SAND2014-17024PE

Independent Project Review of Optimal Imaging for Treaty Verification

26 August 2014

Project Team

Nathan Hilton, Matt Kupinski, Chris MacGahan, Will Johnson, Erik Brubaker, Pete Marleau, Eric Clarkson

SAND2014-XXXX

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Agenda

Project overview and goals	Nathan Hilton
Introduction to neutron coded-aperture imager	Peter Marleau
Task-based imaging and observer models	Matthew Kupinski
Results from unclassified simulations	Chris MacGahan Will Johnson
Future directions	Will Johnson Chris MacGahan

Image reconstruction is neither required nor optimal for many tasks

- We seek a method to verify the presence of treaty-accountable items using imaging devices without requiring an information barrier.

- Task-based, or optimal, imaging methods should enable meeting both desired objectives.
  - Superior task performance
  - Avoidance of classified-information barriers

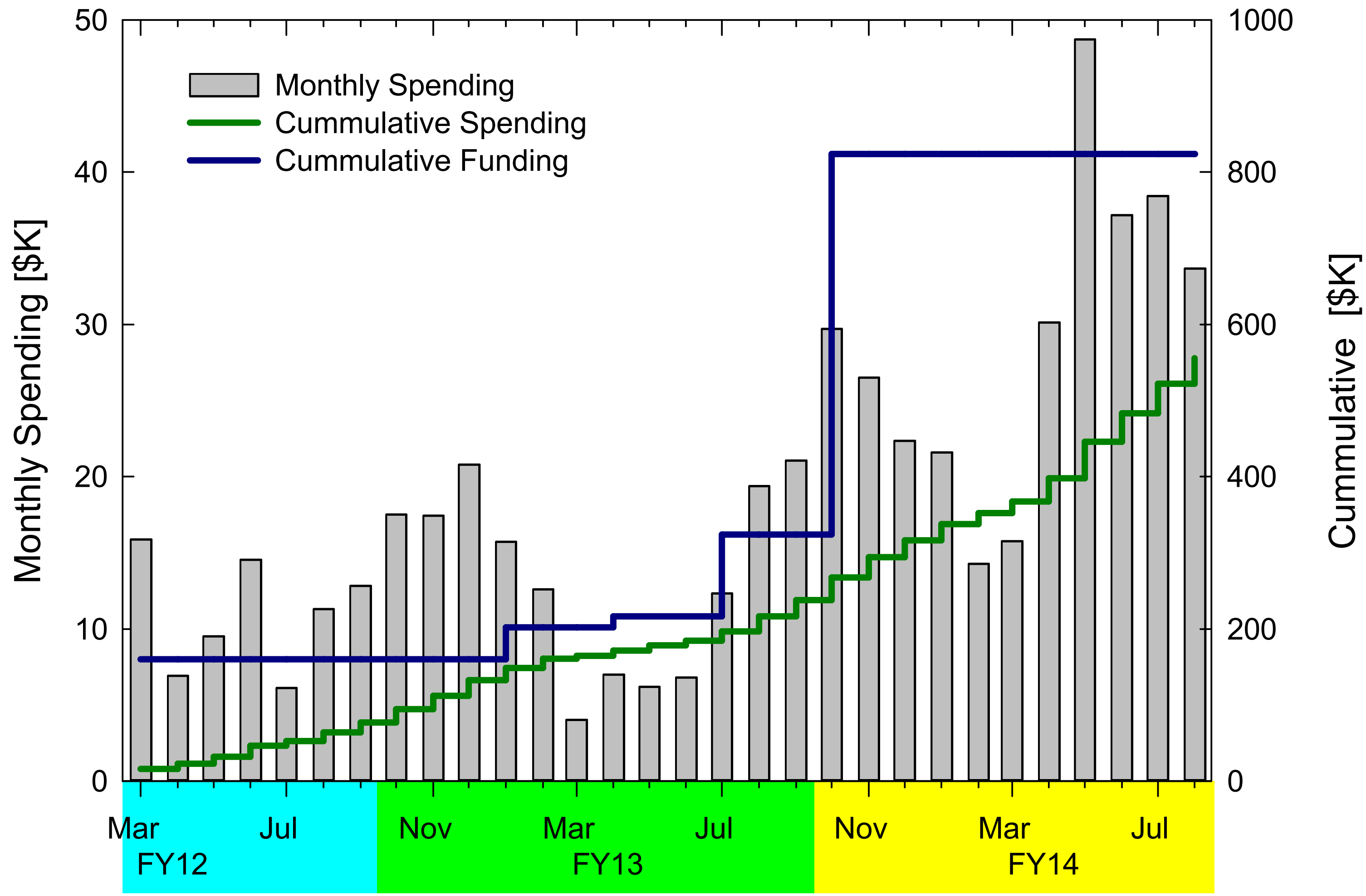
Pursuing this hypothesis since 2006 for DOE and DNDO wide-area search

- 2007 DNDO Stand-off Radiation Detection System proposal
- 2007-2010 LDRD project "Active Coded-Aperture Neutron Imaging" (funded)
- 2008 DNDO proposal "Optimal, Automated Threat Detection and Localization in a Cluttered Radiation Background"
- 2010 3-month LDRD (funded)
- 2011 DNDO white paper
- 2011 NA-22 proposal "Optimal SNM Detection, Localization, and Classification in a Cluttered Radiation Background (Optimal Imaging of SNM)" (approved pending funding)

Project approved in 2012 with a new objective of treaty verification

- Project is “in the third year of its first year”.
- Launched in March 2012 with $160K in seed funding as “Optimal Detection, Localization, and Classification of Treaty-Accountable Objects in a Cluttered Radiation Background (Optimal Imaging for Treaty Verification)”
  - $77K spent in FY12
- Partial FY13 funding allocation
  - $164K eventually arrived, mostly at the end of FY13
  - Project in warm hibernation
  - $155K spent in FY13
- FY14 allocation is $500K
  - Staff slowly returning and being joined by new team members
  - $323K spent YTD in FY14

Spending and funding timeline shows time-varying effort



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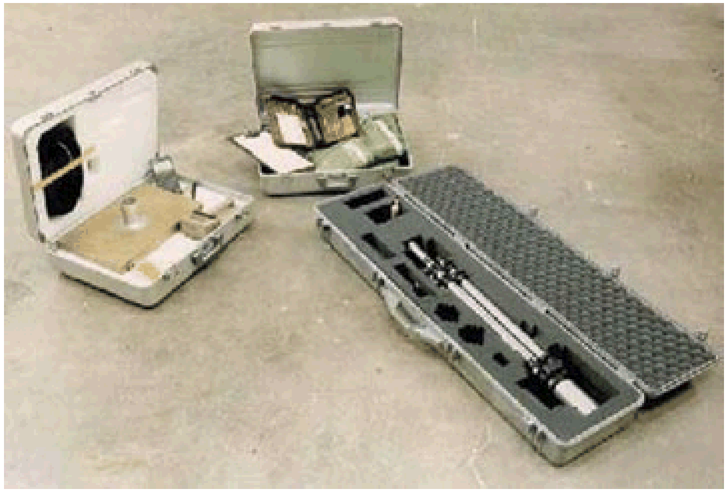
Treaty verification now confirms declared absence of accountable items

Past and current treaty-verification protocols seek to protect classified nuclear-weapon information:

- use only simple radiation detection equipment (i.e., neutron counter)
- verify only the declared absence of treaty-accountable items



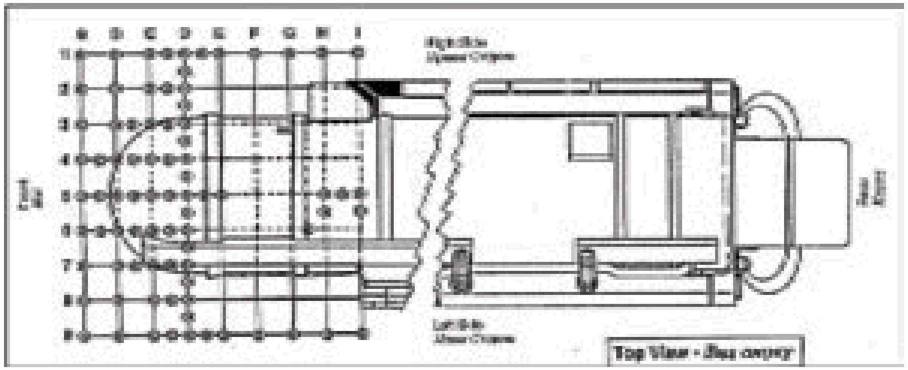

Images from "Radiation Detection Equipment: An Arms Control Verification Tool", DTIRP Product No. 211P at http://dtirp.dtra.mil/Products/Products.aspx#NewStart.

Treaty verification now confirms declared absence of accountable items

SS-25

SS-20

INF treaty (1989-2001) protocol confirmed that no SS-20 missiles were in launchers converted to hold the SS-25.



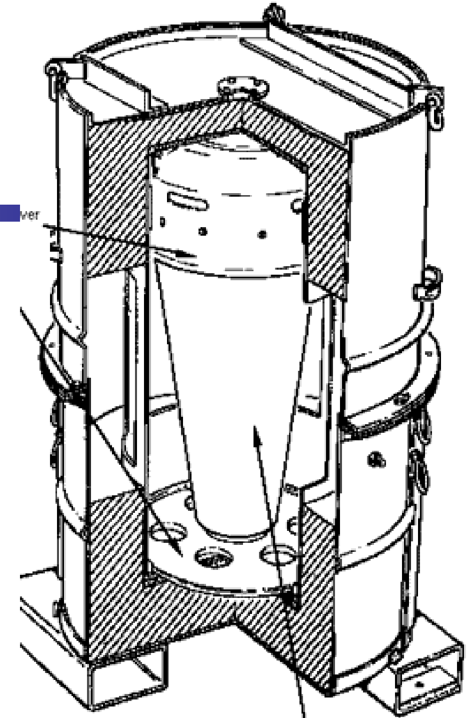
Measurement grid

Images from "Radiation Detection Equipment: An Arms Control Verification Tool", DTIRP Product No. 211P at http://dtirp.dtra.mil/Products/Products.aspx#NewStart.

Treaty verification now confirms declared absence of accountable items

- START (1994) and New START (2011) confirm the declared absence of nuclear material in:
  - cruise missiles outside of designated storage areas (START)
  - an object located on or in a designated bomber (New START)
  - an object in the front section of an ICBM or SLBM (both)

Treaty verification R&D is an "undiscovered country"



- Future treaties may verify the declared presence of treaty-accountable items.
  - Negotiated information sharing could alter the definitions of classified information.
  - Can IB be trusted?
  - Can a monitoring system without an IB (1) work and (2) be trusted?
- R&D must demonstrate what is possible.

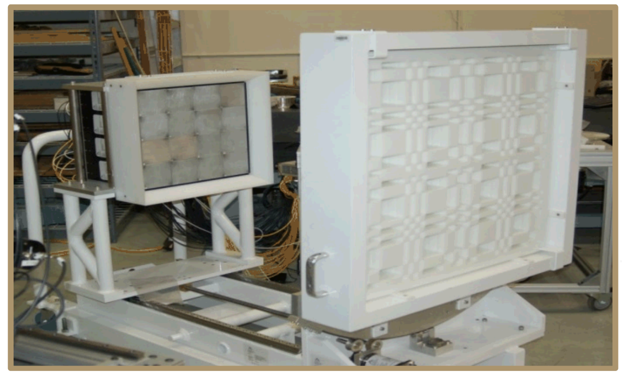
Our charter is to examine methods for imaging without an information barrier

- Task-based imaging should enable the system to do its job.
- Minimum system requirements without an information barrier:
  - No storage of classified templates etc.*
  - No image reconstruction
  - Event-by-event data processing
  - No storage of event data
  - No storage of processed data that reveals classified information*
- *In-depth vulnerability analysis is neither within project scope nor well defined.
- We are to create, demonstrate, and assess the performance and limitations of methods meeting basic requirements.
  - Additional goals include insensitivity to any temporal or spatial inhomogeneity of radiation sources

Our task is verifying the presence of treaty items without revealing classified data

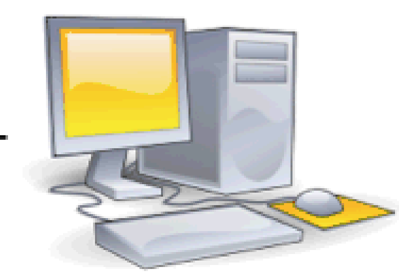
Target

Gamma / Neutron Emissions



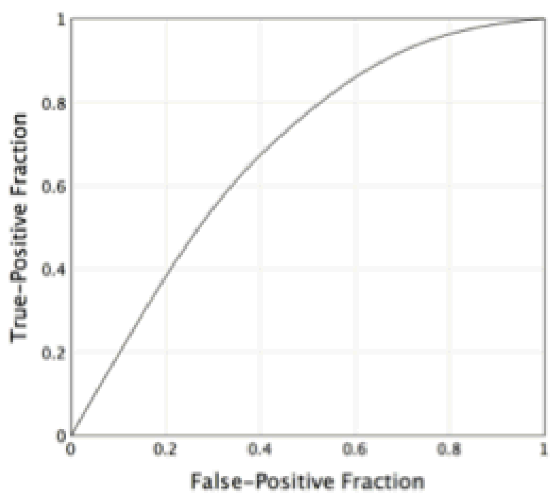
Detector

List-mode spectra



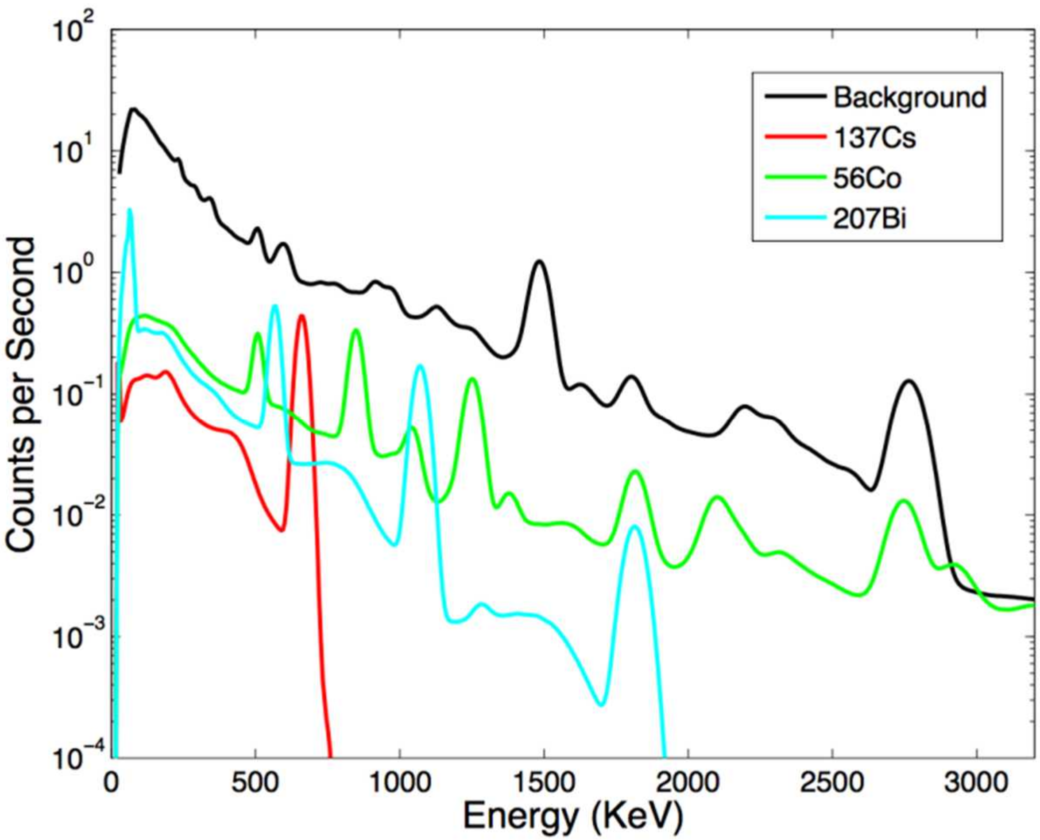
Observer Model

Signal Likelihood



Decision / Performance Metric

List-mode data-processing demo



- Demo task is detecting the presence of ^{137}Cs, ^{207}Bi, and ^{56}Co signals using event-by-event processing of data from a single detector – no imaging.
- Background/Signal ratio varies from 20 to 75

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Observer model processes one event and then deletes it

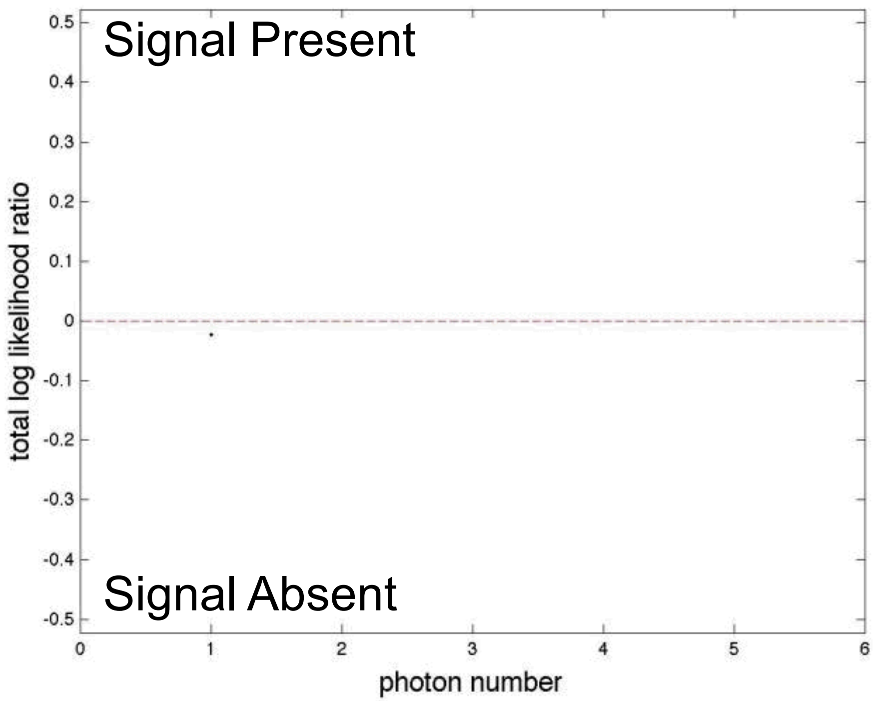
Event N

...

Event 3

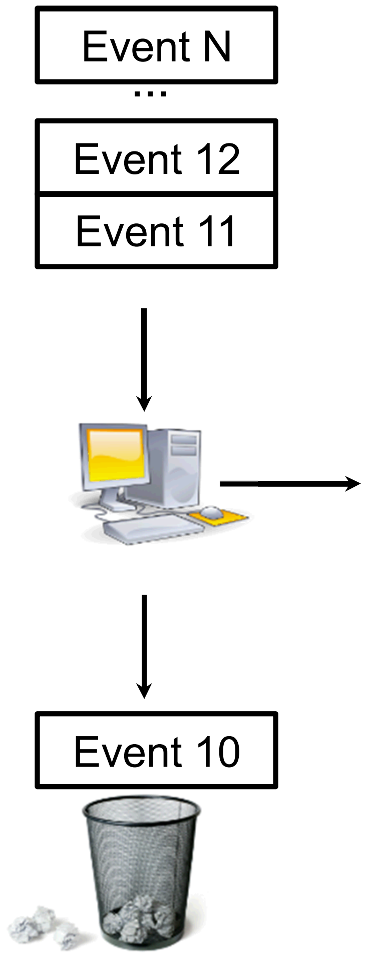
Event 2

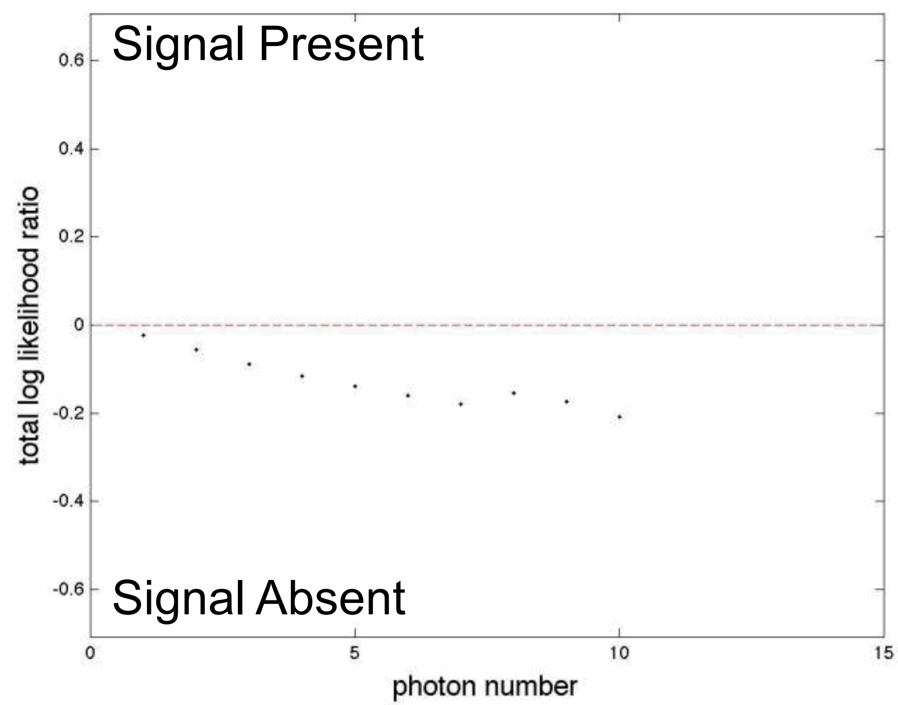
Event 1



Output running sum is the likelihood of a signal being present, which is thresholded to make a decision.

