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

D. Hellfeld

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University of California, Berkeley
Department of Nuclear Engineering

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OUTLINE

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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**.

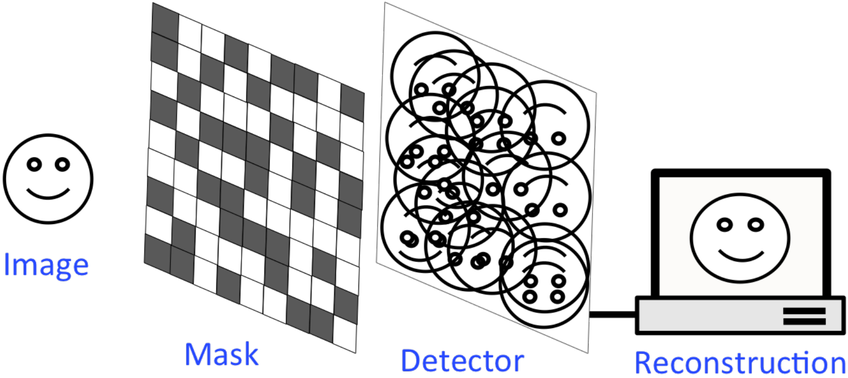
Need

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 gird (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]

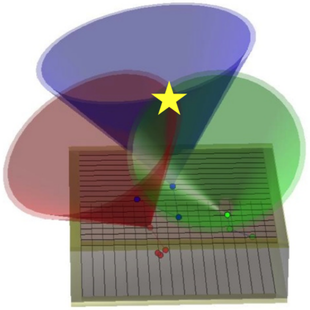
- Most fail to include relevant physics, produce blurry images.

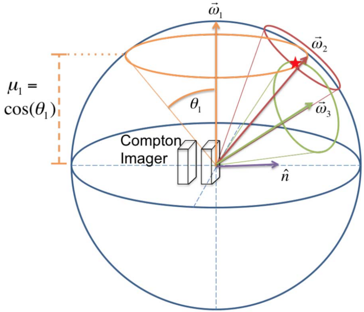
Focus on iterative method - **Maximum Likelihood Expectation Maximization (MLEM)** [4]

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

- 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

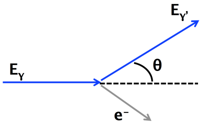




[5]

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.

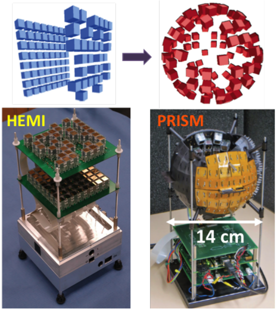
Provide each cone with a width and intensity described by a Gaussian function to avoid pixellation effects. Sum n cones together to produce back-projection image [5]

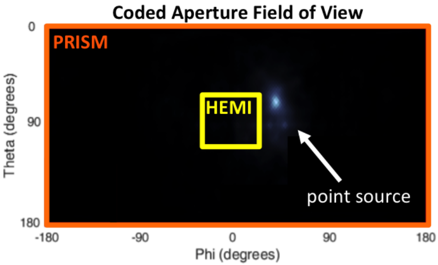
$$b(\hat{\vec{x}}) = \sum_{i=1}^{n} \frac{w_i}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(\hat{\vec{x}} \cdot \hat{\vec{\omega}} - \mu_i)^2}{2\sigma_i^2} \right)$$

- $\hat{\vec{x}}$ 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]) $\rightarrow$ suffer from **limited field-of-view**, especially in coded aperture mode.
- Rearrange into a spherical configuration to facilitate 4π imaging.



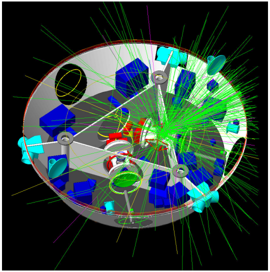


- 192 available detector locations.
- Depth-of-interaction (DOI) readout.

MONTE CARLO SIMULATION, GEANT4

Geant4 [7] is a *Monte Carlo toolkit* use 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?

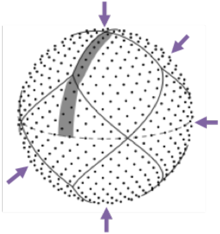
1. Upgraded simulation to include scattering, electron production, multi-interaction tracking, geometry and source modifications.
   - User interaction via macro files passed to executable
   - Track energy deposition, detector ID, DOI, ...

