

Monte Carlo Simulation and Reconstruction Framework for a CdZnTe-based Spherical Coded Aperture and Compton Gamma-ray Imager

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NE 255 - Numerical Simulation in Radiation Transport
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December 14, 2016

OUTLINE

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- Monte Carlo Simulation - Geant4
- Results
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INTRODUCTION

Motivation

Efficiently detect, image, identify, and characterize weak radioactive sources in complex environments.

- Applications in astronomy, medical imaging, and **nuclear security**.

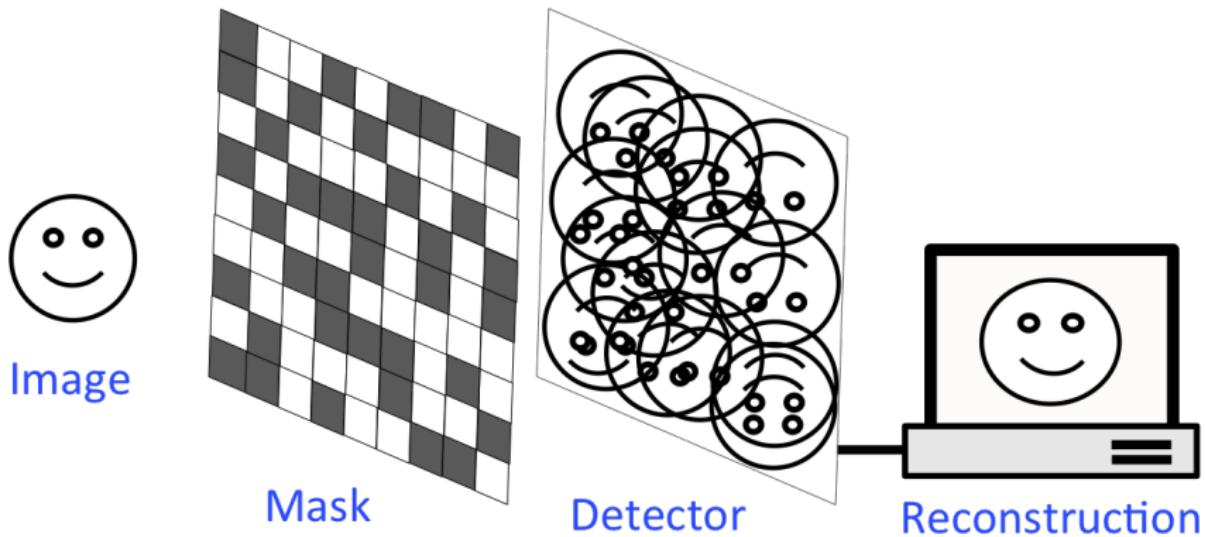
Need

Hand-held, portable 3D imaging system with high efficiency, wide field-of-view, broad energy sensitivity, and high energy resolution.

Approach

Multiple room-temperature operated cm^3 CdZnTe (CZT) coplanar grid (CPG) [1] detectors arranged to facilitate coded aperture and Compton imaging modalities.

CODED APERTURE IMAGING - CONCEPT



The mask modulates photon flux to create detectable *shadowgrams* that are unique to each point in the image space.

CODED APERTURE IMAGING - IMAGE RECON.

Fast analytical reconstruction methods exist (simple back-projection, filtered back-projection, cross-correlation) [2, 3]

- Most fail to include relevant physics, produce blurry images.

