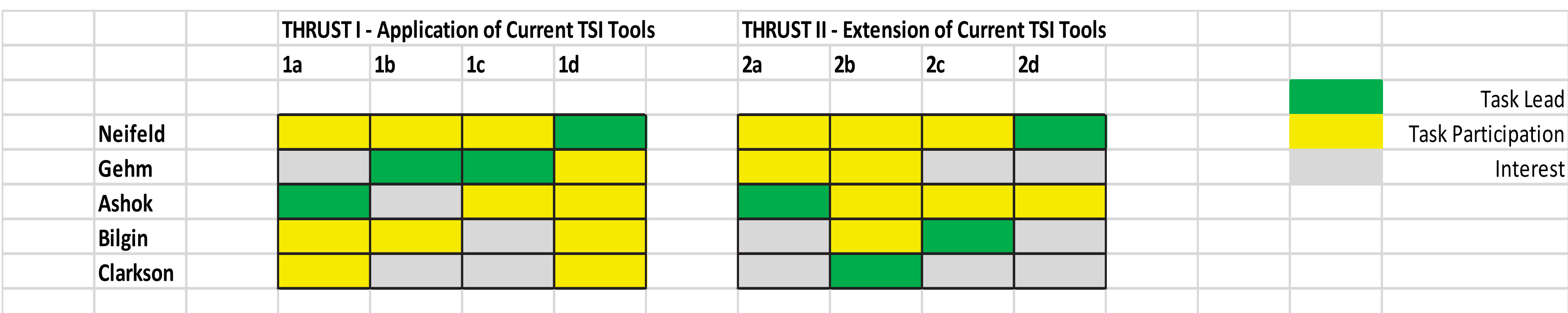
Thrust 2 – Extension of Current TSI Tools (*Ashok*)

Task 2.1
Game Theoretic Approaches
Amit Ashok–U. Arizona

Task 2.2
Joint Detection and Estimation
Eric Clarkson–U. Arizona

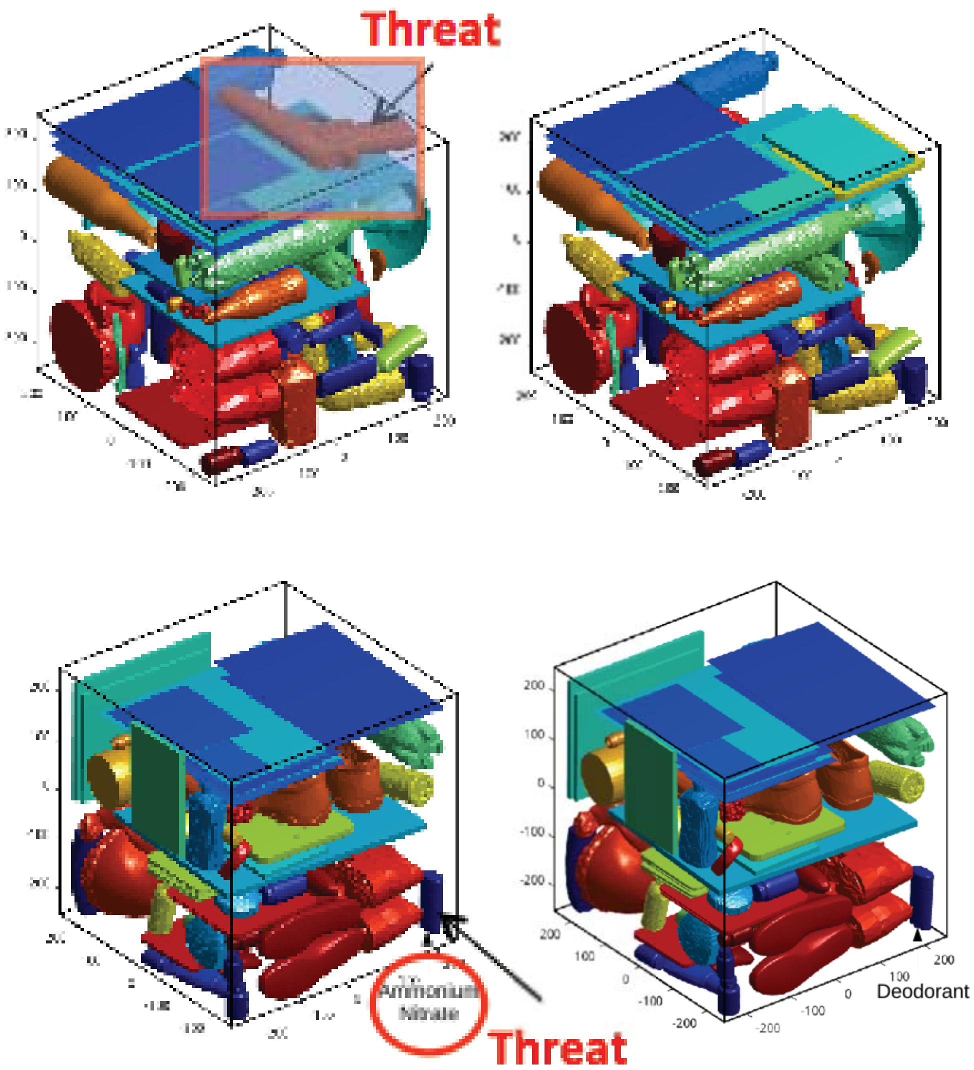
Task 2.3
TSI Fusion from Heterogeneous Data
Ali Bilgin–U. Arizona

Task 2.4
TSI Measurements on Graphical Models
Mark Neifeld–U. Arizona



Information content is task/context dependent

Shape/material threats



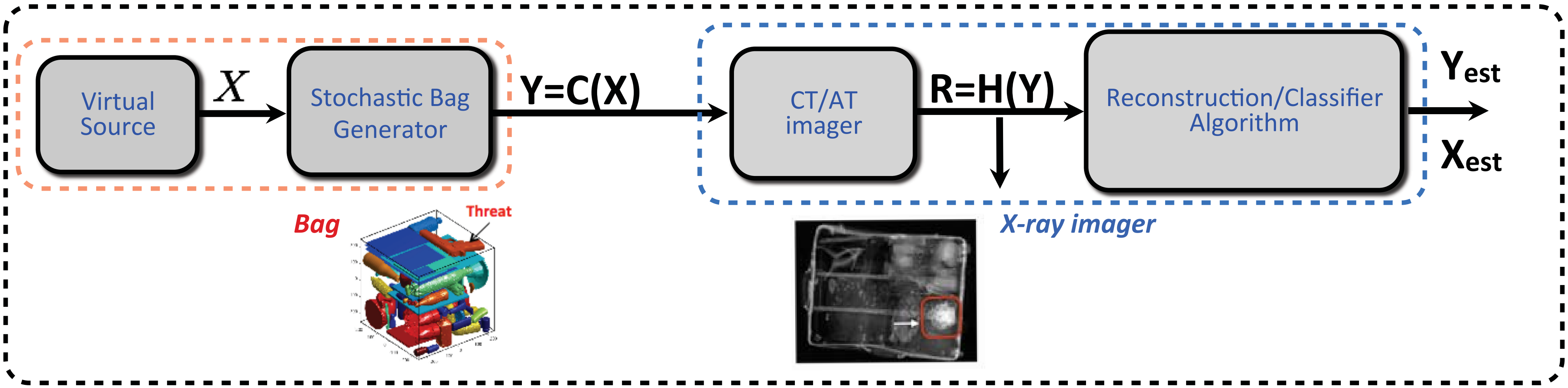
Threat detection task:
Probability of presence/absence = ½
Information content ≤ **1** bit

Threat detection/localization task:
Probability of absence = ½
Probability of occurrence in a region = 1/256
Information content ≤ **8** bits

Threat type (N types) classification task:
Probability of each threat type = 1/N
Information content ≤ **log(N)** bits

