

Mathematical Methods for Treaty Verification without an Information Barrier

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Outline

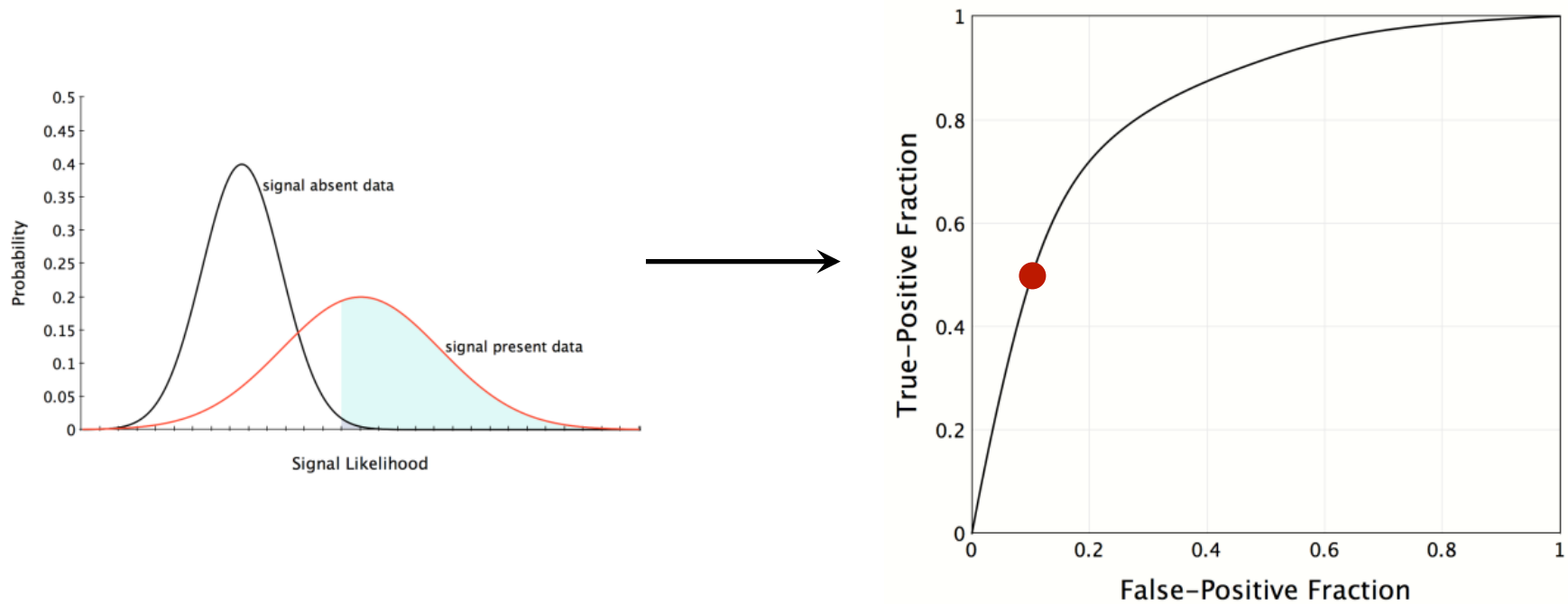
- Introduction to task-based imaging
 - Threat detection example
- Approach to arms-control-treaty verification
 - List-mode processing
 - Models that store non-sensitive information
- Data simulation
 - Objects, image
- Bayesian ideal observer
- Channelized Hotelling observer
 - Reducing stored data while maintaining performance
 - Storing non-sensitive information
- Null hypothesis test

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?
Characteristics
- Figure of Merit
Measure the ability of the observer to perform the task

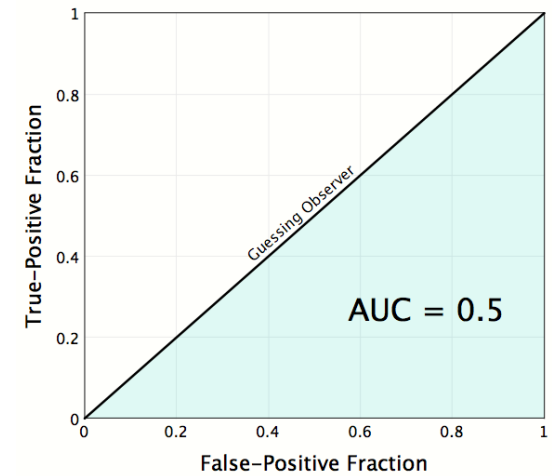
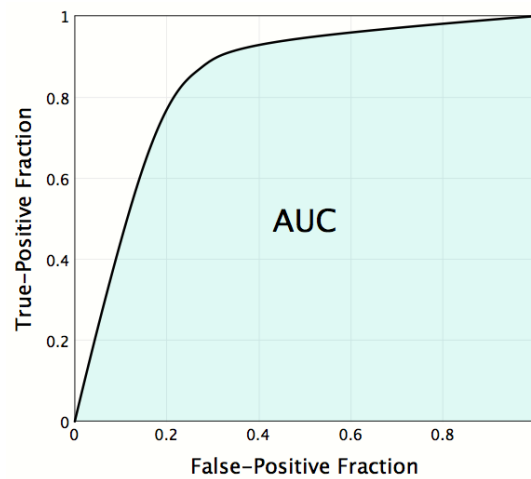
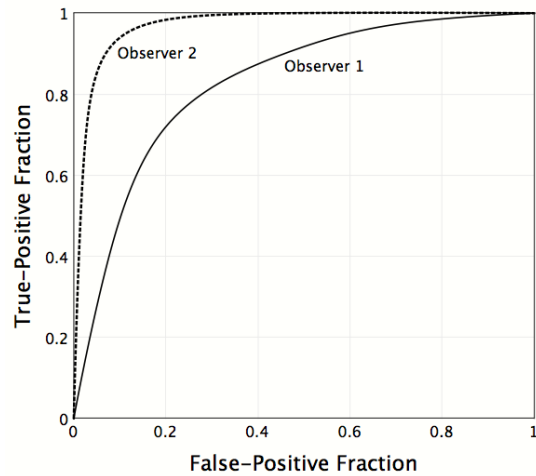
Task performance of observer models are assessed and compared



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

Figure of Merit

Observer models evaluated by comparison of area under ROC curve



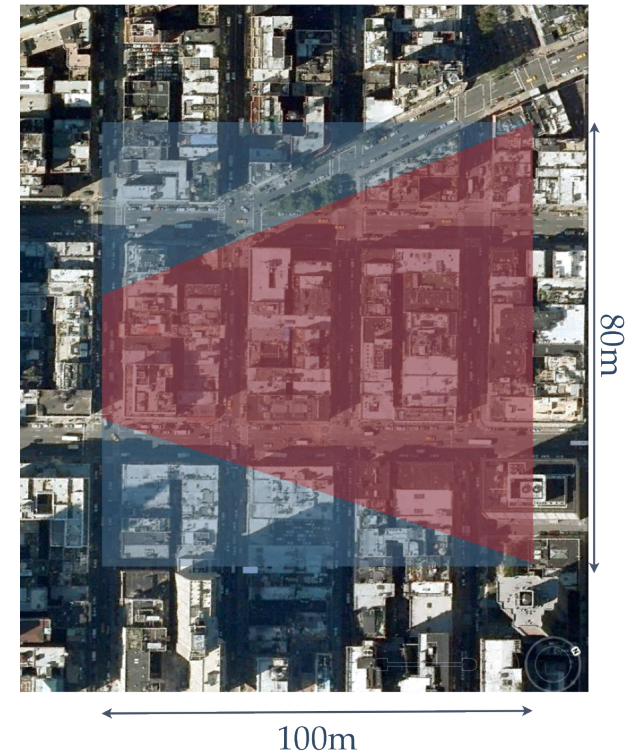
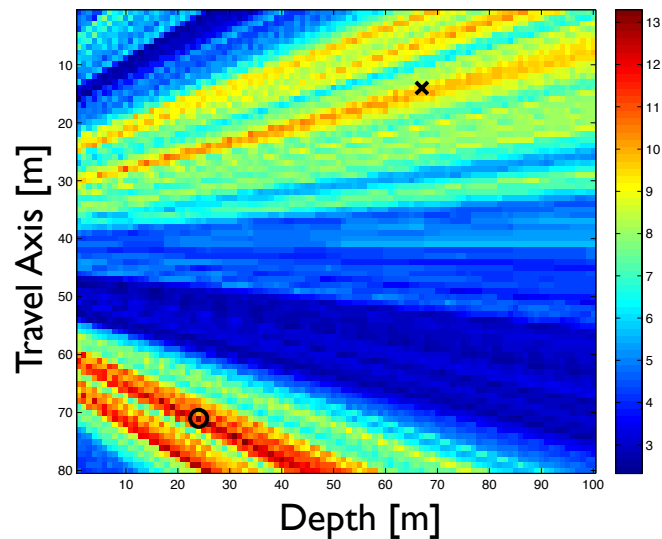
Task-based imaging

- We develop mathematical methods to optimally perform tasks
 - Utilize probabilistic nature of detector data
- Optimize detector for task performance
 - pixel size, mask element size, mask-detector spacing, etc

Task-Based Imaging

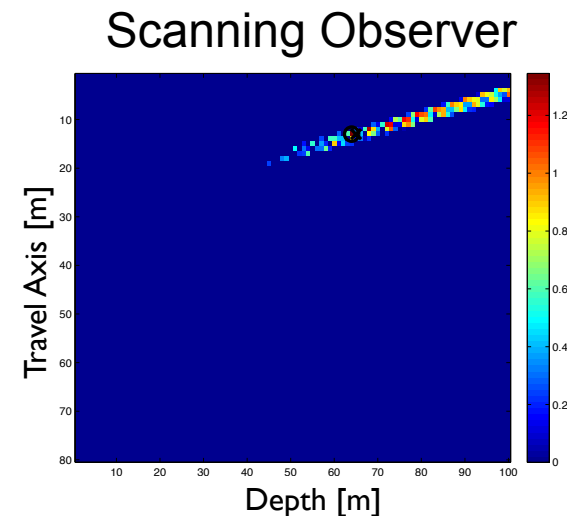
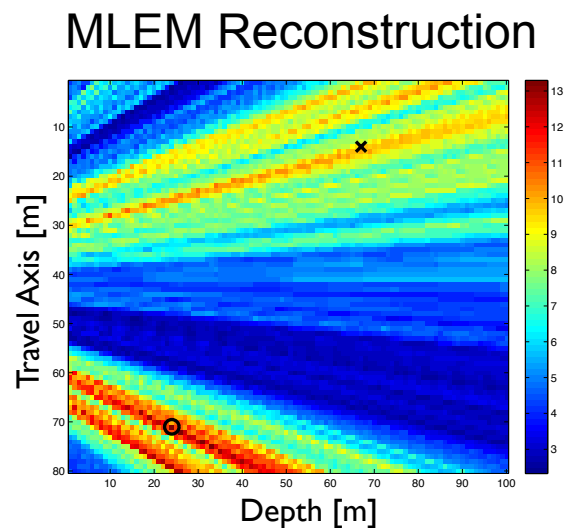
Example:

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

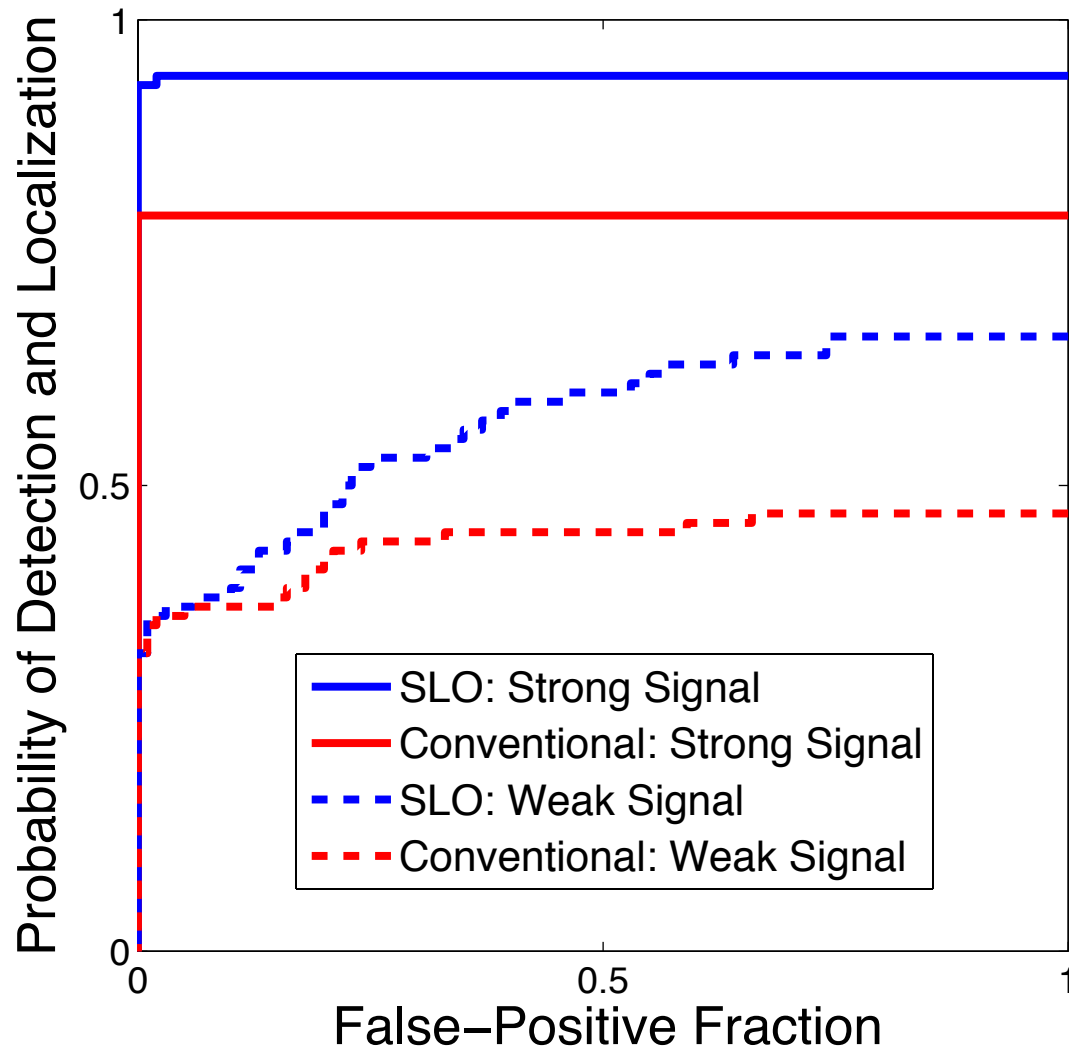


Task-Based Imaging

- Task: Detection and localization of SNM
- Observer: Scanning-linear observer (assumes multivariate Gaussian distribution on pixel data)
- Objects: Simulated SNM in an urban environment
- Figure of merit: Area under LROC curve



Task-Based Imaging



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Arms-Control-Treaty Verification

- Current treaties hold number of delivery systems accountable
 - New START treaty limits US to 1550 warheads on 700 delivery systems
- Future treaties may want to count warheads.
- Monitor wants to verify presence of warhead, host wants to preserve sensitive information on construction.
- Many current proposed methods utilize an information barrier (IB)
 - IB: hardware or software

Verification task

Is it really a warhead?

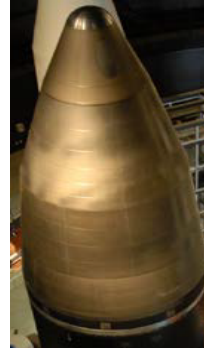


Photo from National Museum
of the USAF

- What is a warhead?
- What sort of spoofs do we want to be able to reject?

Verification Task

Is it really a warhead?



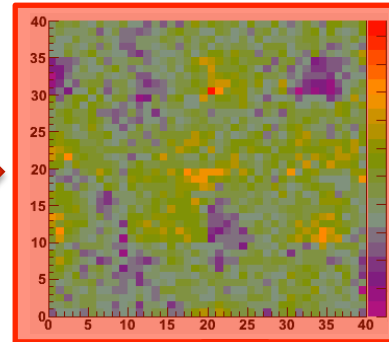
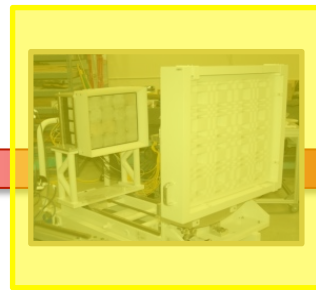
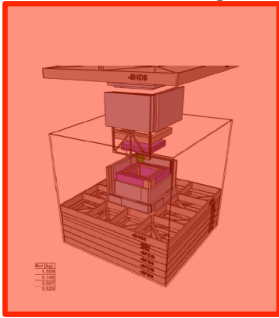
Photo from National Museum of the USAF

Is it warhead A or warhead B?