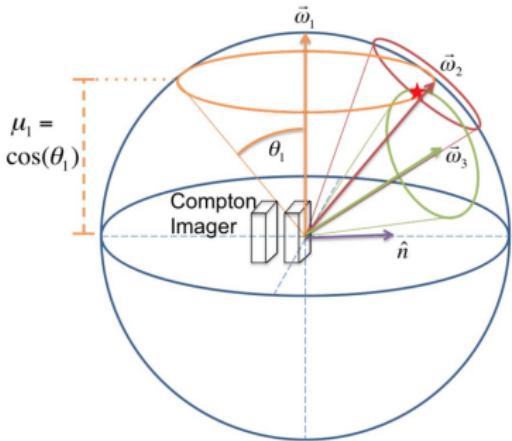
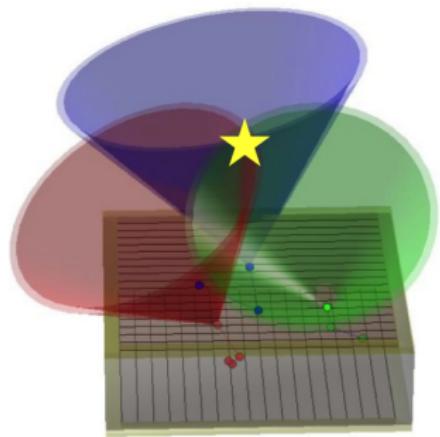
Focus on iterative method - **Maximum Likelihood Expectation Maximization (MLEM)** [4]

$$\lambda_j^{n+1} = \frac{\lambda_j^n}{\sum_{i \in J_j} C_{ij}} \sum_{i \in J_j} \frac{C_{ij} g_i}{\sum_{k \in I_i} C_{ik} \lambda_k^n}$$

- C_{ij} is the probability an event in detector i came from image pixel j
- g_i are the counts in detector i
- λ_j^n is the intensity of image pixel j for iteration n
- I_i are the set of image pixels that contribute to detector i
- J_j are the set of detectors to which image pixel j contributes

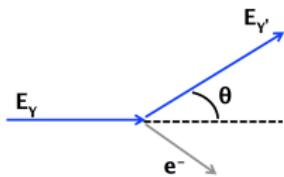
COMPTON IMAGING - CONCEPT

[5]



Kinematics of correctly sequenced multi-site events define a cone of possible source directions. Cones back-projected into \mathbb{R}^3 (3D) or \mathbb{S}^2 (2D).

$$\mu = \cos(\theta) = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E'_\gamma}$$



COMPTON IMAGING - IMAGE RECON.

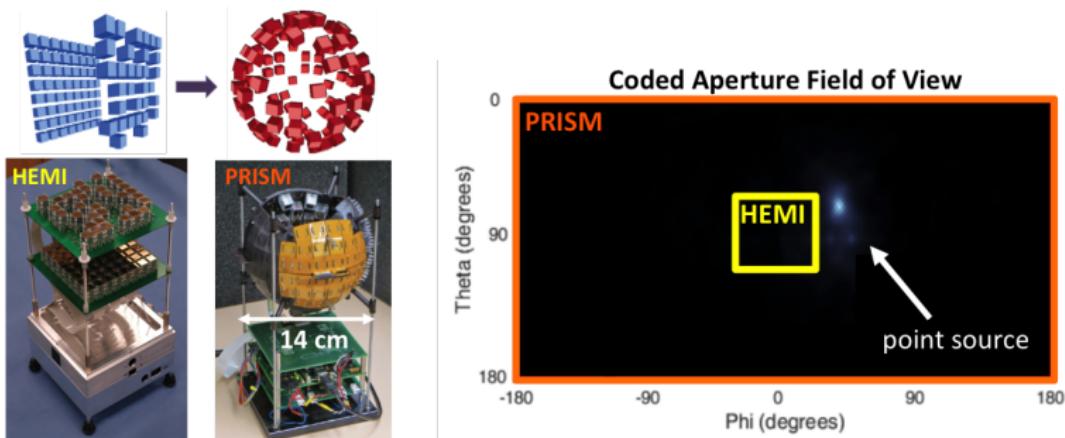
Provide each cone with a width and intensity described by a Gaussian function to avoid pixellation effects. Sum n cones together to produce back-projection image [5]

$$b(\hat{\vec{x}}) = \sum_{i=1}^n \frac{w_i}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(\hat{\vec{x}} \cdot \hat{\vec{\omega}} - \mu_i)^2}{2\sigma_i^2}\right)$$

