SAND2015-9631C

A Channelized Hotelling Observer for Treaty-Verification Tasks

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Outline

- Background on arms-control-treaty verification & project summary
- GEANT4 simulations to acquire data on inspection objects
- Applying mathematical observer models developed by medical imaging community to arms-control-treaty verification
  - Observer: human or mathematical model that makes decisions

Arms-Control-Treaty Verification

- Current treaties holds accountable number of delivery systems
  - 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

Verification Task

Is it really a warhead?

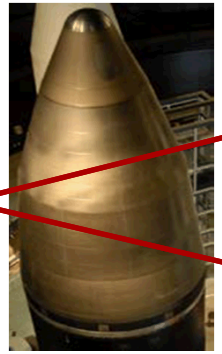
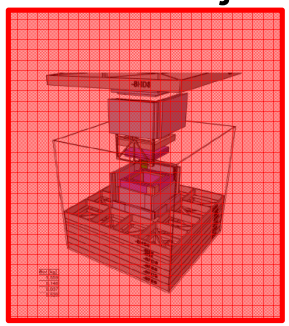


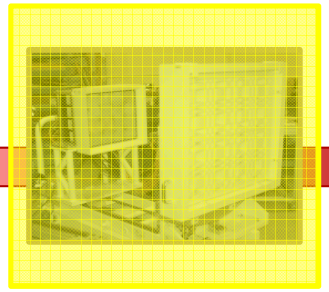
Photo from National Museum of the USAF

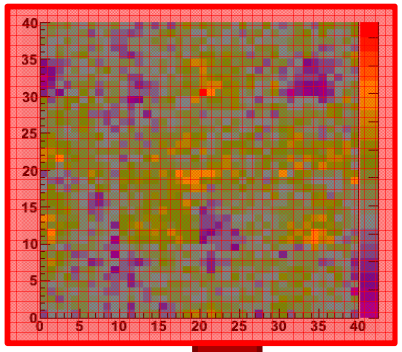
Is it warhead A or warhead B?

“Traditional” Template Matching

Trusted object



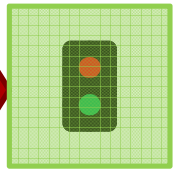




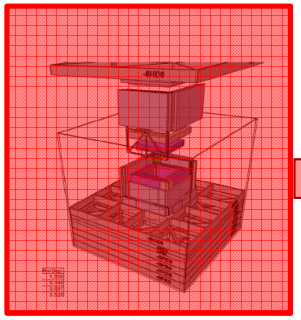
Calibration data is sensitive
IB required

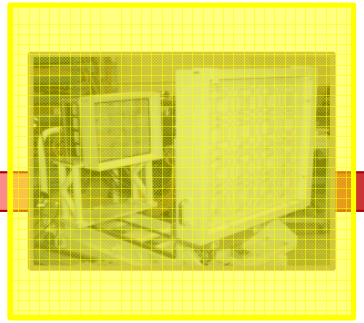
LEGEND	
Red	No Access
Yellow	Access Before & After
Green	Full Access

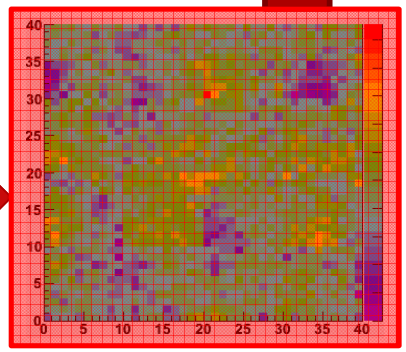
=?



Tested object



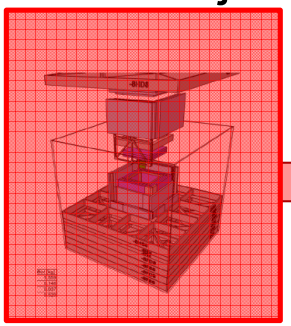


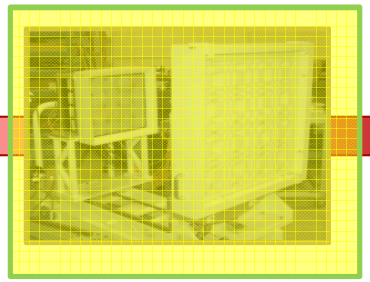


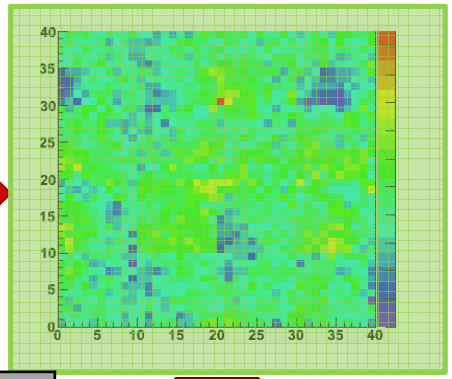
Tested detector data is sensitive
IB required

Our proposal

Trusted object

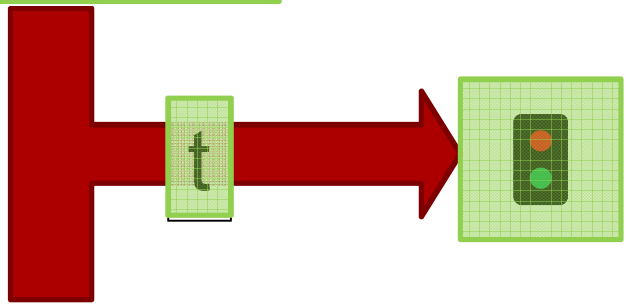




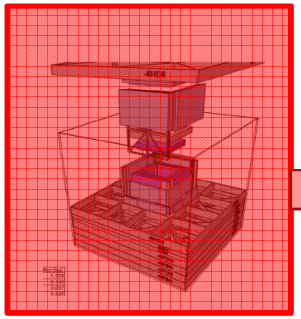


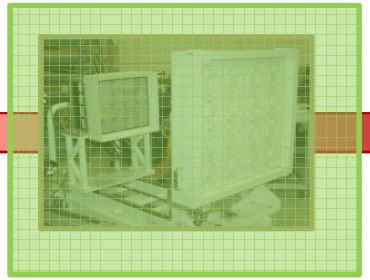
Hypothetical observer stores info sufficient for confirmation but not sensitive