Observer model processes one event and then deletes it





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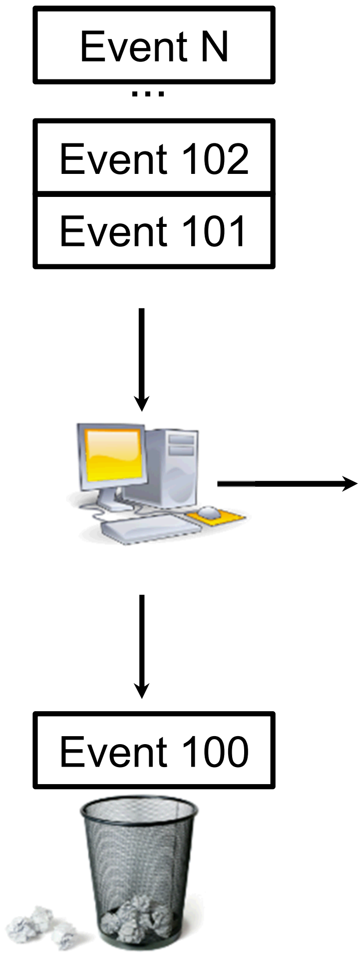

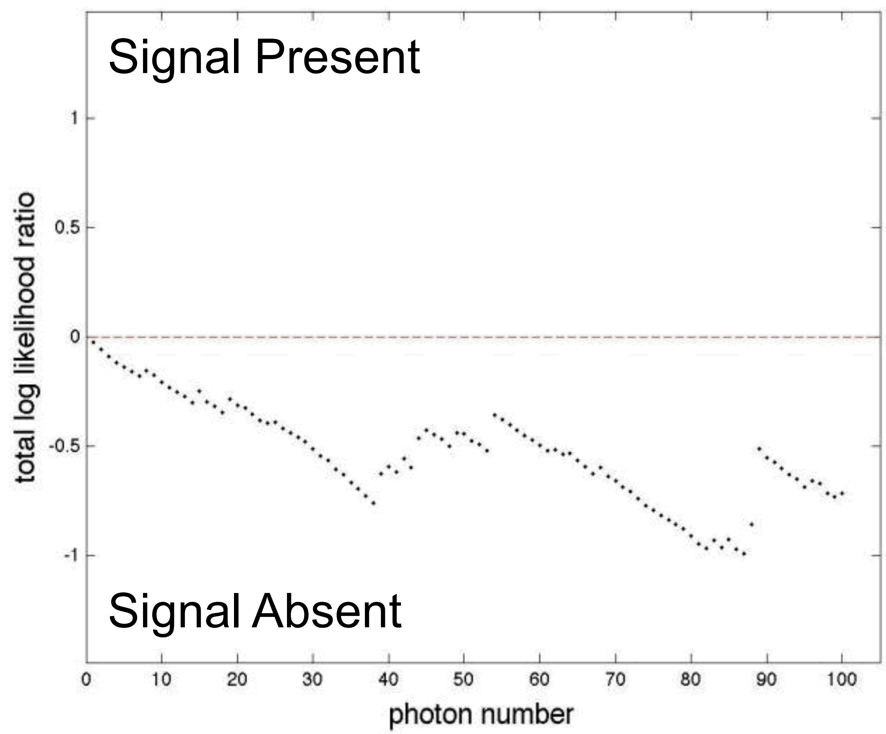

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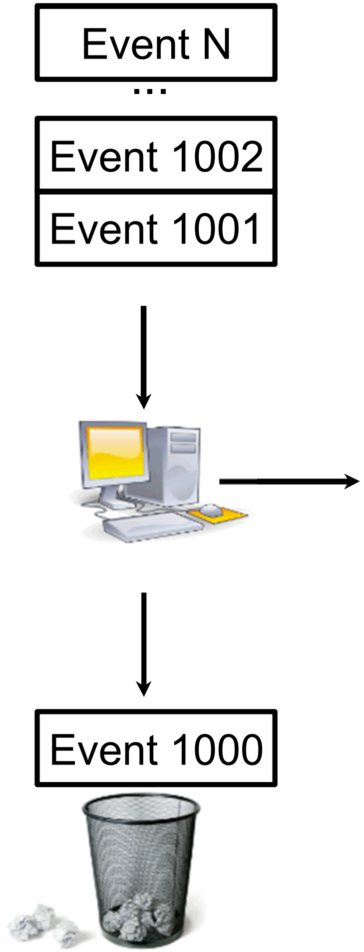
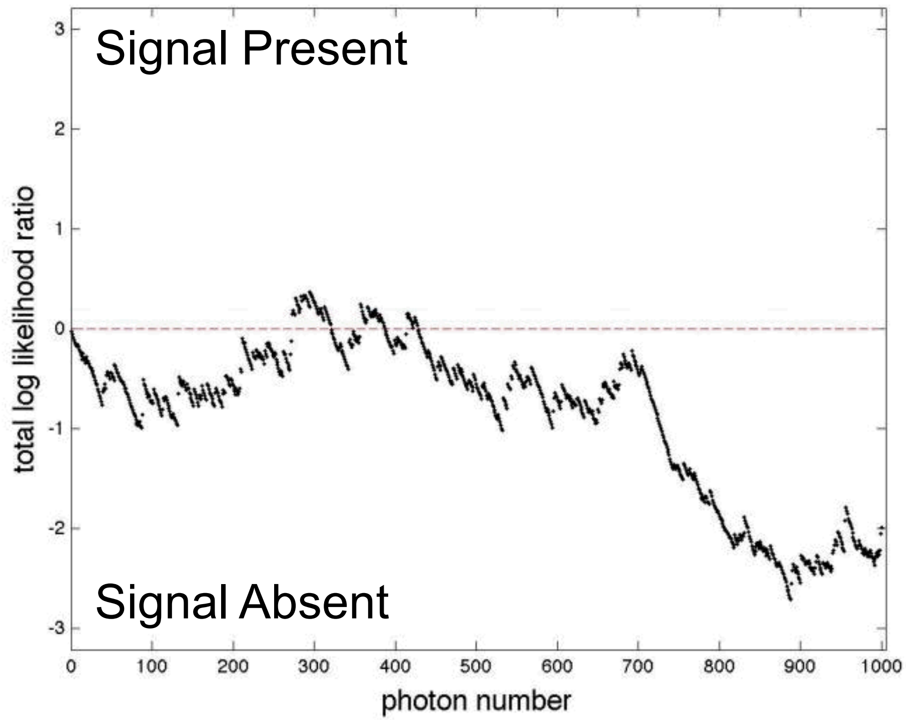
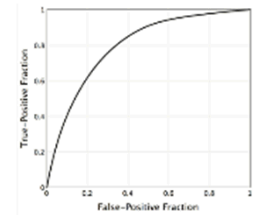
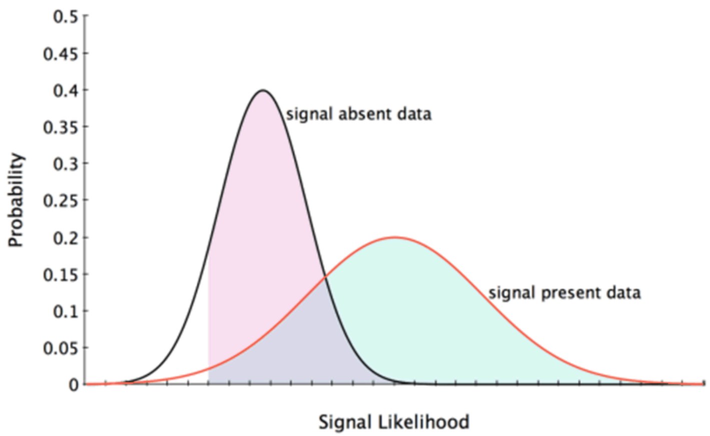


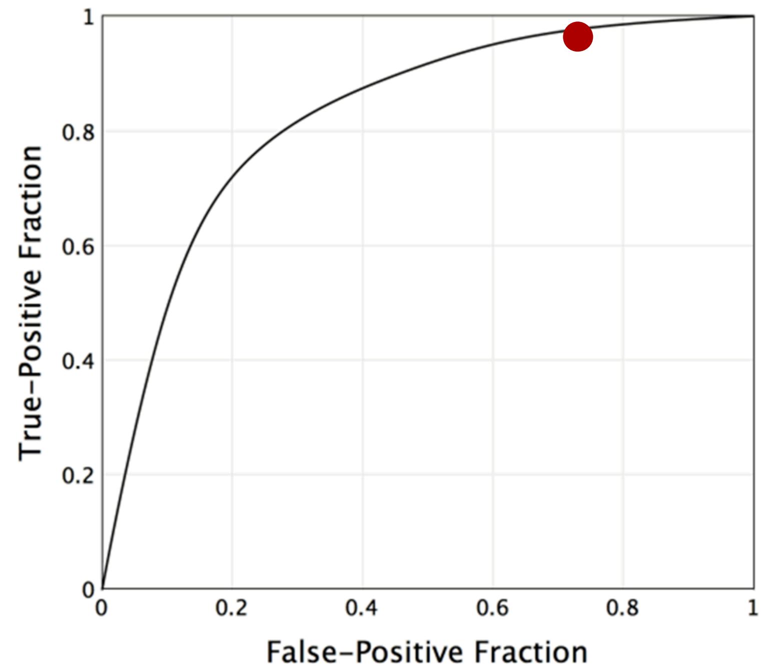


Output running sum is the likelihood of a signal being present, which is thresholded to make a decision.

Task performance of observer models are assessed and compared







ROC curve plots the sensitivity vs. the false-positive fraction for all possible thresholds.

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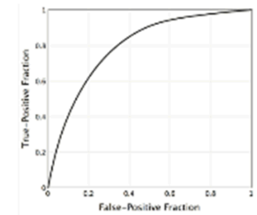
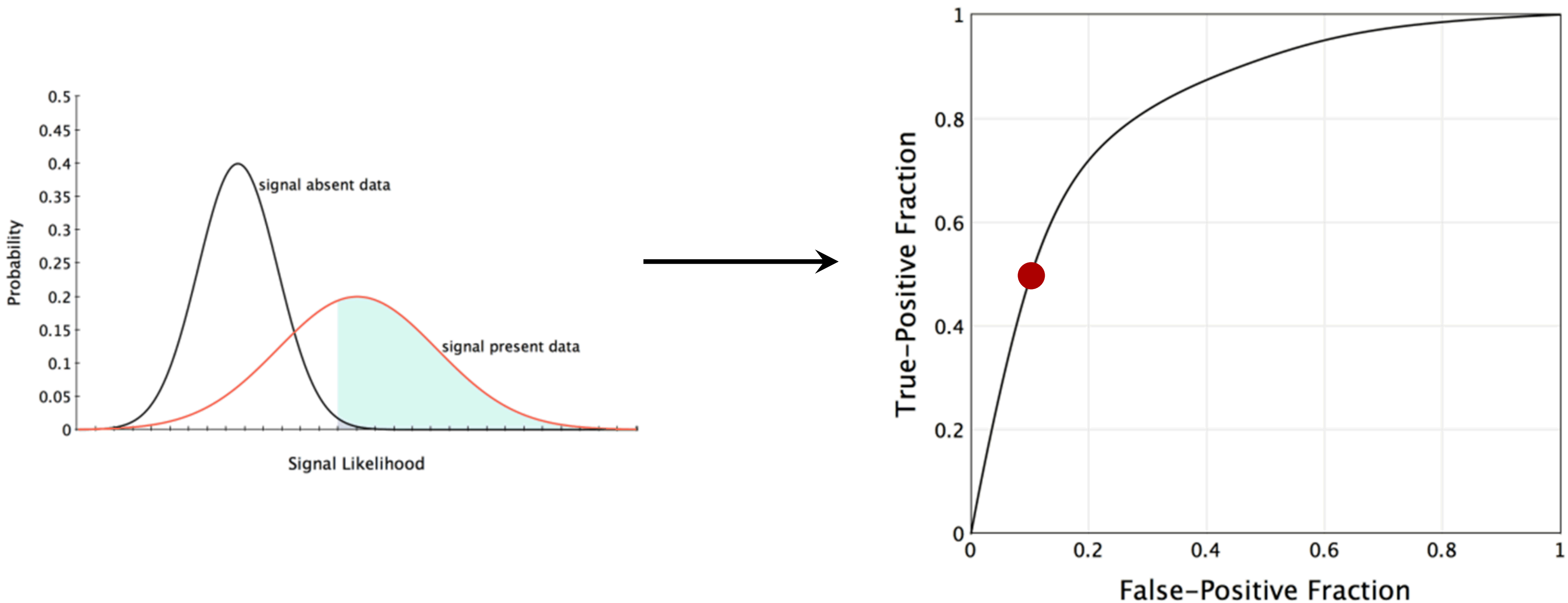
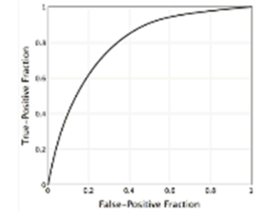
Task performance of observer models are assessed and compared

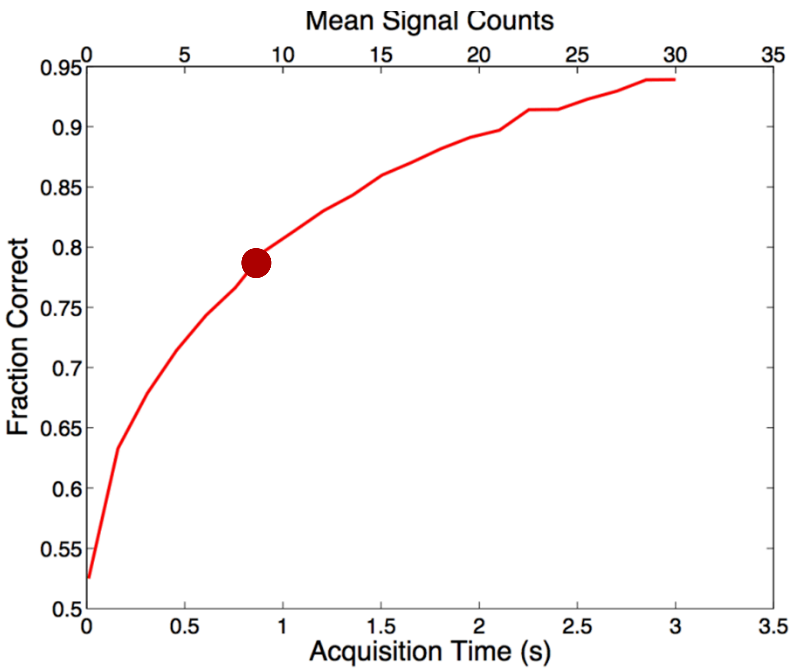


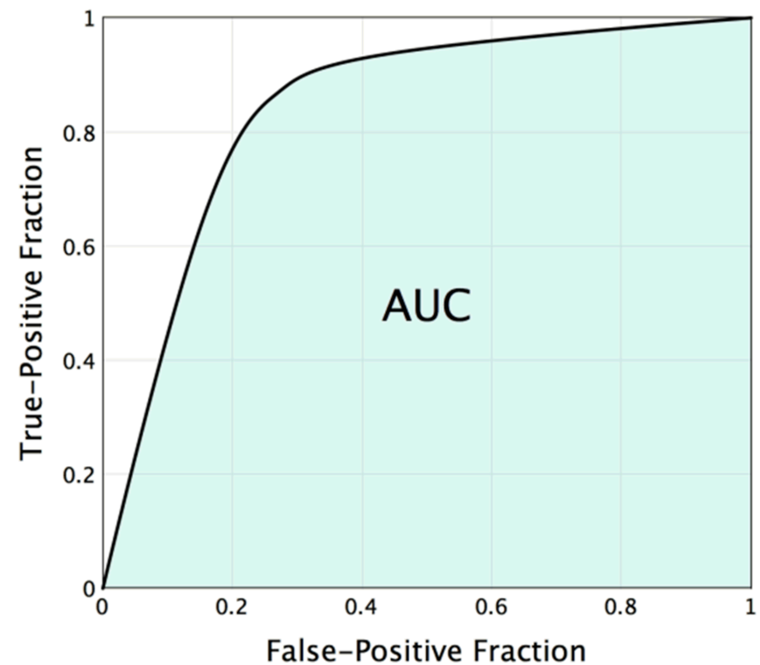


ROC curve plots the sensitivity vs. the false-positive fraction for all possible thresholds.

Fraction Correct/Area Under Curve is used to assess performance

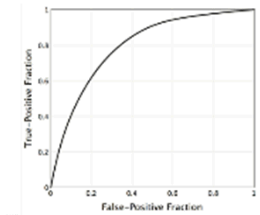


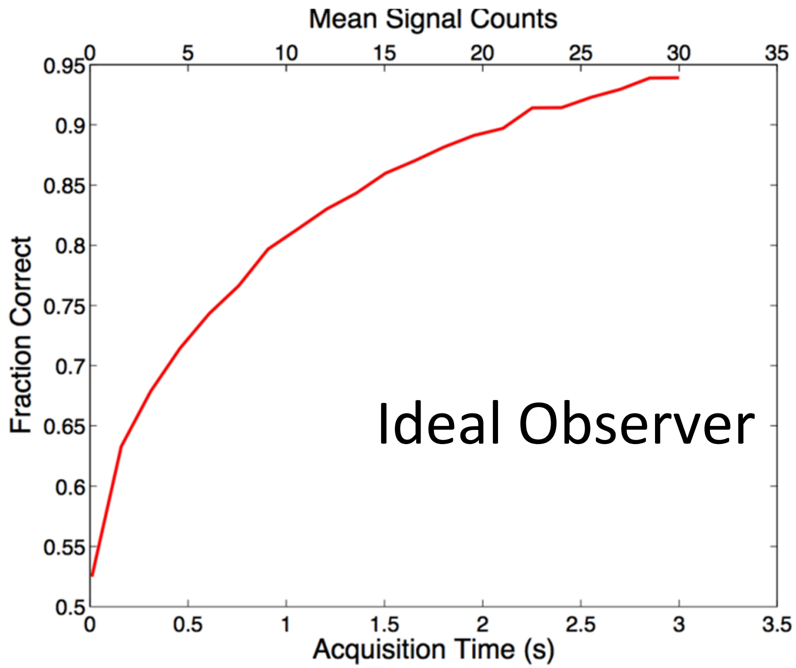


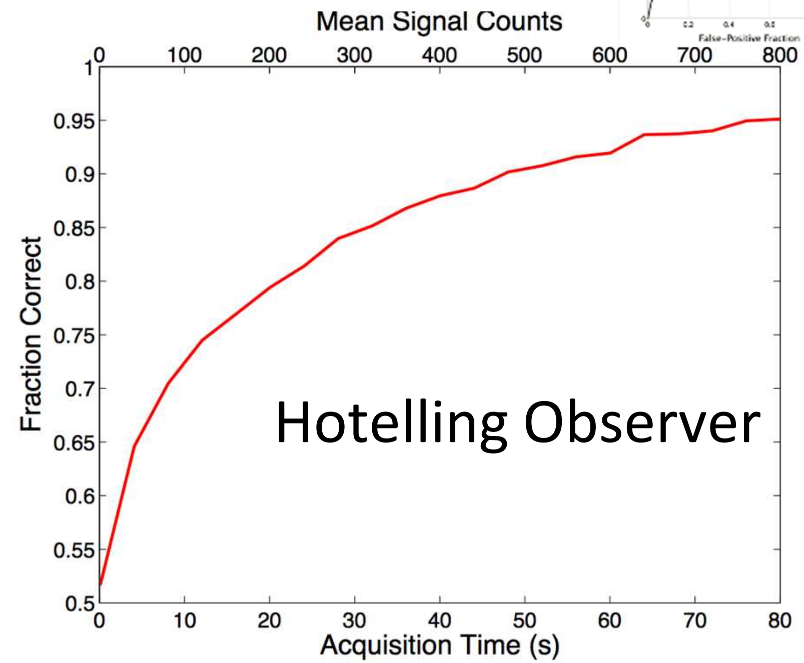


Area under ROC curve (AUC) is equivalent to the fraction of correctly classified datasets when the observer must classify which of two datasets has a signal

Demo results for finding if variable-strength ^{137}Cs signal is present







- Computationally difficult
- Requires classified information
- Standard for comparison

- Simpler, linear observer model
- Requires only means and covariances of spectra
- Longer acquisition to achieve similar results

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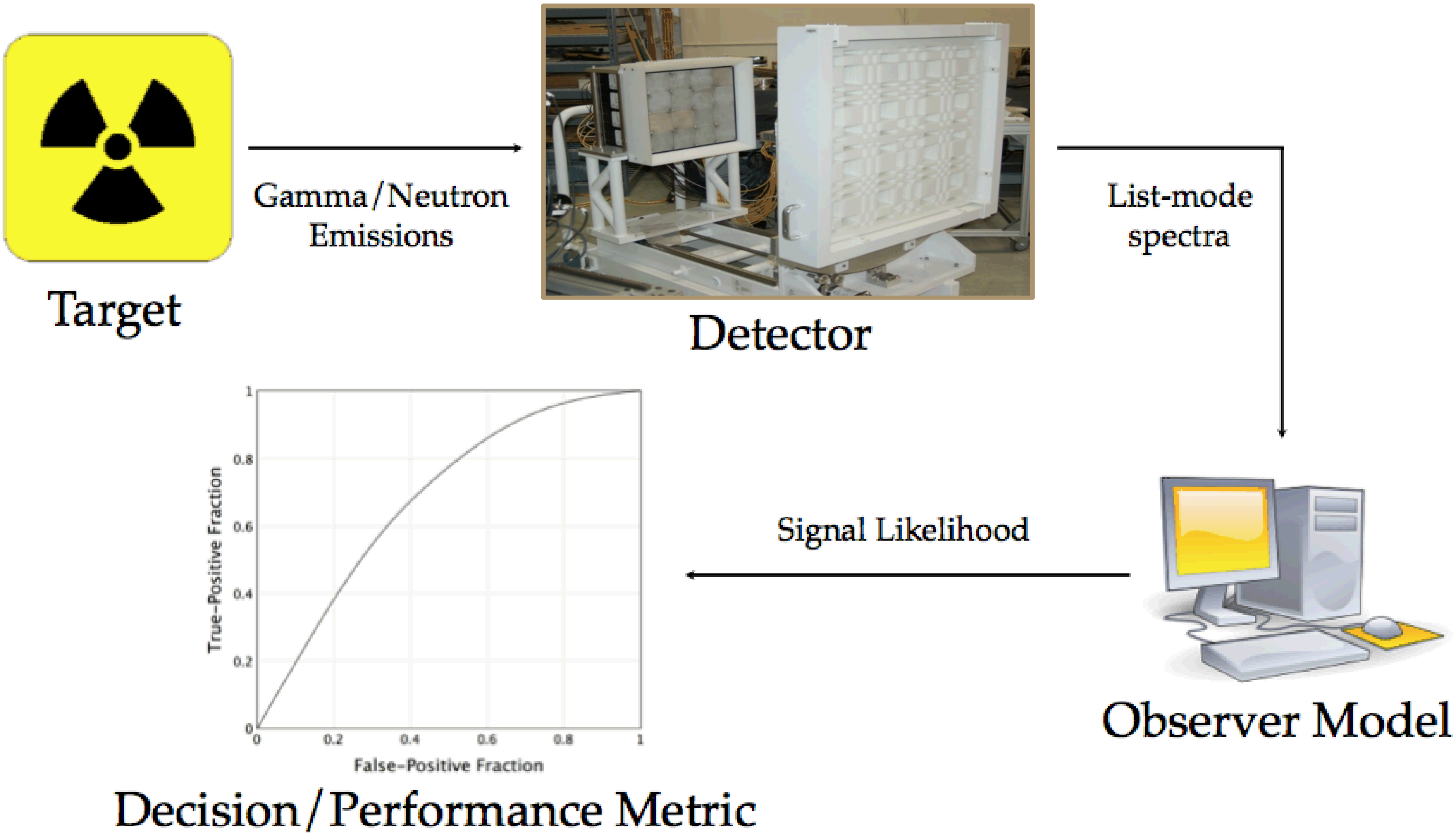
Methodology is independent of the detection system



Year	Major Tasks and Milestones
FY12	**Milestone**: Analysis of alternatives for treaty verification using task-based imaging methods. **Tasks**: Analyze approaches to the problem; begin implementing forward models for gamma-ray coded-aperture imaging, including energy-dependent transport and detection.
FY13	**Milestone**: Concept demonstration of task-based imaging methods suitable for treaty-verification applications without a need for an information barrier. **Tasks**: Continue implementing forward models for imaging systems, specifically a system for combined neutron and gamma-ray coded-aperture imaging; remove the need for an information barrier by altering and/or adopting analysis methods that process detection data event by event; begin simulating data for observer models and comparing results.
FY14	**Milestone**: Demonstrate and quantify comparative advantage of task-based imaging methods with various levels of information barriers. **Tasks**: Model test objects; develop and test methods with various levels of information barriers; acquire calibration and test-object data for observer models for the fast-neutron coded-aperture imager data; compare all methods.