Task Specific Information (TSI) = Channel Capacity

Imaging chain block diagram



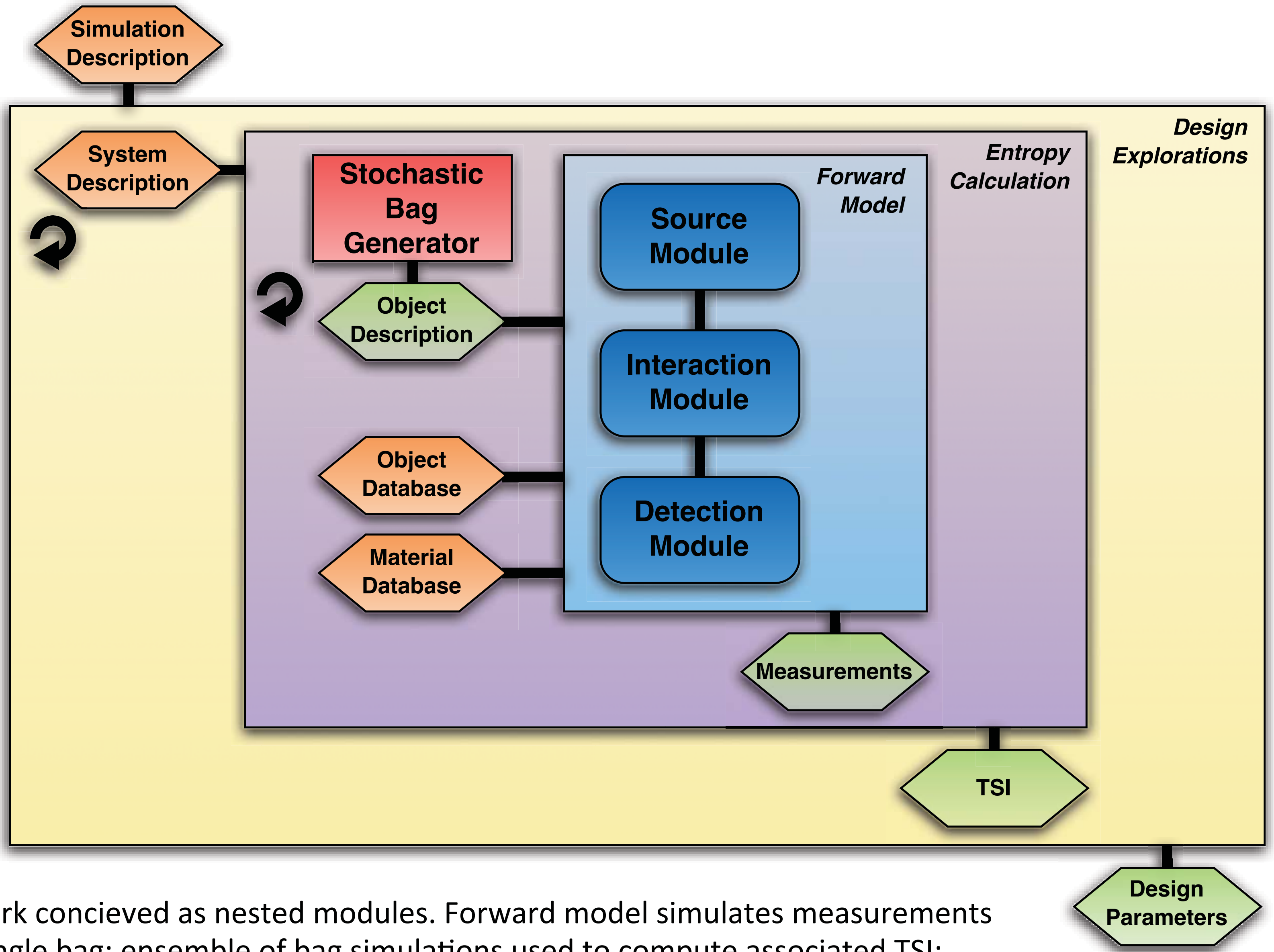
- Task-specific Information (TSI) can be defined as:

Mutual-information between X and R → $$TSI \equiv I(X;R) \leq J(X)$$ ← Upper-bounded by source entropy

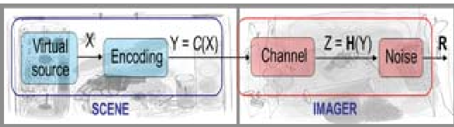
Algorithm and measurement **Dependent** → $$I(X;X_{est}) \leq I(X;Y_{est}) \leq I(X;R)$$ ← ***Algorithm agnostic, measurement limited***

- TSI is analogous to Shannon's channel capacity for communication channels
- Defines ***fundamental limit*** on information transfer via a channel/imager

Information-theoretic Analysis Framework Diagram



Framework concieved as nested modules. Forward model simulates measurements from a single bag; ensemble of bag simulations used to compute associated TSI; variation in system description produces parameter sweep or ultimately optimization.

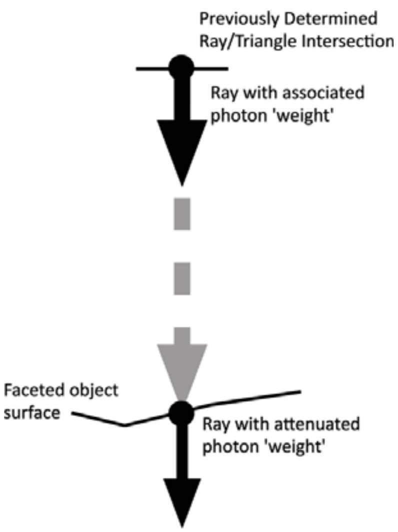


Task 2.1: *Task-Specific Information for Analysis and Design of Advanced X-ray Explosive Threat Detection*

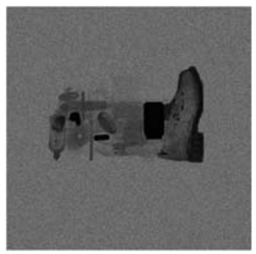
Framework components

Radiography Forward model

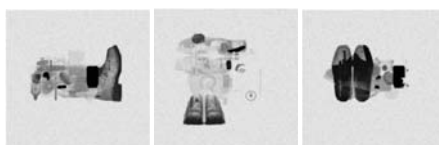
- We had developed a ray-tracing-based forward model of transmission imaging that utilized high-performance graphics APIs to allow ultra-rapid measurement of simulated bags on arbitrary system configurations



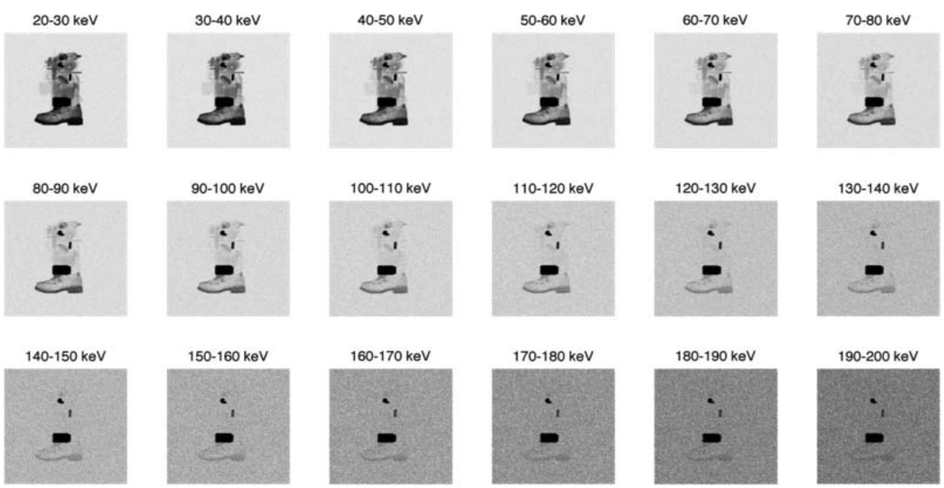
Film



Counter—3 orthogonal views

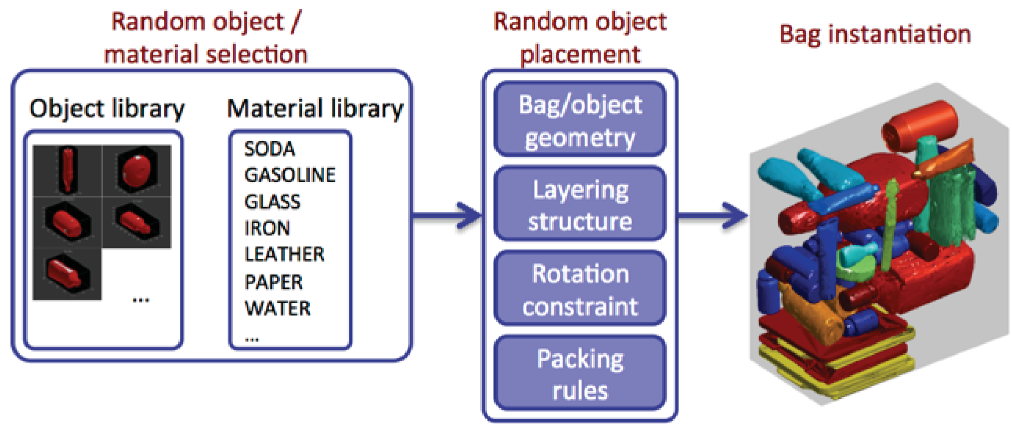


Energy-resolving



Stochastic bag generator

- We had developed a tool for automatically creating large numbers of simulated bags—the *Stochastic Bag Generator (SBG).* The SBG draws from object / material libraries and uses tunable heuristics to pack the bags.