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



Tested object





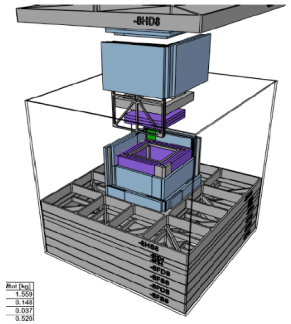
Testing data is processed event by event, only updating test statistic.

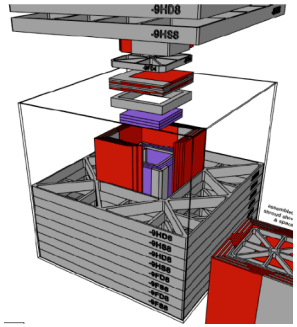
Data not aggregated

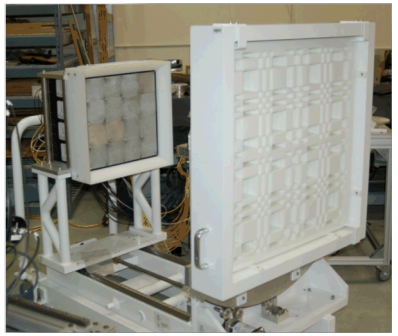
Think snapchat!

Task – Discriminate Idaho Inspection Objects

- Binary discrimination using spectral information.
  - Distinguish objects 8 (Pu surrounded by DU) and 9 (Pu surrounded by HEU) developed by Idaho National Laboratory.
  - Fast-neutron coded-aperture detector with liquid scintillator.





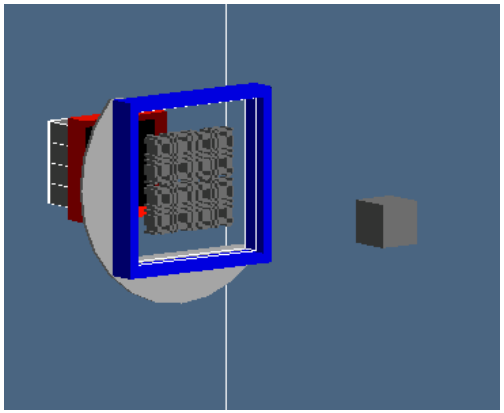


INL/EXT-11-20876

- Rotational variability included (simulated grid of orientations)

GEANT4 Simulations

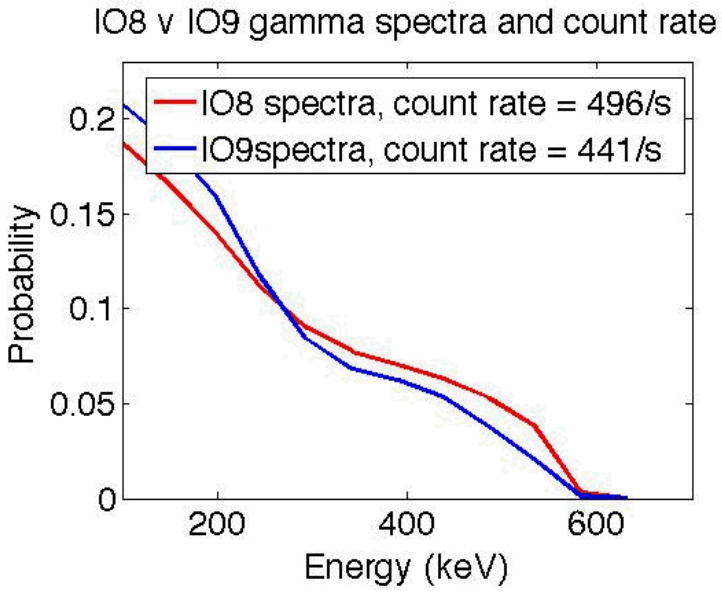
- Models built into transport application using GEANT4 toolkit to acquire testing and training data.



- Difficult to simulate gamma transport in plutonium objects with thick high-Z shielding.
  - Set gamma-energy threshold, applied linear energy bias
  - Used multithreaded capability of GEANT4.10
  - Ran on high-performance-computing clusters at SNL.

Simulation Data

- Similar geometries, no significant spatial difference in detector data.
- Observers make decisions based on gamma spectra differences
  - Data is summed over pixels



Definitions

- List-mode data A_n :
  - Estimated energy, pixel, and particle type (photon or neutron) for event *n.* Define *N* to be total number of detected events.

- Nuisance parameters :
  - Characteristics of the objects being imaged that affect the data but are of no interest
  - Examples include orientation, material age, construction, storage container characteristics.

Linear Template Observers

- Testing and training event data $\{A_n\}$ binned into data vector ***g*** (P x 1).

$$g_p = \sum_{n=1}^{N} f_p(A_n)$$

- ***g*** is binned detector data – image, spectra or both.