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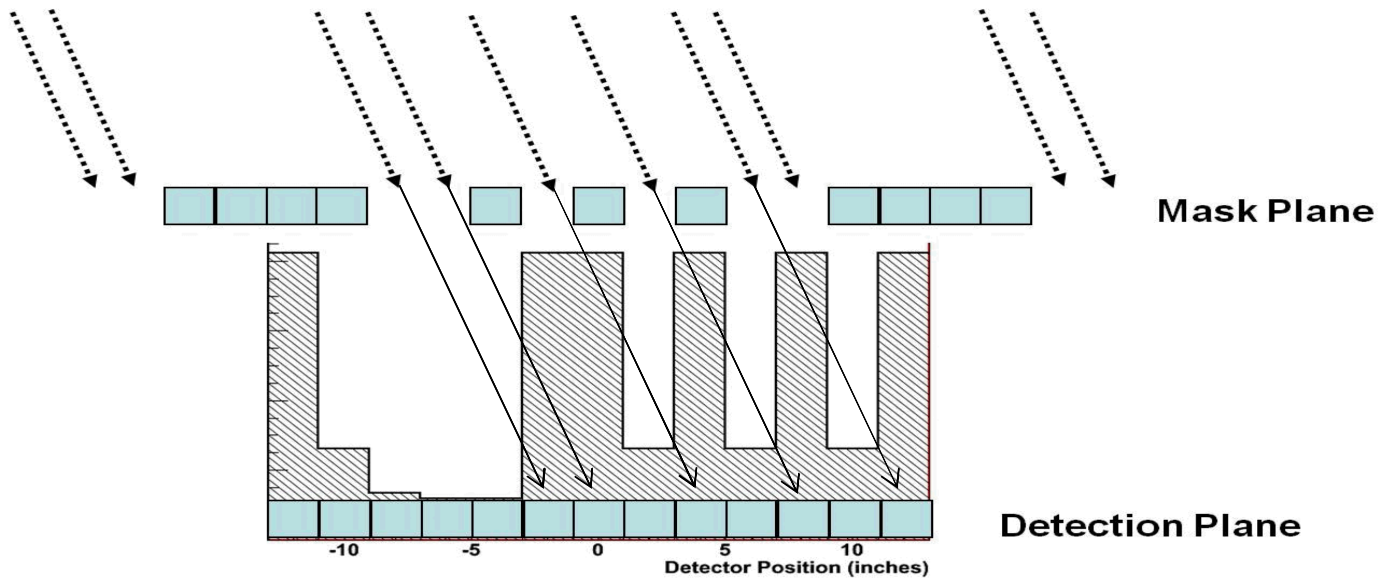
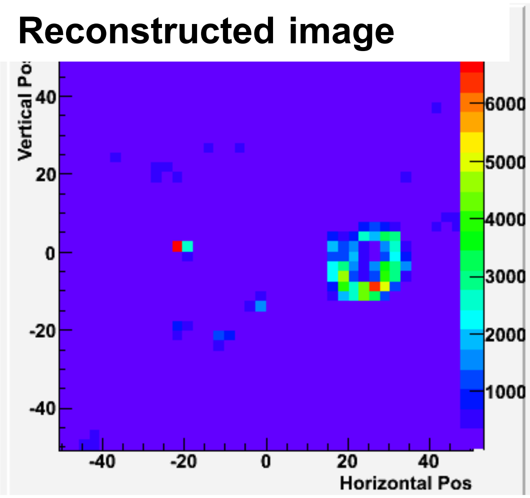
Coded-aperture imaging

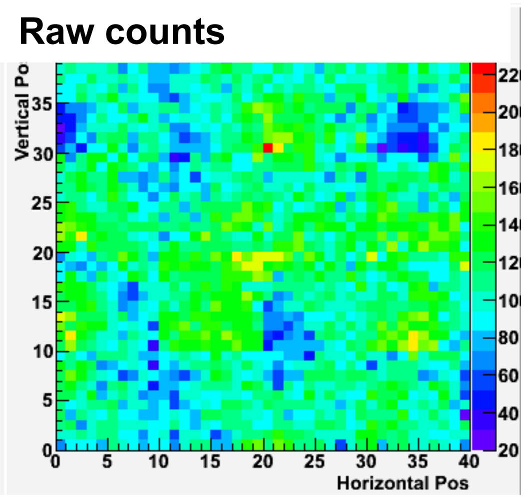
- Can't lens energetic neutrons (or gammas)
- Coded aperture is ~ an extension of pinhole imaging
- Aperture is used to modulate the flux emitted by an unknown source distribution
  - Modulated flux intensity is measured at the detector plane by a position sensitive detector
- Ideal theory vs fast neutron reality



Neutron coded-aperture imager

- ORNL/SNL fast neutron coded-aperture imager developed for arms control treaty verification.
- Image plane consists of 16 organic scintillator pixelated block detectors
  - Each block consists of a 10x10 array of 1 cm. pixels.
  - PSD and pixel id accomplished by 4 photomultiplier tubes.
- Mask plane consists of 2.5 to 10 centimeters of HDPE.

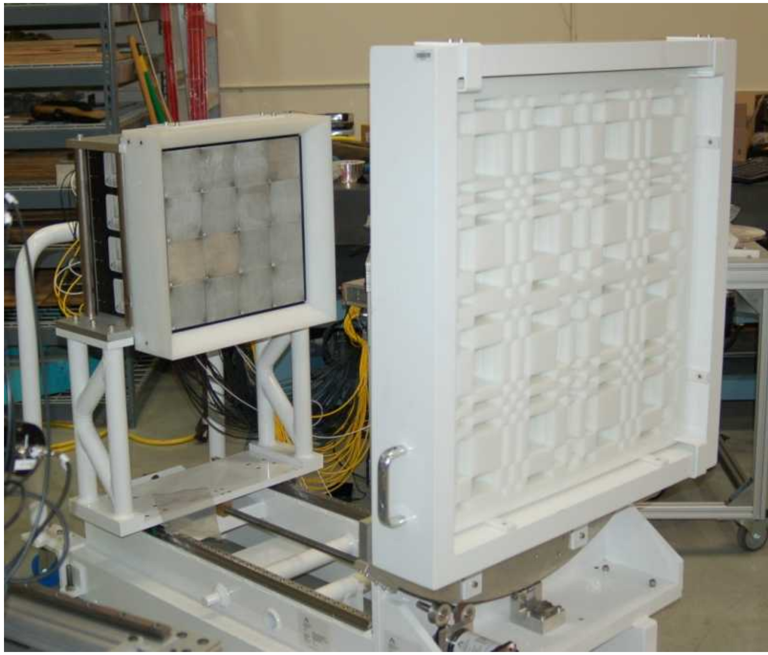




Detector developed in collaboration with ORNL: P. Hausladen, J. Newby, M. Blackston

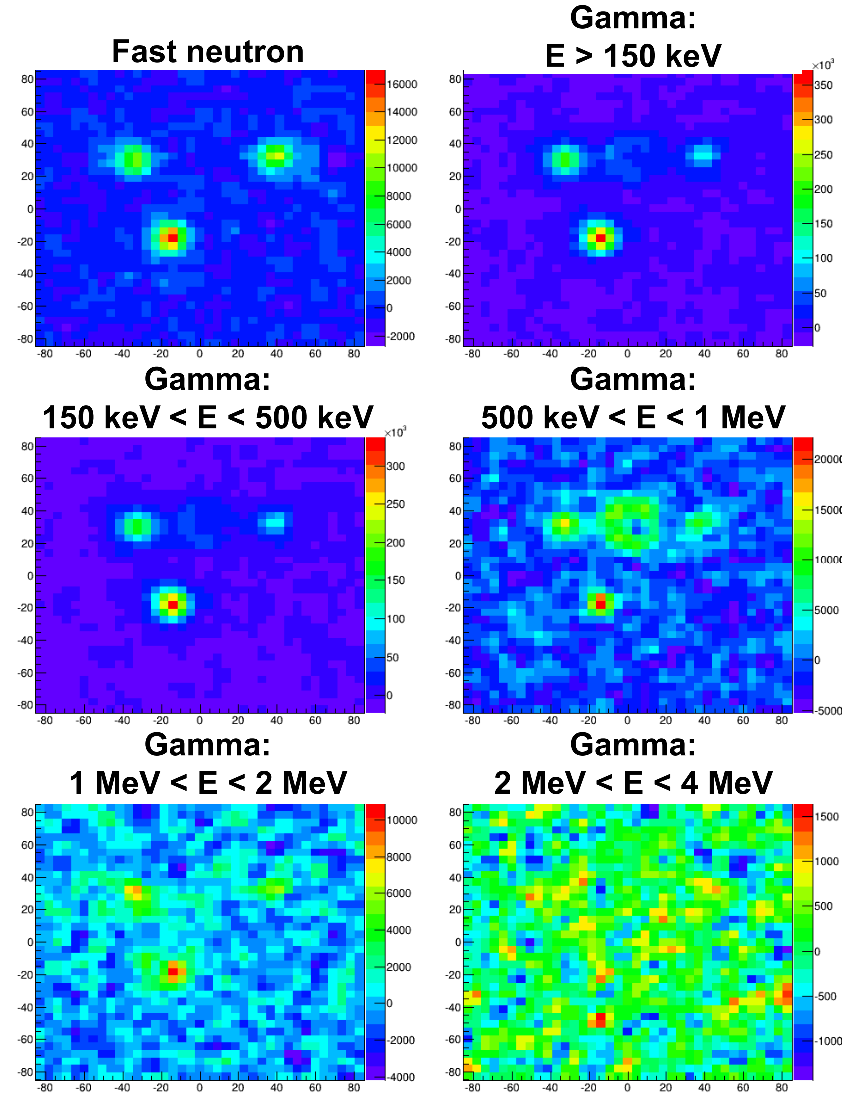
Neutron coded-aperture imager

- Advantages:
  - Excellent system angular resolution.
  - Good detection efficiency.
- Disadvantages:
  - Poor event angular resolution.
  - Complex detectors.
  - Performance degrades with multiple/extended sources.
- Potential use:
  - High-resolution, good S:B applications: arms control treaty verification, emergency response.



Neutron/gamma sensitivity

- Although optimized for neutron imaging, the system detects and images energetic gammas as well.
  - Gammas are typically more numerous, but SNM is self-attenuating
    - So image surface of SNM
  - Neutrons are more scarce, but penetrating
    - So image line-of-sight, allowing to detect features such as hollowness
- Example at right from imaging multiple objects containing Pu/DU with varying amounts of shielding.



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Measurements of inspection objects?

- Found data with IO8 and IO9 in the field of view (according to the directory name). Need to copy & process.

Data contents

- **Raw data**
  - Block detector ID
  - Time stamp
  - ~5 gate integrals x 4 PMTs
  - Pileup flag (from digitizer)
- **Processed/calibrated data**
  - X, Y PMT ratios
    - Pixel X
    - Pixel Y
  - Amplitude
    - Energy
  - Pulse shape parameter
    - Neutron likelihood
    - Gamma likelihood

Analysis (e.g. observer models) is generally at this calibrated level.

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Task-Based Imaging

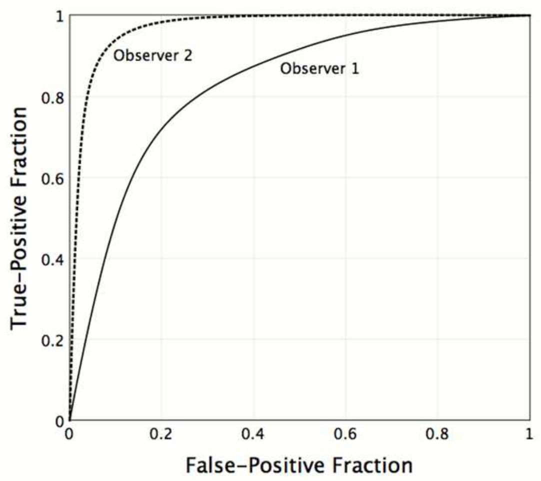
Task-based assessment

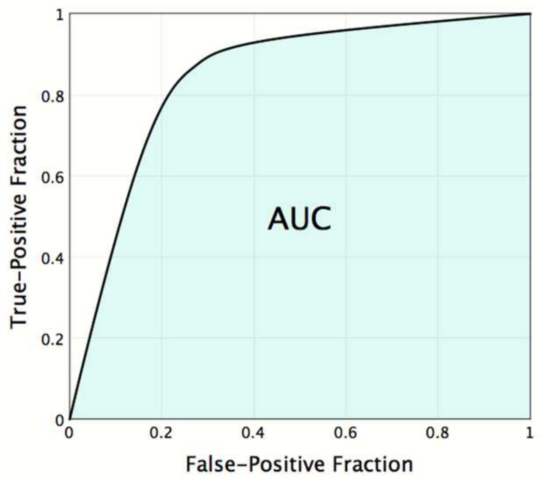
- Task
  What is the image to be used for?
- Observer
  Method of performing the task. (e.g., Likelihood ratio test)
- Objects
  What are you imaging?

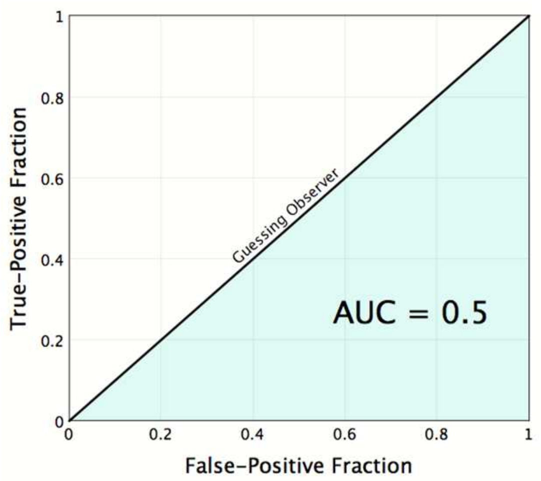
Measure the ability of the observer to perform the task

Task-Based Imaging

Figure of merit







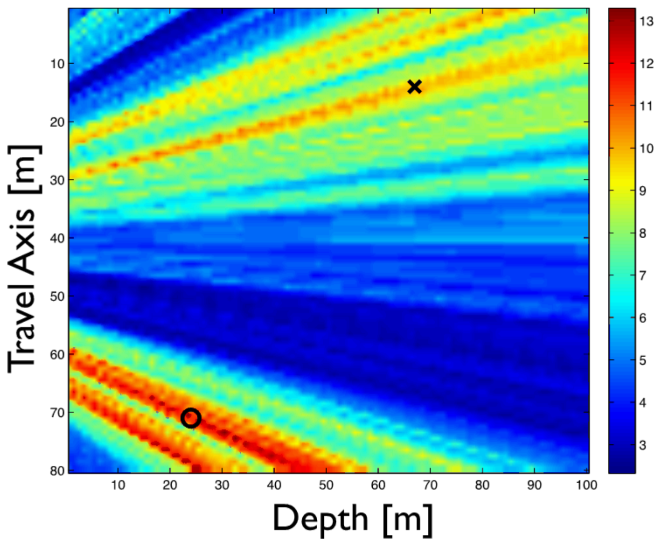
ROC Analysis

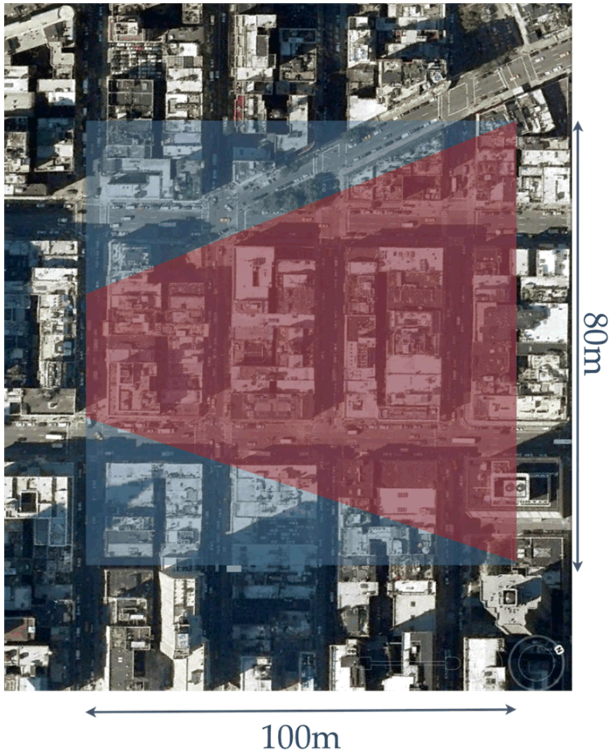
Estimation ROC Analysis

Task-Based Imaging

Example:

- Search for special nuclear materials (SNMs) in urban environments
- Limited-angle tomography
- Traditional reconstruction has limited utility





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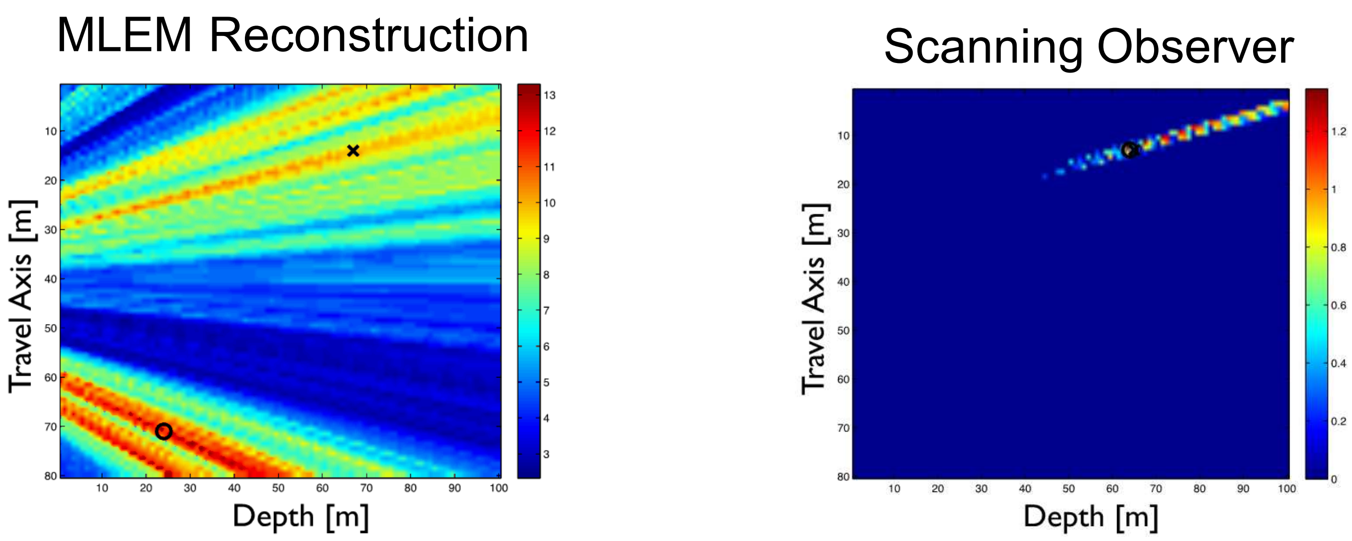
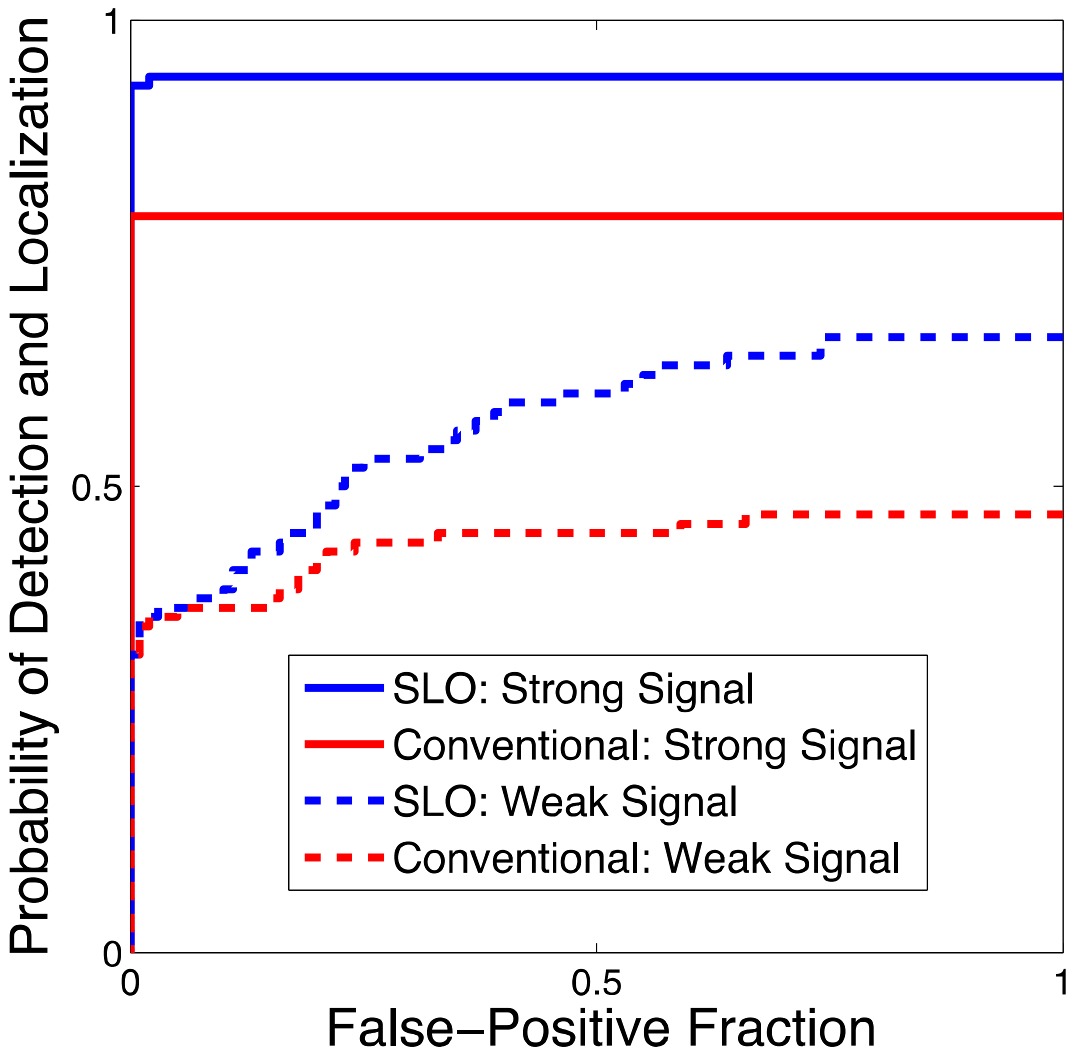
Task-Based Imaging