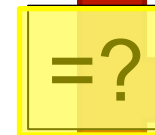
“Traditional” Template Matching

Trusted object

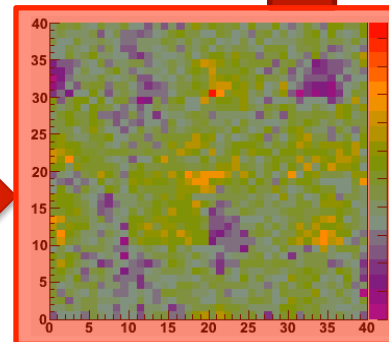
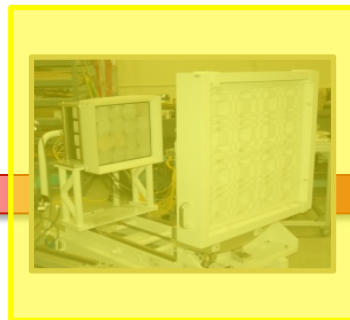
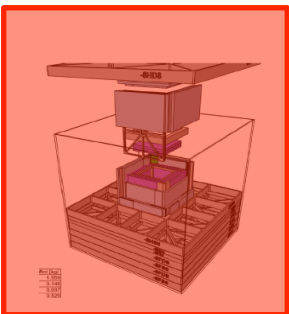


Training data is sensitive
IB required

LEGEND	
Red	No Access
Yellow	Access Before & After
Green	Full Access



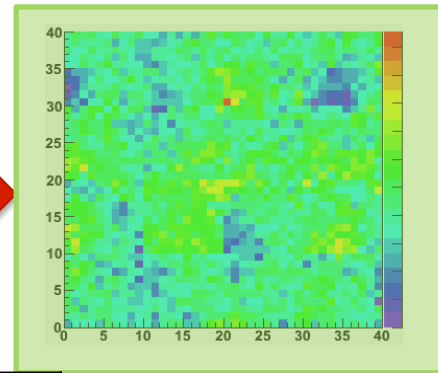
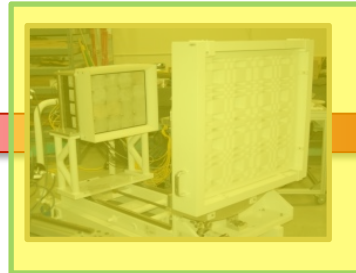
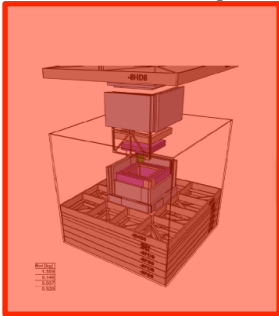
Tested object



Tested detector data is sensitive
IB required

Our proposal

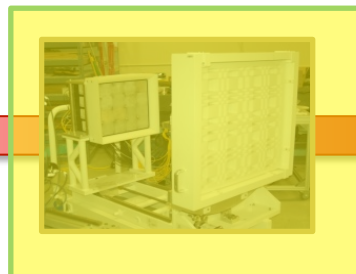
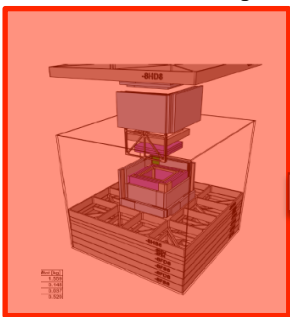
Trusted object



Hypothetical observer stores info sufficient for confirmation but not sensitive

LEGEND	
Red	No Access
Yellow	Access Before & After
Green	Full Access

Tested object

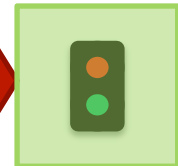


Testing data is processed event by event, only updating test statistic.

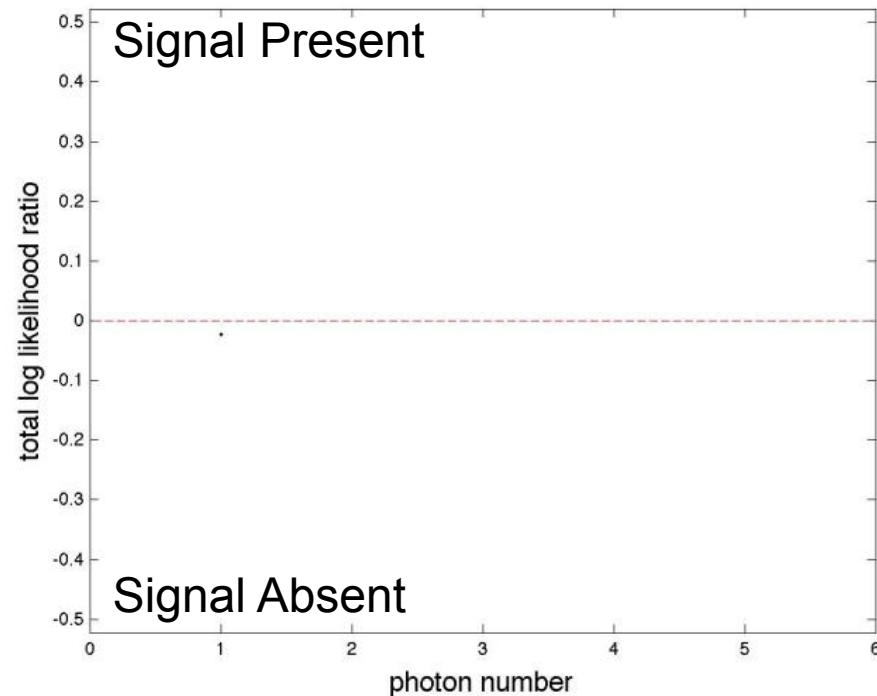
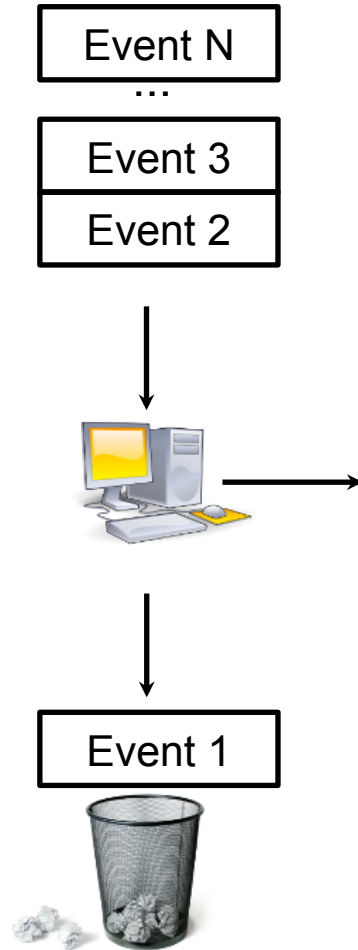
Data not aggregated

Think snapchat!

t

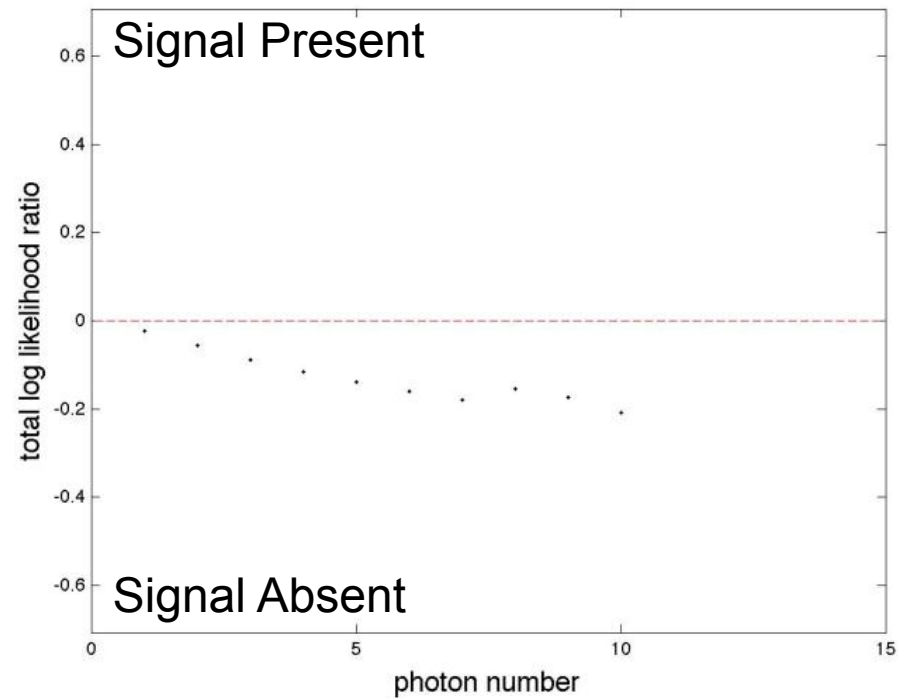
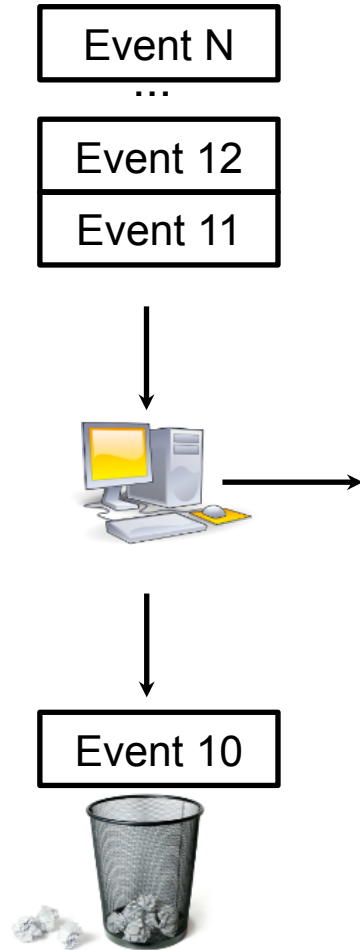


List-mode Processing



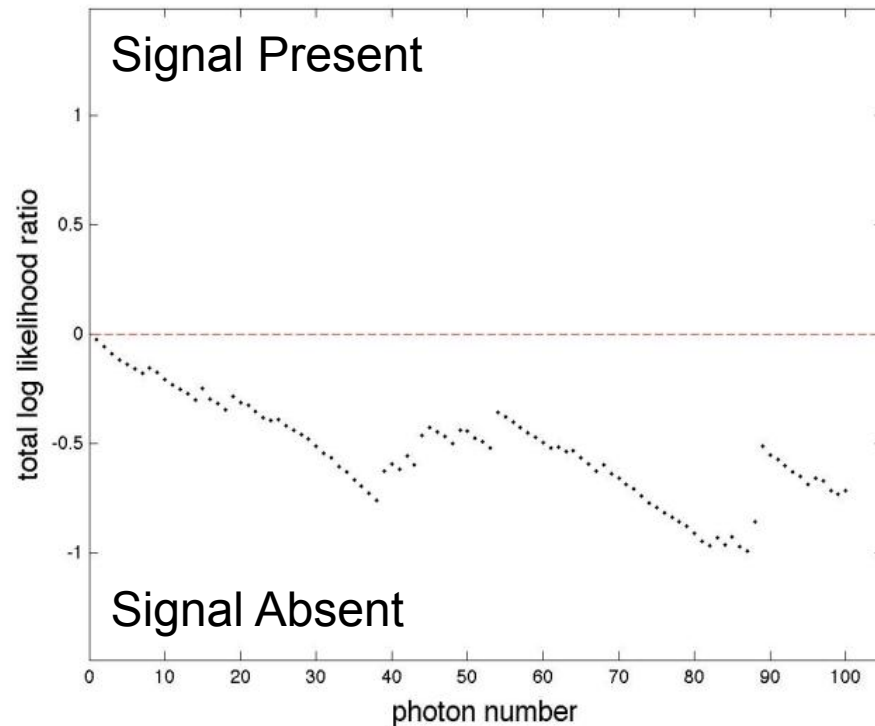
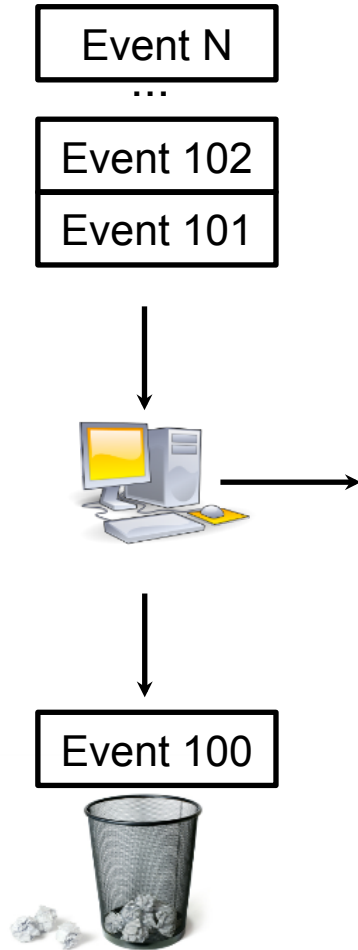
Output running sum is the likelihood of a signal being present, which is thresholded to make a decision.

List-mode Processing



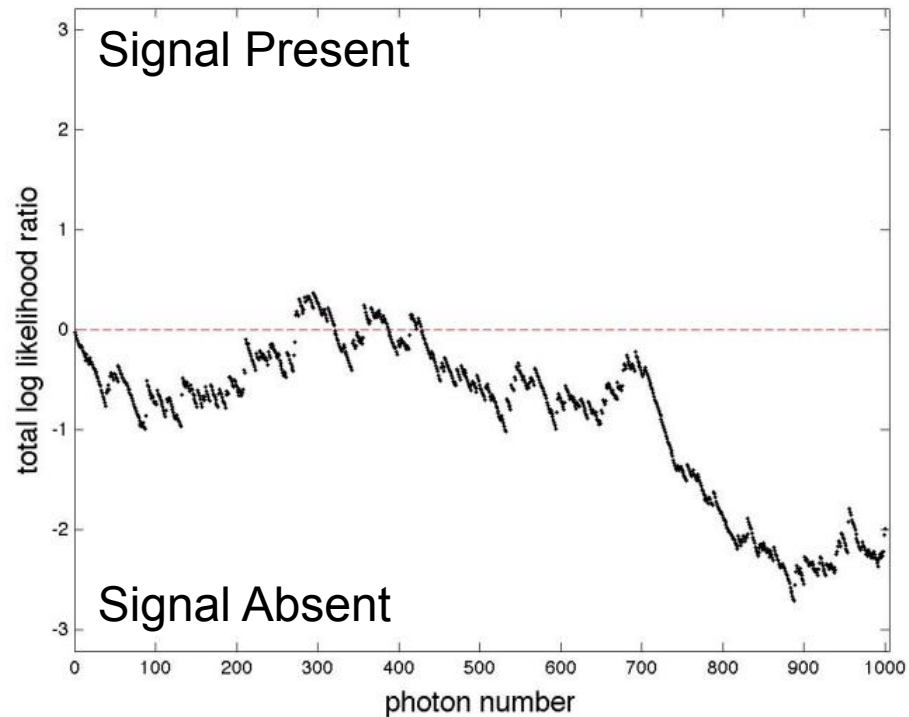
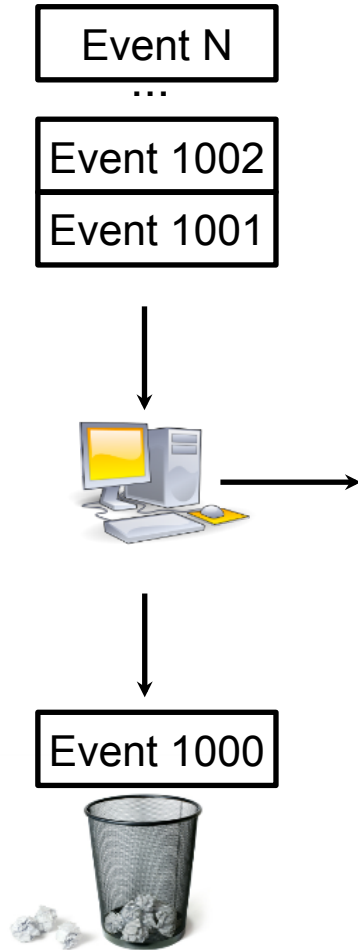
Output running sum is the likelihood of a signal being present, which is thresholded to make a decision.

List-mode Processing



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

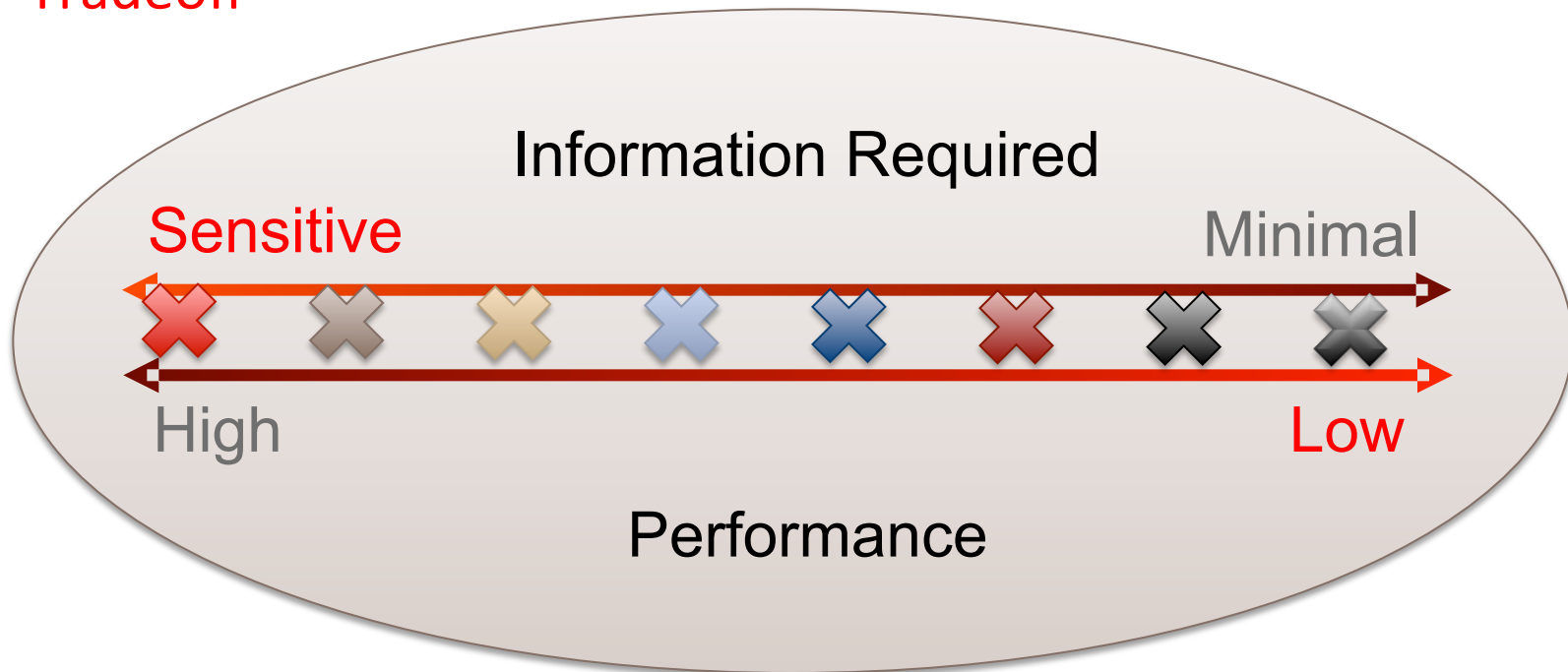
List-mode Processing



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

Non-sensitive Observer

Tradeoff



Does an observer model exist that provides confident confirmation without revealing sensitive information?