- $\hat{\vec{x}}$ is the unit vector to image pixel
- $\hat{\vec{\omega}}$ is the unit vector cone axis
- μ is the cosine of the scattering angle
- w is the cone weight (from Klein-Nishina and lever arm distance)
- σ is the cone width (smaller than expected resolution)

PRISM

- Multimodal active planar imagers exist (HEMI [6]) → suffer from **limited field-of-view**, especially in coded aperture mode.
- Rearrange into a spherical configuration to facilitate 4π imaging.



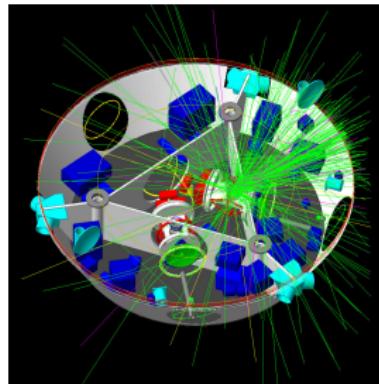
- 192 available detector locations.
- Depth-of-interaction (DOI) readout.



MONTE CARLO SIMULATION, GEANT4

Geant4 [7] is a *Monte Carlo toolkit* used to simulate the transport of particles through matter.

- The user writes and compiles their own simulation.
 - Requires knowledge of C++ and CMake.
-



Simple raytracing simulation was developed over the summer to determine coded aperture system response to far-field point sources.

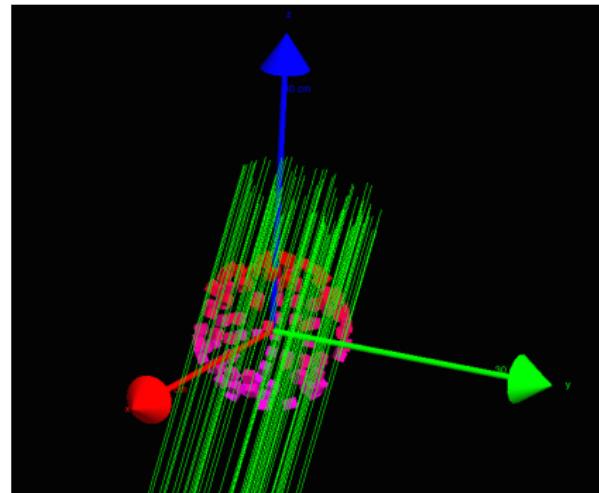
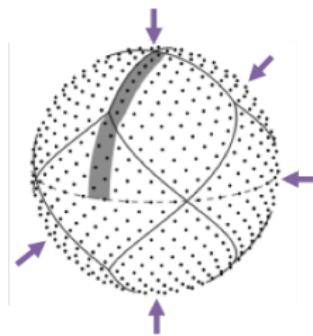
WHAT DID I DO?

- ① Upgraded simulation to include scattering, electron production, multi-interaction tracking, geometry and source modifications.
 - User interaction via macro files passed to executable
 - Track energy deposition, detector ID, DOI, ...
 - Output to structured binary data files
- ② Developed Python tools to
 - Parse output data
 - Perform MLEM coded aperture image reconstruction
 - Collect coincident Compton events and sequence tracks
 - Perform Compton cone back-projection image reconstruction

2D CODED APERTURE SYSTEM RESPONSE

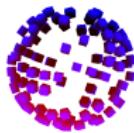
Simulate far-field point sources (parallel rays at infinity) at each image pixel in 4π .

- *Hierarchical Equal Area isoLatitude Pixelization (HEALPix)* [8] discretization of a sphere with 3072 pixels.