- Task: Detection and localization of SNM
- Observer: Scanning-linear observer
- Objects: Simulated SNM in an urban environment
- Figure of merit: Area under LROC curve



Task-Based Imaging



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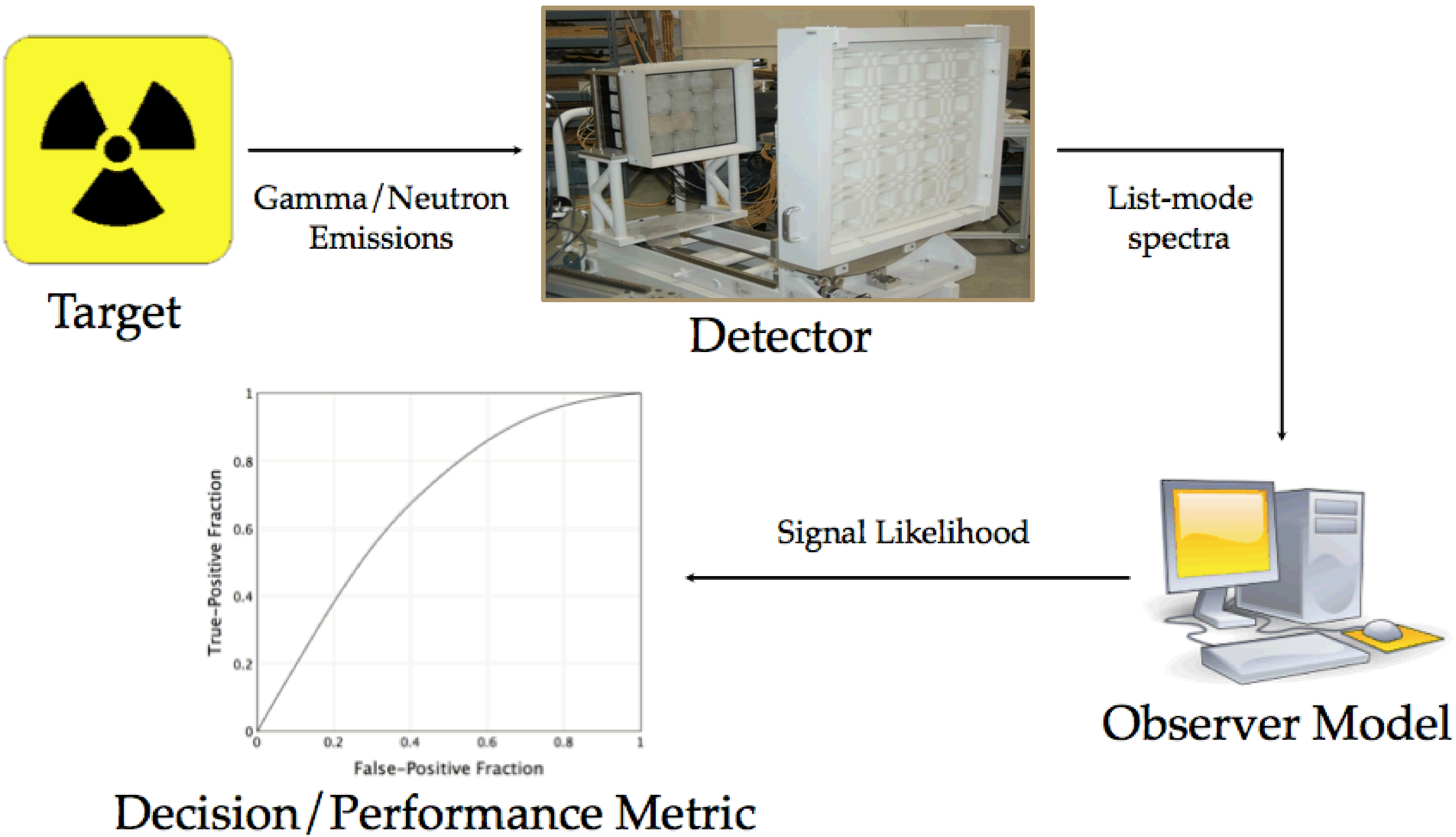
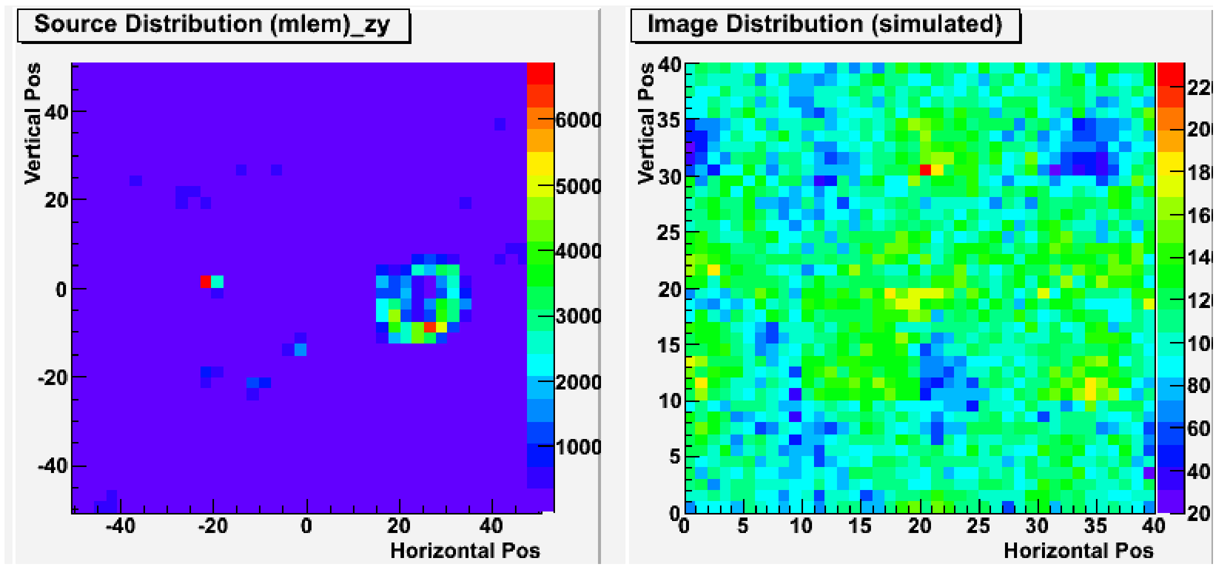


Task-Based Imaging

- Traditional method – Analyze images



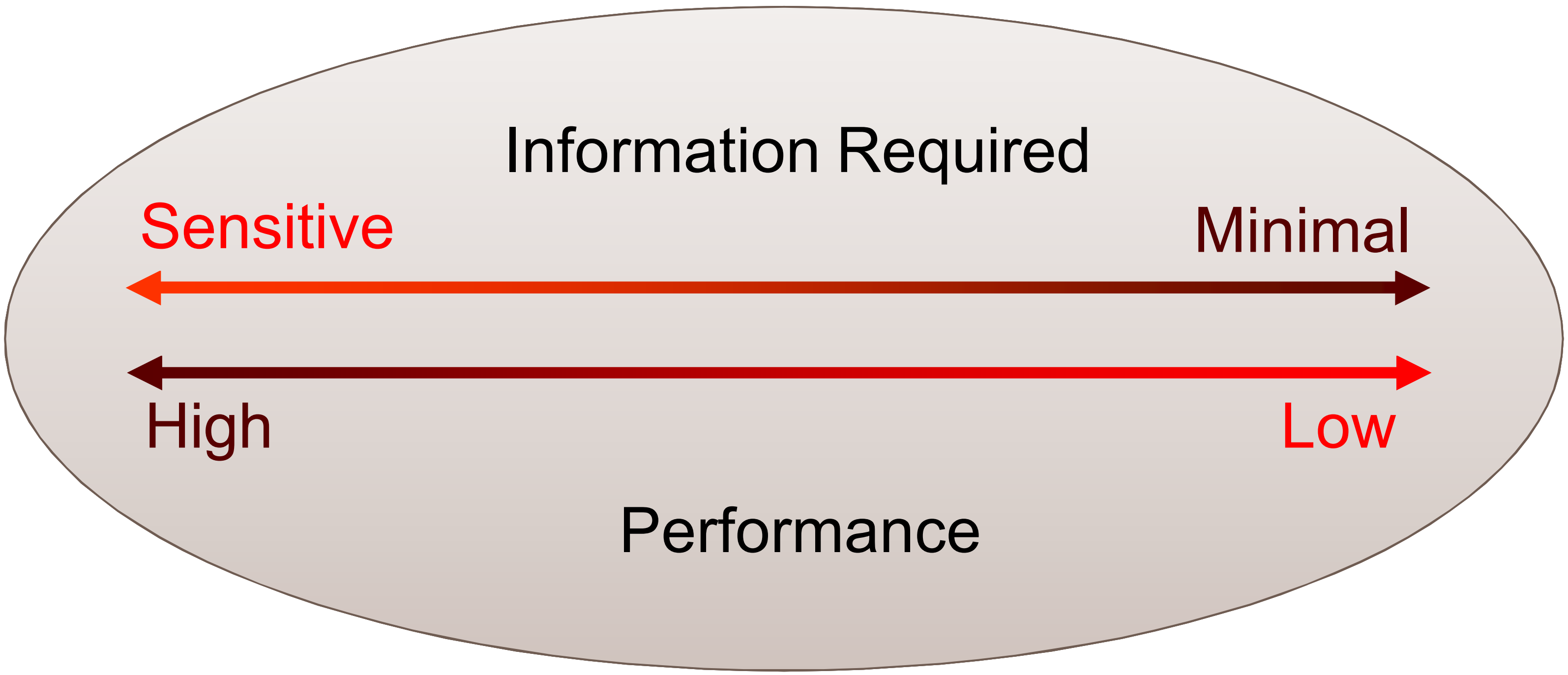
- Task-based approaches – shift in information from images to observer

Task-Based Imaging

- Relevant tasks:
  - Distinguish type of treaty object
  - Distinguish one object vs. two objects
  - Verify the absence of treaty object
  - Distinguish treaty object vs. spoof object
  - Estimate parameters of object
- Observer models
  - Bayesian ideal observer
  - Hotelling observer
  - Scanning observers

Other Observer Models

Tradeoff



Observer Models

Bayesian ideal observer

- Provides optimal performance – an upper bound
- Used to design simpler models
- Basis for an efficiency calculation

$$\Lambda(\boldsymbol{g}) = \frac{pr(\boldsymbol{g}|H_2)}{pr(\boldsymbol{g}|H_1)}$$

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List-mode Ideal Observer

- $A_n = \{d_n, E_n, p_n\}$
  List-mode entry for event *n*
  Each detected event has a detector label, an estimated energy, and particle type (gamma or neutron)
- List-mode ideal observer:

$$\Lambda(\{A_n\}) = \frac{pr(\{A_n\}|H_2)}{pr(\{A_n\}|H_1)}$$

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Data likelihood

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List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$
$$Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

- N : Total number of events
- N_0 : Number of background events
- N_j : Number of primary events
- $\overline{N_0}, \overline{N_j}$: Mean associated with background and primary events, respectively

List-mode Ideal Observer

$$pr(\{A_n\}, N | H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\} | N, \overline{N_j}, \overline{N_0}, H_j)$$

$$Pr(N | \overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

$$pr(\{A_n\} | N, \overline{N_j} \ldots$$

$$= \prod_{n=1}^{N} [pr(A_n | \ldots Pr(h_j | \overline{N_j}, \overline{N_0}, H_j)]$$

Probability associated with the list-mode data when the number of events and randomness associated with events is known

List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$

$$Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

$$pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j) = \prod_{n=1}^{N} pr(A_n|\overline{N_j}, \overline{N_0}, H_j)$$

$$= \prod_{n=1}^{N} \left[pr(A_n|h_0) Pr(h_0|\overline{N_j}, \overline{N_0}, H_j) + pr(A_n|h_j) Pr(h_j|\overline{N_j}, \overline{N_0}, H_j)\right]$$

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List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$
$$Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

$$pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j) = \prod_{n=1}^{N} pr(A_n|\overline{N_j}, \overline{N_0}, H_j)$$
$$= \prod_{n=1}^{N} \left[pr(A_n|h_0) Pr(h_0|\overline{N_j}, \overline{N_0}, H_j) + pr(A_n|h_j) Pr(h_j|\overline{N_j}, \overline{N_0}, H_j) \right]$$

Probabilities of primary vs. background events

List-mode Ideal Observer

$$pr(\{A_n\},N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N,\overline{N_j},\overline{N_0},H_j)$$
$$Pr(N|\overline{N_0},\overline{N_j},H_j)pr(\overline{N_0})pr(\overline{N_j})$$

$$pr(\{A_n\}|N,\overline{N_j},\overline{N_0},H_j) = \prod_{n=1}^{N} pr(A_n|\overline{N_j},\overline{N_0},H_j)$$
$$= \prod_{n=1}^{N} [pr(A_n|h_0)Pr(h_0|\overline{N_j},\overline{N_0},H_j) + pr(A_n|h_j)Pr(h_j|\overline{N_j},\overline{N_0},H_j)]$$

Distribution of estimated energy, detector position, and particle type for background events

List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$

$$Pr(N|\overline{N_j}, \overline{N_0}, H_j)\, pr(\overline{N_0})\, pr(\overline{N_j})$$

For Simulations:
Determined using GADRAS software

For Measurements:
Estimated from calibration data

$$pr(\{A_n\}|N, \overline{N_j} \ldots$$

$$= \prod_{n=1}^{N} \left[pr(A_n| \ldots Pr(h_j|\overline{N_j}, \overline{N_0}, H_j) \right]$$

Distribution of estimated energy, detector position, and particle type for background events

List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$

$$Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

$$pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j) = \prod_{n=1}^{N} pr(A_n|\overline{N_j}, \overline{N_0}, H_j)$$

$$= \prod_{n=1}^{N} \left[pr(A_n|h_0) Pr(h_0|\overline{N_j}, \overline{N_0}, H_j) + pr(A_n|h_j) Pr(h_j|\overline{N_j}, \overline{N_0}, H_j)\right]$$

Distribution of estimated energy, detector position, and particle type for source events

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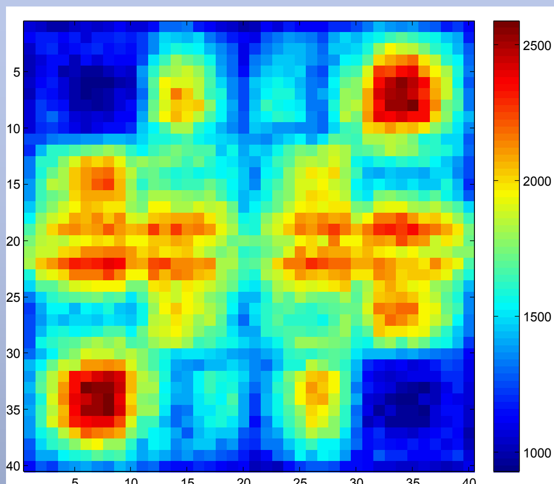
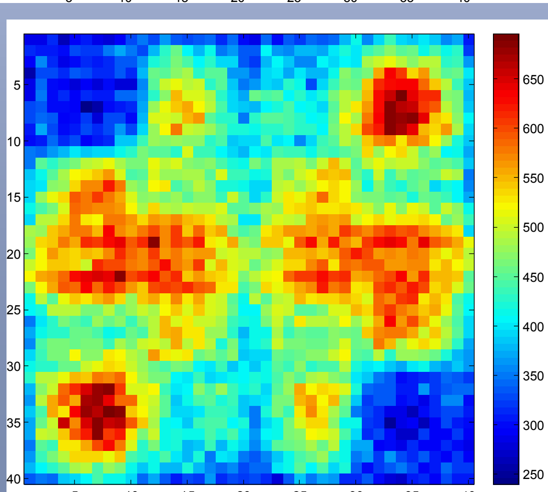
List-mode Ideal Observer

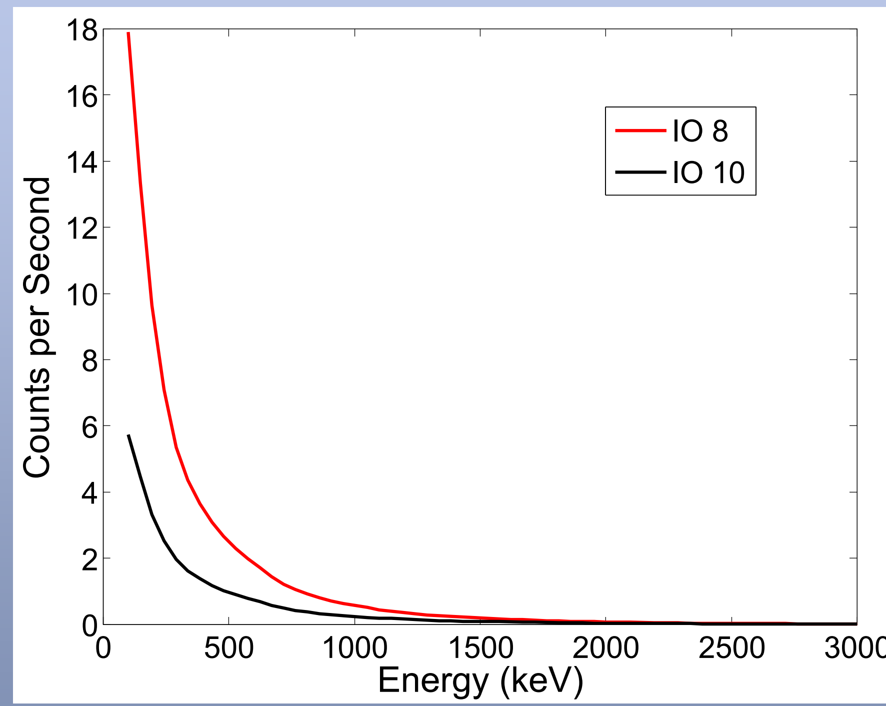
Estimated using GEANT simulations



IO8



IO10



List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \frac{\int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)}{Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})}$$

$$Pr(N|\overline{N_0}, \overline{N_j} H_j) = \sum_{N_0=0}^{N} Pr(N_0|\overline{N_0}) Pr(N - N_0|\overline{N_j})$$

Well-modeled using Poisson distributions

List-mode Ideal Observer

$$pr(\{A_n\}, N|H_j) = \int d\overline{N_j} \int d\overline{N_0}\, pr(\{A_n\}|N, \overline{N_j}, \overline{N_0}, H_j)$$
$$Pr(N|\overline{N_0}, \overline{N_j}, H_j) pr(\overline{N_0}) pr(\overline{N_j})$$

Terms account for background variability and variability in the source (including decay)

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List-mode Ideal Observer

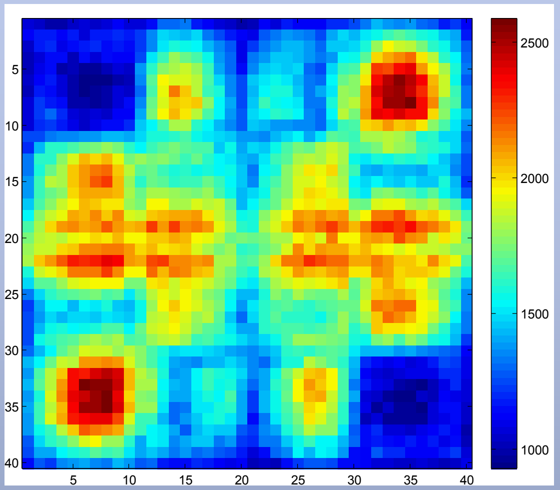
Nuisance parameter: Any variable that affects the data but is not of interest.