- NB: We don't decide what is sufficient confidence or what is sensitive info. We provide tools to develop an analysis subject to constraints TBD.

Characteristics of an ideal non-sensitive template

- 1. Distinguishes objects in classification task
- 2. Needs to perform well in the presence of nuisance parameters
 - Random image registration, object orientation can hurt task performance
- 3. Distinguishes based on non-sensitive information
 - Can we prevent storage of data that can yield sensitive differences between objects.
 - Host could share model with monitor
- 4. Can be used to identify spoofs

Nuisance parameters

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

- Relevant examples:
 - Source material age. Affects detected count rate and energy spectra.
 - Background strength
- More relevant examples:
 - Source orientation
 - Source position

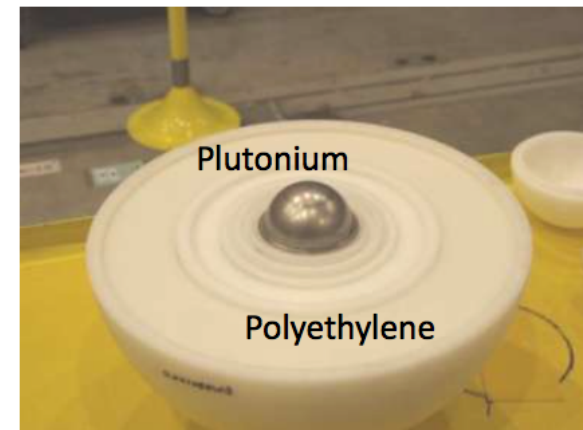
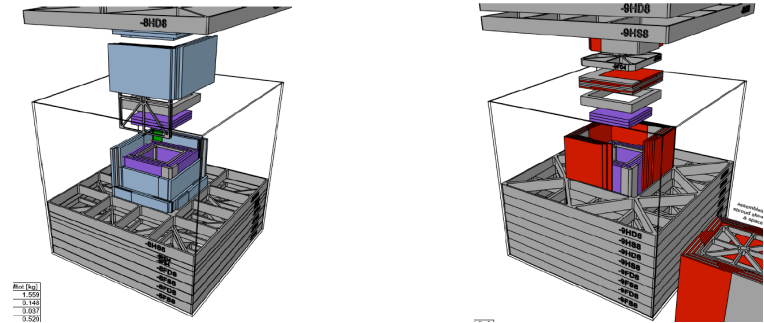
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Tasks

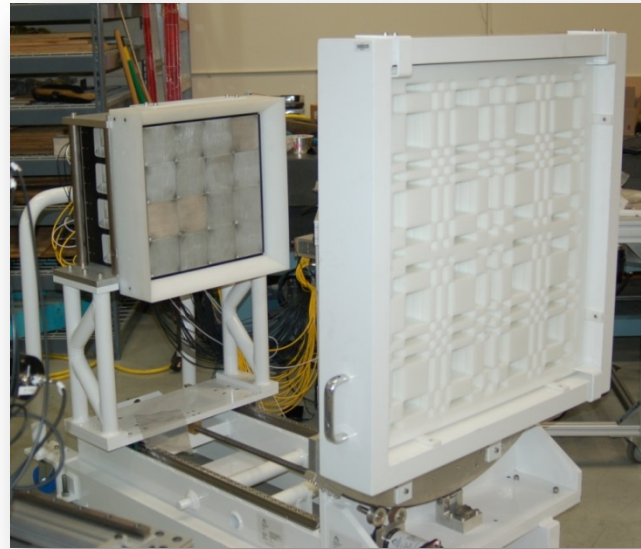
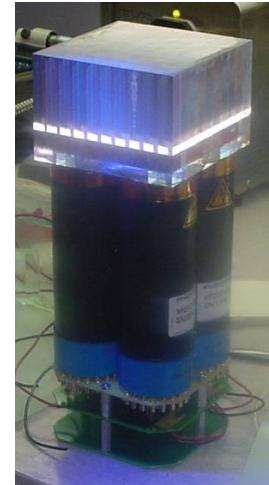
- Discrimination of Idaho National Lab Inspection Objects
 - IO8 (Pu surrounded by DU)
 - IO9 (Pu surrounded by HEU)
- BeRP Ball Location Discrimination
 - Solid plutonium sphere (7.6cm diameter)
 - Polyethylene shielding with varying configurations (not included)
- 2D 20cm Ring vs. 20cm Square Source Discrimination

INL/EXT-11-20876



Imaging System

- 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.



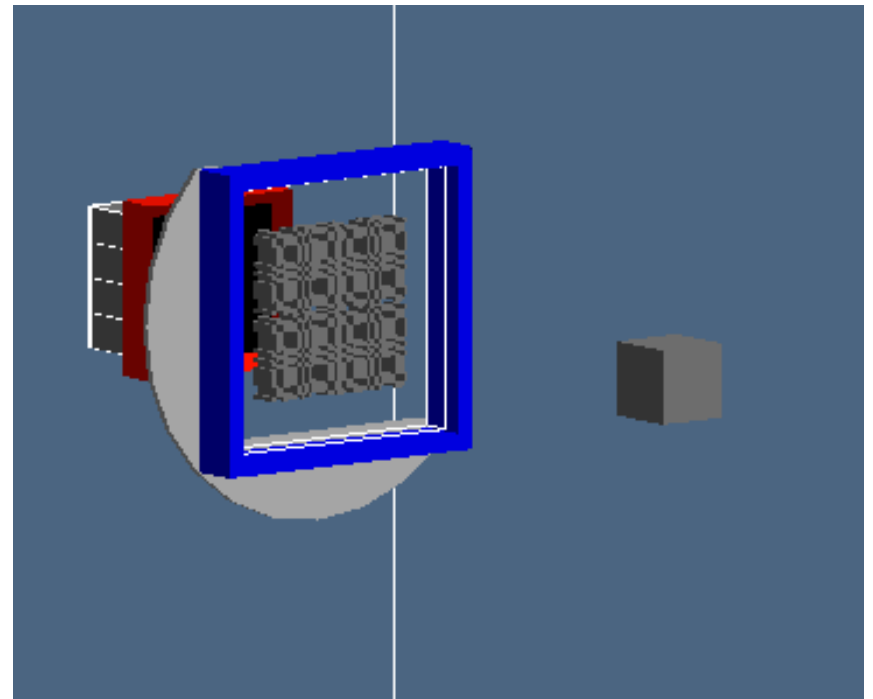
Experiment (Simulation)

- GEANT4 simulations of the imaging system and all objects

Training data (template) and testing data (confirmation measurement) are taken from statistically independent simulated datasets

Tasks

- Discriminate between two objects (i.e., binary discrimination)



Simulation features

- Particle Emission:
 - Gamma simulations: Use SandiaDecay library, based on ENSDF data
 - Neutron simulations: Spontaneous fission library from LLNL (G4FissLib)
- Physics:
 - Gamma simulations, G4EmLivermorePhysics, which retains high fidelity to very low energies
 - For neutron simulations, use GEANT 4 neutron high precision physics models
- Detector response:
 - Experimental data used to create lookup table—used to find particle-dependent light output for a given deposited energy
 - Applies energy smearing

Speeding up GEANT4 – variance reduction

- Gamma simulations in particular were slow
 - Without biasing, one GEANT run imaging IO9 with $2e9$ emissions leads to ~ 2 counts on the detector and takes roughly 20 hours to simulate.
 - We want ~ 400 hits on each pixel of detector. Would take $3.2e5$ runs of GEANT4 or >6.4 million CPU hours.
- Considered energy biasing

VR method	CPU hours required	speedup
none	$6.40E+06$	1
100keV cutoff	17200	372
100keV cutoff + linear E bias	4800	1333

Speeding up GEANT4—Multithreaded Processing

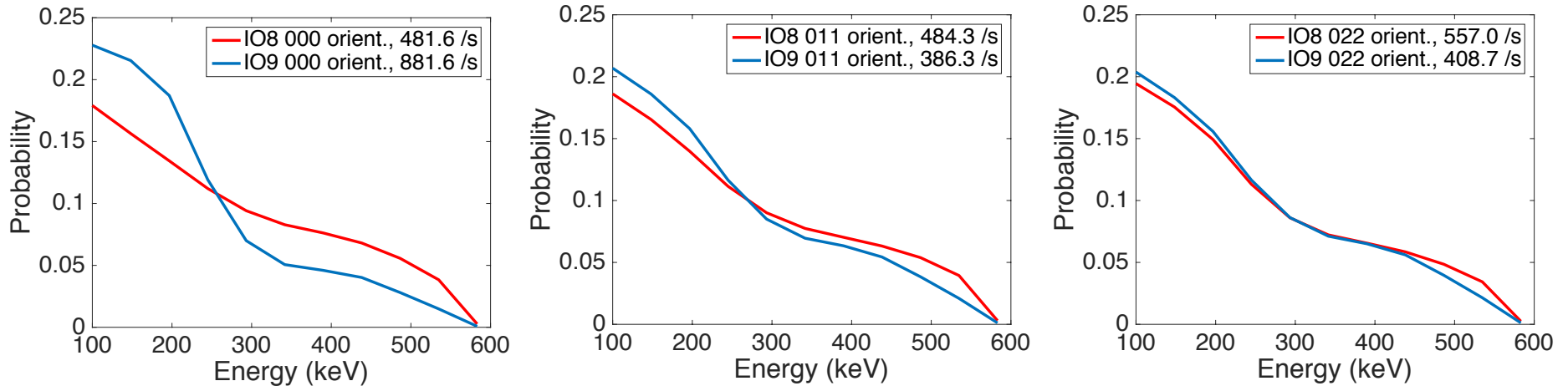
- GEANT4.10, offers a multithreaded build. GEANT4MT incorporates event level parallelism – all track information is stored in separate threads.

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	3.8
8	5.00E+07	514	6.9
12	5.00E+07	390	9.1
16	5.00E+07	345	10.3

- Also ran GEANT on Sandia's high performance computing clusters

IO8 vs IO9 data



IO8 gamma spectra and count rate mostly constant as a function of orientation.

- Due to 1001 keV line

IO9 gamma spectra and count rate change drastically with orientation.

- Due to 186 keV line

BeRP Ball Data

Image of BeRP ball at (0mm,0mm)

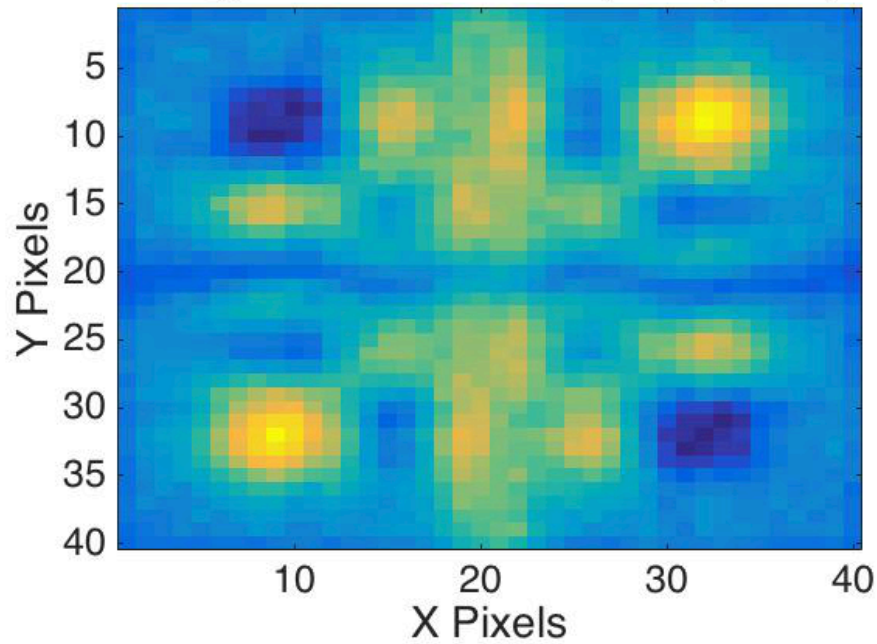
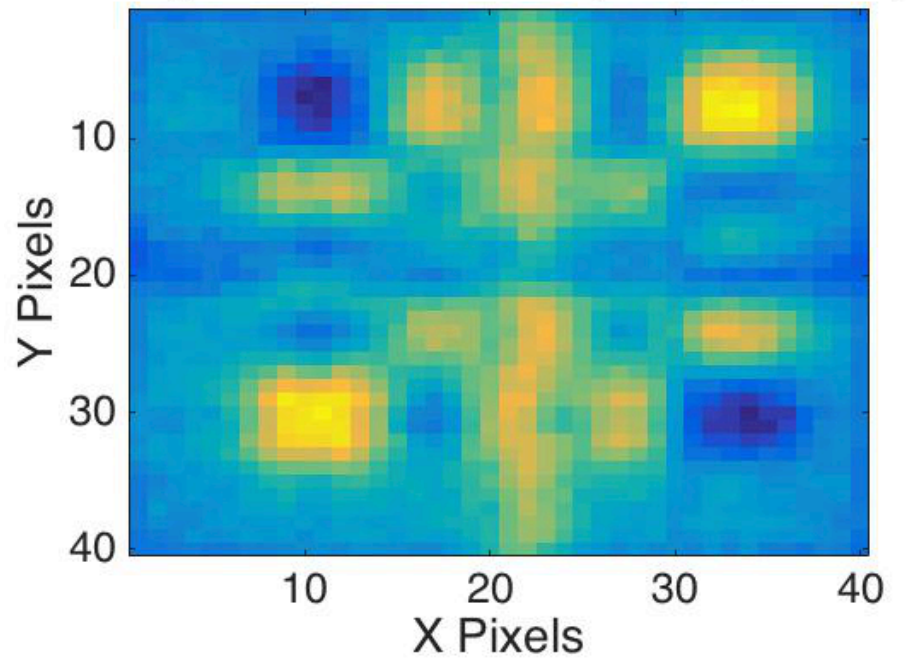
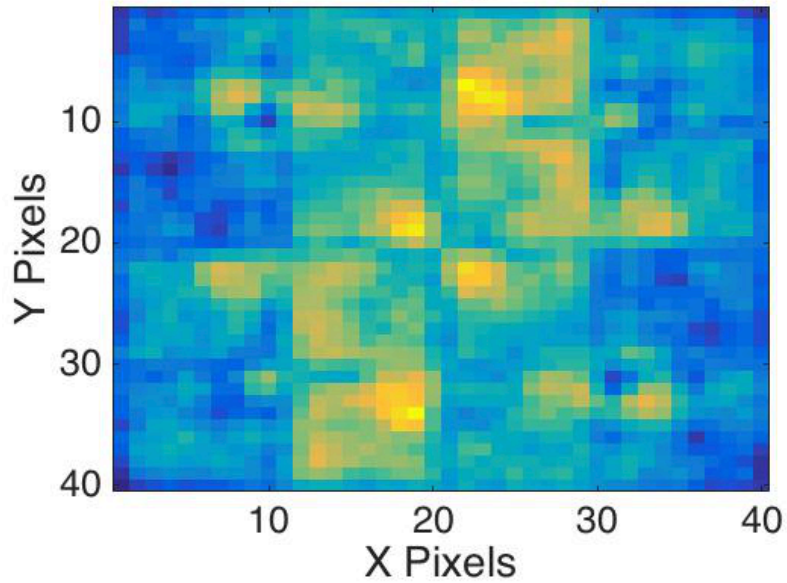


Image of BeRP ball at (20mm,20mm)