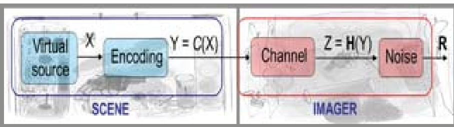


- We had developed a number of methods for generating the surfaces in the object library.

Laser-scanned

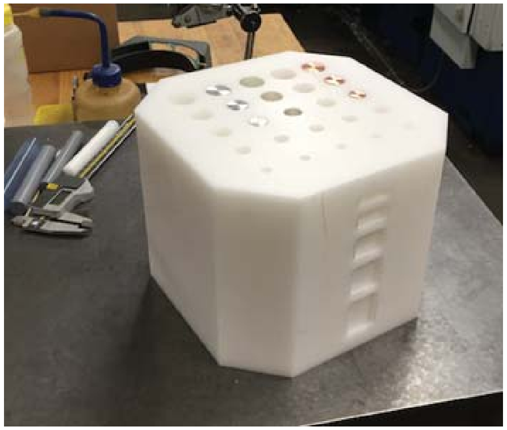
Segmented from CT

Kinect-scanned



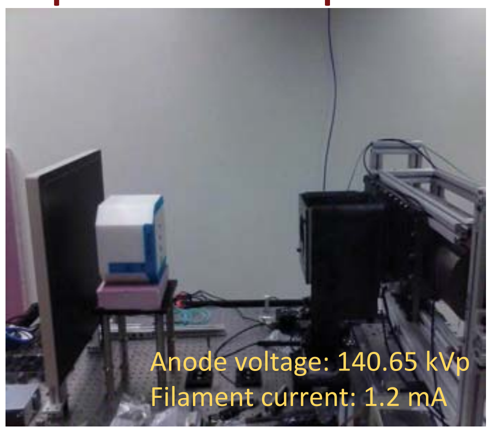
Validation of transmission imaging forward model

Custom phantom



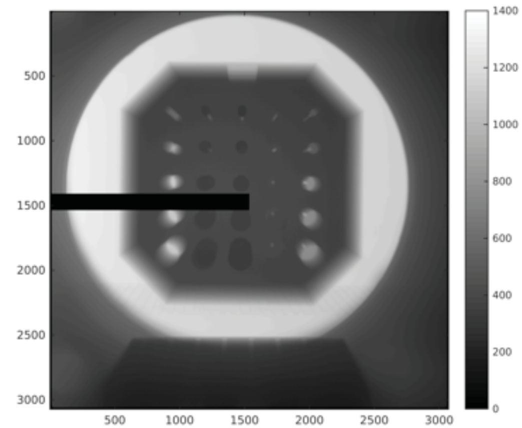
Delrin body;
Variety of 'slug' sizes and materials

Experimental setup



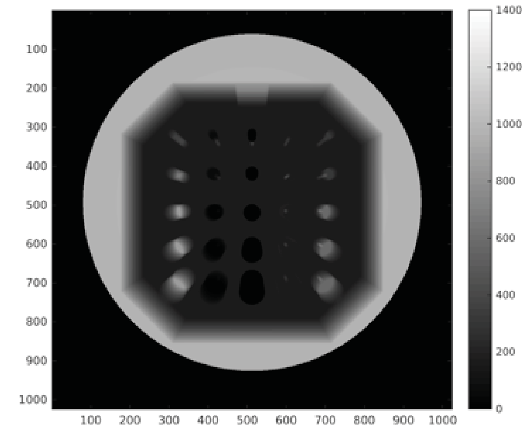
2D integrating detector;
Broadband tungsten cone-beam source

Representative data



Dead pixels on array;
Support table and spatial filter visible

Simulation



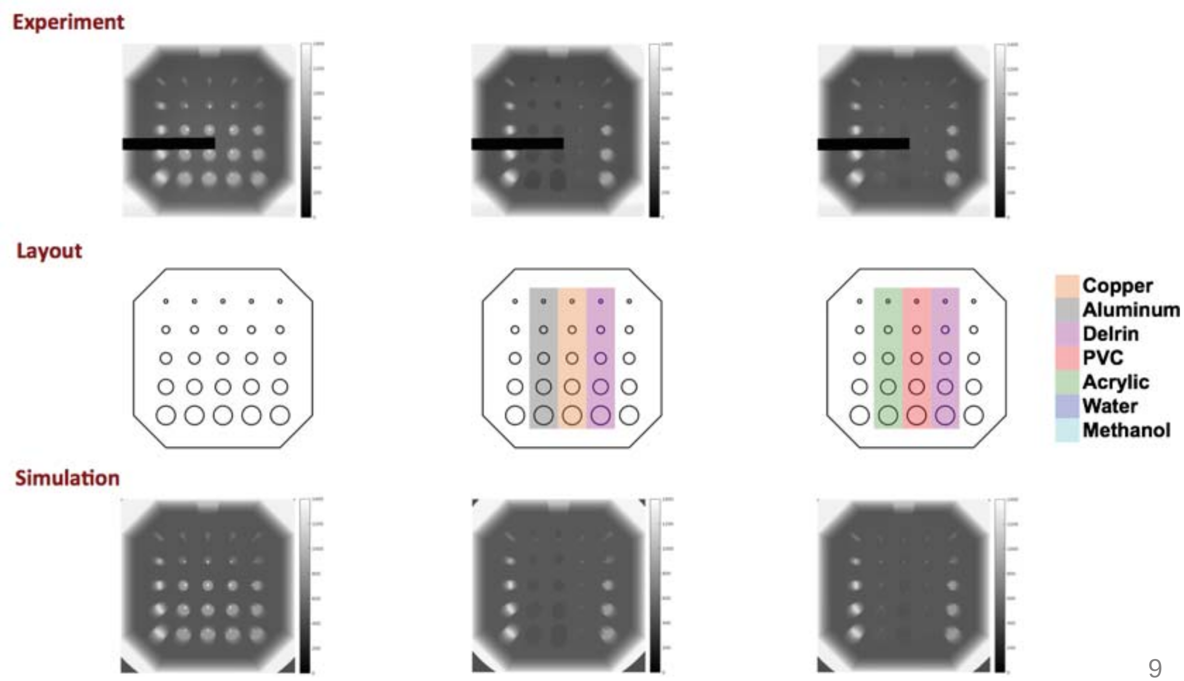
No free parameters;
Good qualitative agreement

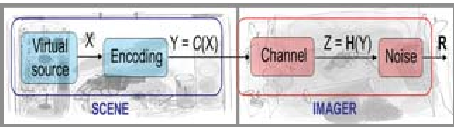
Plotting [ln(counts)]^3 to better use dynamic range of display

When then took all experimental data (12 material configurations from 3 different views) and performed one best fit to extract an overall scale parameter (for ADC vs. photon counts, source uncertainty, etc.) and a DC offset for each configuration (for scatter background)

Representative results shown to right

Agreement now semi-quantitative (few percent)



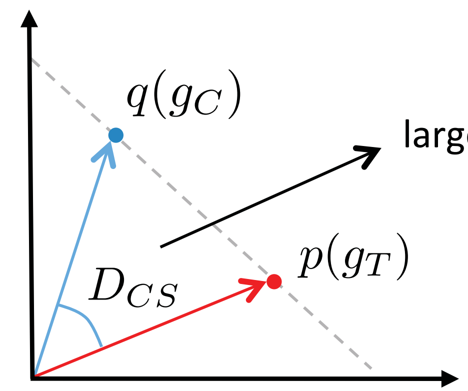


Framework components

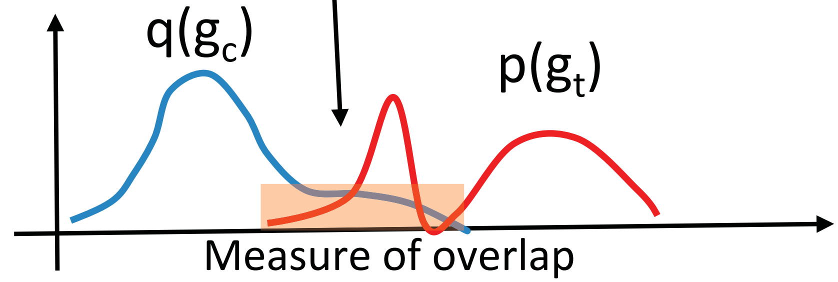
Information-theoretic metric: Cauchy-Schwartz Mutual Information

- Cauchy-Schwarz divergence based mutual information (CSMI) is computationally tractable and scalable

$$D_{CS}(p,q) = -\log \frac{\int p(x)q(x)dx}{\sqrt{\int p^2(x)dx \int q^2(x)dx}} \longrightarrow -\log cos[\angle(p,q)]$$



larger angle → larger class separability



- Scalable CSMI implementation suitable for *Poisson mixture model* (shot noise limited model)

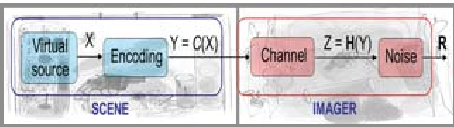
$$J_{CS} = D_{CS}(p(g,\mathcal{C}), p(g)\cdot p(\mathcal{C}))$$

Computational complexity

$O(K^2N)$

bags → K

Measurement dimensionality → N



Stochastic (Threat) Bag Ensembles

Two fundamentally different threat classes
- Shape-based (*object geometry* distinguishes from non-threat objects)
- Material-based (*object composition* distinguishes from non-threat objects)

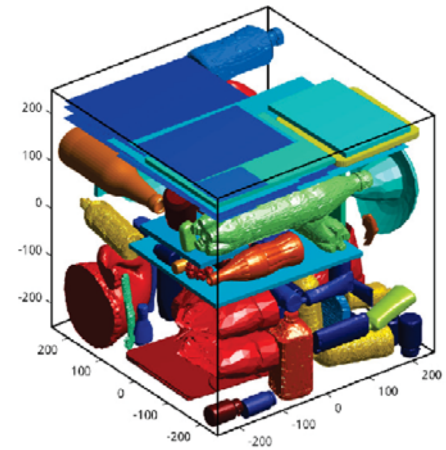
Unrelated to *screening guidelines*
- Currently, prohibit primary alarming based on shape.