- Relevant examples (included in the derivation):
  - Source strength variability
  - Background strength
  - Detector response
  - Variability due to limited counts in GEANT simulations
- More relevant examples:
  - Source orientation
  - Source position

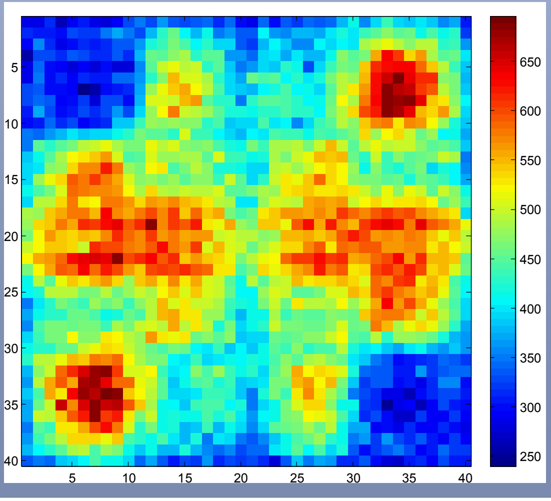
List-mode Ideal Observer

- Estimated using GEANT simulations

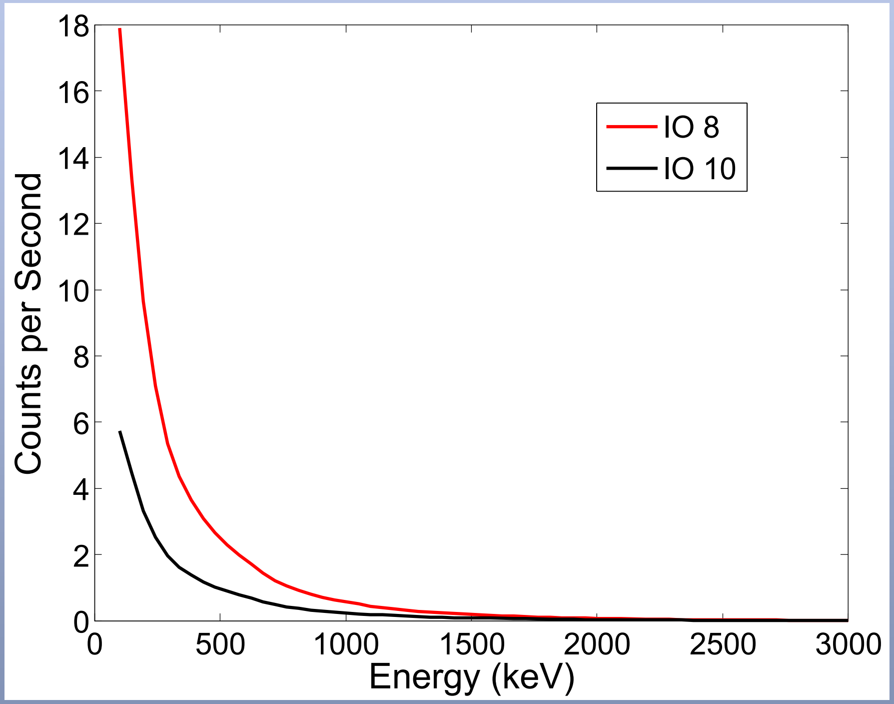
$$pr(A_n|h_j)$$



IO8



IO10



List-mode Ideal Observer

- Source orientation:

$$pr(A_n|h_j) = \int d\theta \, pr(A_n|h_j, \theta)/2\pi$$

- GEANT simulation for all possible source orientations?
- To be discussed in future work

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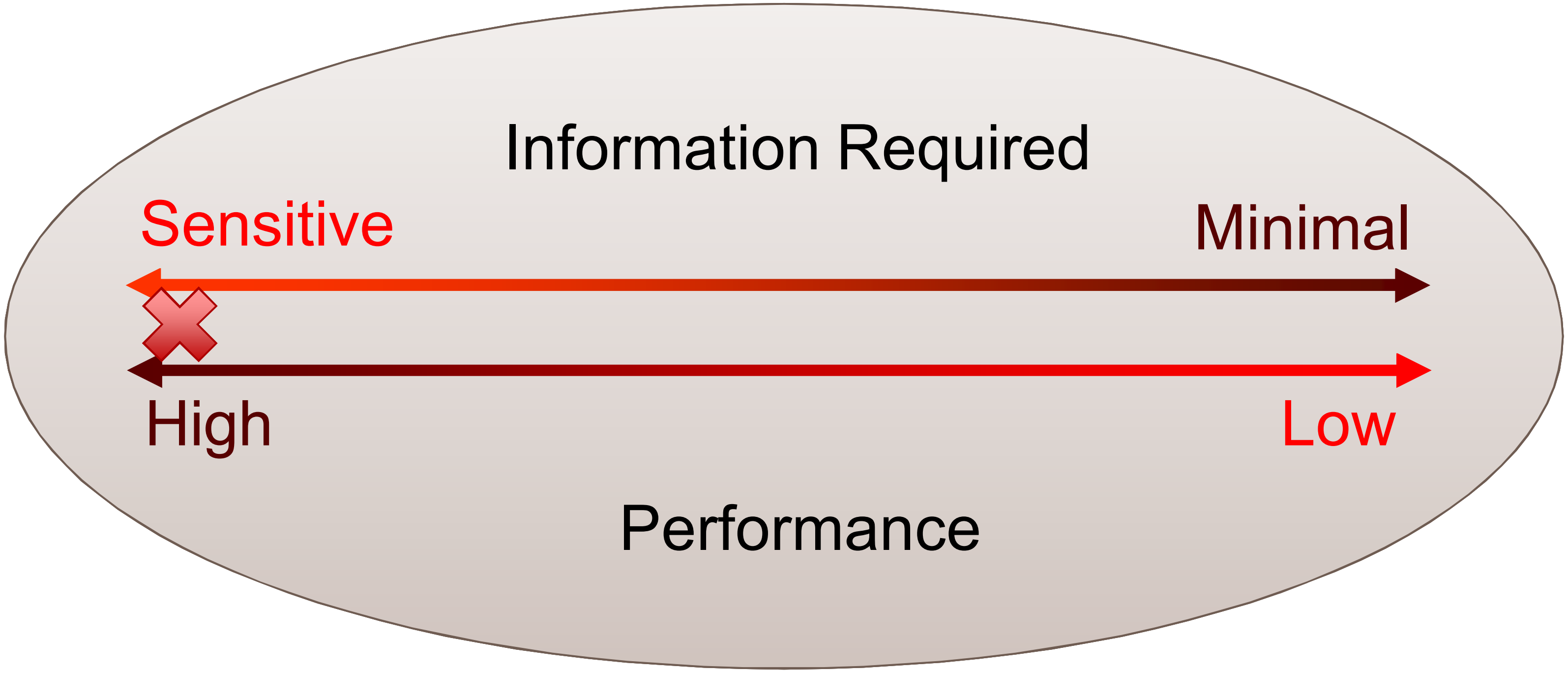
List-mode Ideal Observer

- Note about computation

$$\Lambda(\{A_n\}) = \int dc\, \Lambda(\{A_n\}\,|c) pr(c|\,\{A_n\})$$

Other Observer Models

Tradeoff



Other Observer Models

Hotelling Observers

- Ideal linear observer
- Computed on list-mode data
- Nuisance parameters are easily accounted for
- Template matching using templates that account for data correlations (across pixels)

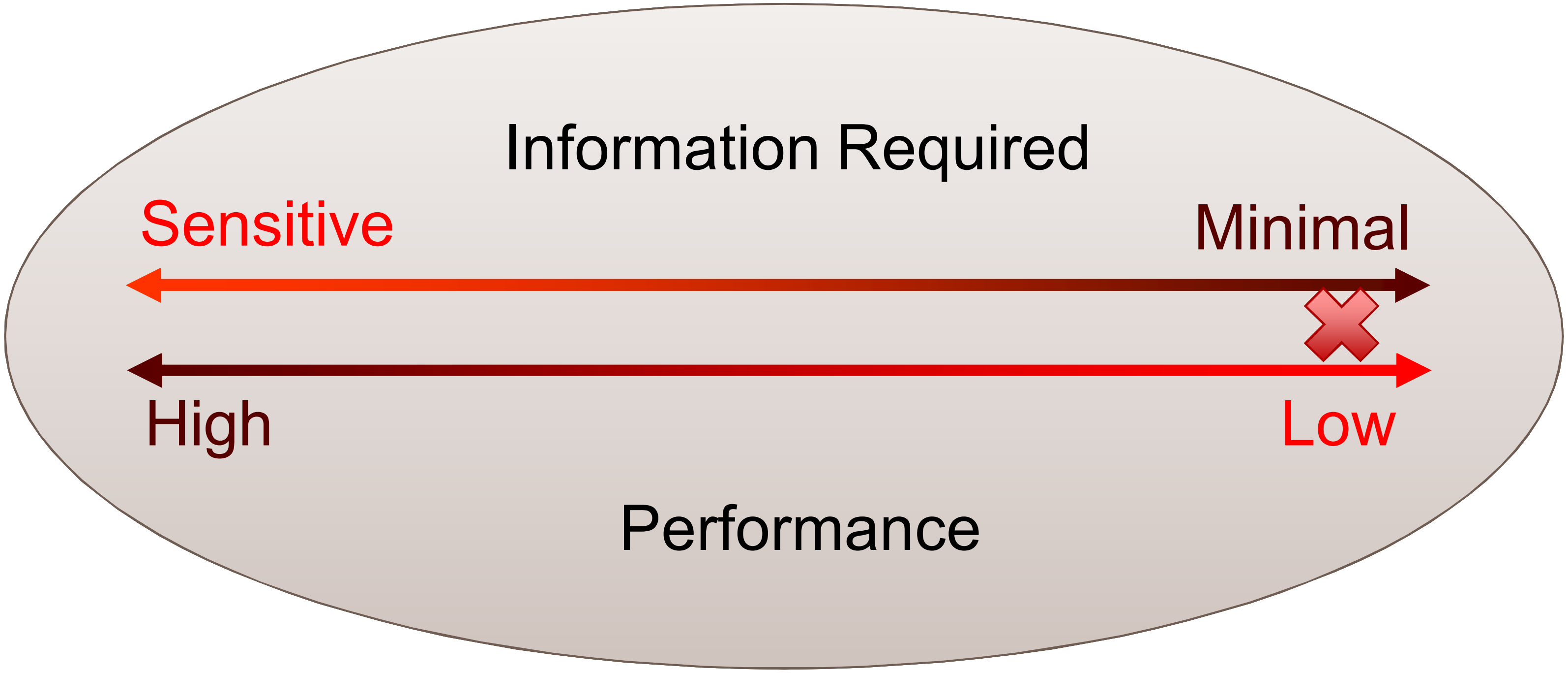
$$t = \sum_{n=1}^{N} \vec{w}^{\dagger} \mathcal{T}(A_n)$$

Template

Known, vector-valued function

Other Observer Models

Tradeoff



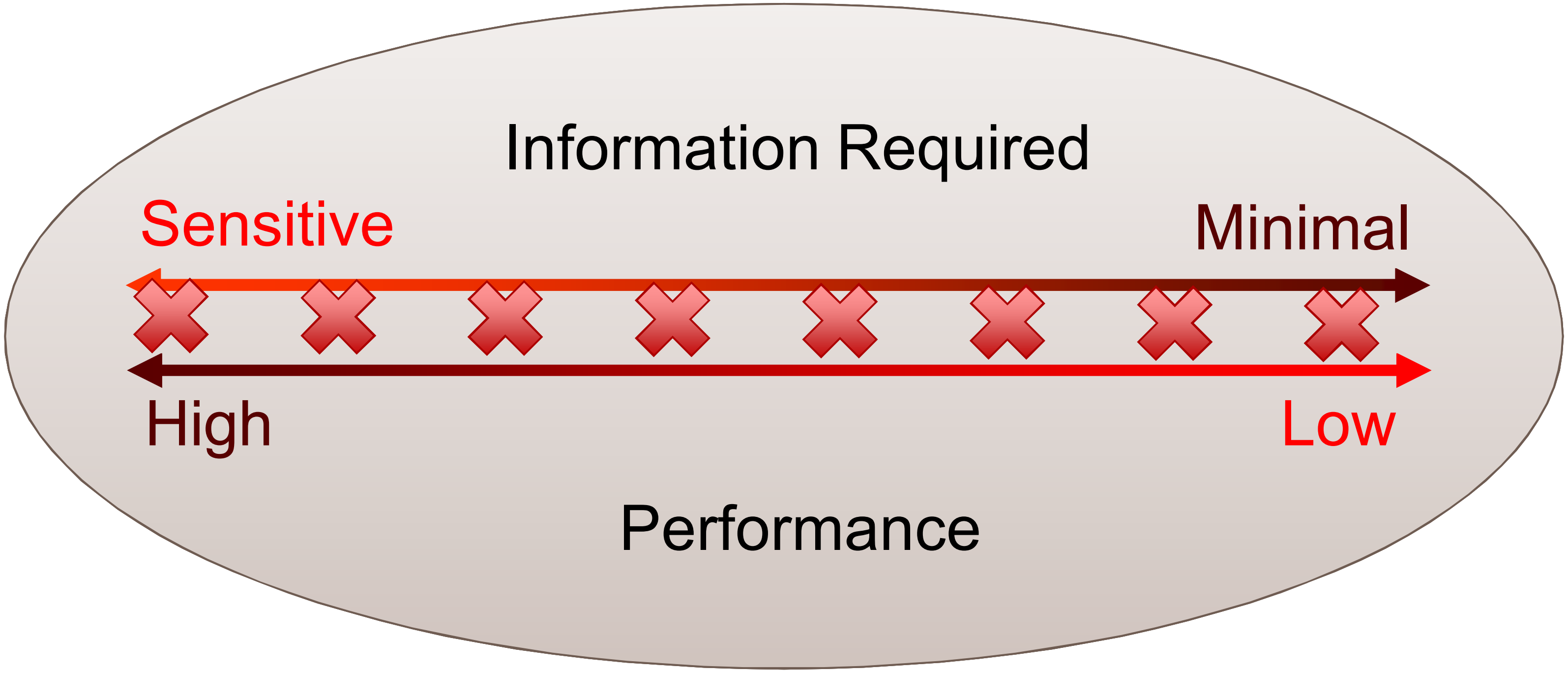
Other Observer Models

Scanning Observer Models

- Estimate and ignore or ignore nuisance parameters
- Related to ideal observer for combined detection/estimation tasks
- Simpler system models

Other Observer Models

Tradeoff



Agenda

Project overview and goals	Nathan Hilton
Introduction to neutron coded-aperture imager	Peter Marleau
Task-based imaging and observer models	Matthew Kupinski
Results from unclassified simulations	**Chris MacGahan** **Will Johnson**
Future directions	Will Johnson Chris MacGahan

Independent Project Review
of
Optimal Imaging for Treaty Verification

GEANT4 Simulation, Data Acquisition and Task Analysis

Christopher MacGahan and Will Johnson

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Introduction to Geant4

- Geant4 is a Monte Carlo particle physics simulation library
  - Primarily developed for high energy (collider) physics, but widely used elsewhere: medical, space, health and safety, radioactive source modeling, etc.
  - An open source library written in C++, with a very active worldwide development community
- We chose to use Geant over MCNP, FLUKA, or other choices because:
  - It provides a highly flexible solution, with 'hooks' at all stages and steps of the simulation to probe interactions, read out information, or influence simulation
  - Allows recording of data in format of users choosing
  - Can easily be extended with user or community developed packages
  - Allows fine-grained selection of physics simulated

Introduction to Geant4 (cont.)

- The selection of physics simulated is left to the user in Geant4, so the physics list we have chosen includes:
  - General Neutron Physics:
    - G4IonBinaryCascadePhysics, G4HadronElasticProcess, G4NeutronInelasticProcess, G4HadronCaptureProcess, G4HadronFissionProcess, G4NeutronHPElastic, G4NeutronHPElasticData, G4NeutronHPInelastic, G4NeutronHPInelasticData, G4NeutronHPCapture, G4NeutronHPCaptureData
    - These are the recommended physics lists for “low energy” neutron physics
  - Fission: Neutron Induced fission library from LLNL (G4FissLib).
    - Simulates produced final state neutrons and gammas (no nuclear fragments), due to neutron fission (<10 MeV),
    - Based on evaluated data libraries where available, models elsewhere

Introduction to Geant4 (cont.)

- Physics simulated (cont.)
  - Electromagnetic Physics:
    - Turned off for neutron processing (computational speed)
    - For gamma simulations use G4EmLivermorePhysics, which retains high fidelity to very low energies, and use G4EmExtraPhysics to cover electro- and photo-nuclear physics
  - Gamma emissions from radioactive decays:
    - Use our own library, SandiaDecay, based on ENSDF data
      - Allows custom aging and isotopic mixtures
      - Integrates with the GEANT geometry model for proper distribution of source gammas
      - Computationally very quick
      - Includes >3k nuclides

ROOT and Geant4

An Object-Oriented Data Analysis Framework

- Simulation intermediate and final results stored using the ROOT framework
  - ROOT is a C++ analysis framework produced primarily by CERN and Fermilab, which is optimized for large particle physics datasets
  - Data from detector is stored in ROOT format as well *(I believe)*
- Data stored to files is customized at each stage of the simulation
  - Structure of data stored is chosen to ensure data needed is available after simulation, but also to ensure good computational performance
  - Output of one stage of the simulation may be used as input to the next stage
  - To Do: Put in diagram of example structure of emissions from test object, then example structure of what gets recorded in the detector

Neutron Coded Aperture

- Pete has covered this I think. Perhaps show our Geant model, give its lineage, and list its weaknesses? Maybye say how we treat resolution and such?

INL Test Sources

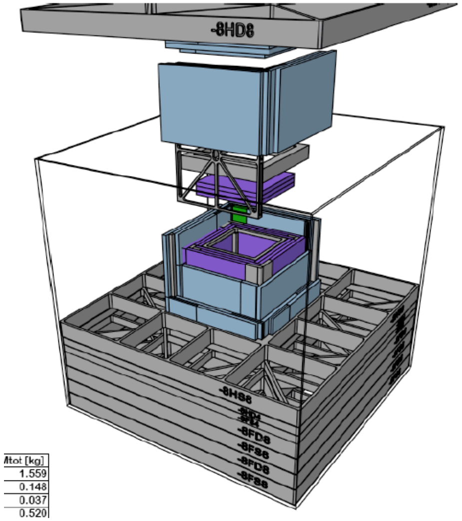
- We are using inspection object developed by Idaho National Lab as benchmark observation objects
  - Six inspection objects available:
    - IO#5: Composite shielding of HEU
    - IO#6: Composite shielding of DU
    - IO#7: DU shielding of HEU
    - **IO#8: DU shielding of PU**
    - IO#9: HEU shielding of PU
    - **IO#10:Composite shielding of PU**
  - Have modeled these inspection objects within GEANT4
  - See **Passive and Active Radiation Measurements Capability at the INL Zero Power Physics Reactor (ZPPR) Facility** http://www.inl.gov/technicalpublications/Documents/5028016.pdf

Outline

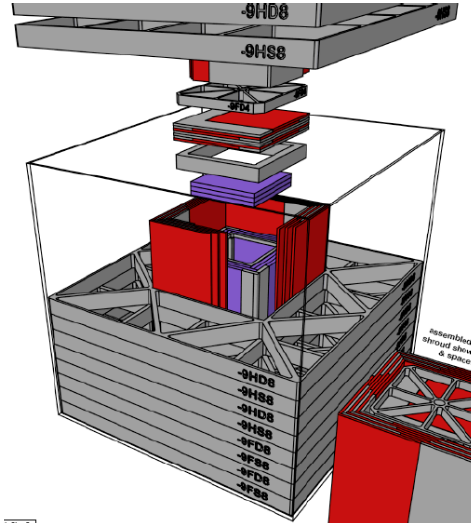
- INL sources
- Initial Simulation setup
- Simulation speed and variance reduction methods
- Detector Data, observer models and classification effectiveness

INL Sources

- We are using unclassified inspection objects in our GEANT4 simulations to acquire data and test observer models. Developed by Idaho National Labs



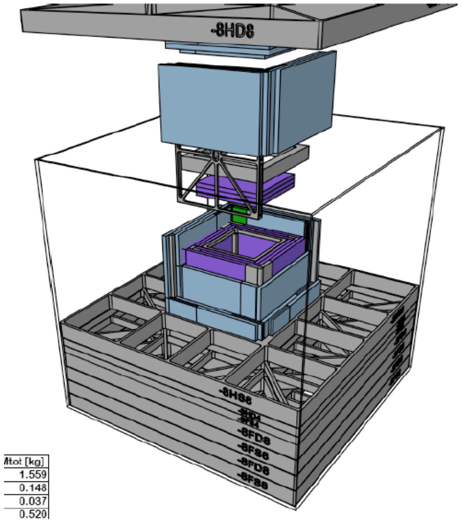
IO8 – plutonium shielded by depleted uranium shielded inside aluminum framework



IO9 – plutonium shielded by highly enriched uranium inside aluminum framework

http://www.inl.gov/technicalpublications/Documents/5028016.pdf

INL Source IO8



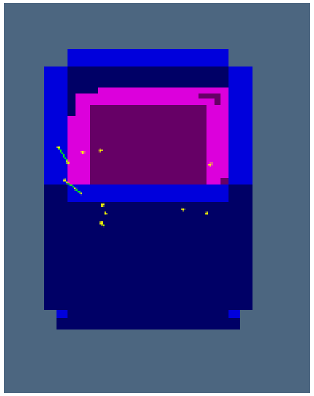
Sources follow similar cubic structure

Empty at center – 0 to 15/16"

source~15/16" to 1+5/16"

Inner shielding ~1+5/16"-1+11/16"

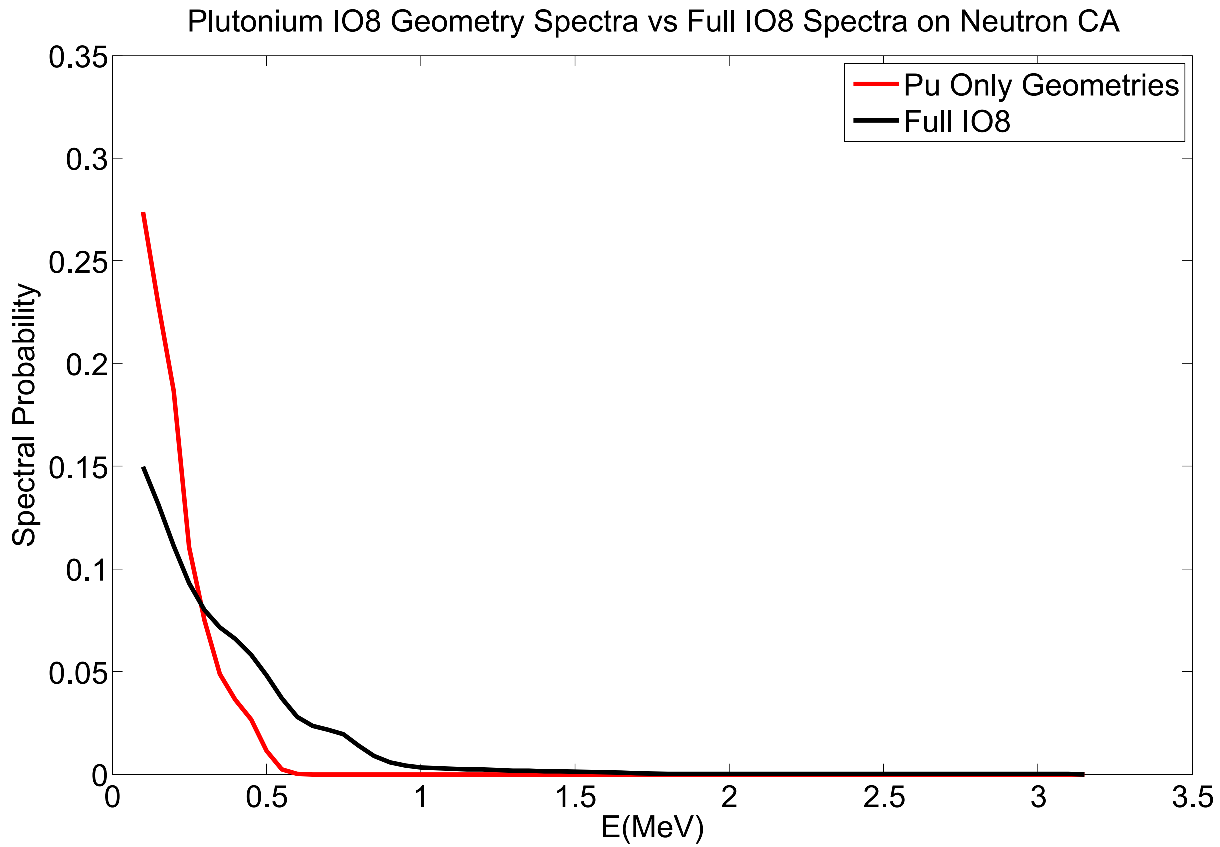
Aluminum stacks 1+11/16" to 4"