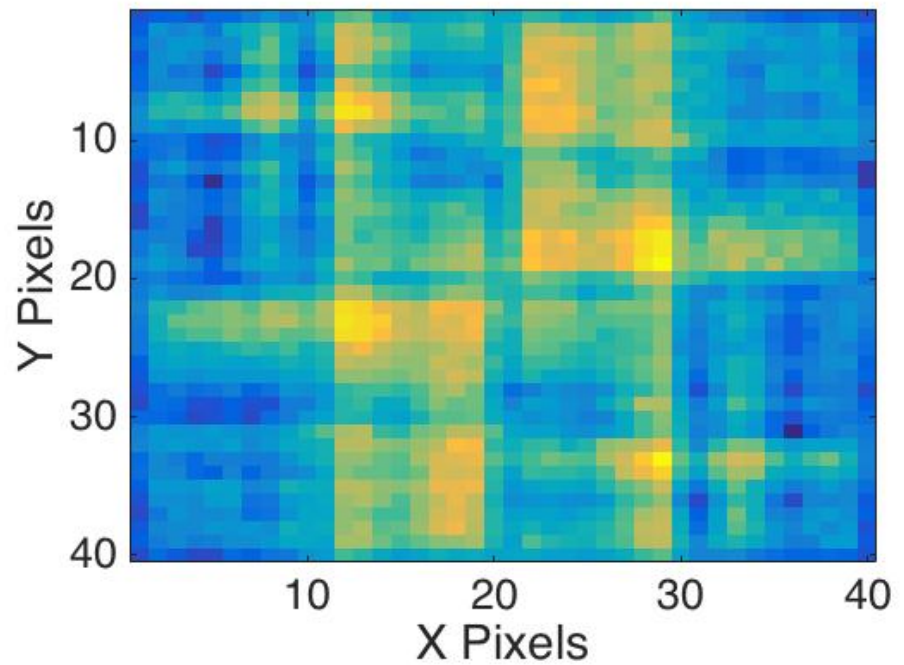


Ring, Square Source Data

20cm diameter ring source image



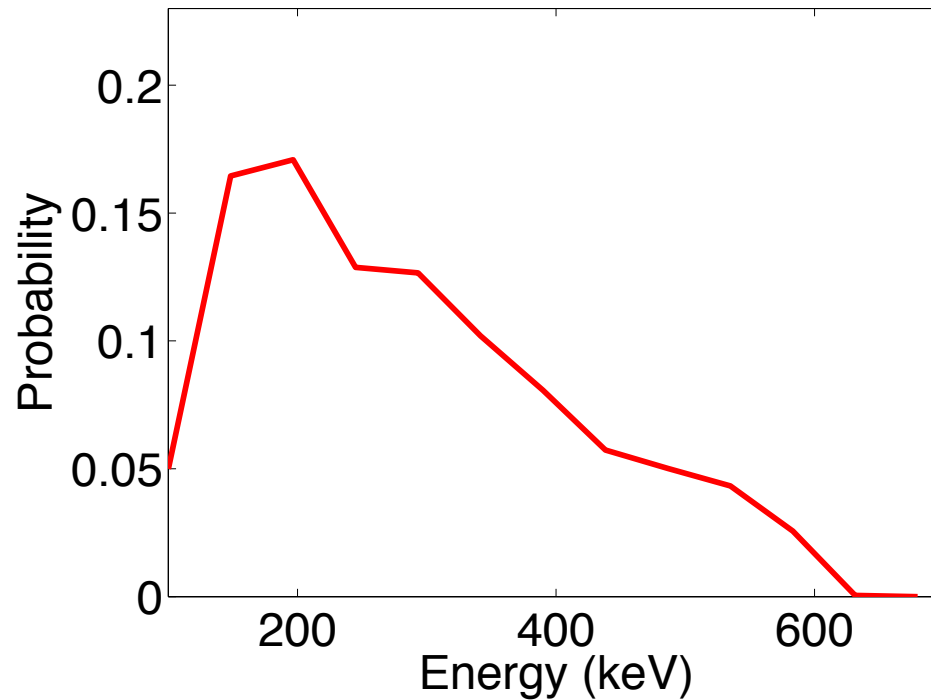
20cm length square source



Gamma Background

There is a spatially dependent gamma background due to cosmic ray interactions, and common radioactive isotopes (uranium and thorium) that are naturally occurring.

Background simulated in GADRAS.



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Bayesian Ideal Observer

- The Bayesian ideal observer thresholds the likelihood ratio for the two sources.

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

List-mode data (particle type, energy, pixel id)

Total number of observed counts in given acquisition time

Bayesian Ideal Observer

- The Bayesian ideal observer thresholds the likelihood ratio for the two sources.

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

- Ideal observer offers best possible performance but is often impractical.
- Observer model stores sensitive information.

MacGahan, C. J., M. A. Kupinski, N. R. Hilton, E. M. Brubaker, and W. C. Johnson (2016). Development of an Ideal Observer that Incorporates Nuisance Parameters and Processes List Mode Data. *JOSA A*, 33(4), pp. 689–697.

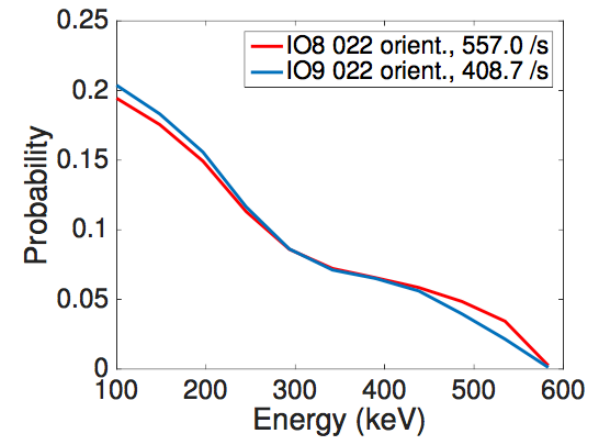
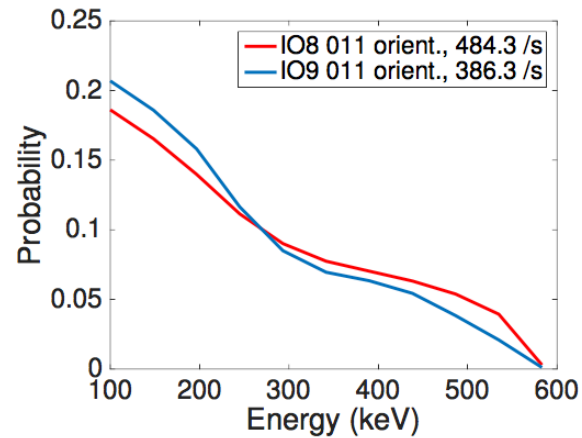
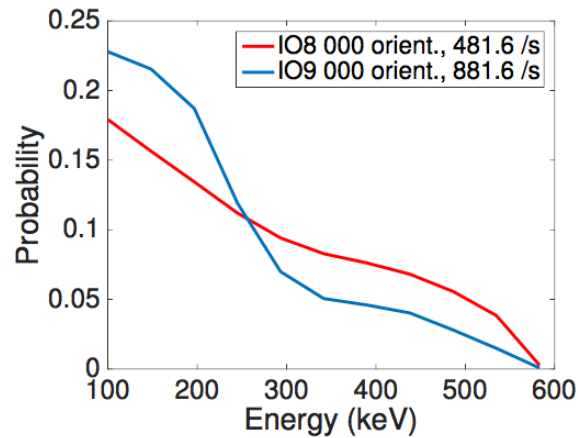
List-mode processing

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

- Training data used to find mean number of observed counts and expected spatio-spectral data distribution to calibrate this model
- Likelihood starts at 1, is multiplied by $pr(A_n|H_j)$ for each detected event

MacGahan, C. J., M. A. Kupinski, N. R. Hilton, W. C. Johnson, and E. M. Brubaker (2014). Development of a list-mode ideal observer to perform classification tasks when imaging nuclear inspection objects under signal-known-exactly conditions. In 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), pp. 1–5. doi:10.1109/NSSMIC.2014.7431051.

Classifying IO8 v IO9

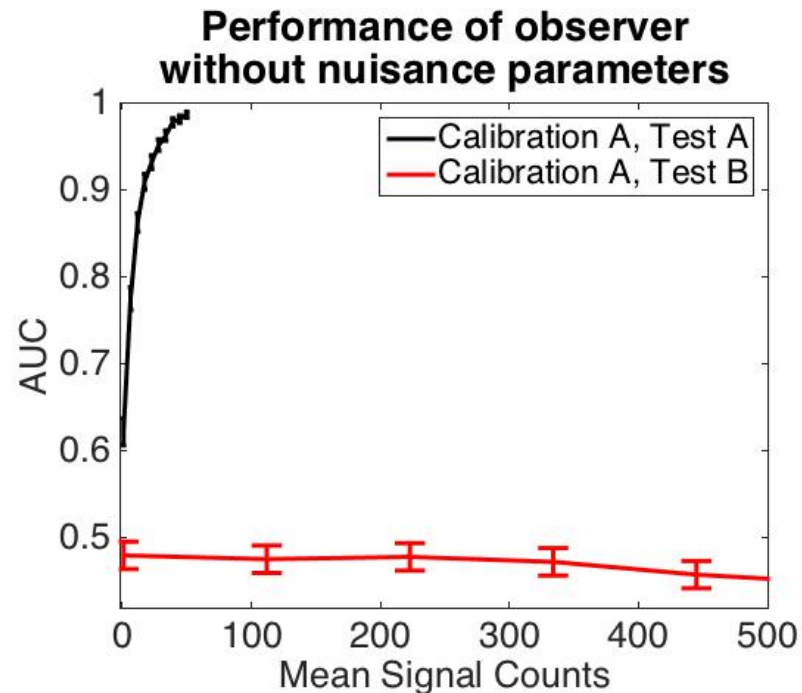


Many different orientations of IO8 and IO9 were simulated

IO9 detected spectra and count rate show greater variation with orientation changes

Importance of Nuisance Parameters

- Nuisance parameters must be taken into account for results to generalize
- Orientation as a nuisance parameter



MacGahan, C. J., M. A. Kupinski, N. R. Hilton, E. M. Brubaker, and W. C. Johnson (2016). Development of an Ideal Observer that Incorporates Nuisance Parameters and Processes List Mode Data. *JOSA A*, 33(4), pp. 689–697.

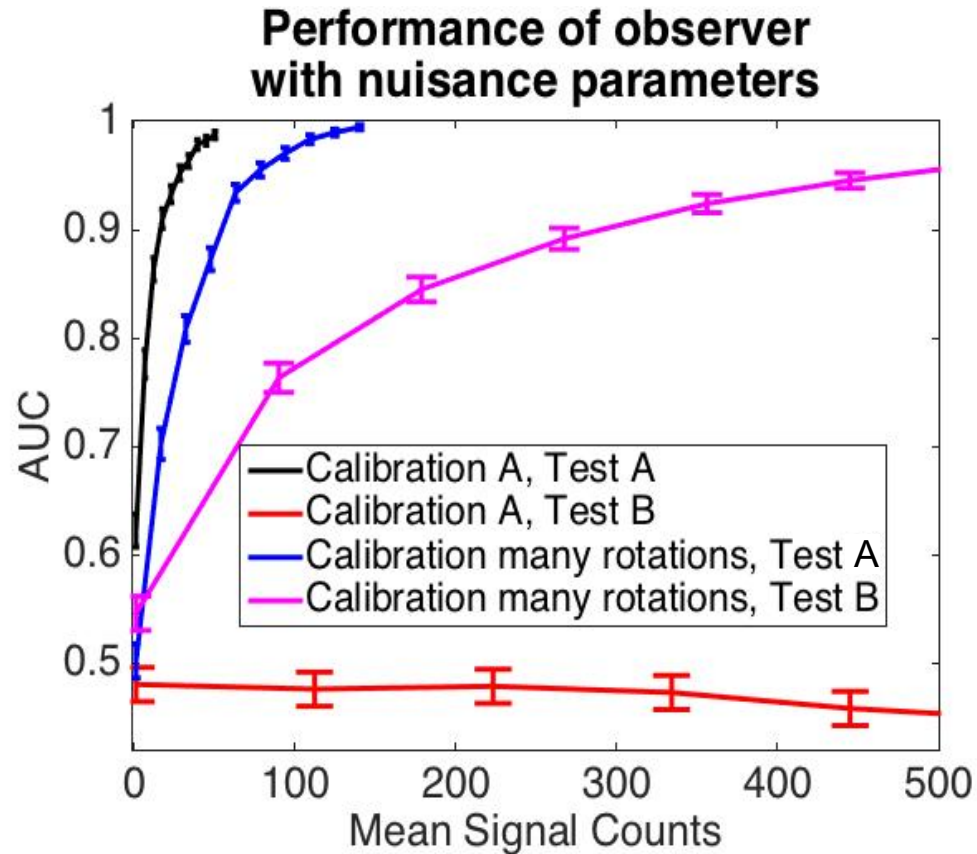
Bayesian Ideal observer integrating over nuisance parameters

$$\Lambda(\{A_n\}, N) = \frac{\int pr(\{A_n\}, N | H_2, \gamma_2) pr(\gamma_2) d\gamma_2}{\int pr(\{A_n\}, N | H_1, \gamma_1) pr(\gamma_1) d\gamma_1}$$

- Need accurate prior densities over nuisance parameters
- Need measurements for many nuisance parameter values
 - May be difficult for host to obtain

Importance of Nuisance Parameters

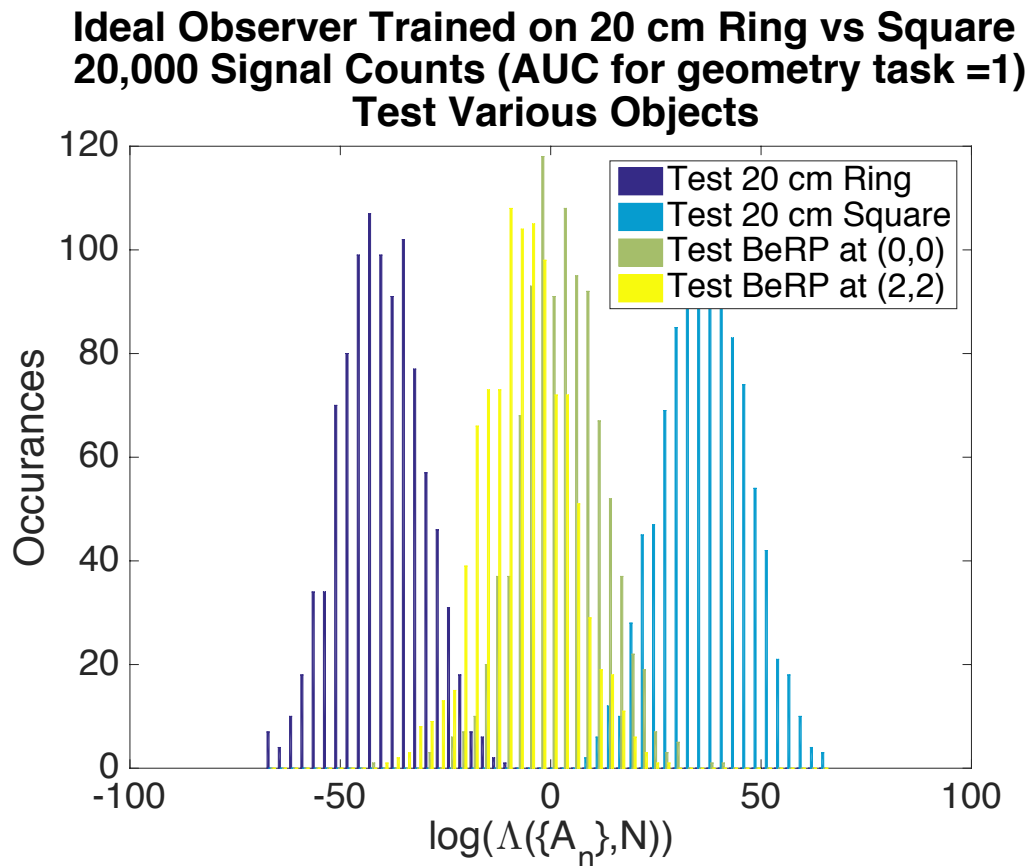
- Including nuisance parameters in model



MacGahan, C. J., M. A. Kupinski, N. R. Hilton, E. M. Brubaker, and W. C. Johnson (2016). Development of an Ideal Observer that Incorporates Nuisance Parameters and Processes List Mode Data. *JOSA A*, 33(4), pp. 689–697.