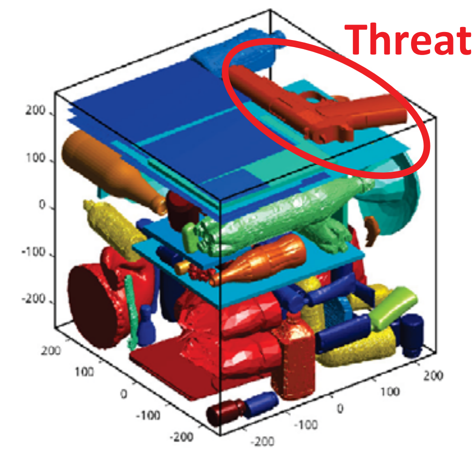
Threat ensembles created via the stochastic bag generator (SBG)
- Stochastic bag ensembles (SBEs)

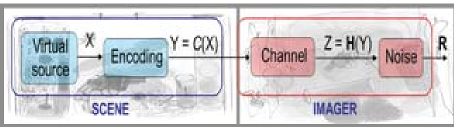
Shape-based SBE
- 10k threat and 10k non-threat bags
- Threat/non-threat bags generated/arranged in pairs
- Threat bags are identical to non-threat partner, except 1-2 items replaced with threat objects
- Threat objects: ***Gun, knife, wiring***

Material-based SBE
- Multiple ensembles at differing *threat volume ranges.*
- At each volume, 10k threat and 10k non-threat bags
- Threat/non-threat bags arranged in pairs
- Threat bags are identical to non-threat partner, except a single object has had its material composition switched from a common false-alarm material to a true threat material
- Common false-alarm materials: Playdoh, peanut butter, NaCl, water/NaCl, water/sugar
- Threat materials: ***Gunpowder, AN, gasoline, H_2O_2, MEKP***

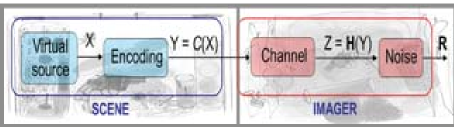
Volume	Volume range (cm^3)	Geometric mean (cm)
A	1–8	1–2
B	64–216	4–6
C	512–1000	8–10
D	1728–3375	12–15
E	4913–8000	17–20





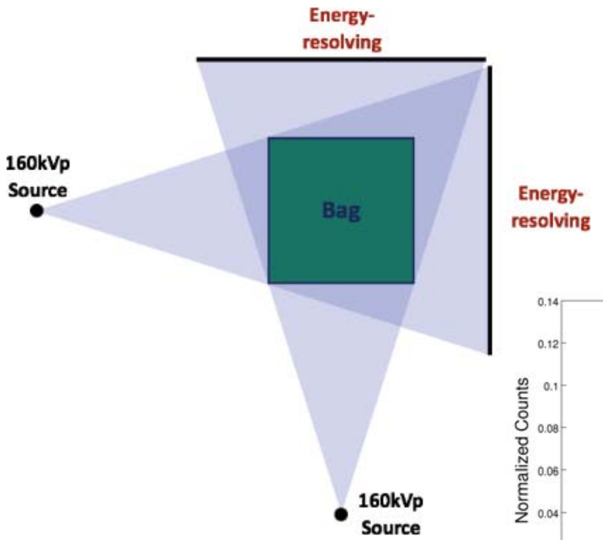


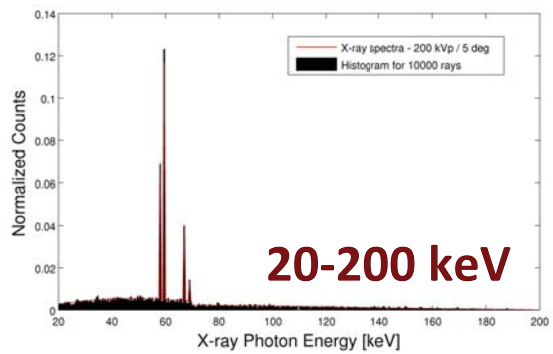
Selected results



Task 2.1: *Task-Specific Information for Analysis and Design of Advanced X-ray Explosive Threat Detection*

Study 2B—Energy-resolving retrofit (material threats)





Threat type: Material

Variation from baseline system: Energy-resolving detectors

Study variations: Number of energy bins, source brightness, threat volume

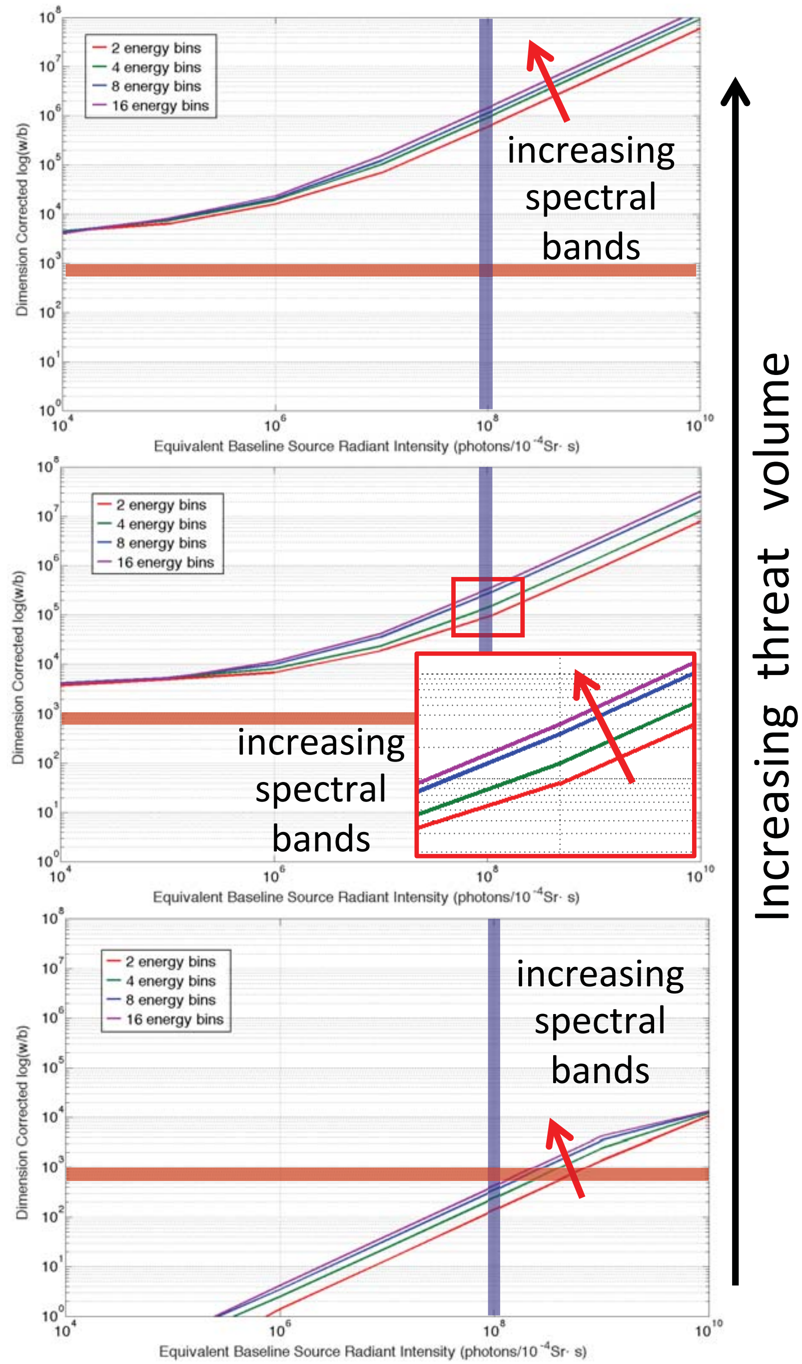
Conclusions:

- Observe general increase in performance with increasing number of energy bins
- Eventually reach diminishing returns
- Smallest threat volume is barely detectable

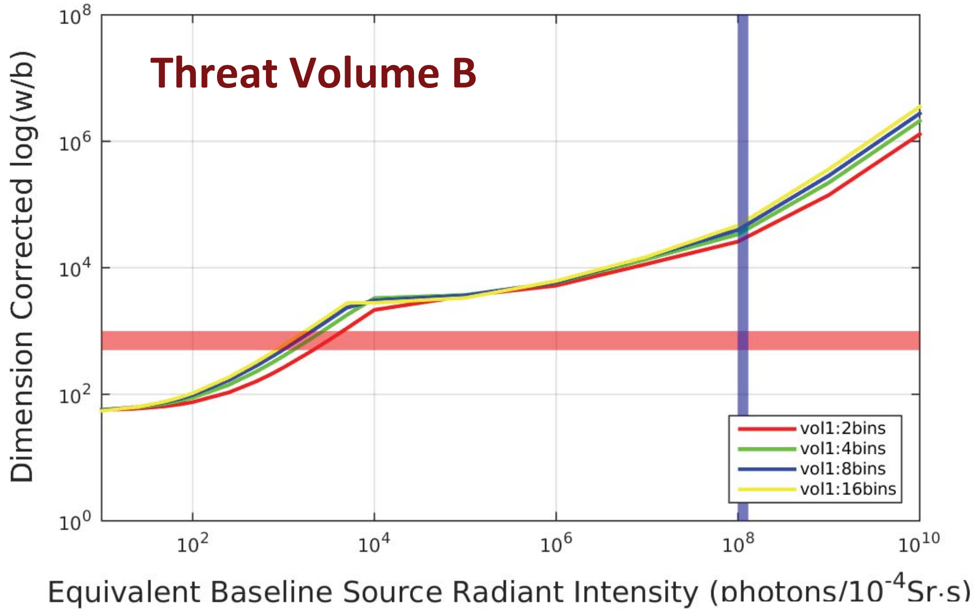
Threat Volume E

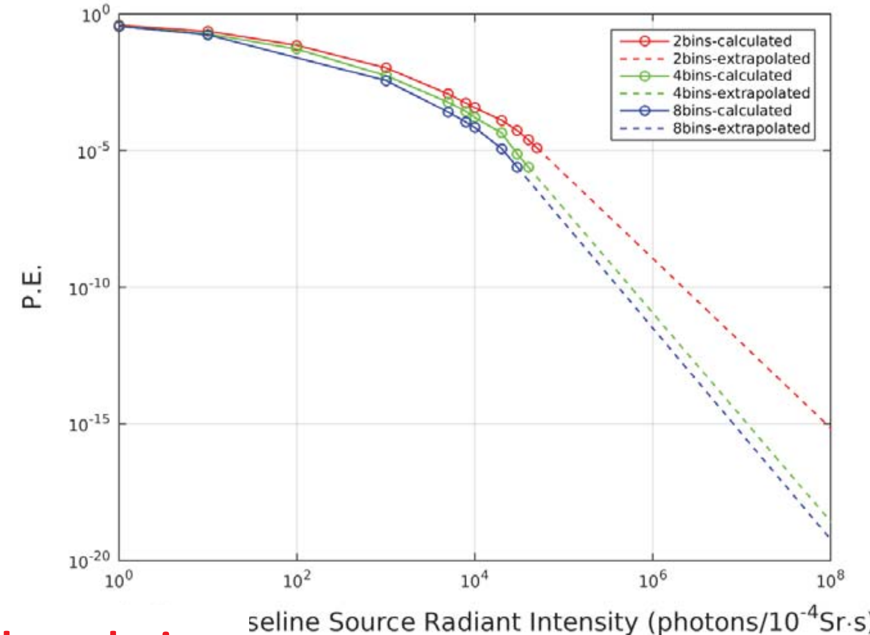
Threat Volume C

Threat Volume A

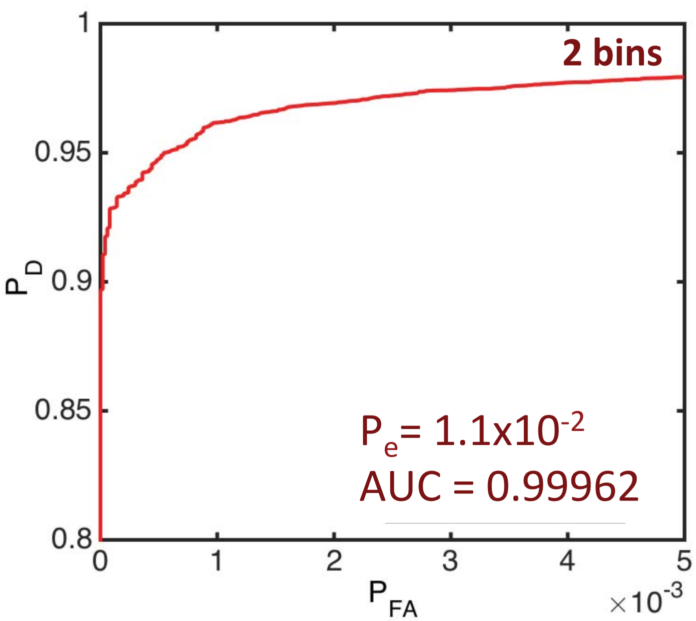


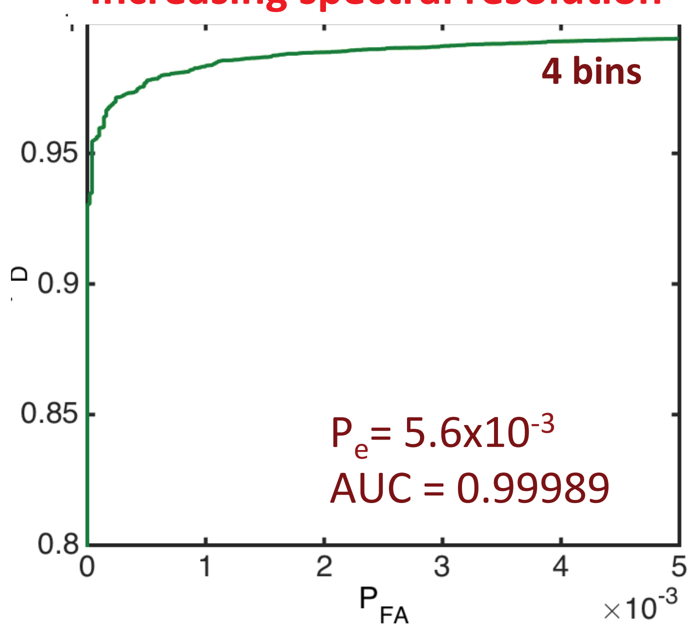
$P_e/P_D/P_{FA}$ and ROC Analysis

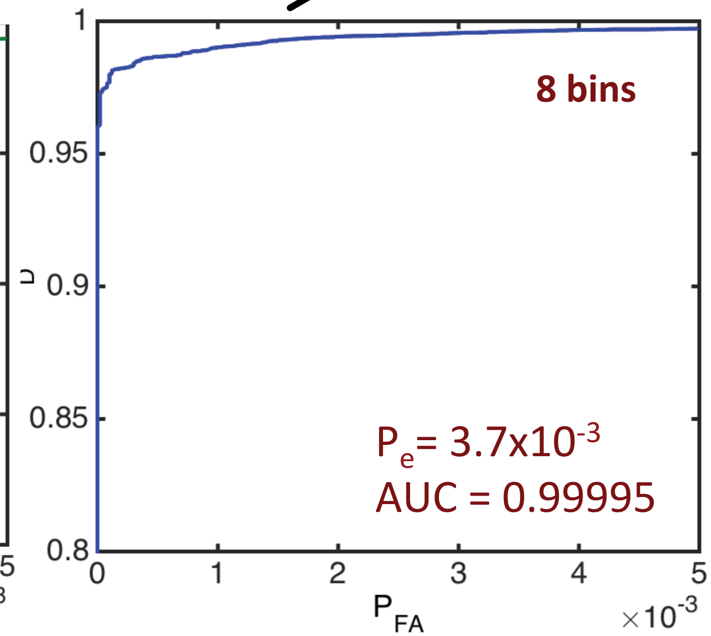




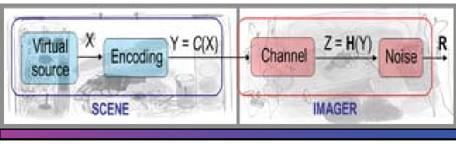
Increasing spectral resolution →



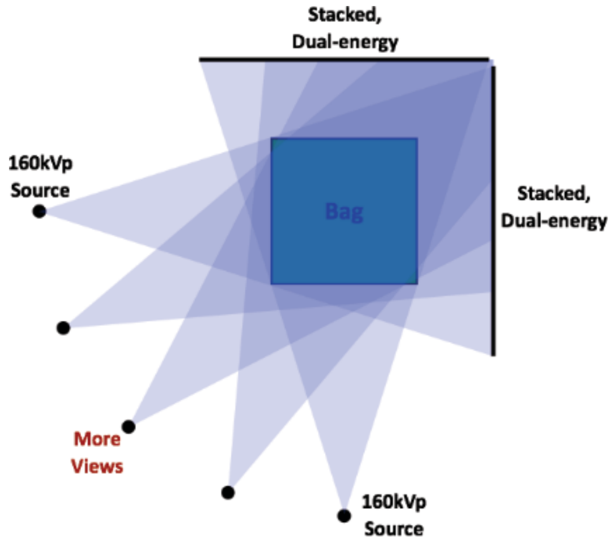