Example model in GEANT4 (without top shielding or aluminum stacks)

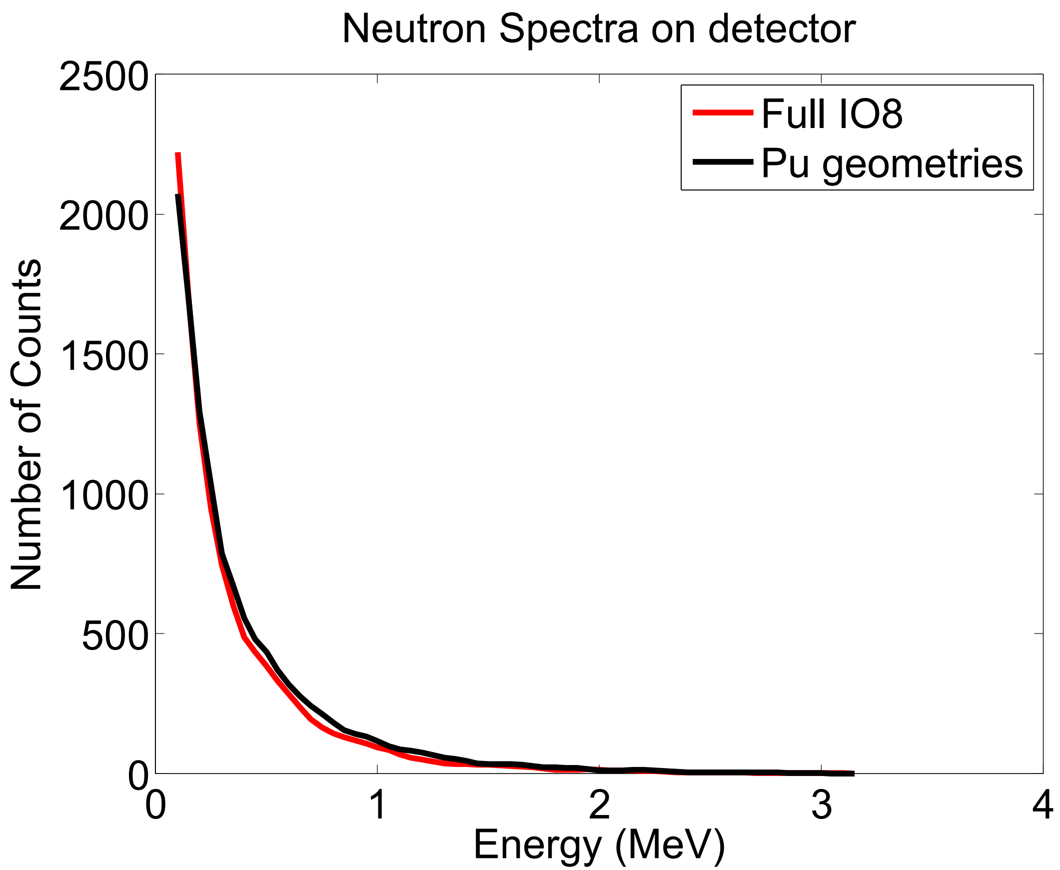
IO8 Gamma Spectra and Count Rate

Pu Geometries Only	Full IO8
Count Rate:1.06e5/s	Count Rate:6.4e3/s



IO8 Neutron Spectra and Count Rate

Pu Geometries Only	Full IO8
Count Rate:25.2/s	Count Rate:23.6/s



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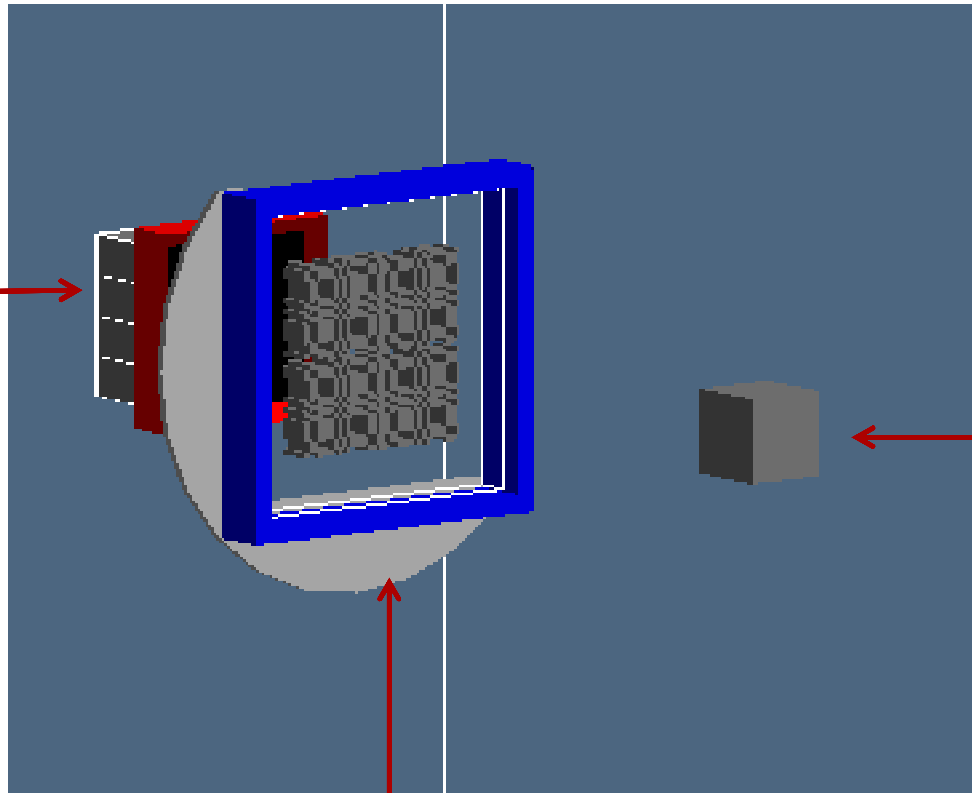
Outline

- INL sources
- Initial Simulation setup
- Simulation speed and variance reduction methods
- Detector Data, observer models and classification effectiveness

GEANT4 Initial Simulation Setup



GEANT4 Simulation Outline

- As discussed by Will, particle emission for neutrons and gammas is done separately. Neutrons emitted via G4LLNLFiss library and gammas from a separate xml database.

- We decided to separate the gamma and neutron simulations because of the disparity in activity and detection rate.

Outline

- INL sources
- Simulation setup
- Simulation speed and variance reduction methods
- Detector Data, observer models and classification effectiveness

Simulation Speed in GEANT4 (Gammas)

- Without biasing, one GEANT run imaging IO8 with 2e9 emissions leads to ~2 counts on the detector and takes roughly 20 hours to simulate. Corresponds to ~0.3ms wall time
- Ideally, we'd want ~400 hits on each pixel of detector. Would take 3.2e5 runs of GEANT4 or >6.4 million CPU hours.
- On top of that, we'd like to run numerous simulations for various orientations and locations to show the usefulness of our observer models

Variance reduction

We considered a few variance reduction techniques

- Primary particle biasing – energy, position, momentum space
  - Bias particles towards the outside of source
  - Bias particles towards detector
  - Bias towards higher energies
- Geometric Importance Sampling and Weight Windowing
  - Parallel mesh geometry created. Particles are split after traveling 1/e length. Goal is to make as many particles as possible count
- Simple Energy cutoff
  - Plutonium has significant peaks at 60keV and 26 keV that do not reach scintillator. Cutoff could be useful.

Chosen Biasing and Current Speed

- 100keV cutoff provides about 3 order of magnitude speedup with no effect on output in energy region of interest
- In addition, a linear energy bias is applied. This is soft enough to avoid complications, but provides about a 3-4x speedup depending on the source

VR method	CPU hours required	speedup
none	6.40E+06	1
100keV cutoff	17200	372
100keV cutoff + linear E bias	4800	1333.33333

- After biasing + cutoff, about 200 2e9 runs are necessary to gain enough IO8 data for detector. Each run ~24 hours. 4800 hrs of computation time
- About 2 weeks of runs on 2 lab servers with 8 cores each

Simulation Speed in GEANT4 (Neutrons)

- Without biasing, one GEANT run imaging IO8 on the neutron detector with 1e8 fission events leads to ~1.3e5 counts on Neutron CA and takes roughly 120 hours. Corresponds to about 80 minutes wall time. About 6 runs would fulfill desired neutron counts on detector.

- Neutrons are not charged and do not easily interact with matter. The large majority of neutrons emitted from the source escape. Low Z materials such as the detector's liquid scintillator and Polyethylene(mask) absorb energy. Primary particle biasing other than directional biasing is therefore unhelpful

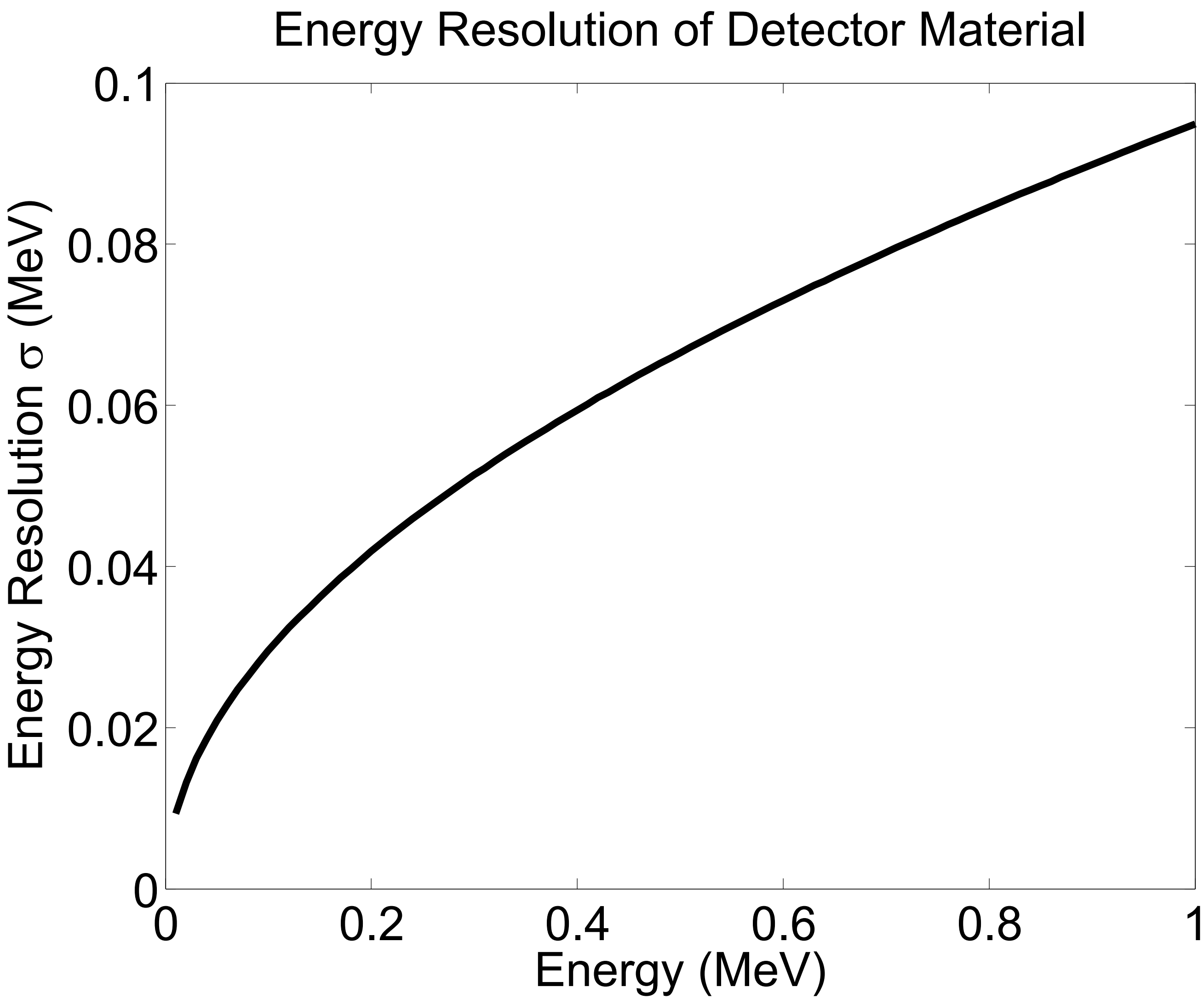
Detector Response

- 40x40 pixel detector matrix is broken into 4x4 blocks. For a single event, many particles will be absorbed in different locations. Total block energy is binned into mean pixel location.

- Absorbed Gammas and electrons are read in as gamma data. Absorbed protons are read in as neutron data

- There is currently no user code to incorporate misclassification of particles

Detector Response Energy Resolution



Splitting up Simulations

- Source of potential improvement– significant computation time was spent in particle transport through the INL source.
- About 16 hours necessary to take list-mode gamma data to detector vs 4800 hours to simulate source data
- About 3 days necessary to take list-mode neutron data to detector vs 24 days to simulate source data
- -Requires hefty storage (100GB-400GB per source)

New Simulation Flow Chart

RadioActive Decay(gamma) emission to spherical surface
- -Outputs List-mode data on flux detector
- -Energy Biasing incorporated
- -100keV minimum emission (reduces low E emissions that won't escape and drastically increase simulation time)

Spontaneous Fission (gamma + neutron) emission to spherical surface
- -Outputs List-mode data on flux detector
- -No Energy Biasing – most particles escape
- -No minimum energy incorporated due to low E neutron Fission

↓

List Mode to detector
- Takes list-mode flux source data in as input
- Processes to fast neutron CA
- Outputs list-mode detected particle info to file

↓

Detector Response Code
- -Takes list-mode Detection data, finds weighted detection position
- -Outputs histogram on counts over 40x40 pixel image plane binned by energy
- -Outputs critical MCNP statistical checks
- -explained in following slides

↓

MATLAB observer models performed

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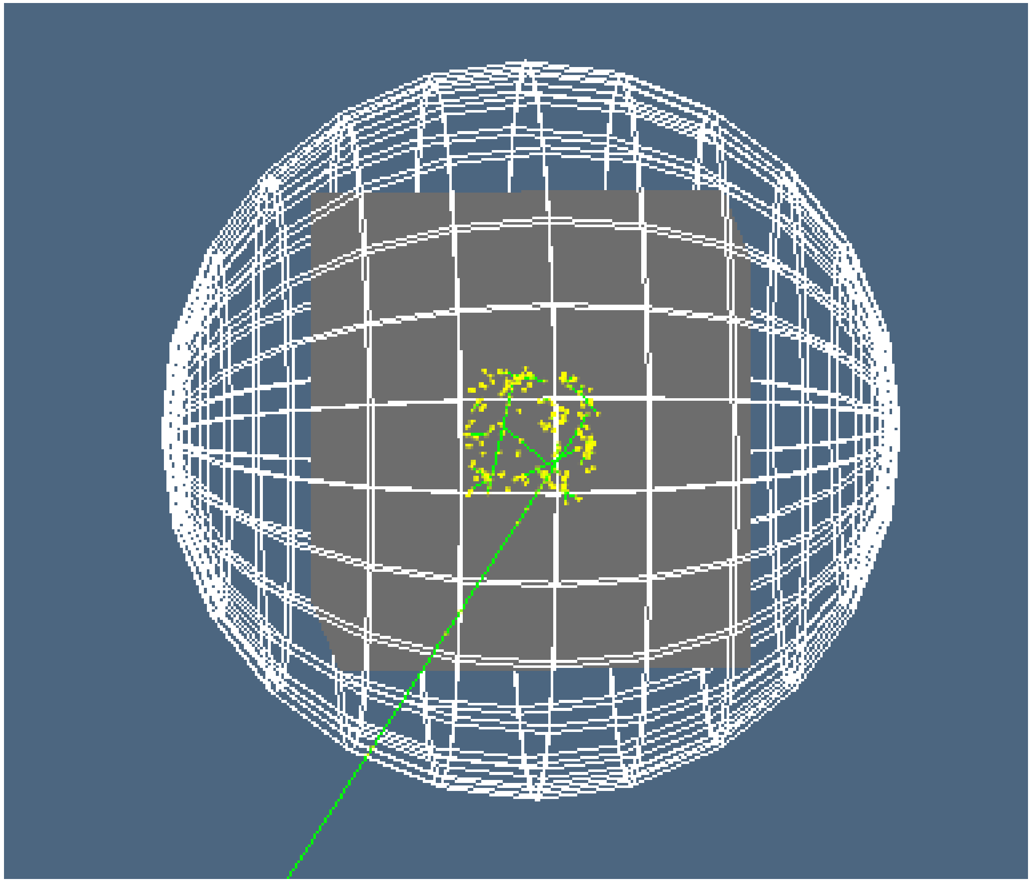
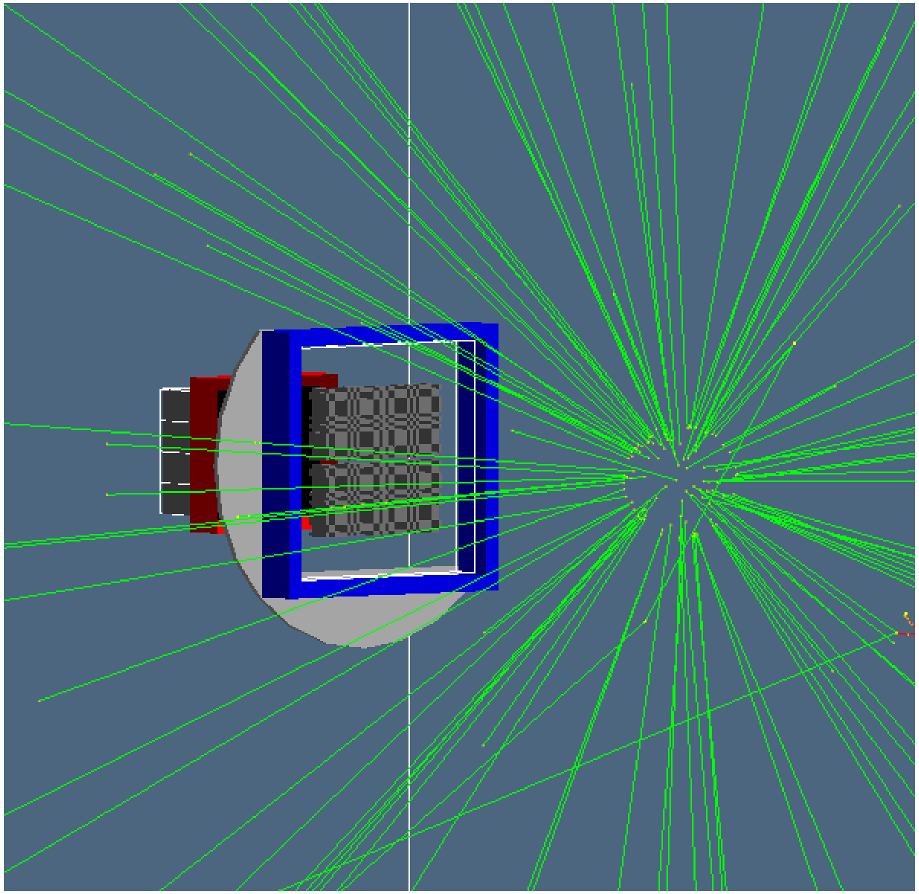
Source to Spherical Detector

This simulation uses the energy cutoff and energy bias



Spherical List Mode Data to NeutronCA

There is no biasing in this simulation.