Identifying spoofs

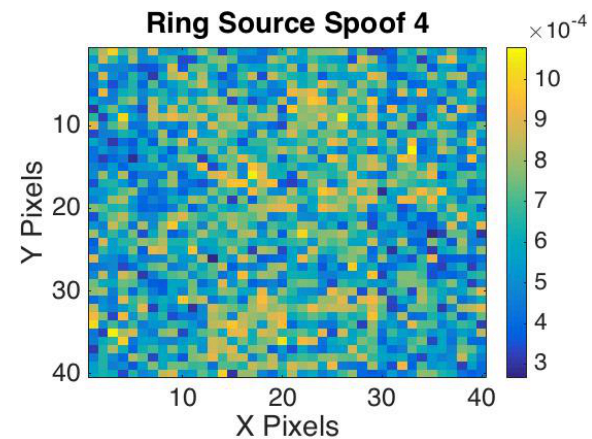
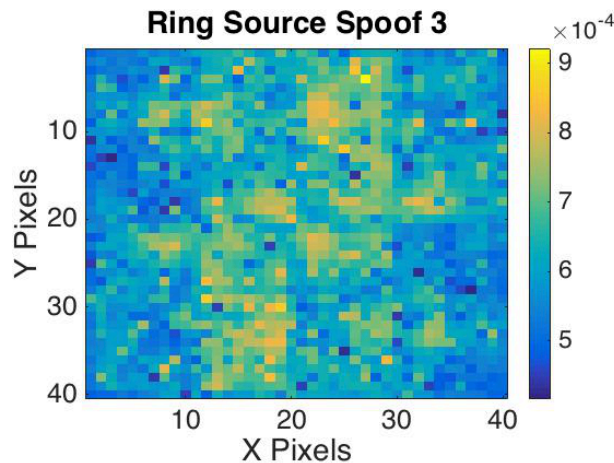
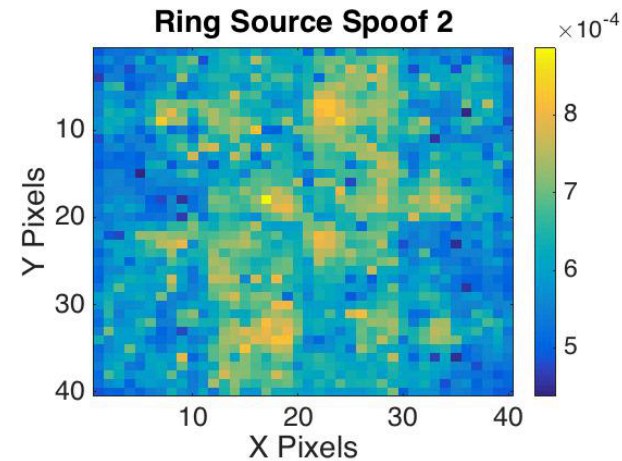
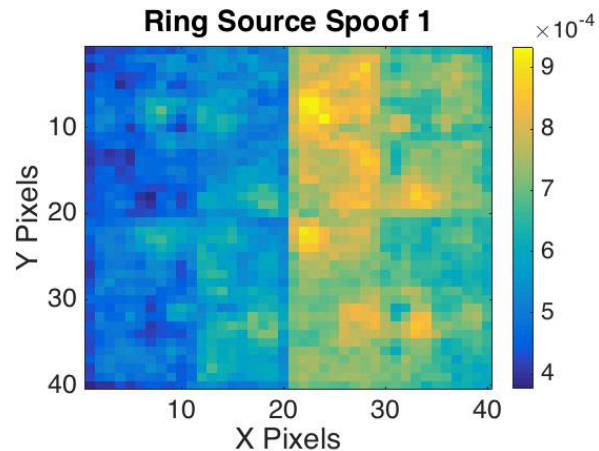
- Test-statistic distributions can be used to identify spoofs



BeRP ball
measurements are
rejected over 90% of
the time

Successful spoofs

- Routine was developed to create projection data spoofs that overlap with 20cm ring source test-statistic distribution



Observer Performance vs Storage Chart

Observer	Information Stored	Performance
Ideal Observer	!!!Extremely sensitive!!! Full probabilities which characterize what the objects look like	Best possible performance

Overview

- + Host has confidence monitor can't back out sensitive information due to LM processing
- Storage of sensitive information requires an information barrier.
- Monitor only would be able to access test-statistic. Can't trust.
- Spoofable

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Linear template observers

- Series of weights \mathbf{W} act on binned testing data \mathbf{g}_{test} , result is scalar that is thresholded to make a decision.

$$t_{test} = \mathbf{W}^\dagger \mathbf{g}_{test}, t_{test} \lesssim t_{thresh}$$

- Hotelling observer is the ideal set of weights \mathbf{W} defined as:

$$\mathbf{W} = \mathbf{K}_g^{-1} \Delta \bar{\mathbf{g}} \quad \mathbf{K}_g = \frac{\mathbf{K}_1 + \mathbf{K}_2}{2}$$
$$\Delta \bar{\mathbf{g}} = \bar{\mathbf{g}}_2 - \bar{\mathbf{g}}_1$$

- Averages are over all sources of randomness (Poisson noise, object variability)

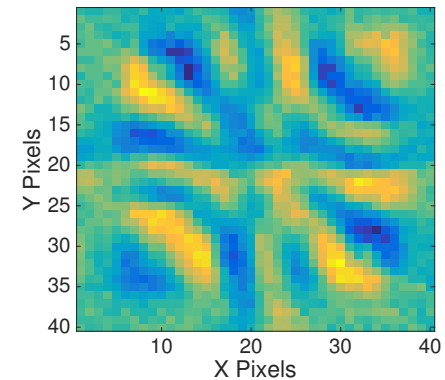
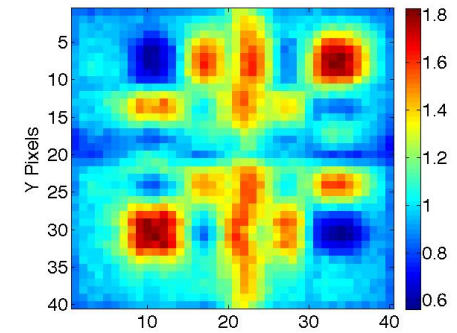
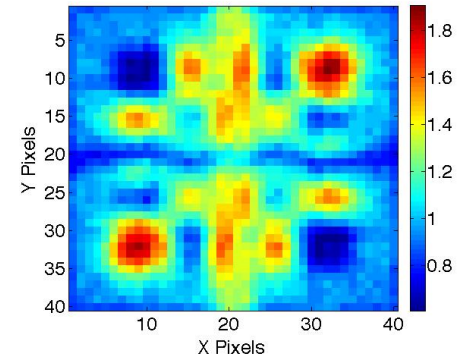
Hotelling observer – location discrimination

- BeRP ball image at (0,0)
- 5M counts

- BeRP ball image at (20mm,20mm)
- 5M counts

- Hotelling weights.

MacGahan, C. J., M. A. Kupinski, E. M. Brubaker, and N. R. Hilton (2015). A Channelized Hotelling Observer for Treaty Verification Tasks. In 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), p. 1.



Storage for Hotelling Observer

- Template W contains product of first and second order statistics, but still constitutes sensitive information

Observer	Information Stored	Performance
Ideal Observer	!!!Extremely sensitive!!! Full probabilities which characterize what the images will look like	Best possible performance
Hotelling Observer	Sensitive— mean difference between data sets stored. Far less than ideal observer	Good performance

Overview

- + Host has confidence monitor can't back out sensitive information due to LM processing
- + If monitor gains access to W , can't back out projection data
- Storage of sensitive information requires an information barrier.
- Monitor would only be given test statistic distributions. Can't trust test-statistic

Channelized Hotelling

- Channelize vector $\mathbf{g}(P \times 1)$ with operator $\mathbf{T}(Q \times P)$ into much smaller vector $\mathbf{v}(Q \times 1)$ with Q values.

$$\mathbf{v} = \mathbf{T}\mathbf{g}$$

- Optimal set of weights for these channelized values are a function of \mathbf{T} :

$$\mathbf{W}_{\mathbf{v}} = \mathbf{K}_{\mathbf{v}}^{-1} \Delta \bar{\mathbf{v}}$$

- Inner product of weights and channelized vector

$$\mathbf{W}_{\mathbf{v}} \mathbf{v}_{\text{test}} \lesssim t_{\text{thresh}}$$

Channelized Hotelling observer

- Weights on \mathbf{g} for CHO are:

$$\mathbf{W}_{\mathbf{g}}^{\dagger} = \mathbf{W}_{\mathbf{v}}^{\dagger} \mathbf{T}$$

- \mathbf{T} can be optimized to maximize SNR^2 between test statistic distributions for best performance.
 - Gradient descent algorithm with backtrack

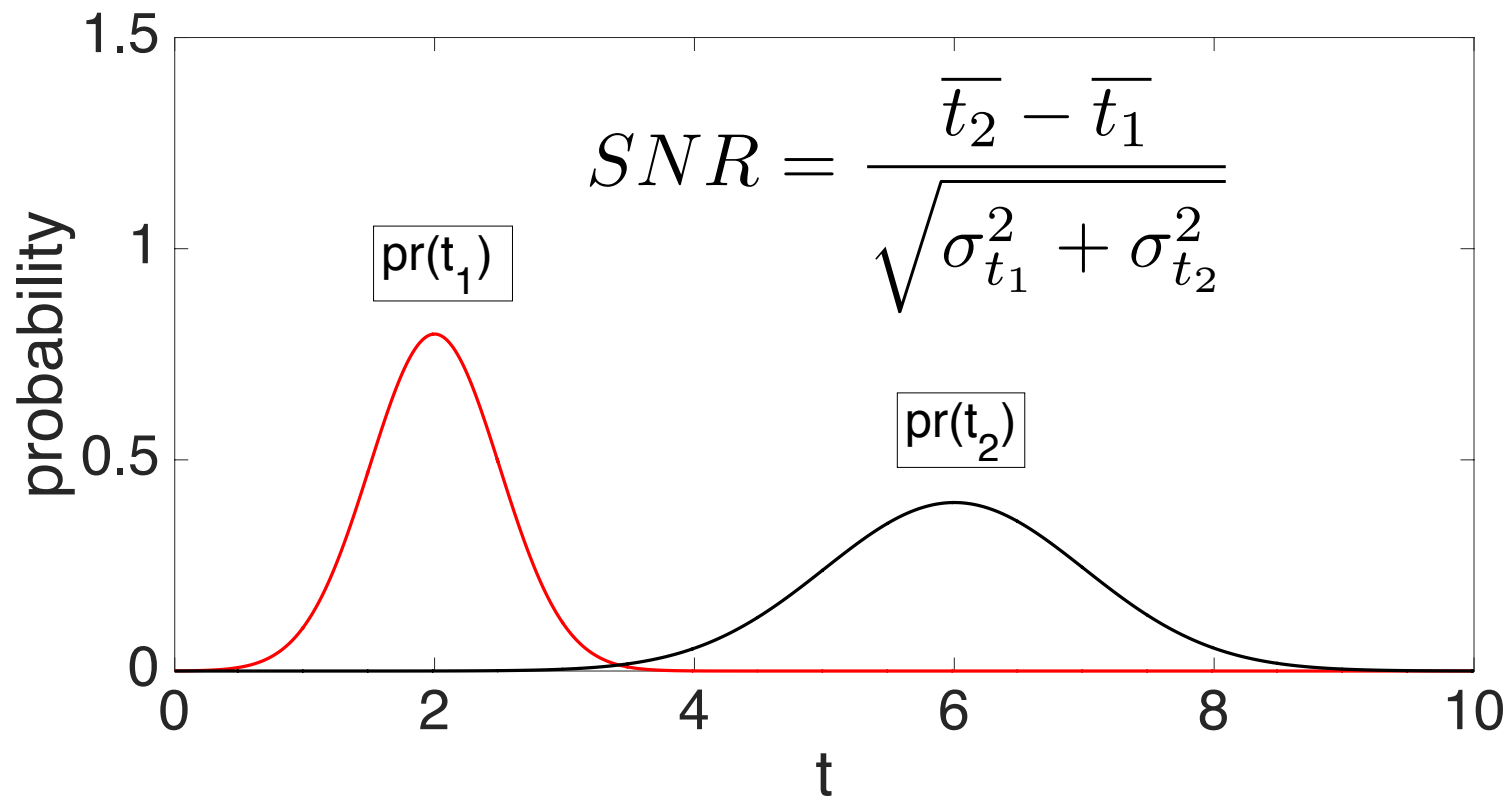
$$f_{obj}(\mathbf{T}) = SNR^2(\mathbf{T}) = (\overline{\Delta \mathbf{v}(\mathbf{T})})^{\dagger} \mathbf{K}_{\mathbf{v}}(\mathbf{T})^{-1} (\overline{\Delta \mathbf{v}(\mathbf{T})})$$

- For optimal \mathbf{T} ,

$$\mathbf{W}_{\mathbf{v}} \mathbf{T} = \mathbf{K}_{\mathbf{g}}^{-1} \Delta \overline{\mathbf{g}}$$

Optimizing SNR²

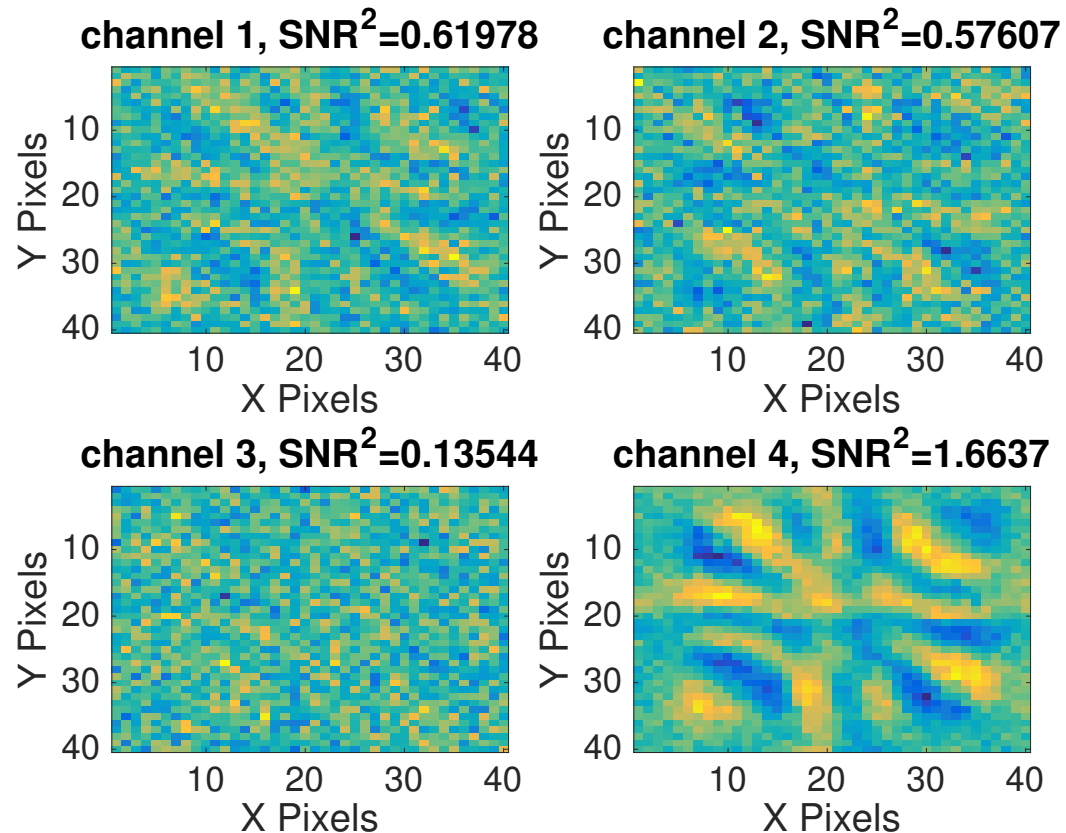
- The signal-to-noise ratio is a measure of separation between the test statistic distributions



Standard Optimization

Each channel corresponds to a template.

The optimally weighted sum of channels corresponds to the Hotelling weights



MacGahan, C. J., M. A. Kupinski, E. M. Brubaker, and N. R. Hilton (2015). A Channelized Hotelling Observer for Treaty Verification Tasks. In 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), p. 1.

Non-sensitive model

- Ideally, the host could be given the channelizing matrix, channelized values and test statistics for its measured TAIs to the monitor.
- Since the monitor has the model, it could measure its own items, trying to replicate the test-statistic distribution of the TAIs.
- The ideal model would return the same test statistic for any TAIs that have sensitive construction parameters (mass, size) within some tolerance.

Addition of penalty term

- The discrimination task is to diagnose a tested item as type A or B
- The host doesn't want the monitor to be able to back out a certain parameter of object A (ex. mass) with constructed value \mathbf{p}_0 up to a value of $\mathbf{p}_0 + \Delta\mathbf{p}$.

$$f_{obj}(\mathbf{T}) = SNR_{[A(p_0), B]}^2(\mathbf{T}) - \eta SNR_{[A(p_0), A(p_0 + \Delta p)]}^2(\mathbf{T})$$

- This objective function optimizes the ability to distinguish objects while penalizing ability to distinguish along sensitive parameter.

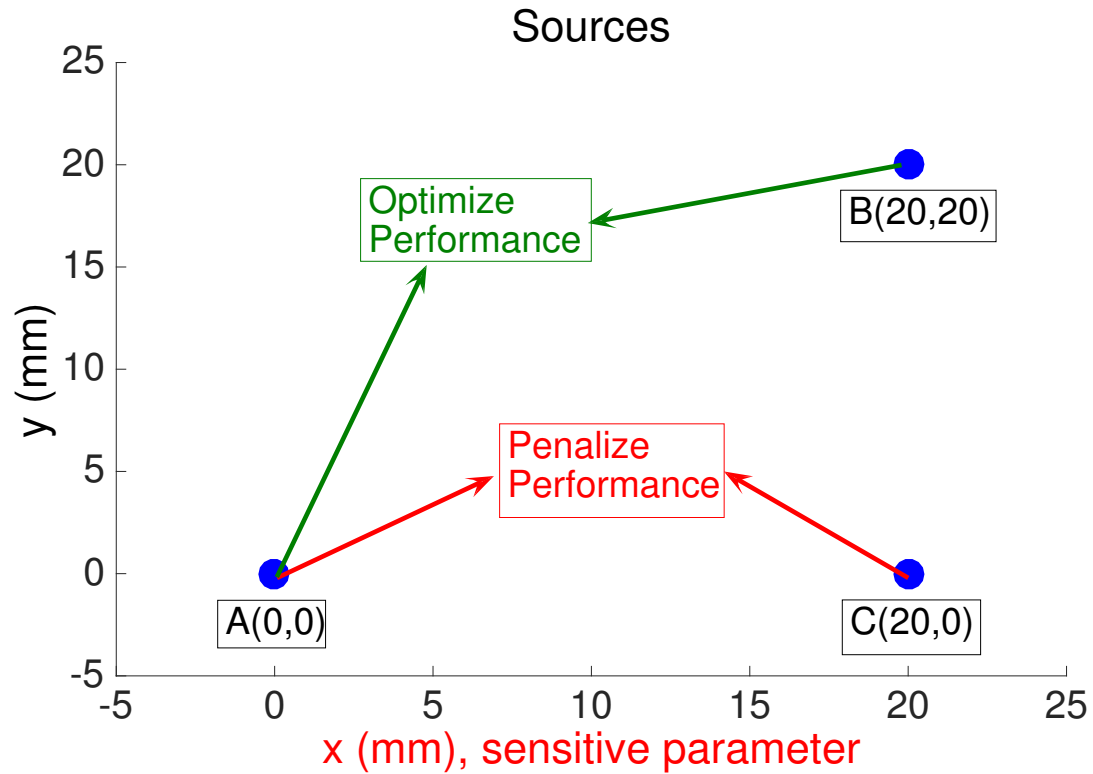
MacGahan, C. J., M. A. Kupinski, E. M. Brubaker, N. R. Hilton, and P. Mar- leau (2016a). Development of a Nonsensitive Template for Arms-Control-Treaty-Verification Tasks. In Symposium on Radiation Measurements and Applications.