- Linear template **W** (P x 1) acts on $\boldsymbol{g}_{test}$, result is thresholded to make a decision

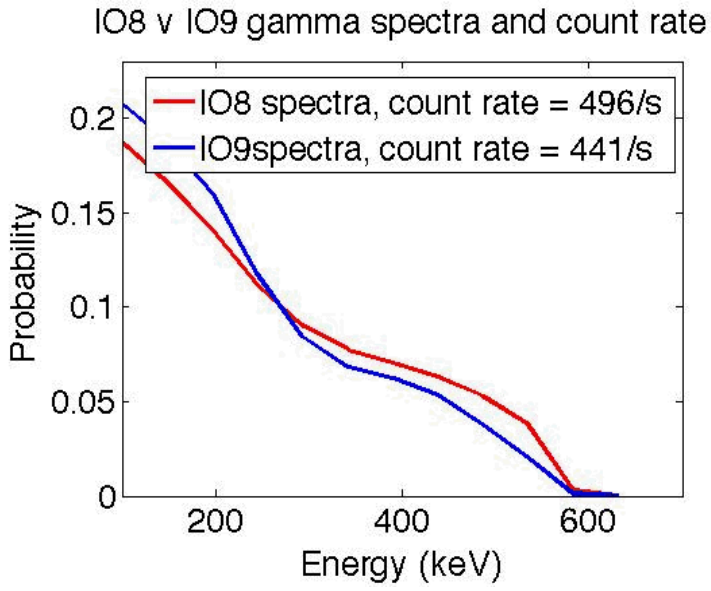
$$t = \mathbf{W}^{\dagger}\mathbf{g_{test}} \quad t \gtrless t_{\mathrm{thresh}}$$

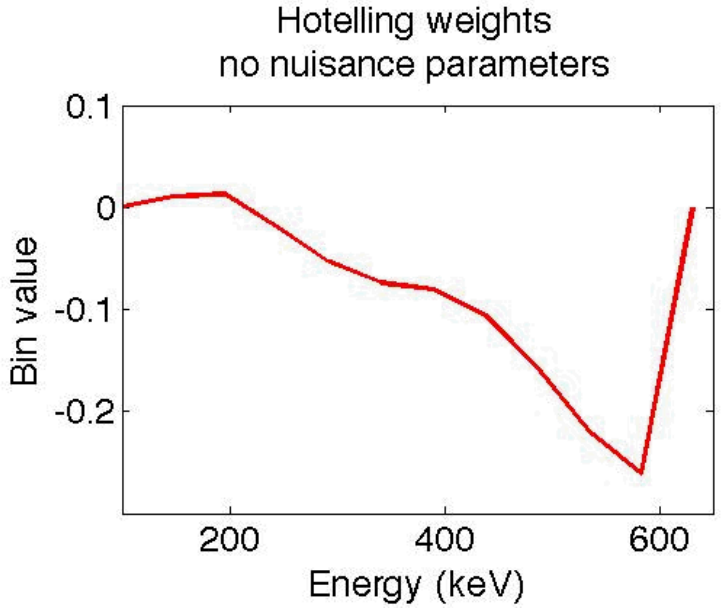
Hotelling Observer

- Hotelling observer is sensitive template *W* defined as:

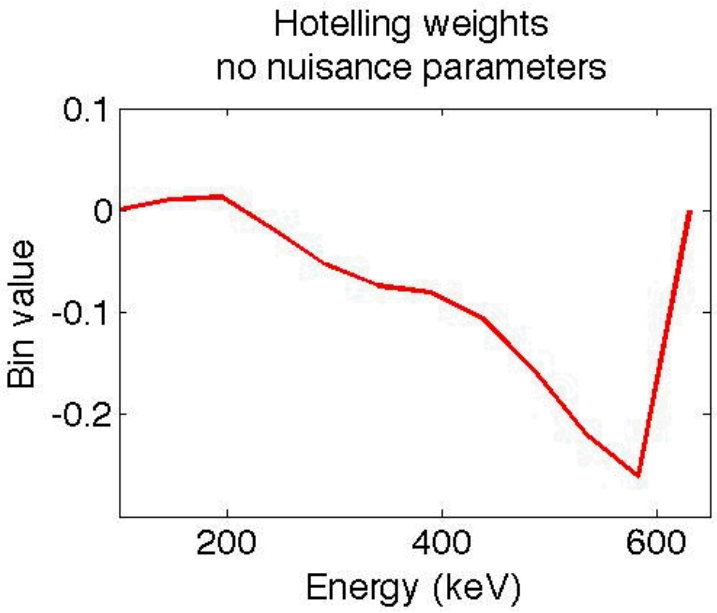
$$\mathbf{W} = \mathbf{K_g}^{-1}\overline{\Delta \mathbf{g}}$$

- ***W*** is optimal template when data statistics are Gaussian.