Increasing spectral resolution beyond 4 bins yields diminishing improvement



Study 4A—Multi-View Retrofit (Shape Threats)



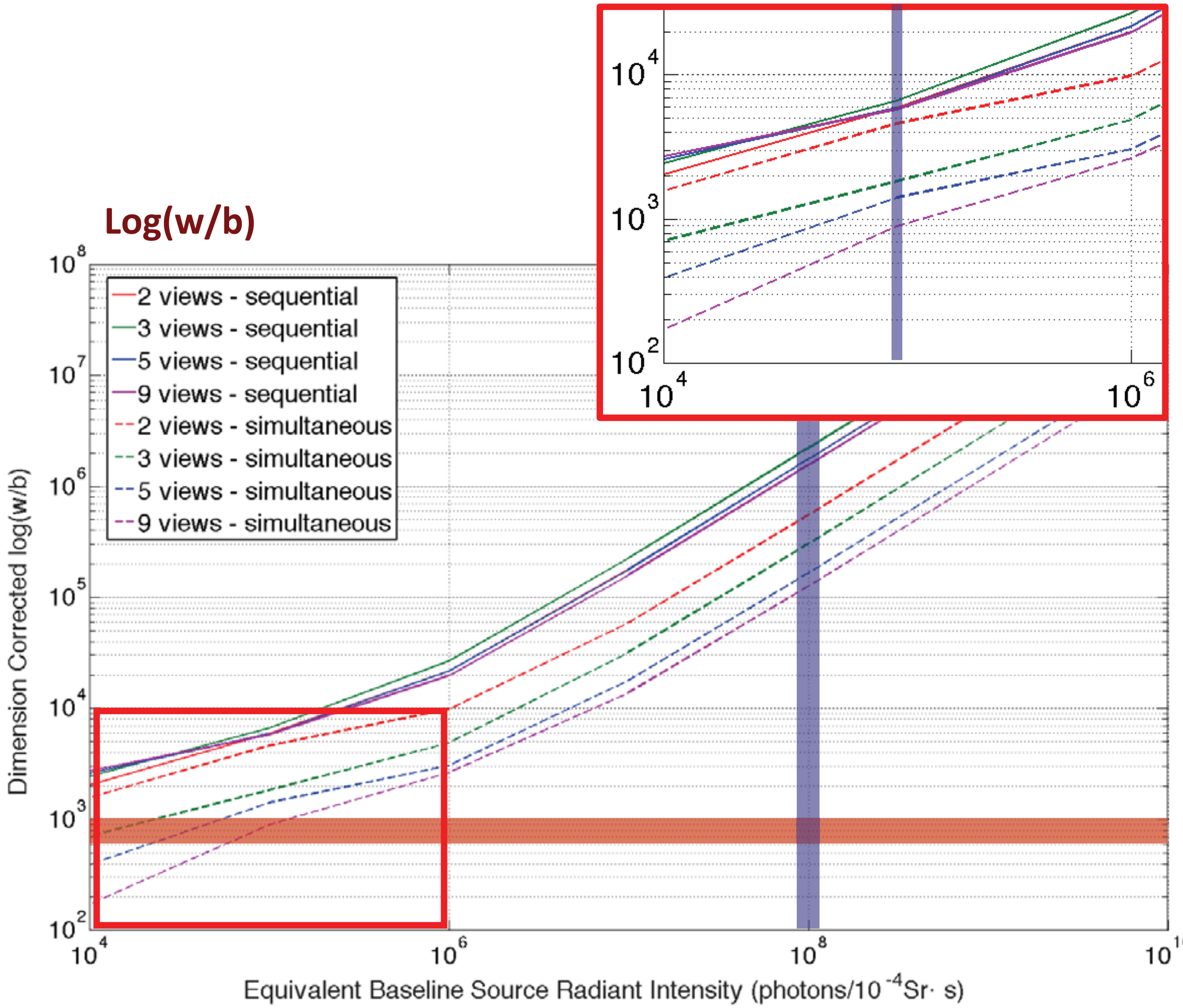
Threat type: Shape

Variation from baseline system: Multiple (>2) views

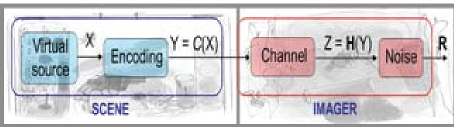
Study variations: Number of views, simultaneous vs. sequential exposures, source brightness

Conclusions:

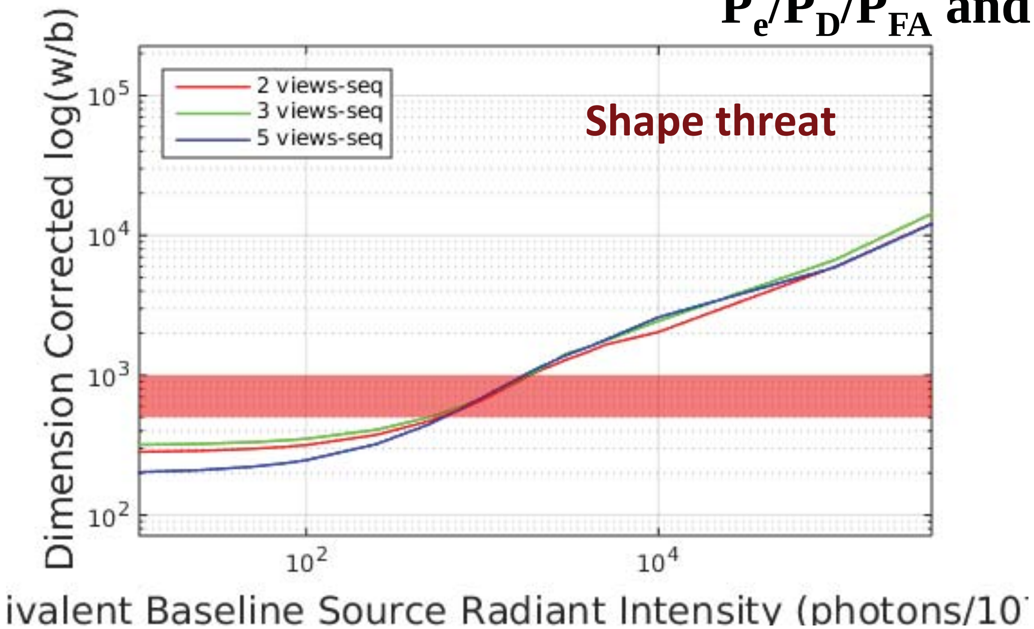
- Observe diversity/SNR tradeoff
  - Sequential: Results improve from 2 to 3 views and the deteriorate with more views
  - Simultaneous: results are uniformly worse than sequential measurement