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Multithreaded GEANT4

- Significant time has been lost resimulating sources due to user error.
- GEANT4.10, offers a multithreaded build. GEANT4MT incorporates event level parallelism – all track information is stored in separate threads.
- All user actions and the sensitive detectors are stored in separate threads. Aside from standard migration changes, only required extra code was thread locking in ROOT input/output

Running on Sandia Servers

- Running on sandia "glory" cluster – 272 nodes with 16 processors per node

INL source gammas to sphere w/MT build on Sandia server

threads	emissions	real time	speedup
1	5.00E+07	3543	1
4	5.00E+07	934	3.793361884
8	5.00E+07	514	6.892996109
12	5.00E+07	390	9.084615385
16	5.00E+07	345	10.26956522

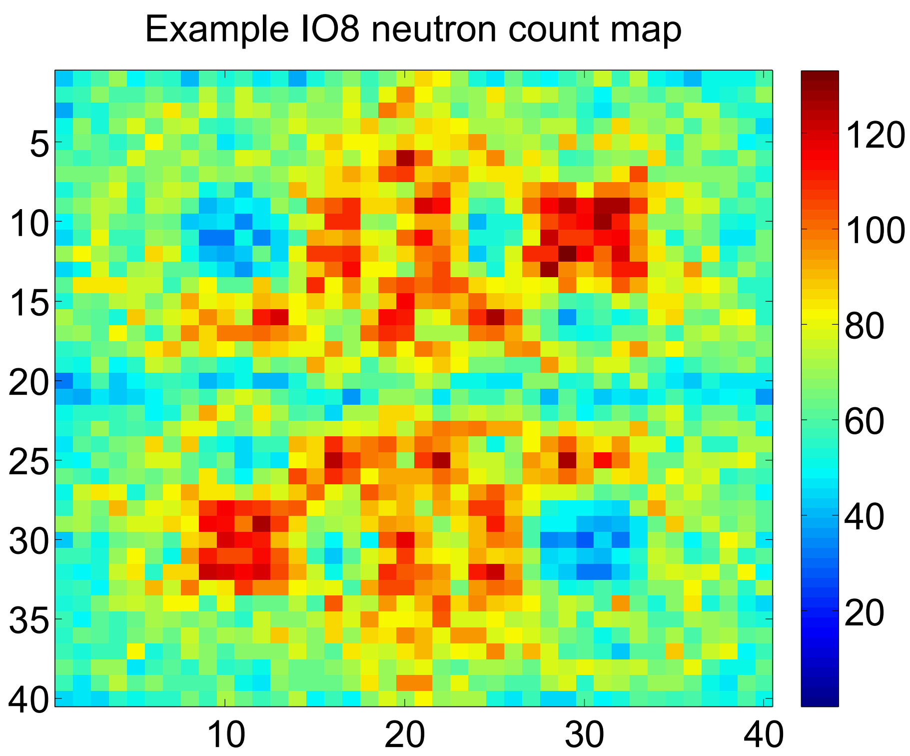
Similar speedup for neutron INL source simulation and neutron detector simulation. We are working on improving gamma detector simulation speed

Outline

- INL sources
- Initial Simulation setup
- Simulation speed and Variance Reduction Methods
- Detector Data, observer models and classification effectiveness

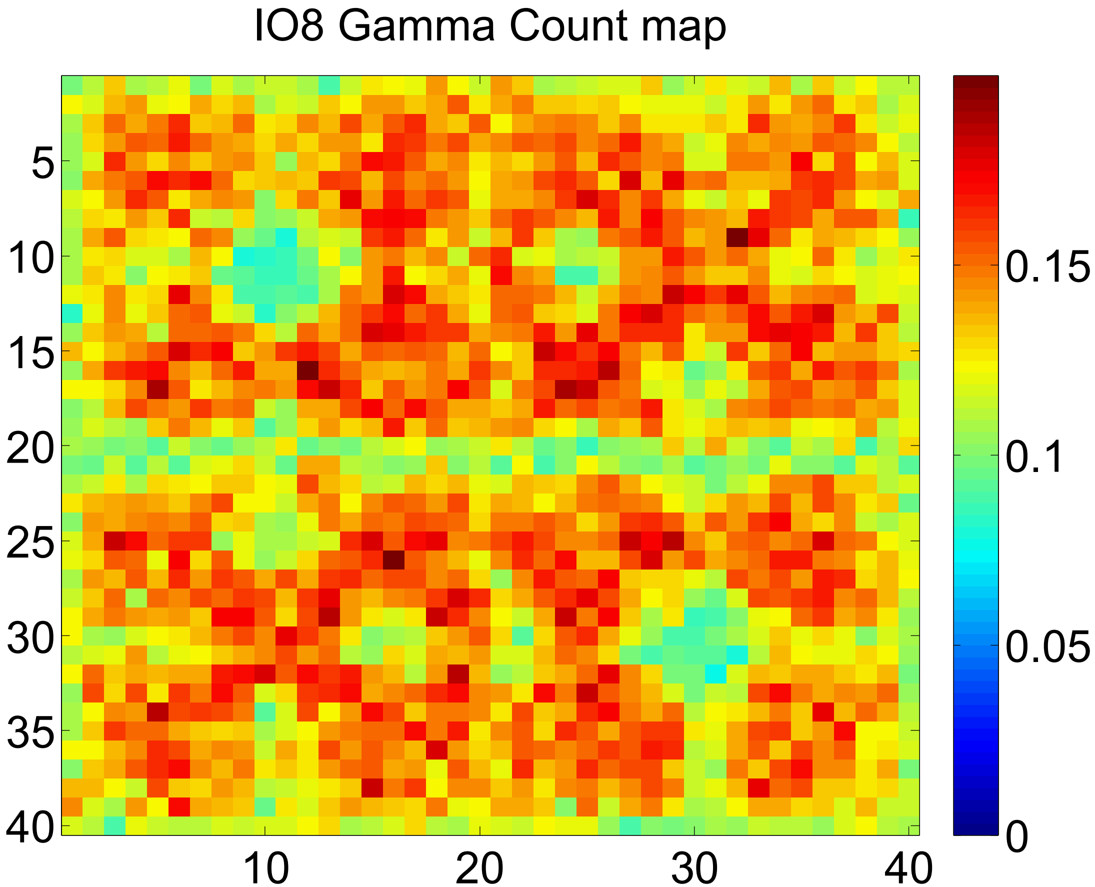
Results -Neutron Count Map

Neutron count map for centered IO8 2.3m from detector



Results – Gamma Count Map

- IO8 gamma count map for source centered on detector
- Note: colorbar shows sum of biased weights



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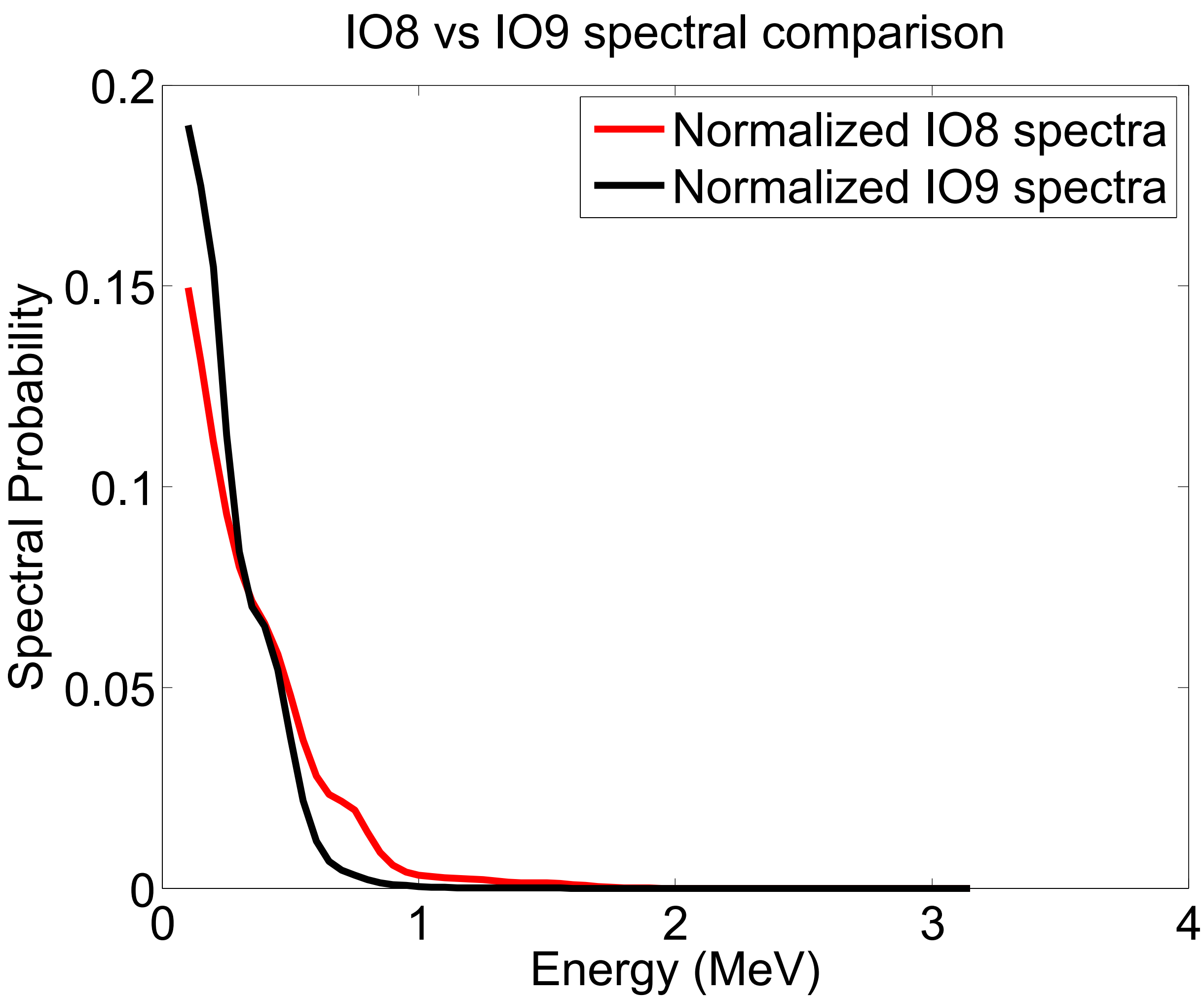
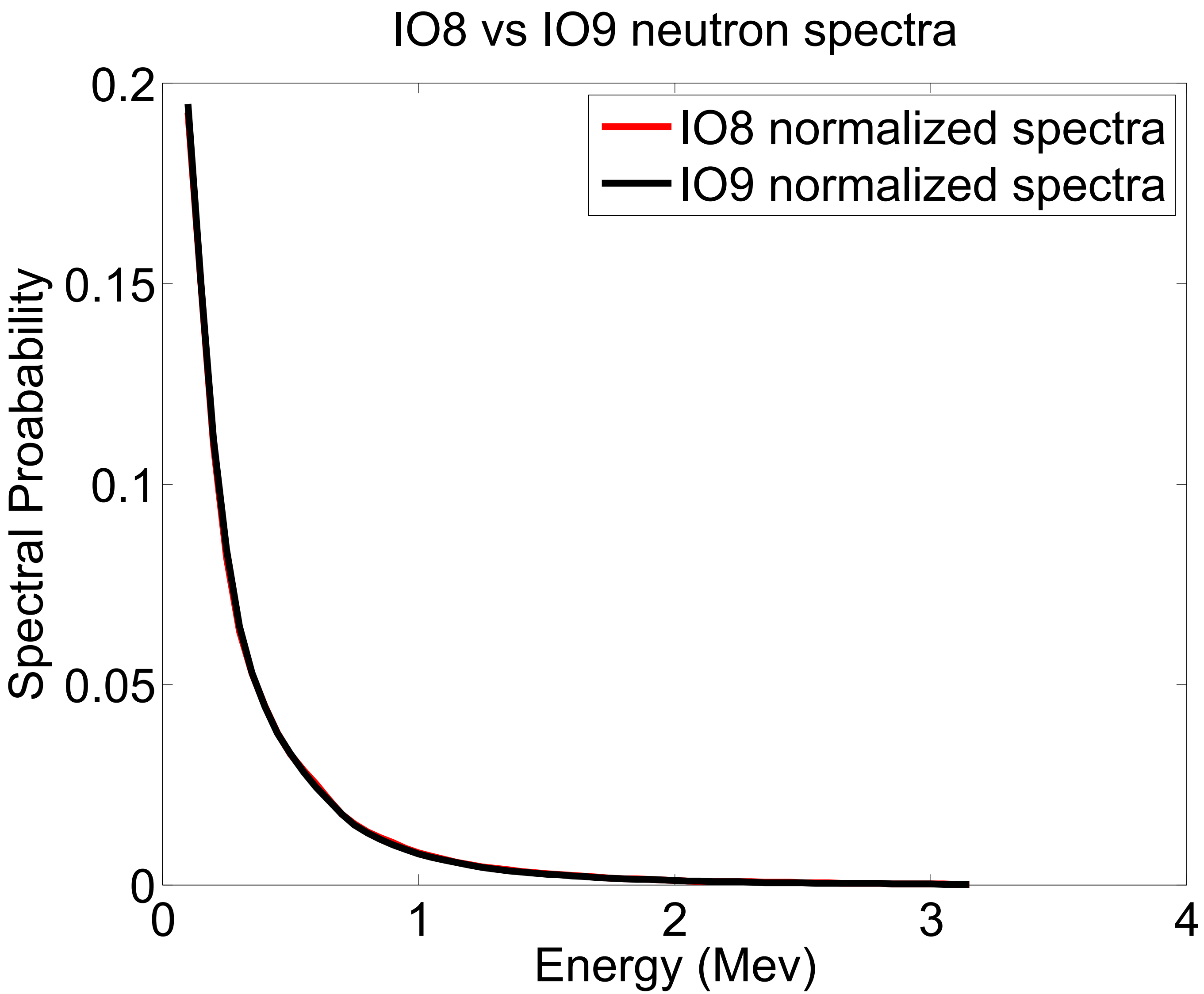
Results – IO8 vs IO9 Gamma Spectra



Results – IO8 vs IO9 Neutron Spectra



Task based imaging

- An observer, human or mathematical, is required to perform a task

- Standard detection theory methods are used to evaluate tasks, specifically area under ROC curve.

Classification studies

- There are many different classification tasks we wanted to look at
- A) correctly classify two different sources under known orientation, position,location. Show observer model capability with heavy background.
- B) Study observer performance with nuisance parameters, both under the signal known exactly model and generalized model
  - orientation variability (unknown orientation of source material in container)
  - Count rate variability (unknown age)
  - Position variability (unknown position)
- C)Compare single source vs multiple sources

Observer Models

- We will look at a few observer models
- SKE – signal known exactly probability model. Sample data is taken from a specific orientation, location and activity and classified with a model that has this information
- Generalized versions of the SKE model – integrated over orientation and activity rate
- Hotelling Observer – Uses only mean and variance of counts in each bin to make decisions (not ready yet)

SKE observer

$$\Lambda(\vec{g}) = \frac{pr(\vec{g}|H_2)}{pr(\vec{g}|H_1)} = \frac{pr(N|H_2)}{pr(N|H_1)} \prod_{i=1}^{N} \frac{pr(g_i|H_2)}{pr(g_i|H_1)}.$$

In the signal known exactly case, there are two components to the observer model:

1) A poisson component on the number of counts hitting the detector in the two hypothesis
2) A spectral probability component for each energy that hits a pixel

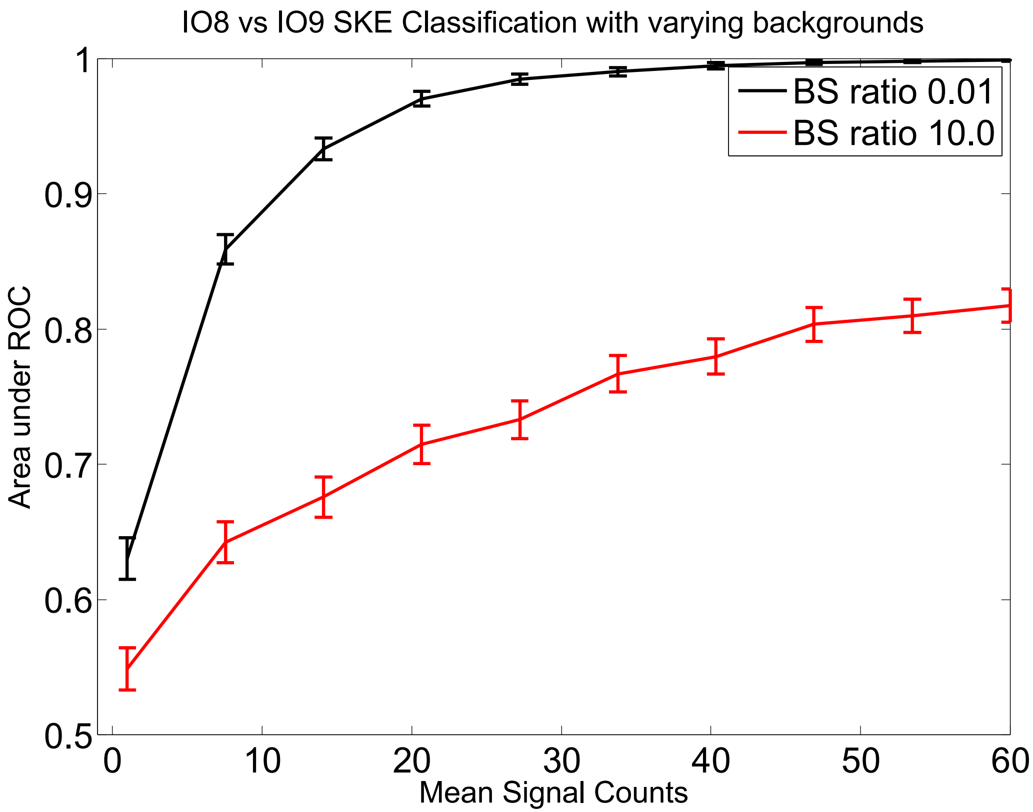
Generalized Ideal Observer Model

$$\Lambda(\vec{g}) = \frac{pr(\vec{g}|H_2)}{pr(\vec{g}|H_1)} = \frac{\int d\overline{N_2}\, pr(N|\overline{N_2})pr(\overline{N_2})}{\int d\overline{N_1}\, pr(N|\overline{N_1})pr(\overline{N_1})} \prod_{i=1}^{N} \frac{\int d\theta\, (2\pi)^{-1} pr(g_i|H_2,\theta,N)}{\int d\theta\, (2\pi)^{-1} pr(g_i|H_1,\theta,N)}$$

This observer averages over source orientation and activity rate.

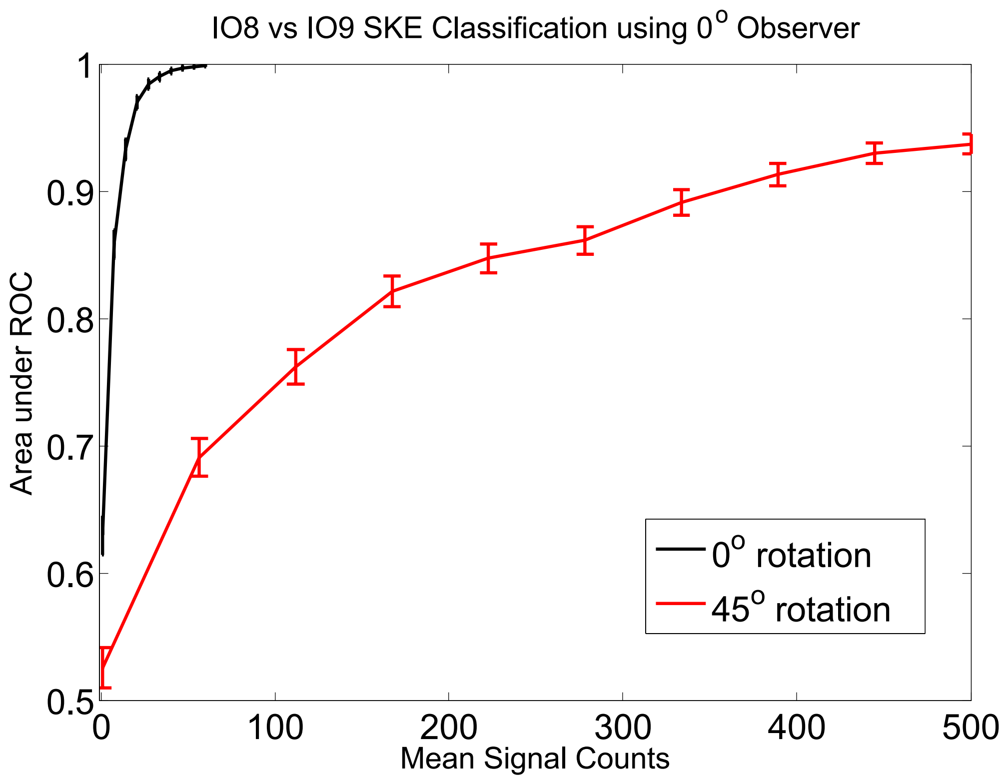
The following example will look at an observer that averages over two orientations – a standard orientation of the INL source and a 45 degree rotation

SKE Observer Results with Background



Background plays a significant role in gamma classification ability.