Toy problem

- Monitor needs to differentiate:
 - A: BeRP ball at (0mm,0mm)
 - B: BeRP ball at (20mm,20mm).
- Host wants to prevent dissemination of x location of source A up to tolerance of 2cm. Penalizes ability to distinguish
 - A: BeRP ball at (0mm, 0mm)
 - A1: BeRP ball at (20mm, 0mm)
- To implement this model, BeRP ball was imaged at (20mm,0mm)

MacGahan, C. J., M. A. Kupinski, E. M. Brubaker, N. R. Hilton, and P. Mar- leau (2016a). Development of a Nonsensitive Template for Arms-Control-Treaty-Verification Tasks. In Symposium on Radiation Measurements and Applications.

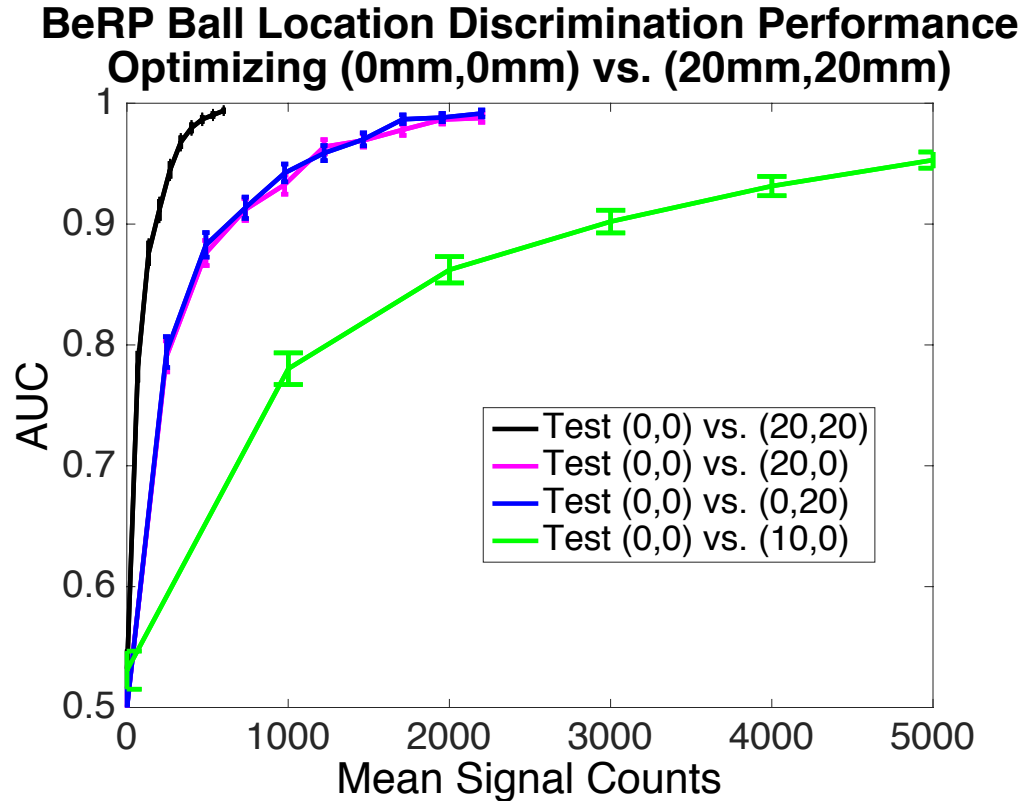
Toy Problem



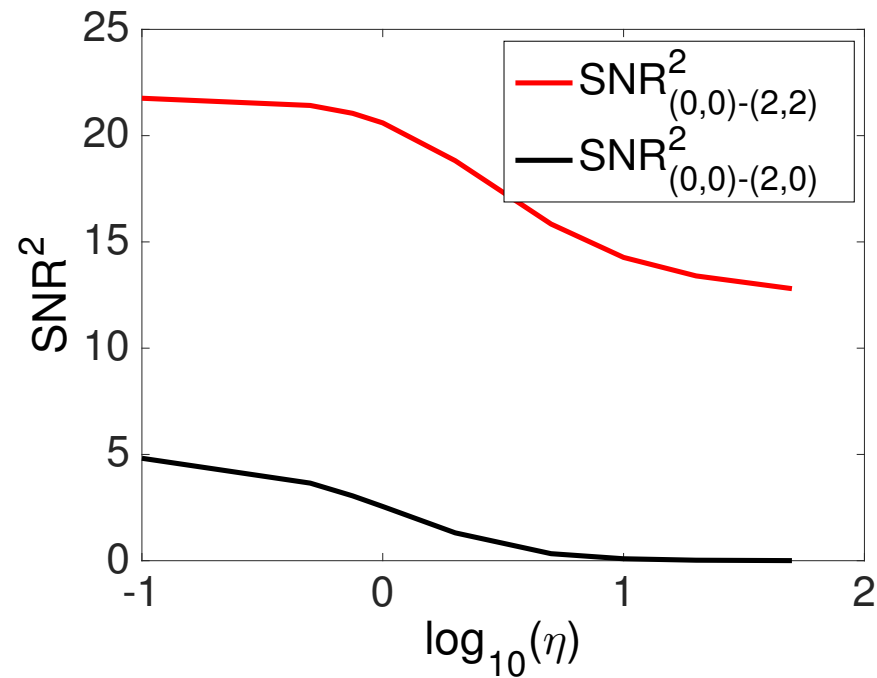
Note: diameter of BeRP ball is 76mm

Unpenalized Optimization

Model can discriminate a source at (0,0) from (20,0) by its test-statistic value.



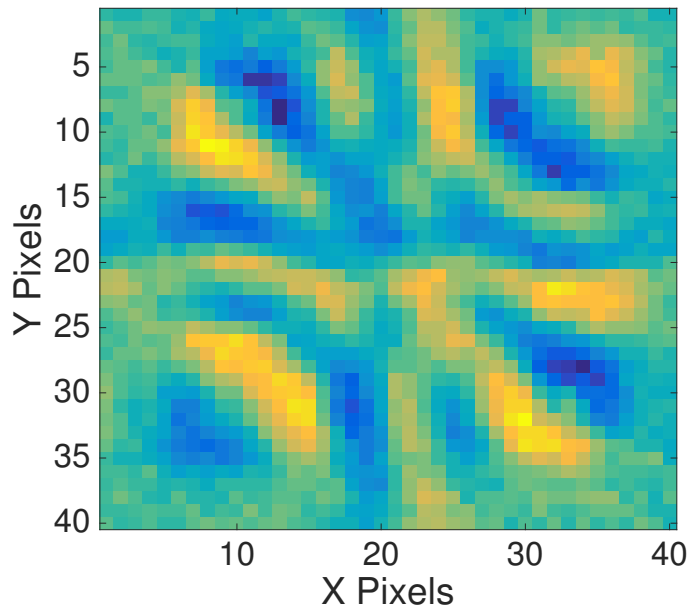
Effect of penalty term



As eta is increased, the resulting channelizing Hotelling observer (while no longer optimal) can't distinguish between the source at (0mm,0mm) and source at (2mm,0mm)

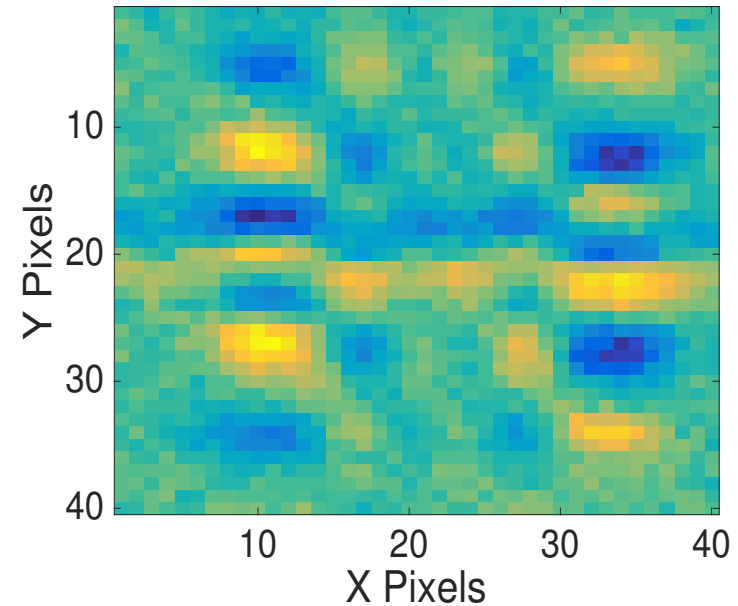
Sensitive Information Removal

- As eta increases, $\mathbf{W}_v\mathbf{T}$ is no longer optimal.



Eta=0

$\mathbf{W}_v\mathbf{T}$ equal to Hotelling weights

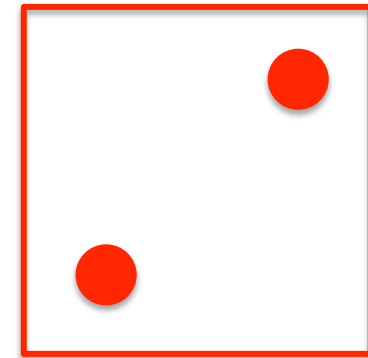
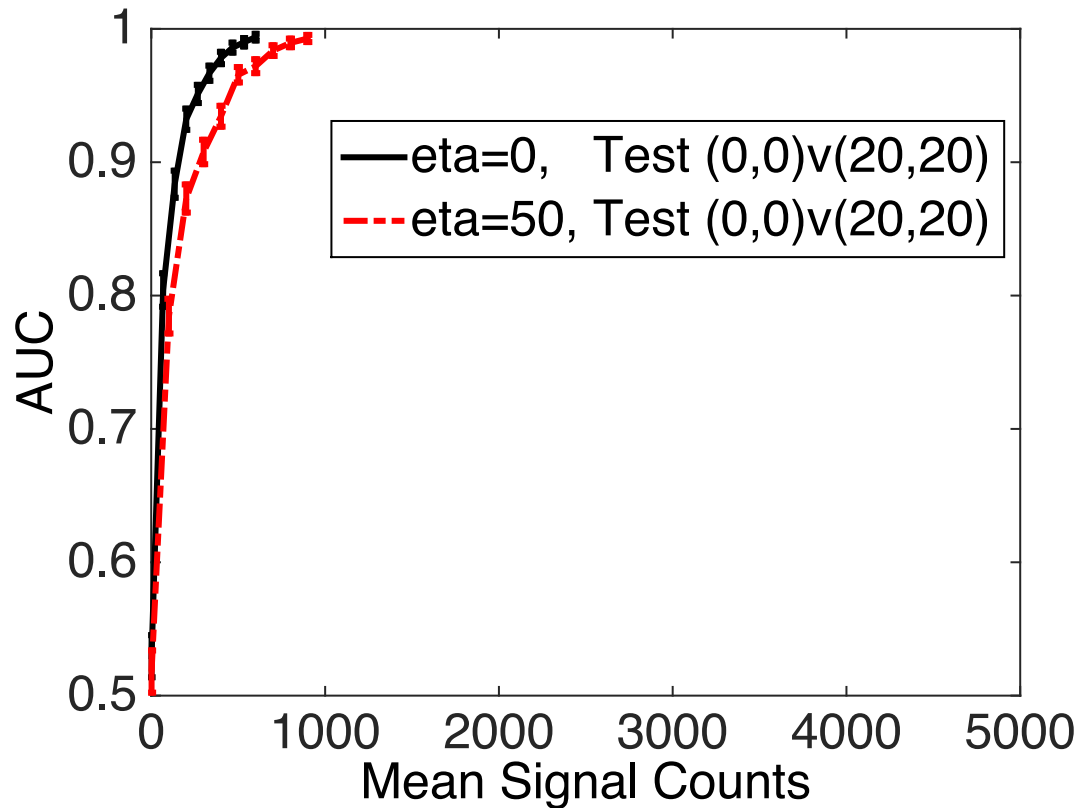


Eta=50

$\mathbf{W}_v\mathbf{T}$ corresponds to vertical shift.
No longer x information in template

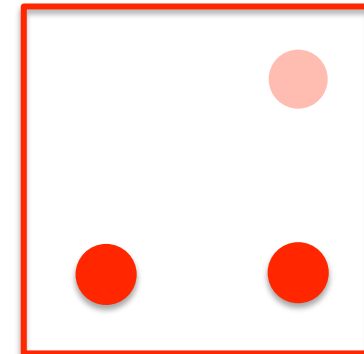
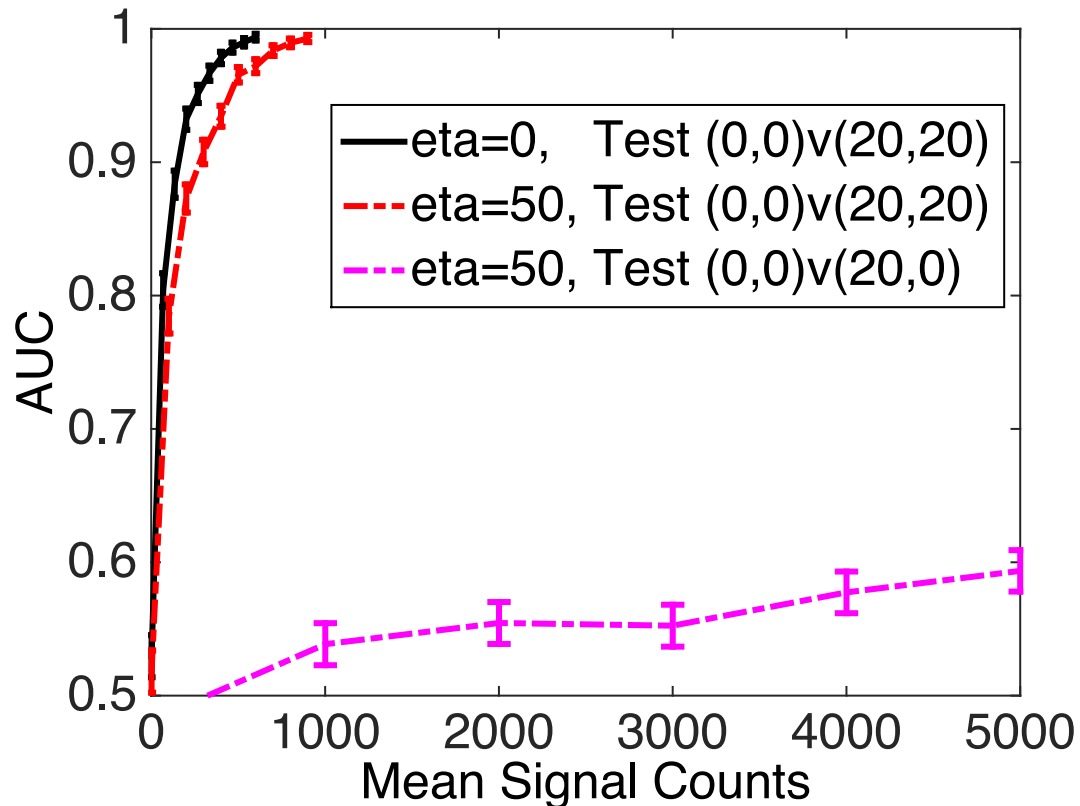
Performance 1

- We see that we can effectively classify the two sources based on their y information while limiting performance based on x information



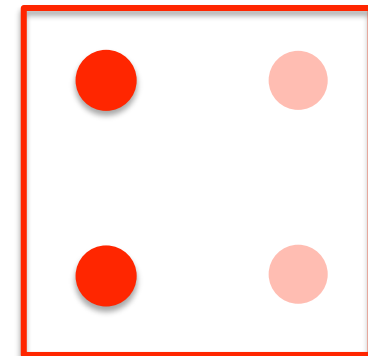
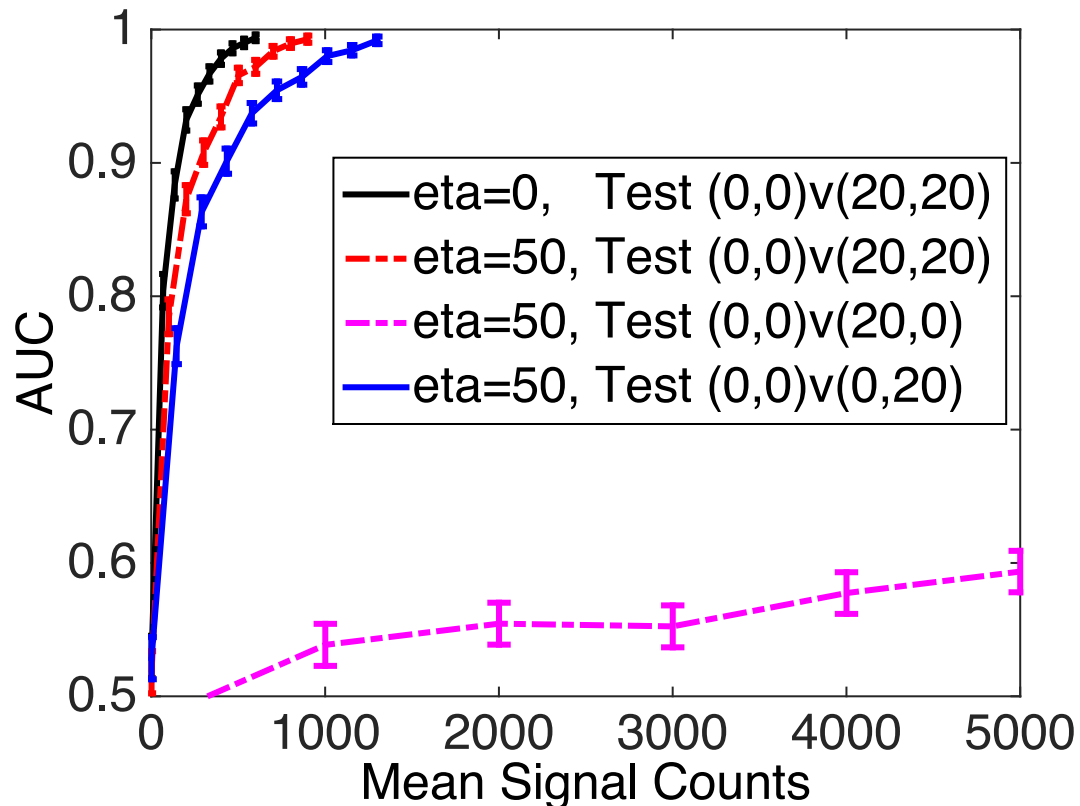
Performance 2