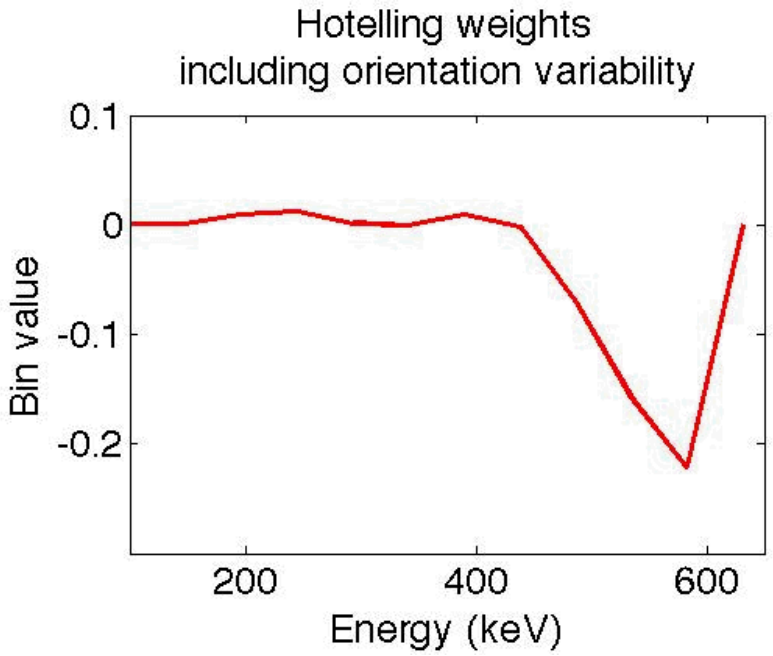


Hotelling Observer with Nuisance Parameters



Relates directly to spectra

Slight difference due to dense **K** matrix



+/- of Hotelling Observer

Positives

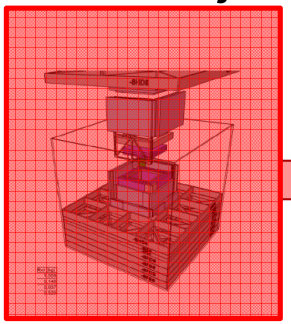
- Only storage is Hotelling template ***W*** – not image data ***g***.
- Average over nuisance parameters smears out data.
- Analogous to secondary imaging system that filters out information other than the differences between objects.
  - Impossible to reconstruct ***g***, only ***W***.

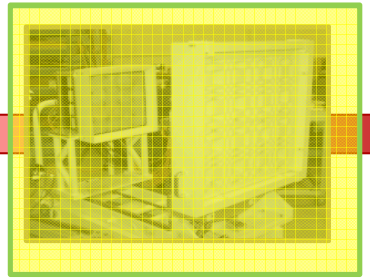
Negatives

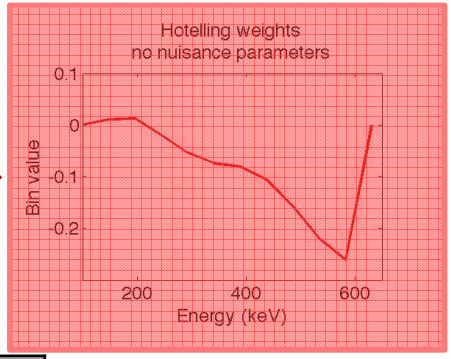
- Template contains product of first and second order statistics, but still (likely) constitutes sensitive information

Hotelling Observer in Practice

Trusted object

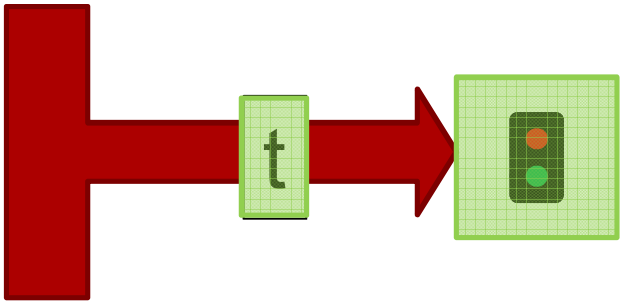




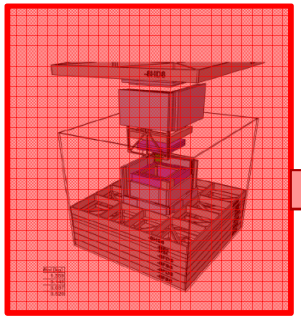


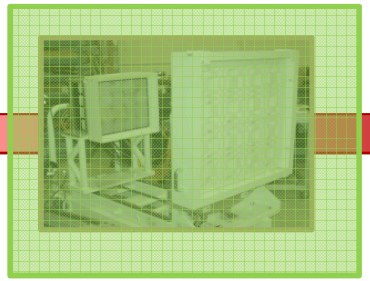
Hotelling template probably sensitive, but can't reconstruct object from *t*

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



Tested object





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

Channelized Hotelling Observer (CHO)

- Can we channelize data into non-sensitive channel values that monitor can work with?
- Channelize data vector ***g*** (*P*x1) with channelizing matrix ***T*** (*Q*x*P*) into much smaller vector ***v*** (*Q*x1).

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

$$Dim(\mathbf{v}) << Dim(\mathbf{g})$$

$$\mathbf{W}_{\mathbf{v}}\mathbf{v}_{test} \lessgtr t_{thresh}$$

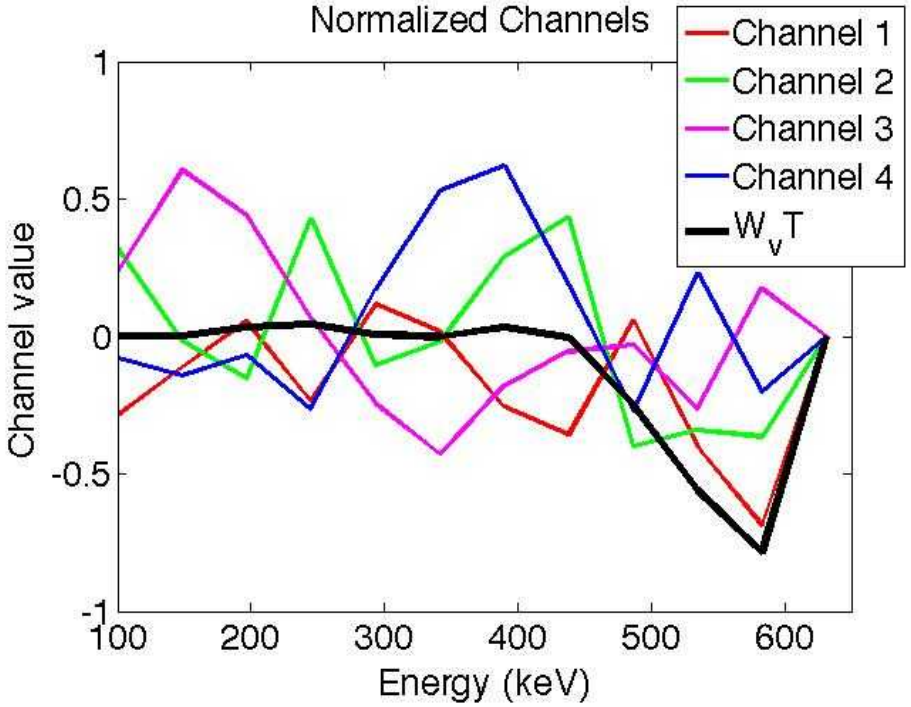
Optimizing *T*

- ***T*** can be optimized to maximize SNR^2 of test statistic distributions for best performance.
  - Gradient descent with backtrack