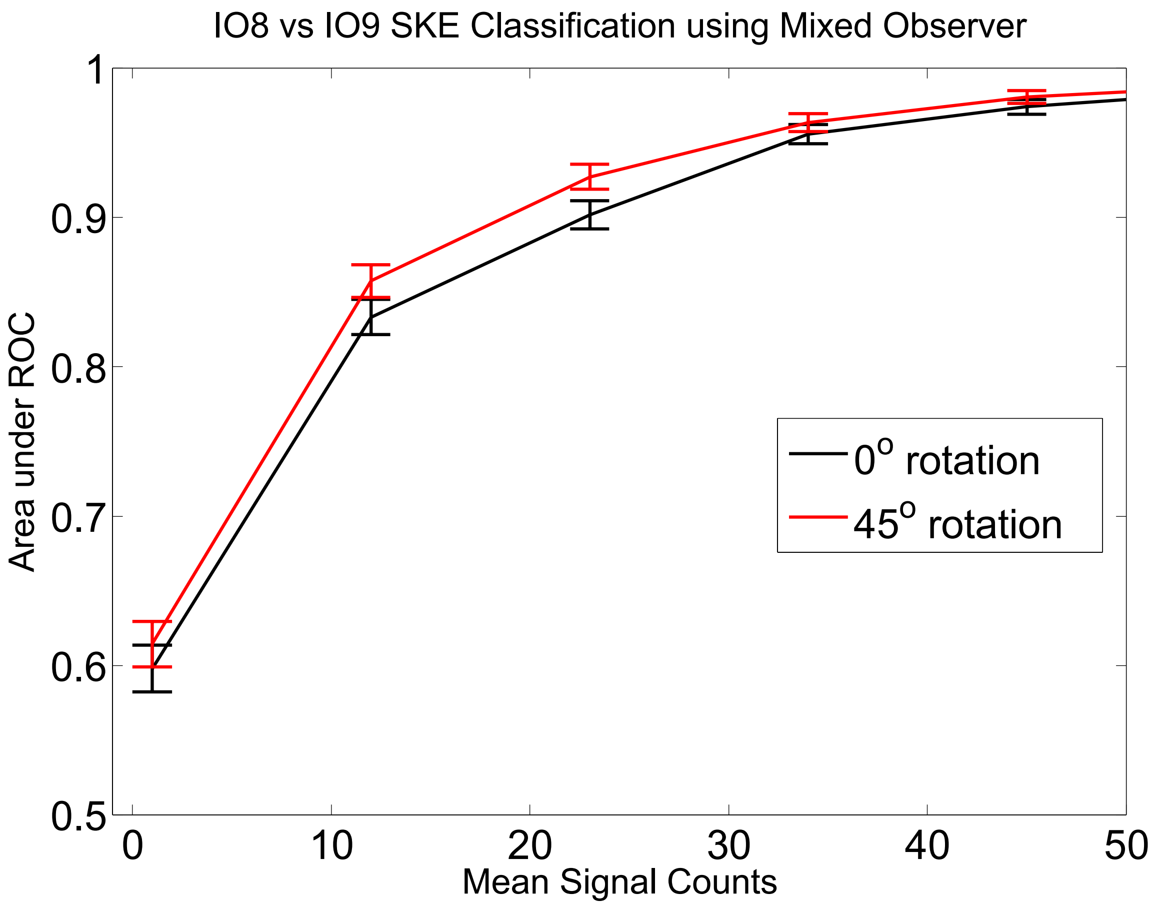
SKE observer Results (gammas only)



When the object matches the orientation of the observer, the results are significantly better than when the object is rotated

Generalized Observer Model

With observer model averaged over 2 orientations, performance improves



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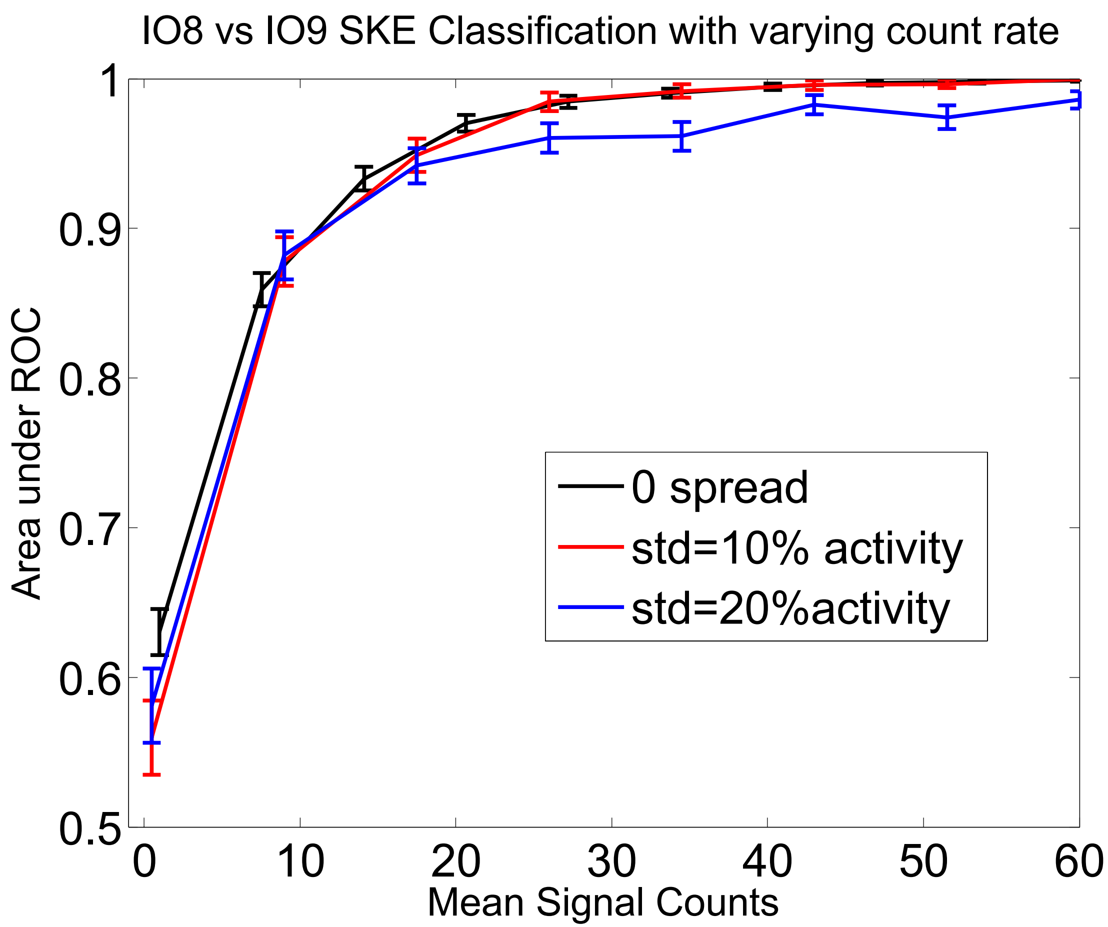
Observer With Count Rate Variability

As assumed spread in count rate of sources increases, performance drops



Agenda

Project overview and goals	Nathan Hilton
Introduction to neutron coded-aperture imager	Peter Marleau
Task-based imaging and observer models	Matthew Kupinski
Results from unclassified simulations	Chris MacGahan Will Johnson
Future directions	**Will Johnson Chris MacGahan**

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Neutron Classification Tasks

- While all of the methods exist to do neutron classification (or a perfect PSD classification task that uses both neutron and gamma data) simulation has just been too slow to produce plots. Multithreaded build will help greatly in bringing second simulation down to a reasonable timeframe.

Imperfect Pulse Shape Discrimination

- PSD is assumed to be perfect at the moment – Gammas always classified as gammas and neutrons always classified as neutrons.

- Algorithms actually use different parameters of the pulse to classify particles. These algorithms are not perfect and misclassifications occur. We hope to use detection theory methods to help optimize particle classification

- Imperfect PSD will be incorporated in the detector response stage and will be accounted for in the observer models

Generalizing Observer Models

- Code put on server right before review
- Should allow fast processing of hundreds of locations/orientations

- We are currently looking into ways of interpolating data between different nuisance parameters in order to avoid executing too many simulations.

- IO location – if object is centered in FOV and far enough from detector, maybe shift invariant approximation can be made. But, these imaging systems are not linear – neutrons and gammas from source A interact with source B.

Comparison to Real Data

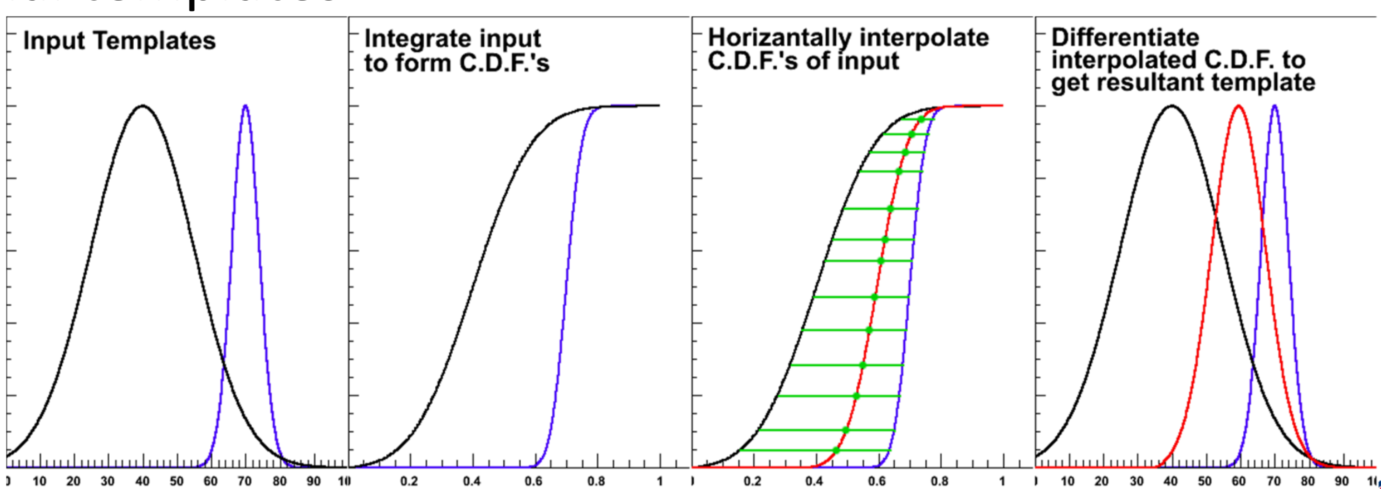
- As of now we have very little in the way of real data on these INL sources. We need a real life study to compare with the GEANT4 model to corroborate our simulations.

Homomorphic Cryptosystems

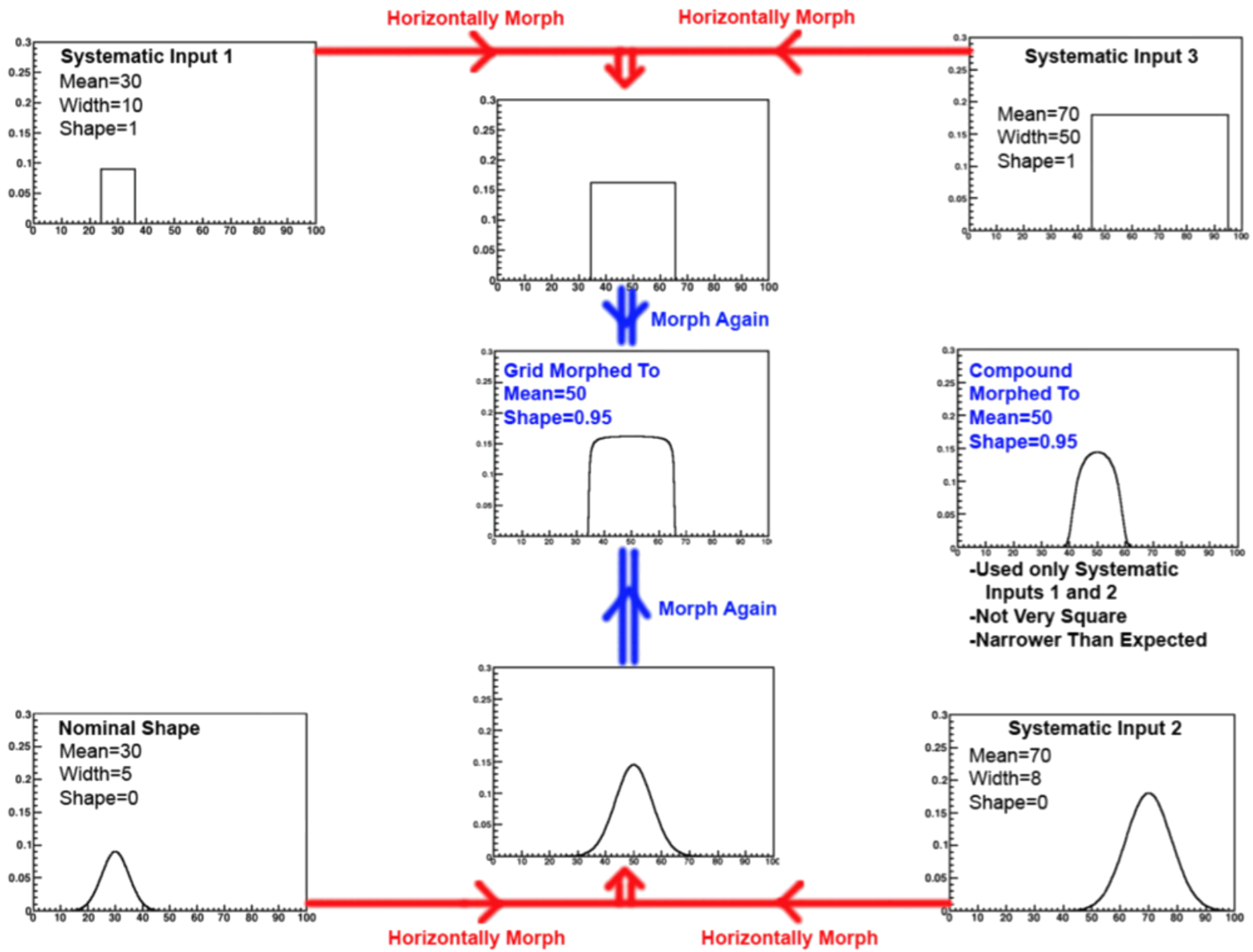
- A major challenge of this project is to keep the information used in the analysis unclassified. One alternative is to instead encrypt the information coming from the detector, and perform the analysis on the encrypted data.
- Homomorphic encryption is a way to perform calculations on encrypted data, without de-crypting it
  - In our case the encrypted data may be energy (or other distributions) templates for sensitive devices, hit positions, etc.
  - Would process data from the detector in list mode still, but allow using potentially sensitive templates, PDFs, or otherwise
- **TODO: finish filling in this section; give references, and flow chart example claculation**

Interpolation of Template Histograms

- In order to account for nuisance parameters, its computationally infeasible to simulate each combination of potential variations of nuisance parameters.
  - Ex: each potential position and orientation of the device, detector response variations, background uncertainties, shielding assumptions, etc.
- Instead we will interpolate between simulated templates as well as "morph" differences variation of parameters would cause onto nominal templates



Template morphing (cont.)



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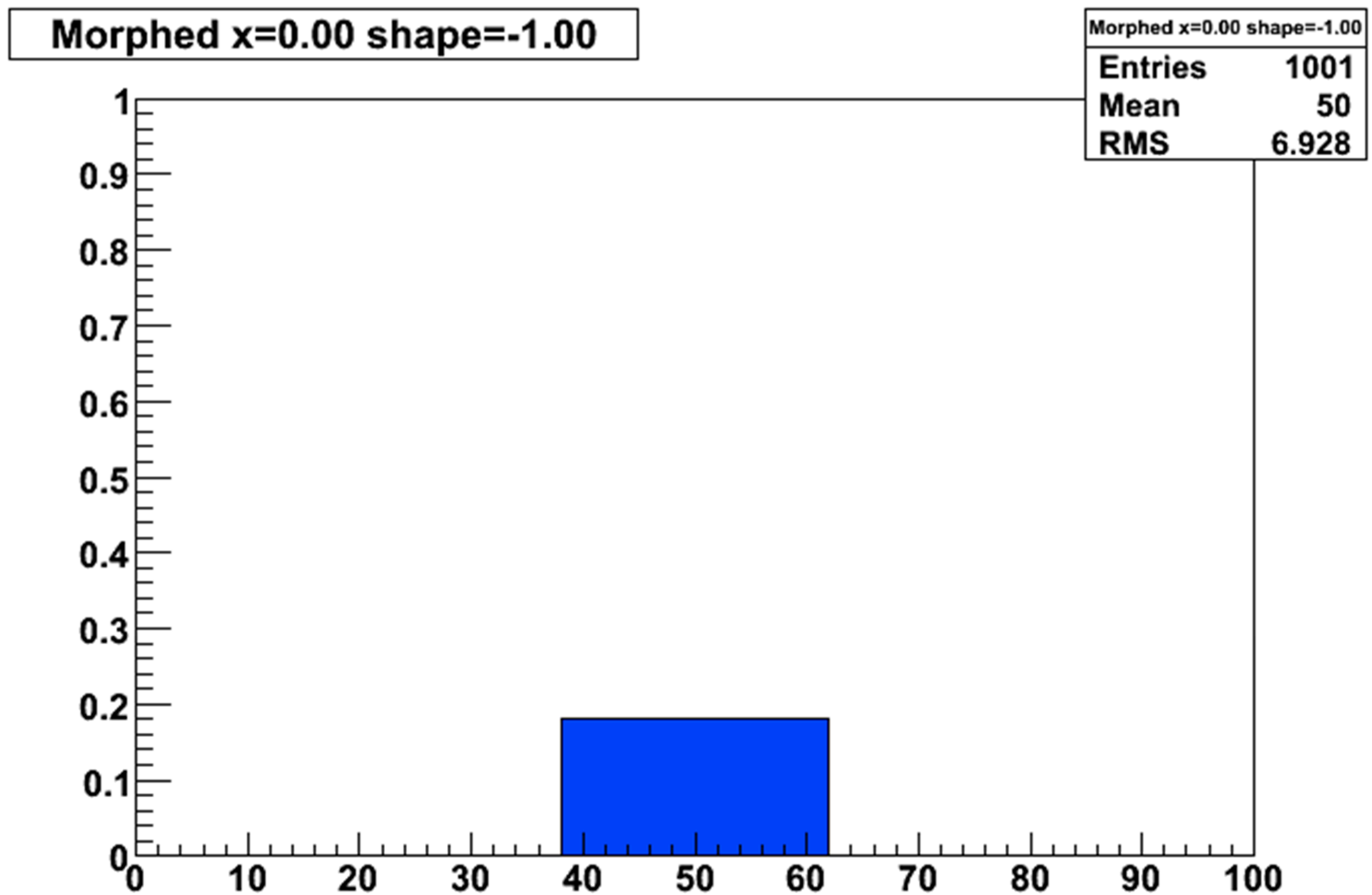
Template morphing (cont.)



Extra Slides

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Primary Particle Biasing

- New sampling distributions are created to sample from more interesting sections of the source phase space/energy spectra.
- However, to maintain accuracy in detector data, each particle needs to be weighted such that the sum of the weights in a given pixel/energy bin are the same.

$$weight\ (r) = \frac{probability\ of\ sampling\ r\ from\ old\ distribution}{probability\ of\ sampling\ r\ from\ new\ distribution}$$

$$= \lim_{\Delta r \to 0} \frac{\int_{r-\Delta r}^{r+\Delta r} pr(r)_{old}\, dr}{\int_{r-\Delta r}^{r+\Delta r} pr(r)_{new}\, dr} = \frac{pr(r)_{old}}{pr(r)_{new}}$$

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Evaluating Variance Reduction

- To evaluate, statistical checks were taken from MCNP software. Best to our knowledge, these have not been implemented in GEANT4:
- Relative Error (std of weights/mean weight) <0.05
- Variance of the variance < 0.1
- 8 more, but relative error was check used in our simulations
- This IS important – too few counts on one pixel could lead to overly certain observer model

- Figure of Merit we'll use is time required to get the same mean RE across all pixels

Primary Particle Biasing

- Position, momentum and energy biasing were all considered and tested. Ultimately, the speedup offered by biasing seemed to be roughly 25x for a simple spherical HEU source. INL sources would probably offer slightly greater improvement.

VR method	CPU hours required	speedup
none	6.40E+06	1
primary particle	2.56E+05	25

- Care needs to be taken to avoid too much biasing – ie when energy biasing, we may be more interested in emitted energies around 600keV to 1MeV, but lower energy emitted gammas can also reach the detector and their weights will be high and throw off the histograms. Too much biasing could therefore slow down simulations. Similarly, gammas emitted away from the detector that end up with a high weight can scatter back to the detector

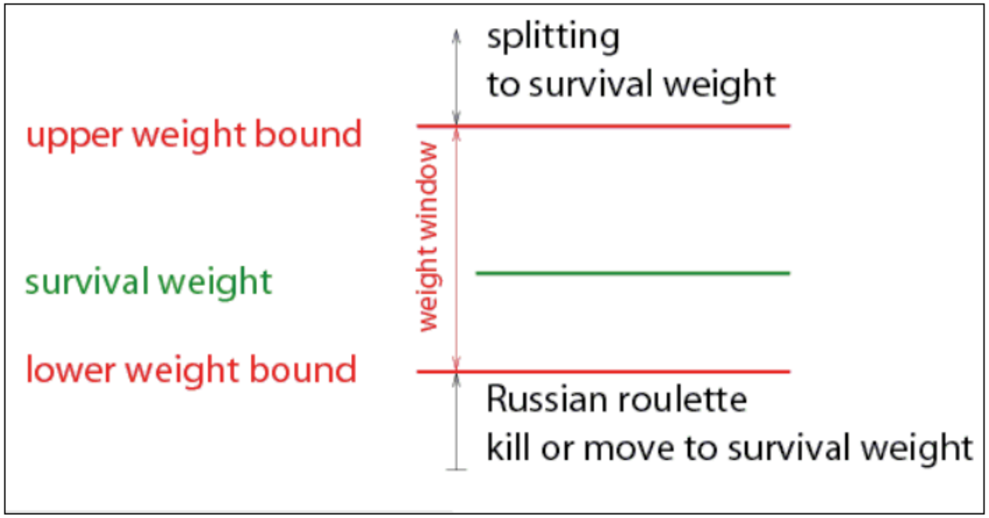
Geometric Importance Sampling

- Goal: Increase number of particles in geometries that are interesting
- Divide geometry up into importance cells, label with importance value
- At boundary, R=Imp2/Imp1
- R>1 – split into R tracks, reduce weight for each track
- R<1 – kill with probability 1-R

- GEANT allows user to set up second geometry “mesh” to define geometries and importance values

Weight Windowing

- User defines Lower Weight Bound, Survival Weight Factor, Upper Weight Factor.
- Upper Weight bound = LowWeightBound*UpperWeightFactor
- SurvivalWeight= Lowweightbound*SurvivalWeightfactor



- Supposed to help control weight fluctuations introduced by other VR techniques

IS + WW Speedup Results

Simulations were done on a spherical geometry, prior to implementing INL sources. Best efforts led to a slight slowdown vs primary particle biasing case

VR method	CPU hours required	speedup
none	6.40E+06	1
primary particle	**2.56E+05**	**25**
IS+WW	5.12E+05	12.50
IS+WW+PP	4.26E+05	15.00

GEANT correctly splits particles and weights at geometry. However, user code was necessary to separate the split particles – otherwise, all weights will be added at the detector stage. We wanted weights to be viewed by independent events.

Energy Cutoff

- Best case scenario from Primary particle + IS biasing was 25x speedup. Leads to about 250,000 CPU hours to simulate IO8. Not even close to what we need

- Most interesting features of gamma spectra are above 200keV + there is a quarter inch lead plate in front of detector pixels that blocks most particles sub 200keV (corresponds to roughly 7 path lengths)

- So, we decided to implement a 100keV cutoff.

Energy Cutoff

Example plutonium object:

- Pu239 takes up 185g of this which corresponds to an isotope activity of 11.48Ci (unbiased)
- Pu240 takes up 8.0g of this which corresponds to an isotope activity of 1.83Ci (unbiased)
- Pu241 takes up 0.9g of this which corresponds to an isotope activity of 102.17Ci (unbiased)

Largest Emission Lines by intensity:

- PU241 -Adding 59.54 keV gamma at unbiased intensity 27.3287/second
- PU241 -Adding 26.35 keV gamma at unbiased intensity 1.82699/second
- PU239 -Adding 51.62 keV gamma at unbiased intensity 0.115553/second
- PU241 -Adding 33.2 keV gamma at unbiased intensity 0.0959168/second
- PU241 -Adding 43.42 keV gamma at unbiased intensity 0.0555709/second
- PU240 -Adding 45.244 keVgamma at unbiased intensity 0.0305252/second
- PU240 -Adding 104.23 keV gamma at unbiased intensity 0.00480264/second
- PU241 -Adding 98.97 keV gamma at unbiased intensity 0.0154533/second
- PU241 -Adding 102.98 keV gamma at unbiased intensity 0.0148465/second

- PU241 -Adding 208 keV gamma at unbiased intensity 0.007452/second
- PU239 -Adding 375.05 keV gamma at unbiased intensity 0.00659697/second
- PU239 -Adding 413.71 keV gamma at unbiased intensity 0.0062234/second
- PU239 -Adding 345.01 keV gamma at unbiased intensity 0.00236031/second
- PU239 -Adding 332.85 keV gamma at unbiased intensity 0.00209711/second