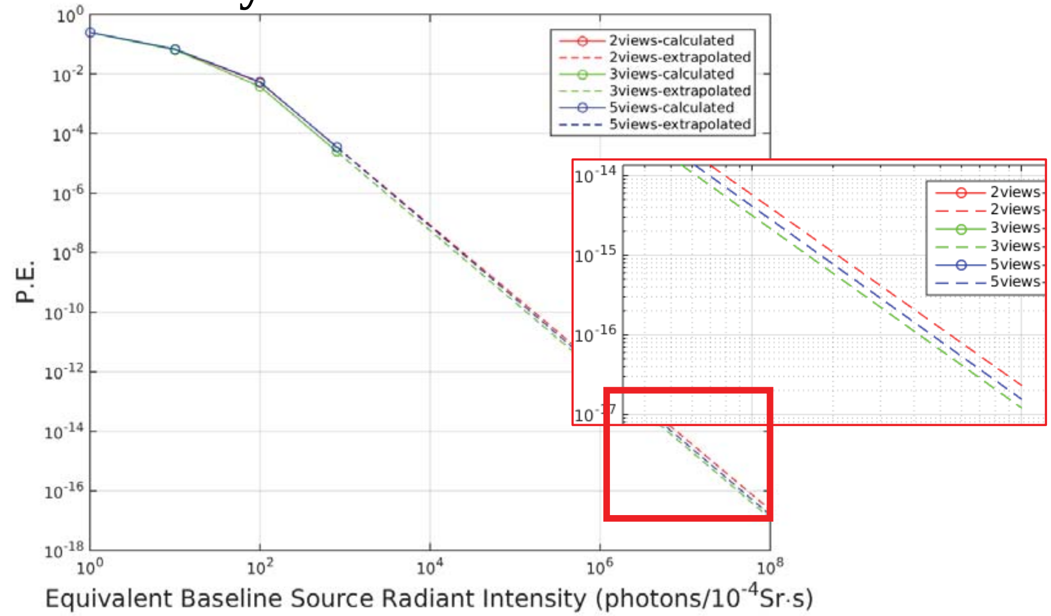


Adding more view beyond 3 views does not yield improved detection for this AT geometry

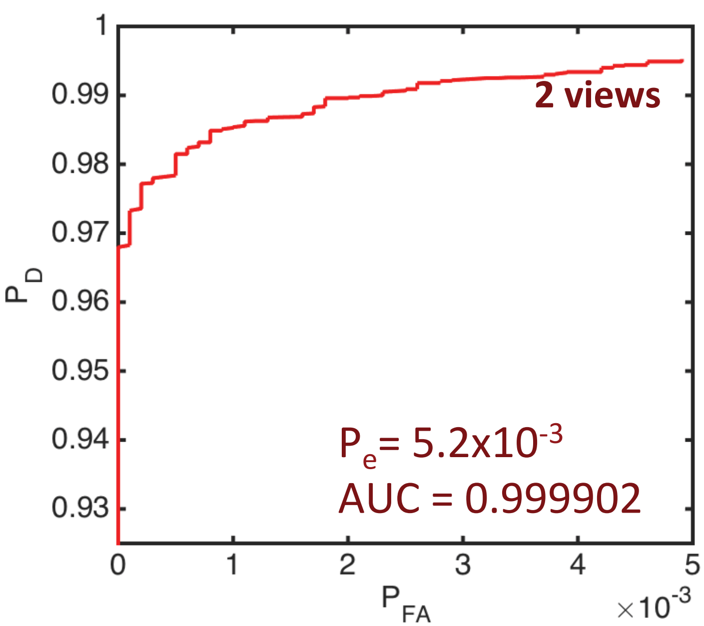


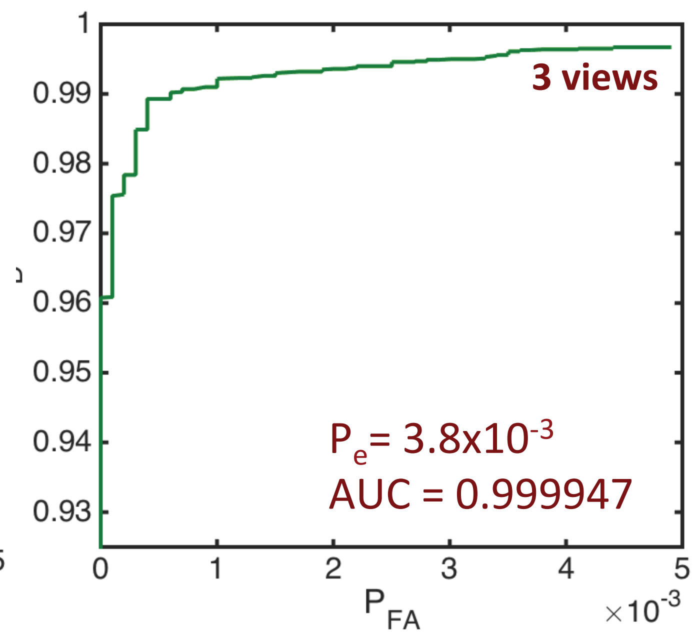
$P_e/P_D/P_{FA}$ and ROC Analysis

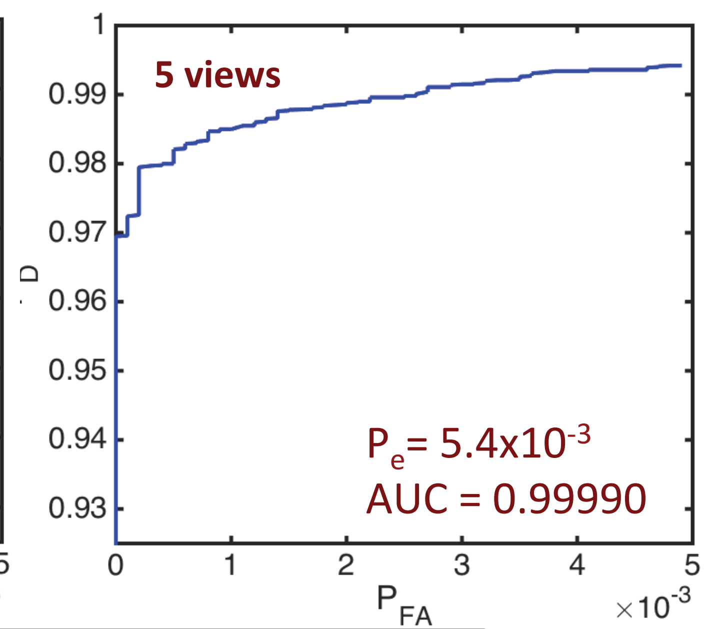




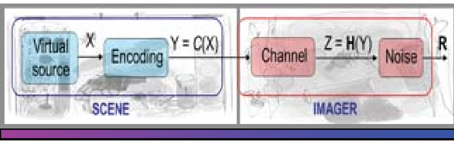
Increasing number of views







Adding more views beyond 3 views does not yield improved detection for this AT geometry



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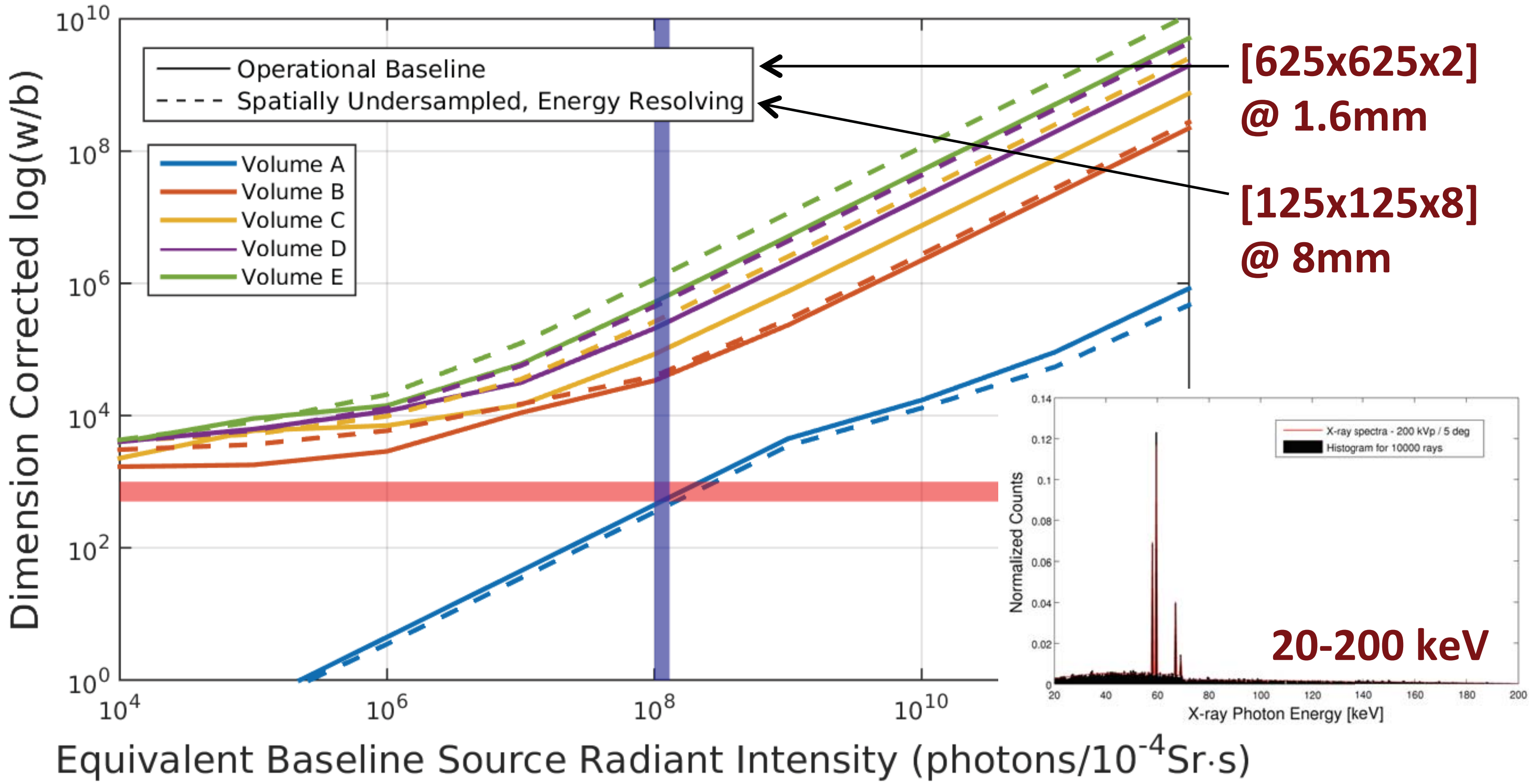
Reduction in measurements with no loss of performance