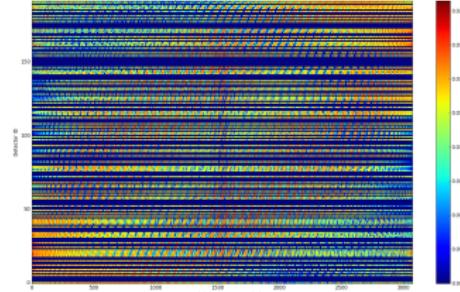


2D CODED APERTURE SYSTEM RESPONSE

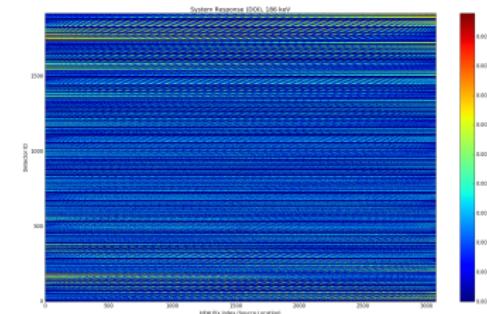
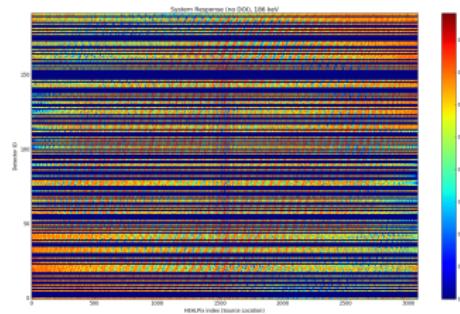
Random mask



60 keV



186 keV

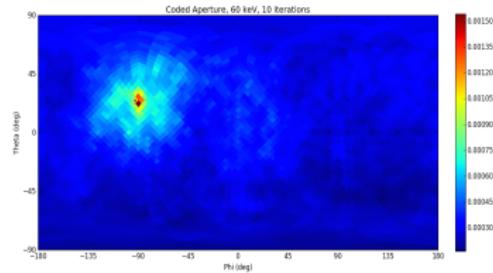


MLEM IMAGES

60 keV, random mask

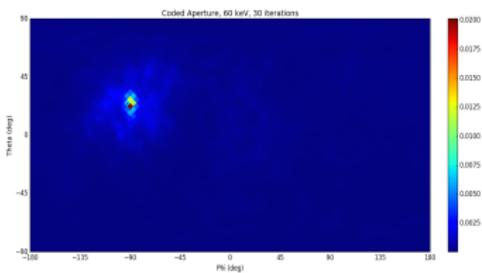


10 iterations

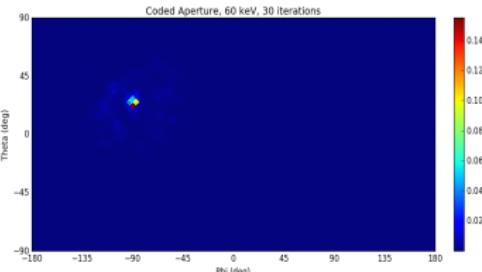
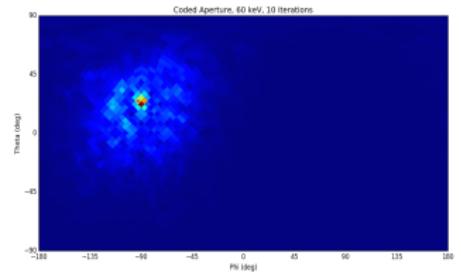


Without
DOI

30 iterations

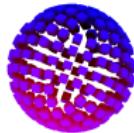


With
DOI
(inner)