- We see that we can effectively classify the two sources based on their y information while limiting performance based on x information



Performance 3

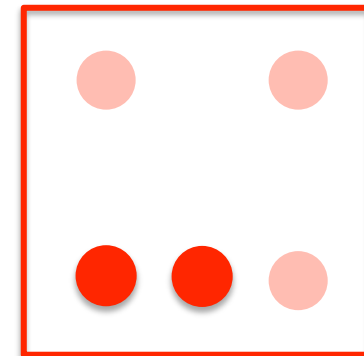
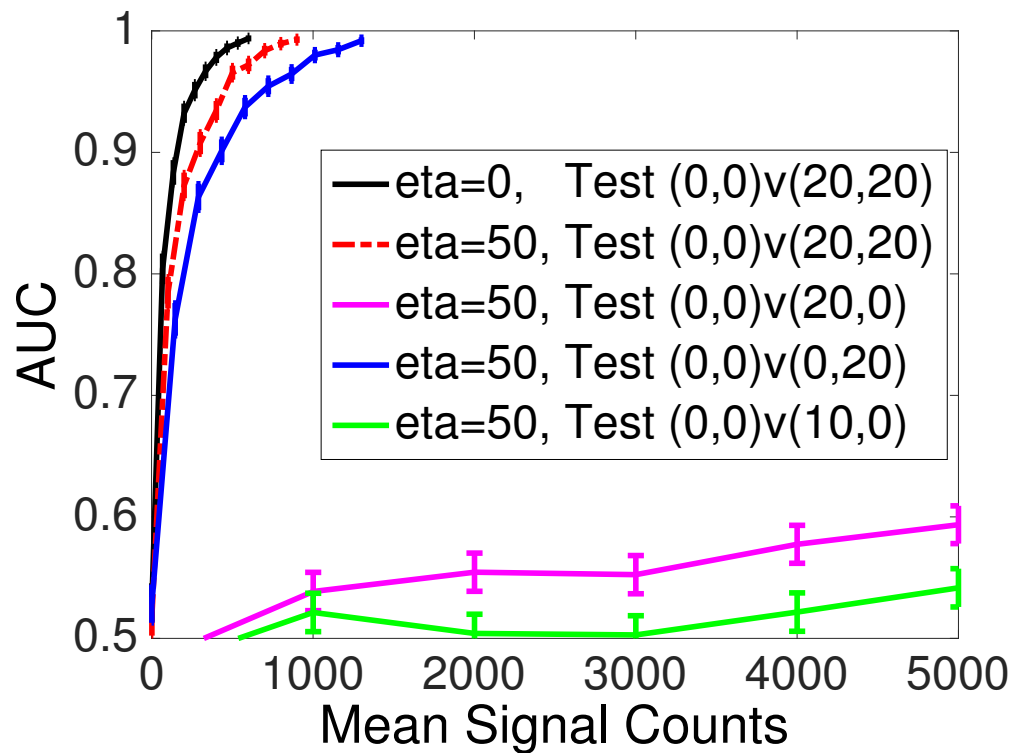
- We see that we can effectively classify the two sources based on their y information while limiting performance based on x information



Easier to distinguish (0,0) from (20,0) because model only contains y information.

Performance 4

- We see that we can effectively classify the two sources based on their y information while limiting performance based on x information



Discrimination performance within tolerance is poor as well

Observer model summary

Observer	Storage	Performance
Ideal Observer	!!!Extremely sensitive!!! Full probabilities which characterize what the images will look like	Best possible performance
Hotelling Observer	Sensitive— mean difference between data sets stored. Far less than ideal observer.	Good performance
Channelized Hotelling Observer penalizing decisions made on sensitive info	Done correctly, offers confirmation without revealing sensitive information	Task-dependent

Outline

- Introduction to task-based imaging
 - Threat detection example
- Approach to arms-control-treaty verification
 - List-mode processing
 - Models that store non-sensitive information
- Data simulation
 - Objects, image
- Bayesian ideal observer
- Channelized Hotelling observer
 - Reducing stored data while maintaining performance
 - Storing non-sensitive information
- **Null hypothesis test**

Null Hypothesis test

- Standard null-hypothesis tests cannot process list-mode data
 - List-mode processing requires operations that can be presented linearly.
 - Null hypothesis tests based on distance metrics

$$\chi^2 = \sum_{m=1}^M \frac{(g_m - \overline{g_m})^2}{\overline{g_m}} \quad d = (\mathbf{g} - \overline{\mathbf{g}})^\dagger K_g^{-1} (\mathbf{g} - \overline{\mathbf{g}})$$

Null Hypothesis tests

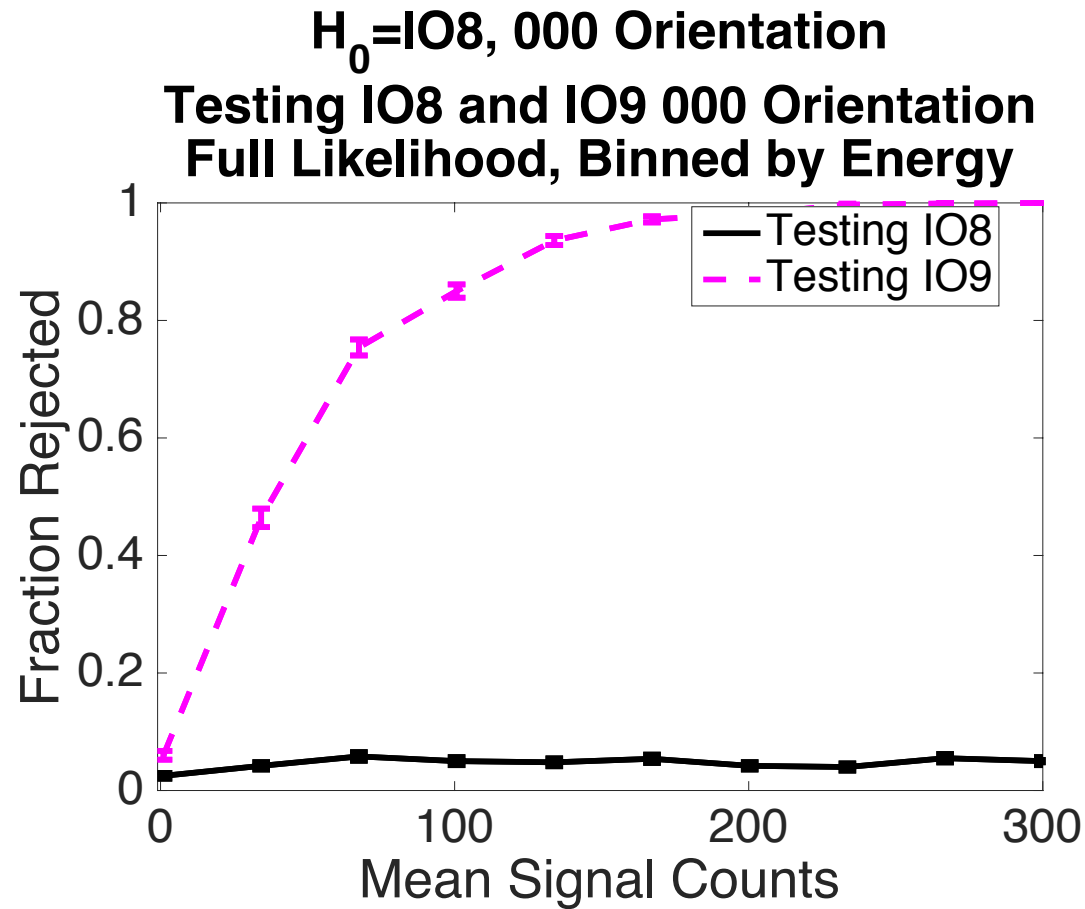
$$pr(\{A_n\}, N|H_0, T) = Pr(N|H_0) \prod_{n=1}^N pr(A_n|H_0)$$

- Incorporates count rate and LM probability
- # of LM products dependent on N.
- Extra variability in cases where count rates are similar.

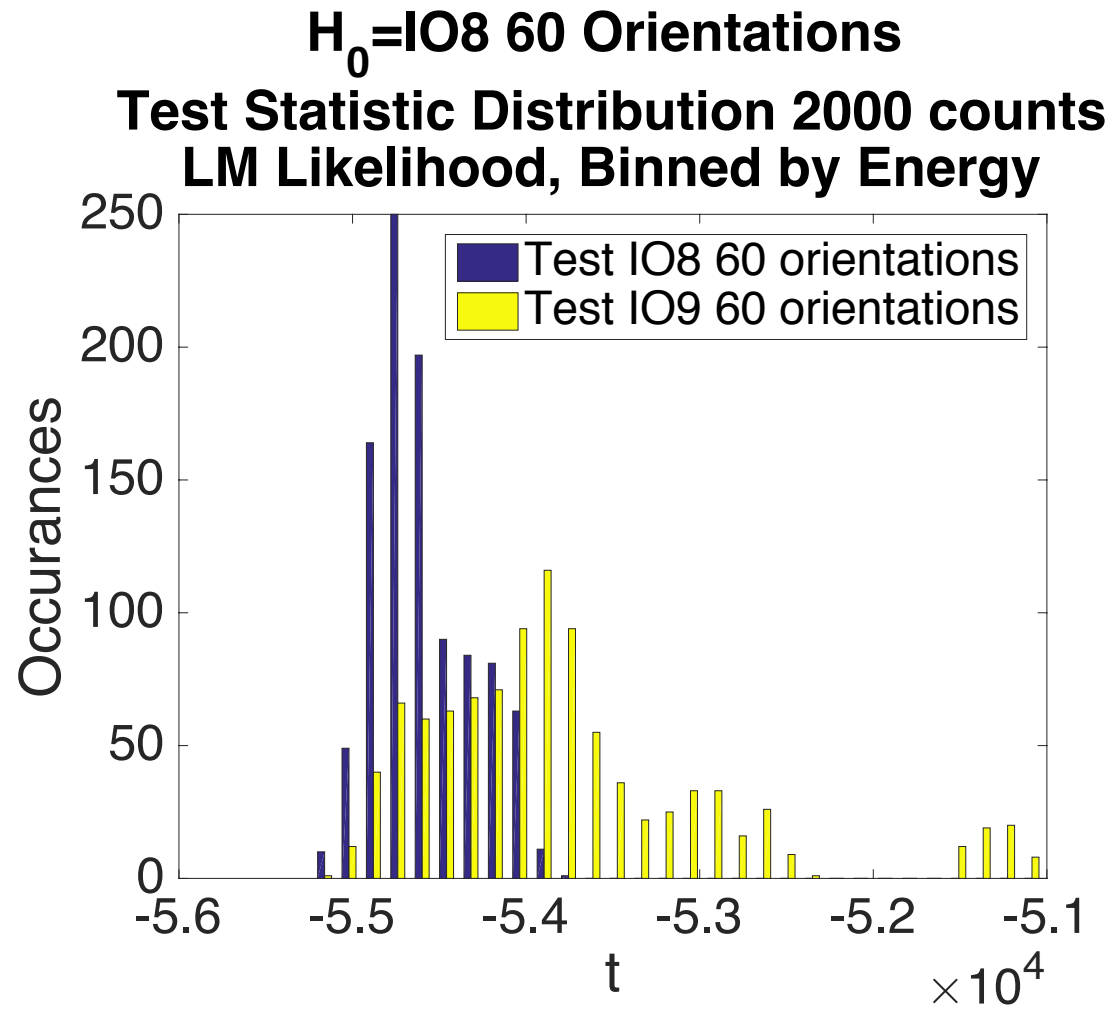
$$pr(\{A_n\}|N, H_0) = \prod_{n=1}^N pr(A_n|H_0)$$

- LM likelihood model conditioned on counts
- Better discrimination rejection ability when count rates are equal and other cases.

Full likelihood, $H_0=I08$, Test I09



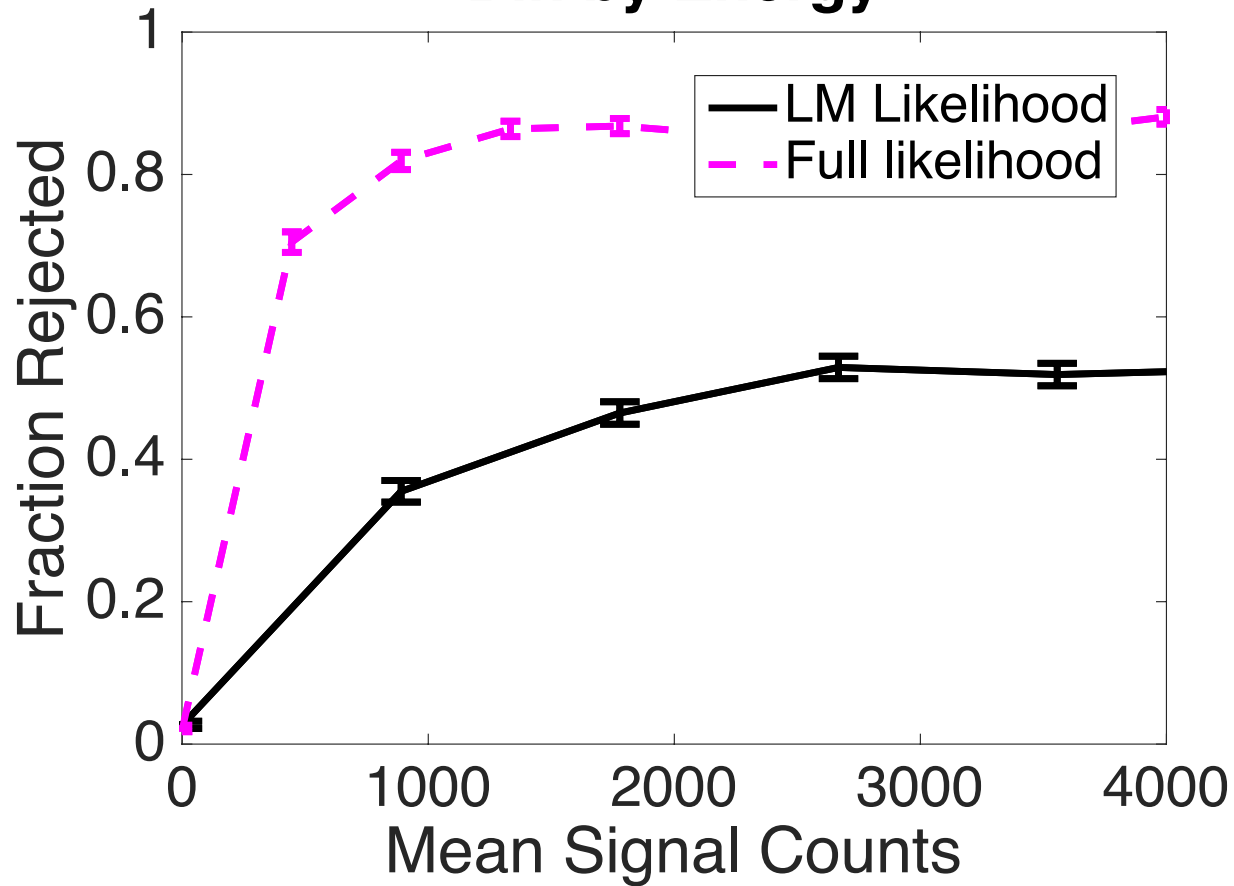
Null hypothesis incorporating nuisance parameters



Can't reject a large percentage of IO9 measurements regardless of number of counts detected.