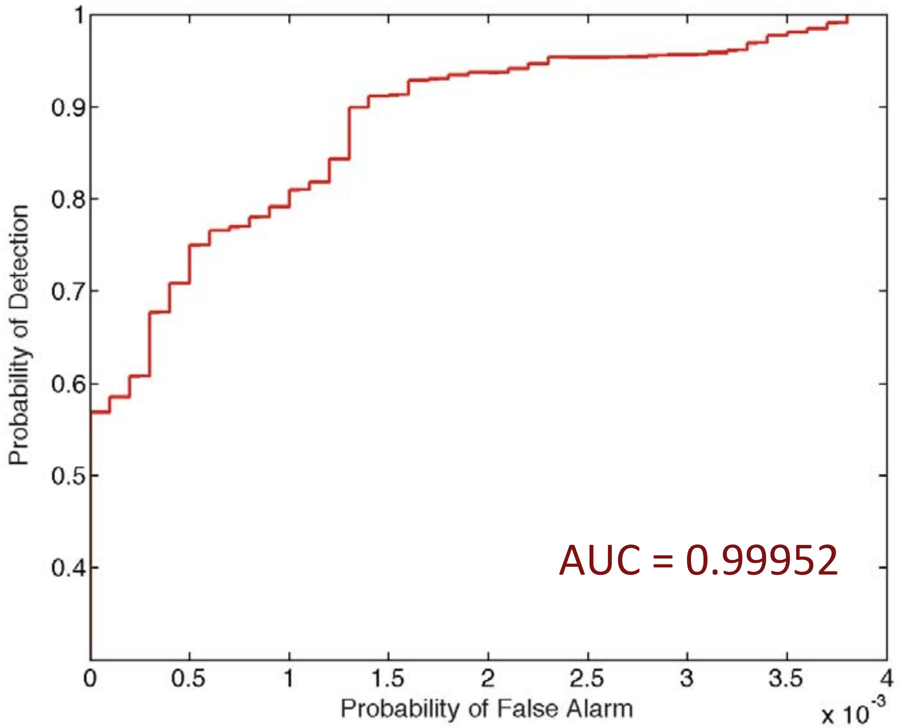


- Spatially undersampled, energy-resolving system outperforms operational baseline system
- Spatial undersampling *reduces* measurements by 25x while energy-resolution *increases* measurements by 4x.
- Net reduction of measurement number is 25/4 = 6.25

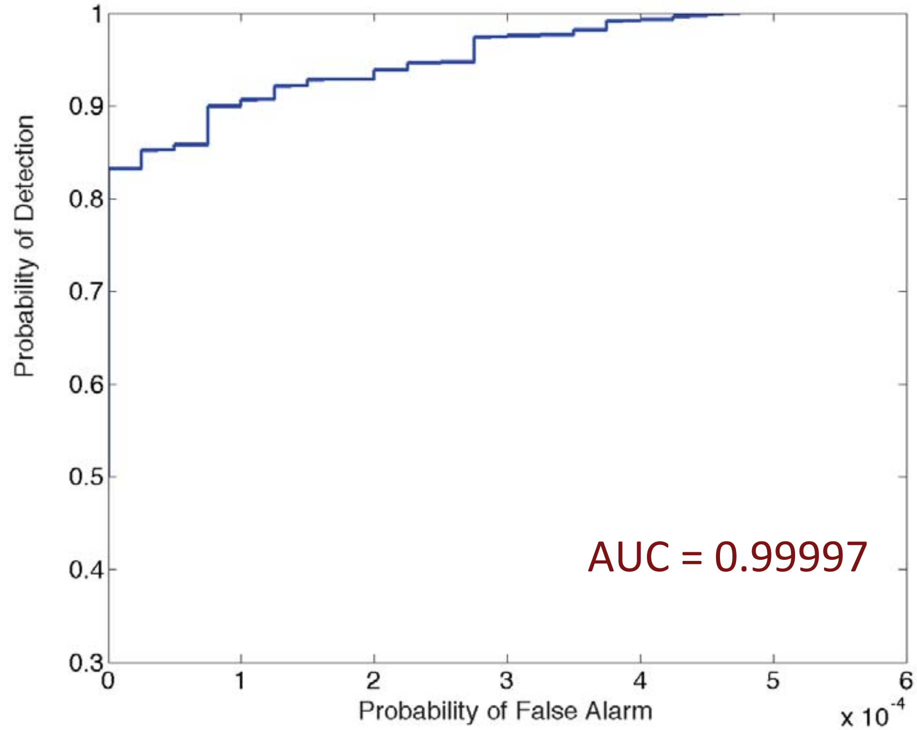
Reduction in measurement number by > 5x while improving information-theoretic performance limit.

$P_e/P_D/P_{FA}$ and ROC Analysis

Operational Baseline [625x625x2]



Spatially undersampled, Energy resolving [125x125x8]

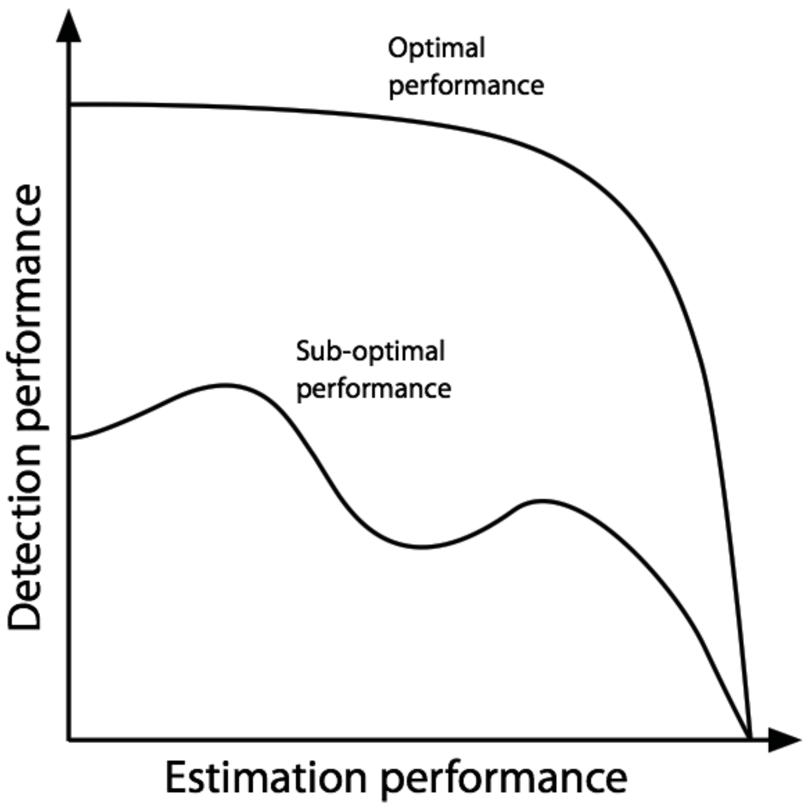


Threat Volume B

- ROC analysis confirms the log[w/b] comparison between operational baseline and spatially undersampled, energy resolving system

Reduction in measurement number by > 5x while improving information-theoretic performance limit.

Joint Estimation/Detection Information (JEDI)



- Our information-theoretic exploration of the fundamental performance of joint estimation/detection problems (such as image formation combined with threat detection) has revealed a striking fact
- The detection performance of an optimal system ***must*** decrease monotonically with increasing estimation performance
  - In other words, improving the image will necessarily *degrade* detection performance
  - There may be broad ranges of parameter space for which the degradation is minimal, but it must exist
- Conversely, if image improvement is observed to improve detection capability, the ATR algorithm ***must*** be non-optimal and is underachieving in detection given the information present in the measurements