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

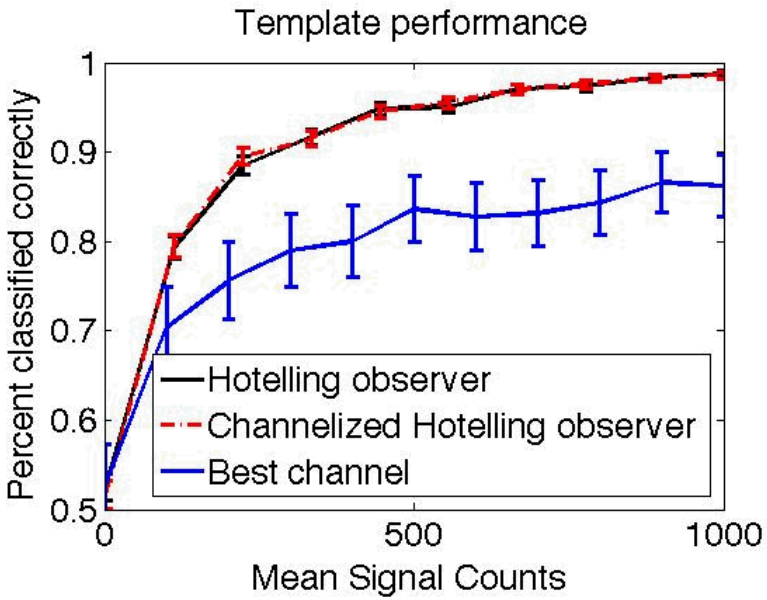
Example Channelization

- Standard optimization leads to fairly nonsensitive channels.
- Optimal performance requires sum of optimally weighted channels to equal Hotelling weights.



Performance of HO & CHO

- Task is to discriminate IO8 and IO9 when orientation is unknown



- However, best channel in other tasks has equal performance to CHO

+/- of CHO

Positives

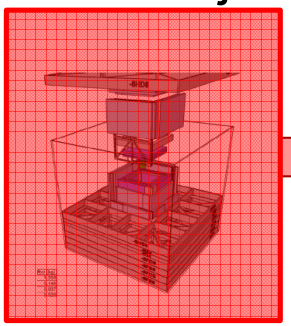
- Q non-sensitive channel values that monitor can use to make decisions
  - More channels = improved ability to verify tested sources is one of two in discrimination task, and not a spoof
- Optimizing SNR^2 results in optimal performance
  - Impossible to reconstruct ***image***, only ***Hotelling weights (difference in images)***.

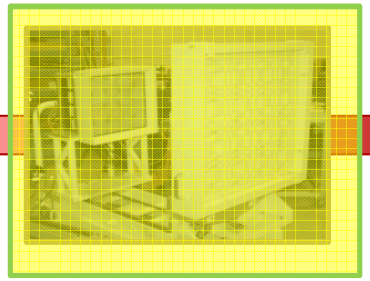
Negatives

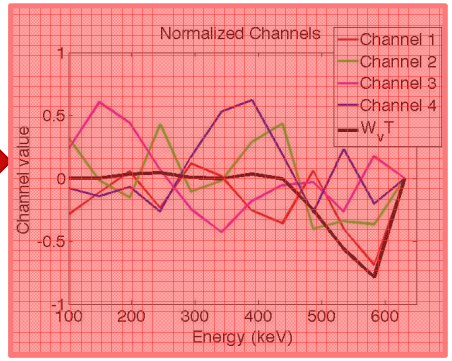
- Optimally weighted sum is sensitive information
- ***Channelizing matrix itself*** often sensitive, cannot be shared.

CHO in practice

Trusted object



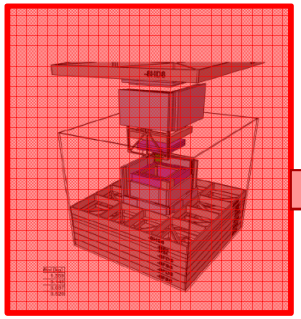


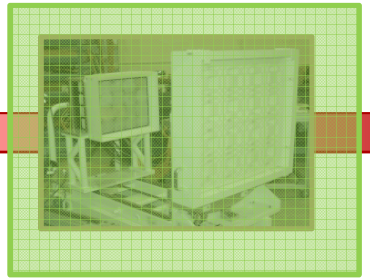


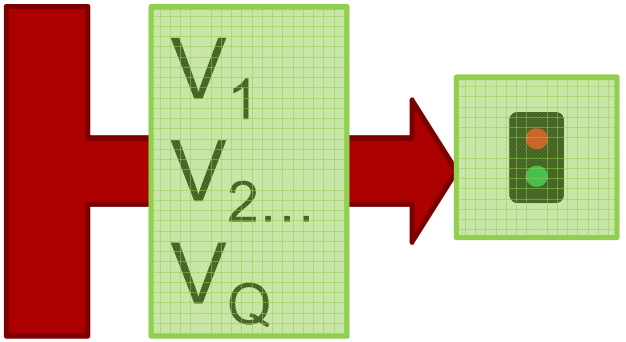
Channels may/may not be sensitive, but W_v*T is

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

Tested object







Testing data is processed event by event, updating Q channelized values

Current/Future work

- Build off channelized Hotelling observer groundwork
- Create nonsensitive channels by penalizing channel performance

$$f_{obj} = SNR^2_{Qchannels} - \eta \sum_{q=1}^{Q} SNR^2_{channel\ q}$$

- Add noise to channels to reduce sensitive storage and performance.
- If host defines sensitive parameters in geometry construction, we can penalize the ability to discriminate between slight differences in the object