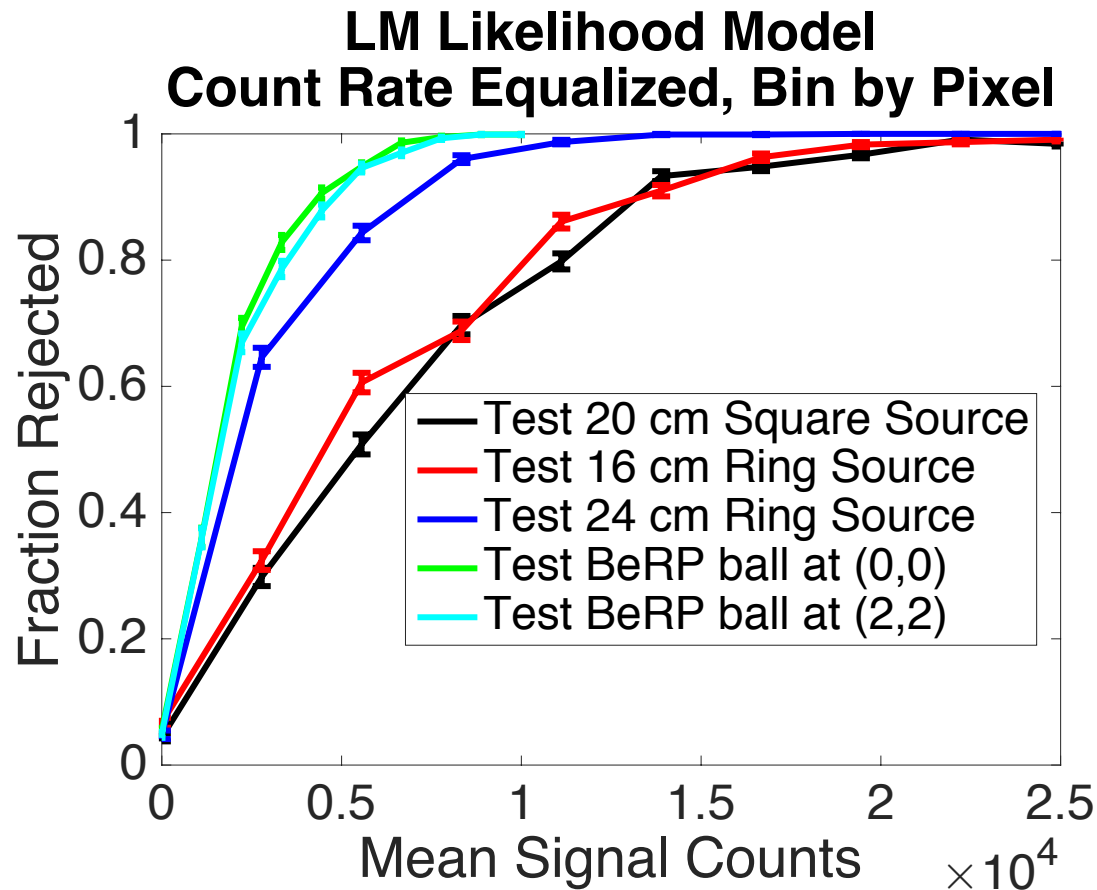
$H_0=108$, Test 109

$H_0=108$ 60 orientations
Test 109 60 orientations
Bin by Energy



Null Hypothesis

$H_0 = 20\text{cm Ring Source, Test Other Objects}$

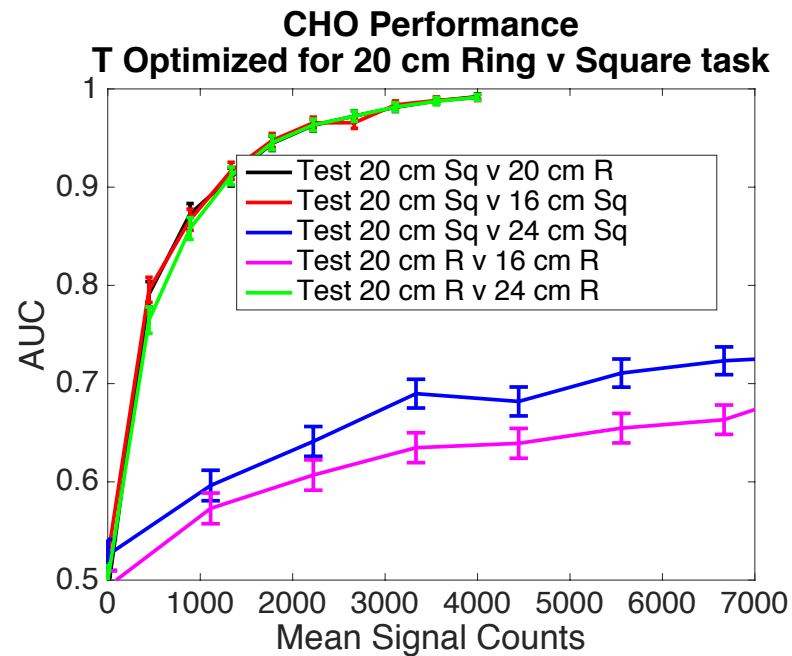


Summary

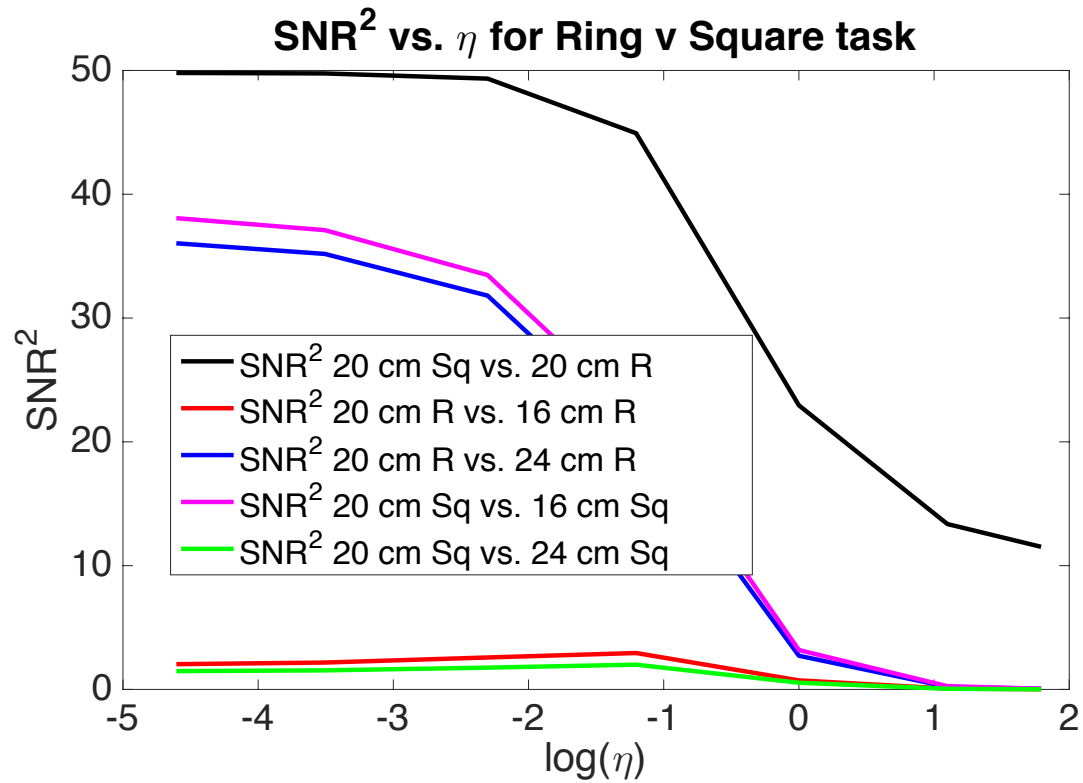
- Taken a task-based approach to development of a non-sensitive template that processes list-mode data.
- Ideal observer and Hotelling observer are optimal classifiers at the price of sensitive storage.
- Developed a procedure to generate non-sensitive template through channelized Hotelling observer.
 - Host needs to declare what parameters are sensitive and put a tolerance on those parameters.
 - Prevents need for information barrier

Future work – Ring vs Square

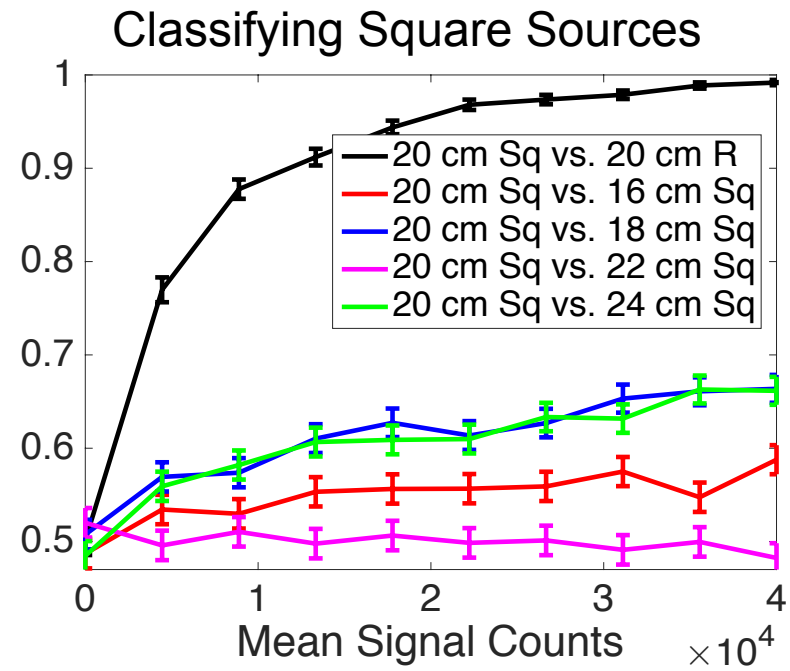
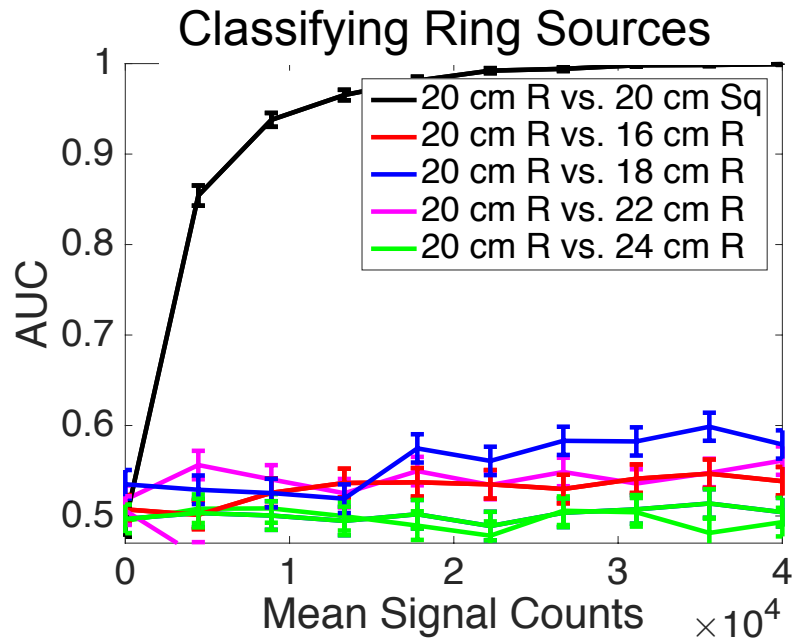
- Second discrimination task with sensitive information has been developed.
- Desire is to classify a 20cm ring vs a 20cm square source without being able to discriminate ± 4 cm size



Future work – Ring vs. Square



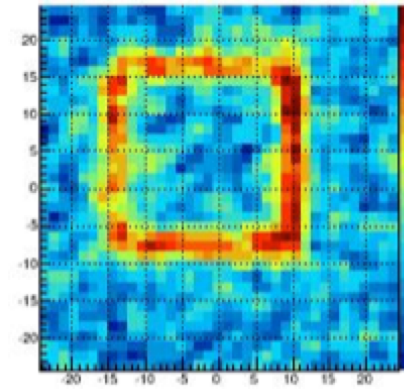
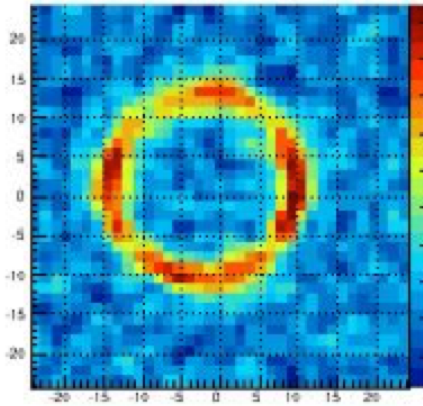
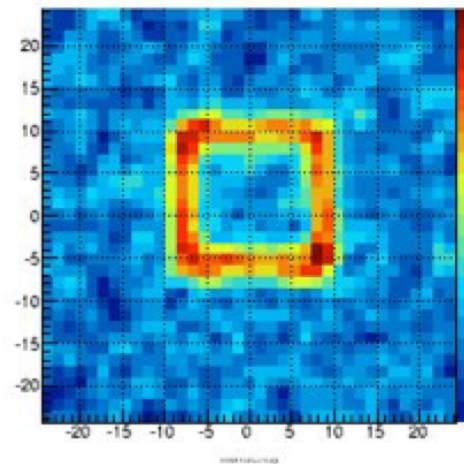
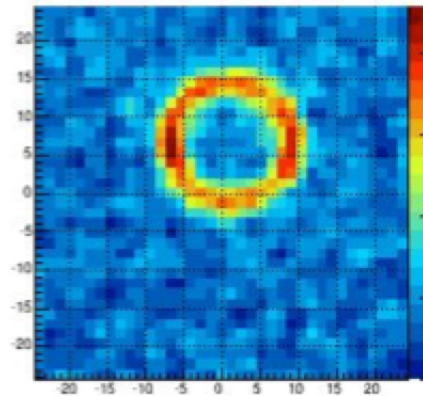
Future work – Ring vs. Square



Effective penalization of ± 4 cm objects, but model can distinguish 20cm square from 18,22 cm square.

Future work – Ring vs. Square

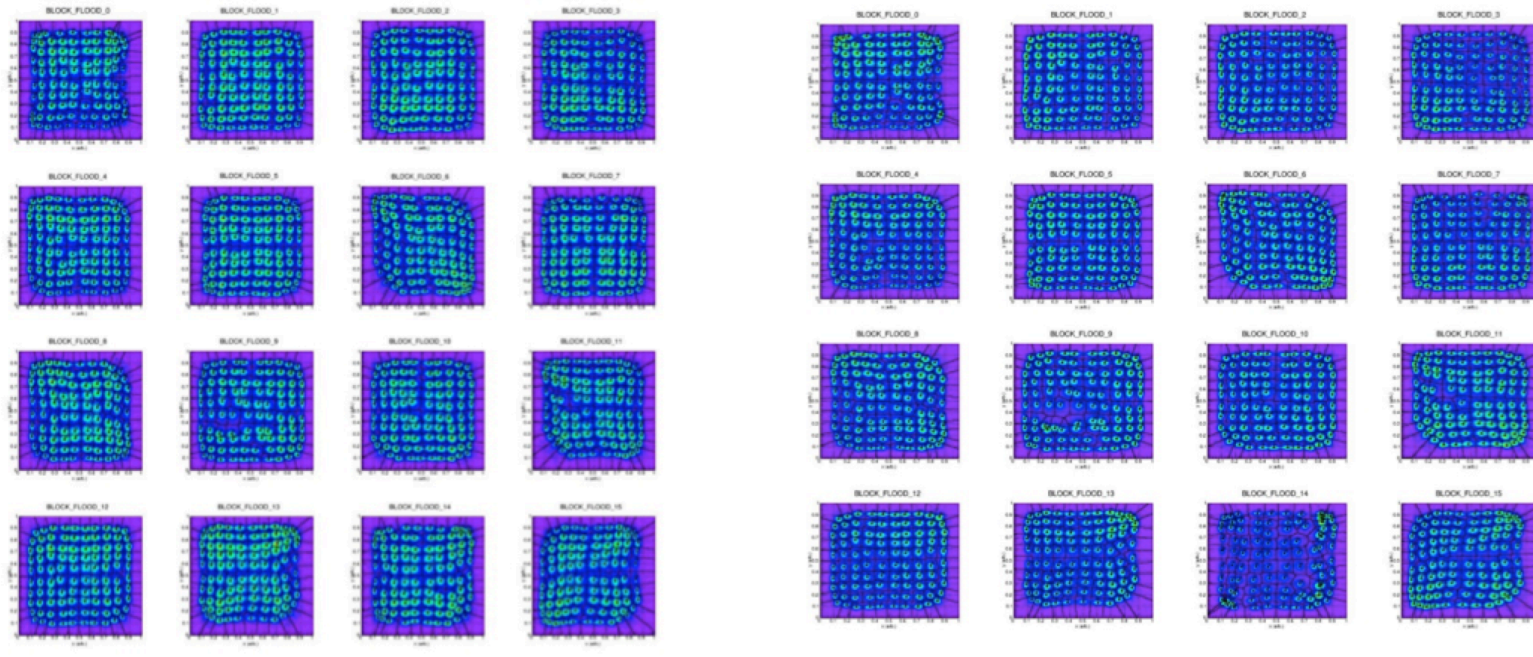
Experimental data has been taken on these square and ring sources at Sandia National Laboratories. Penalization effectiveness will be compared to simulations. We intend to publish results in TNS.



Future Work-Detector Response

- Penalization along sensitive parameter requires:
 - 1. Experimental data on H_1 and H_2 .
 - 2. Simulation data on objects that differ from H_1 and H_2 along sensitive parameters.
- A detector calibration measurement is required to find the detector response at that moment in time.
 - Detector response changes with temperature and can change in transit.

Future work - Detector Response



April (Cf252)

November (AmBe)

Detector is flooded with neutrons. Ratio of 4 PMT outputs used to determine location.

Significant changes require calibration measurements.

Thank you!

Project Team

Dr. Matthew Kupinski

Dr. Nathan Hilton

Dr. Erik Brubaker

Dr. Peter Marleau

Dr. William Johnson



Support

Sandia High Performance Computing Services

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- NA-20
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- Technology Research Initiative Fund (TRIF)



Questions?