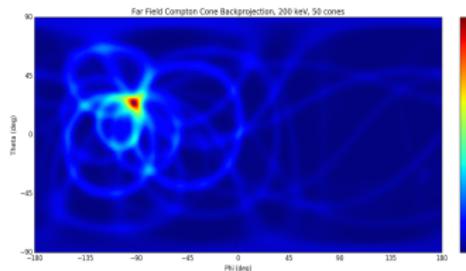
COMPTON CONE BACK-PROJECTION IMAGES

Fully populated mask, 2-interaction sequences

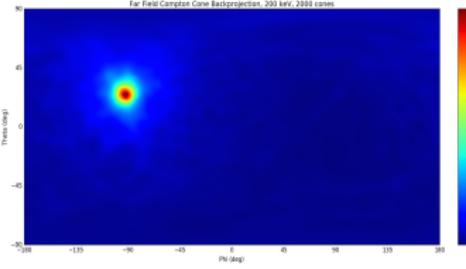


50
cones

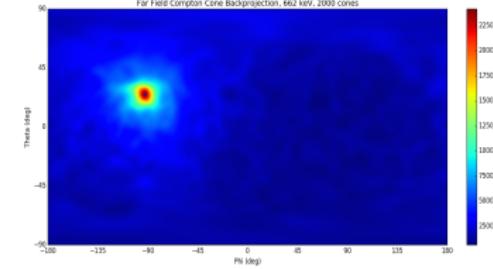
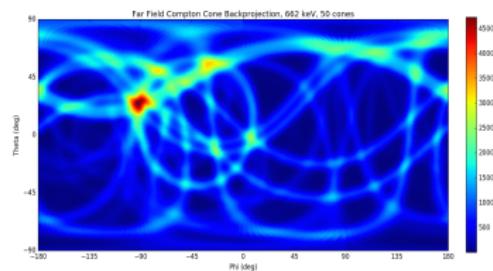
200 keV



2000
cones



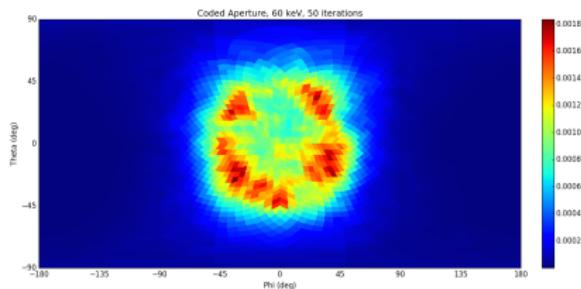
662 keV



FAR-FIELD RING SOURCE

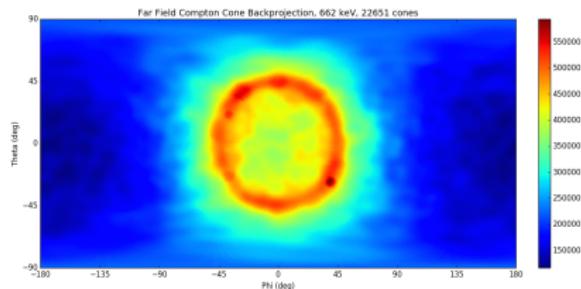
Coded Aperture

60 keV, inner DOI, 50 itr
Random mask
 1.0×10^5 total counts



Compton Imaging

662 keV, without DOI
Full mask
 2.2×10^4 cones



CONCLUSIONS/FUTURE WORK

- PRISM is a handheld, broad energy sensitive, high efficiency gamma-ray imager with a multi-modal 4π FOV.
- Geant4 simulation was upgraded.
- Reconstruction code was written and tested.
- Test reconstructions behaved as expected.

Future Work

- Multiple point sources, near-field sources, distributed sources.
- List-mode MLEM.
- > 2 interaction Compton sequencing.
- Static 3D imaging, 3D tomographic motion imaging.
- Real-time imaging, fused with contextual sensors (RGB, LiDAR) [9].
- Detection efficiency, charge collection, coincidence gating.
- ...

Questions?

REFERENCES

- [1] P. N. Luke, IEEE Trans. Nucl. Sci. 4, 207 (1995).
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- [8] K. Gorski et al., The Astrophysical Journal 662, 759 (2005).
- [9] R. Barnowski, A. Haefner, L. Mihailescu, and K. Vetter, Nucl. Instrum. Methods A 800, 65 (2015).