Summary

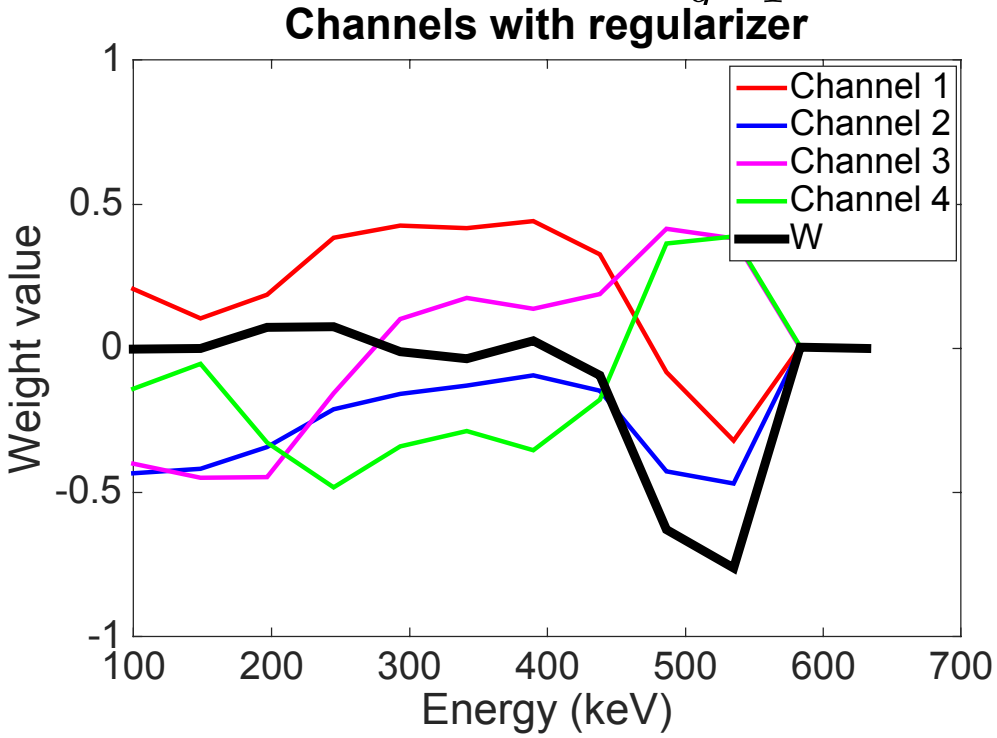
- Applying methods developed by medical imaging community to arms-control-treaty verification tasks
- Modeled inspection objects in transport application using GEANT4 toolkit to simulate data
- Hotelling observer gives optimal results while only storing differences between objects
- Channelized Hotelling observer gives monitor access to more information
  - Adding terms to optimization routine offers paths to non-sensitive storage

Extra slides

CHO with penalty

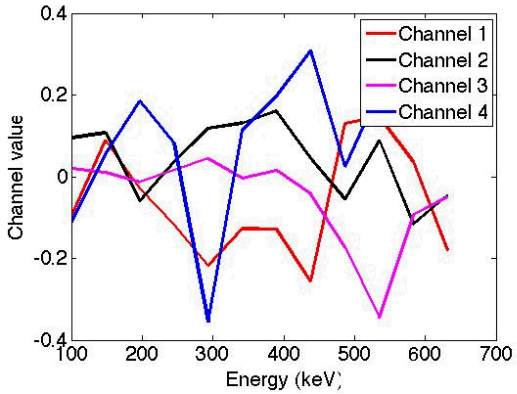
- Use penalty term in optimization to limit channel performance

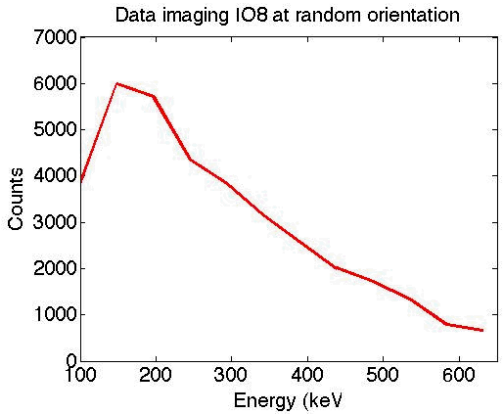
$$f_{obj} = SNR^2_{Qchannels} - \eta \sum_{q=1}^{Q} SNR^2_{channel\ q}$$



CHO inverse problem

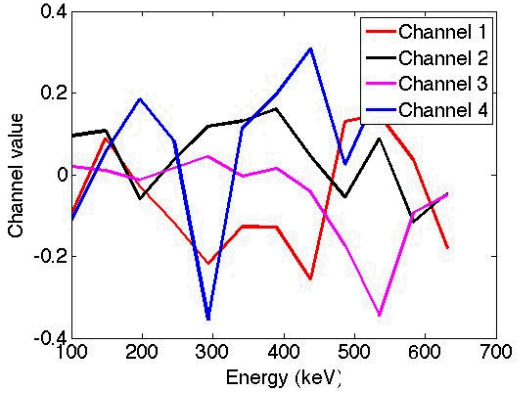
T x g = v



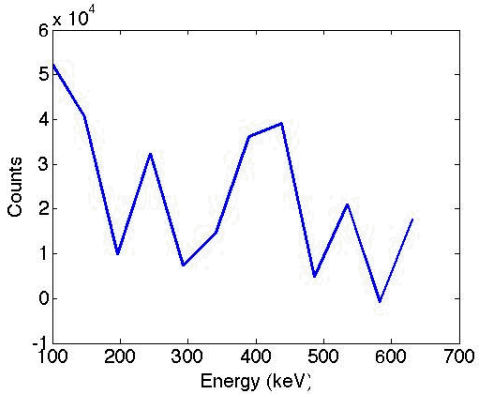


-365
-5589
223
-3030

T^{-1} x v = g_{rec}



-365
-5589
223
-3030

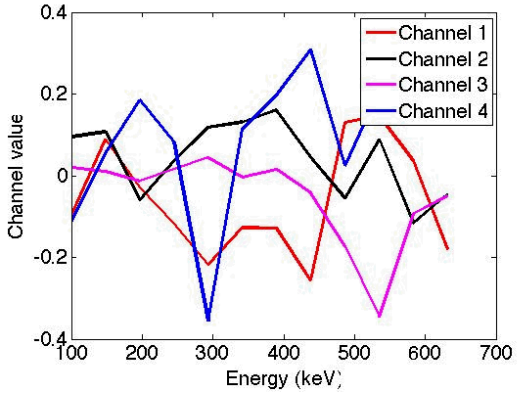


CHO inverse problem

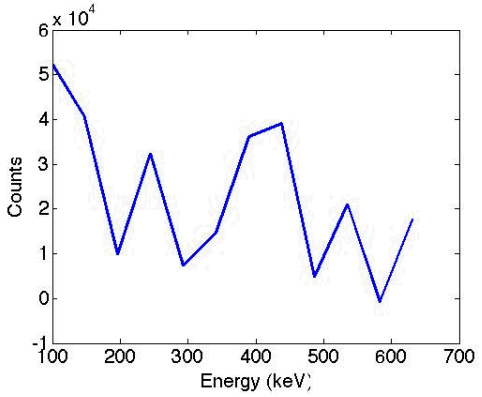
T x g = v

Channel value

Channels, singular vectors, reconstruction are all very noisy,
But channel 3 looks like W

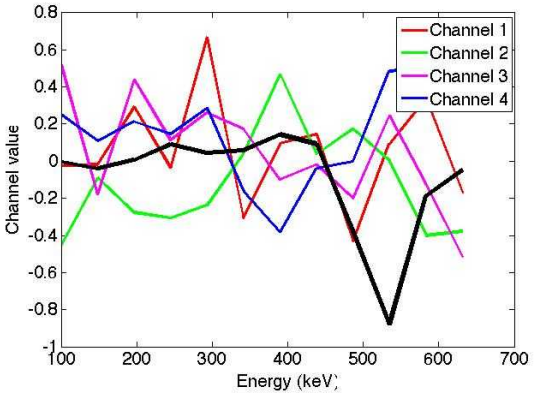


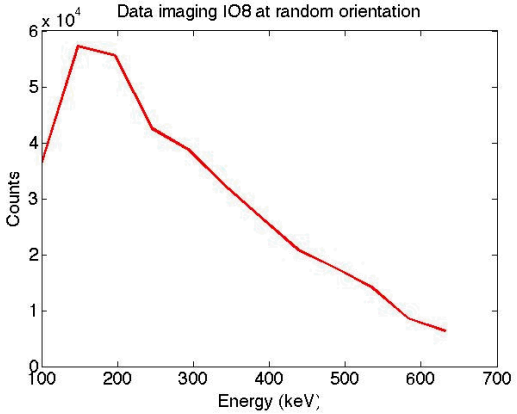
-365
-5589
223
-3030



CHO inverse problem w/ perform. penalty

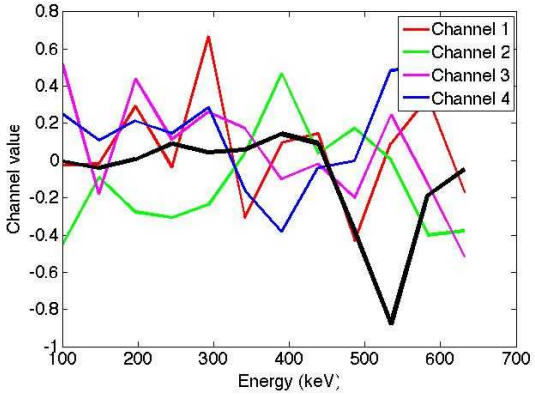
T x g = v



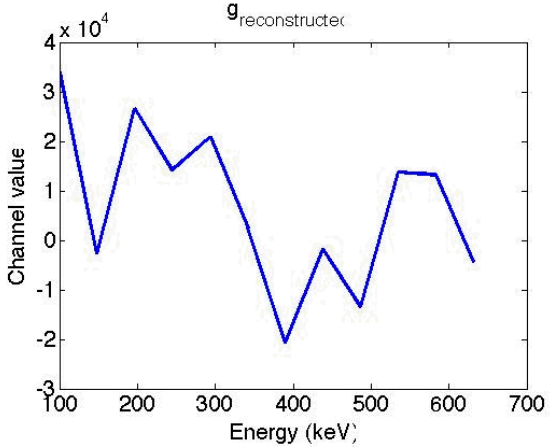


1.38e4
-2.25e4
2.26e4
2.19e4

T^{-1} x v = g_{rec}

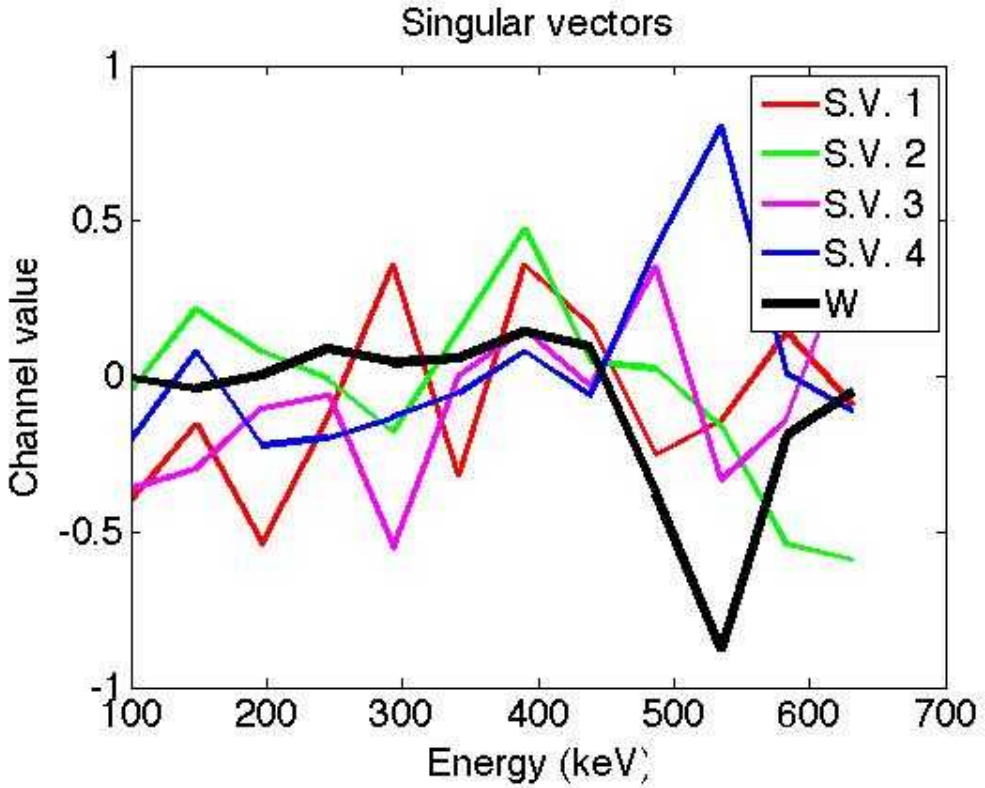


1.38e4
-2.25e4
2.26e4
2.19e4



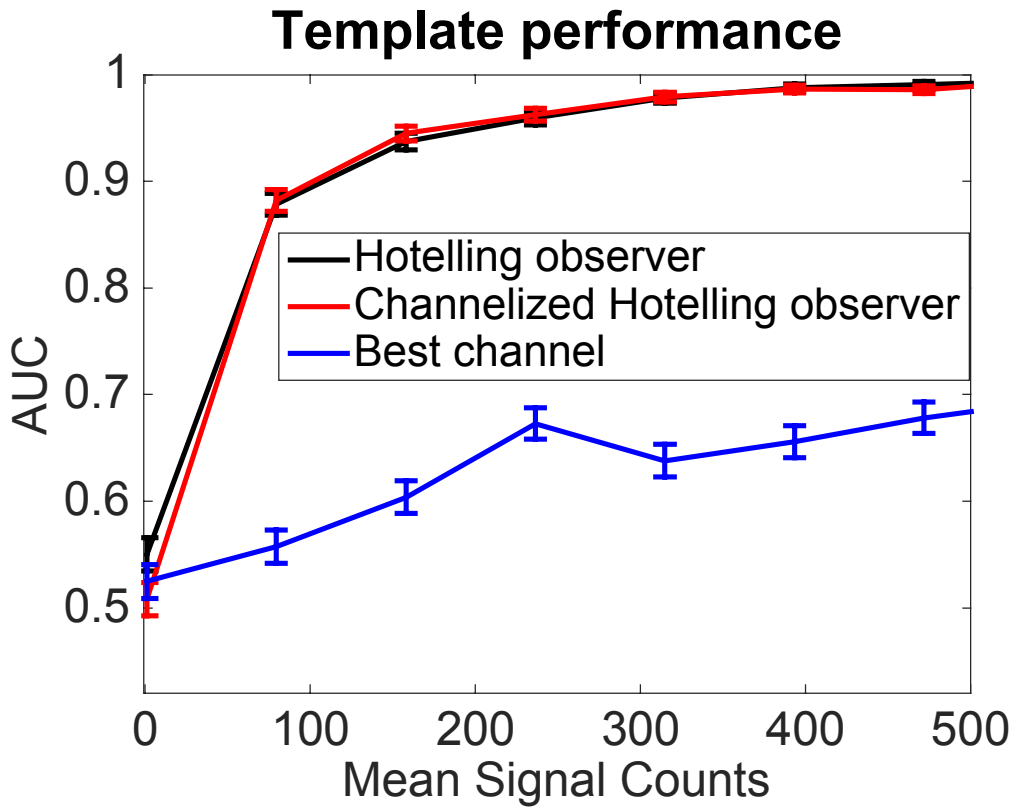
CHO inverse problem w/ perfom. penalty

- SVD of channelizing matrix: S.V. 4 looks like Hotelling weights



Channelized Hotelling penalty

- Hotelling and channelized Hotelling perform well
- Individual channels perform poorly



Future work – reducing sensitive info

- Example: Source A is a BeRP ball with 1” of poly shielding. The host country doesn’t want the monitor to know what source A’s poly thickness is down to a tolerance of Δt

$$f_{obj} = SNR^2_{(B-A)} - \eta SNR^2_{(A_{(1”+\Delta t)} - A_{(1”)})}$$

- Will lead to drop in performance with benefit that host needn’t worry.

Future work – reducing sensitive Info

$$f_{obj} = SNR^2_{(B-A)} - \eta SNR^2_{(A_{(1"+\Delta t)} - A_{(1")})}$$

- A channelizing matrix that optimizes this objective function wouldn't be based on sensitive data
- Likewise, sensitive data could not be gained through the inverse problem

Future work – null hypothesis test

- Need an observer to address “Is this source A or not source A?”
- We developed a model based on likelihood expression, but it is spoofable.
- Standard tests based on distance metrics
- Is there a linear model similar to the Hotelling observer?