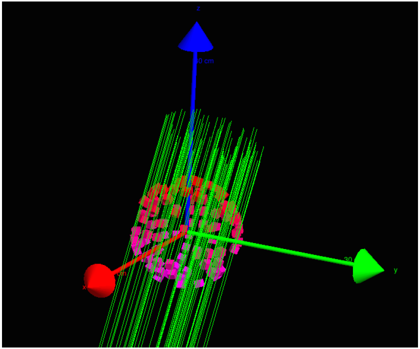
2. Developed Python tools to
   - Parse output data
   - Perform MLEM coded aperture image reconstruction
   - Collect coincident Compton events and sequence tracks
   - Perform Compton cone back-projection image reconstruction

2D Coded Aperture System Response

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

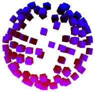
- *Hierarchical Equal Area isoLatitude Pixelization* (HEALPix) [8] discretization of a sphere with 3072 pixels.

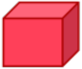


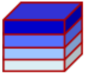


2D Coded Aperture System Response

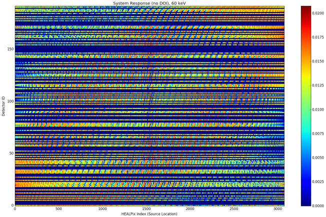
Random mask

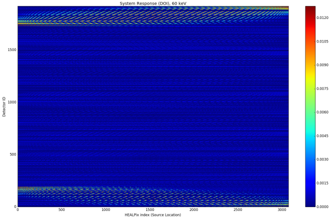


Without DOI 

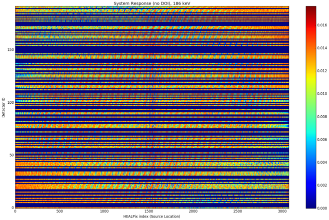
With DOI 

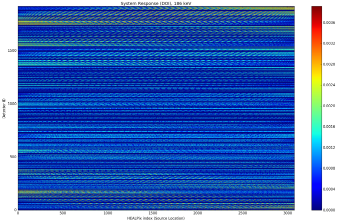
60 keV





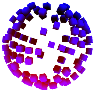
186 keV





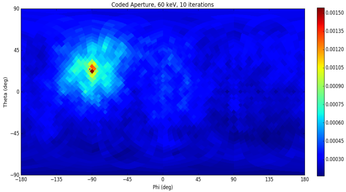
MLEM Images

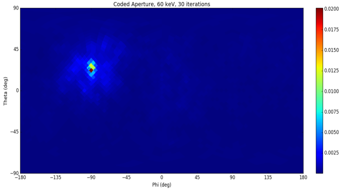
60 keV, random mask



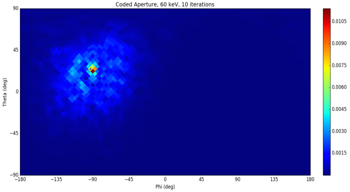
10 iterations | 30 iterations

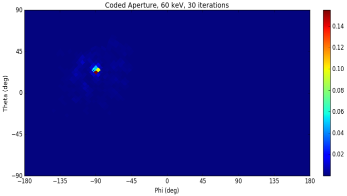
Without DOI





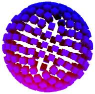
With DOI (inner)

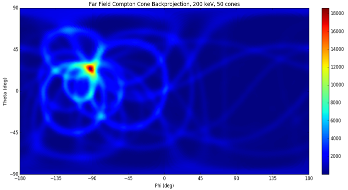
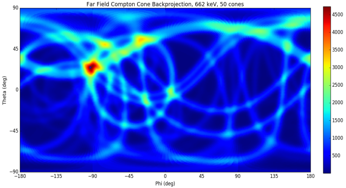
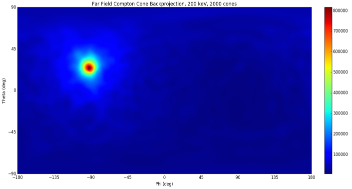
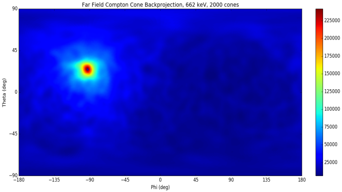




COMPTON CONE BACK-PROJECTION IMAGES

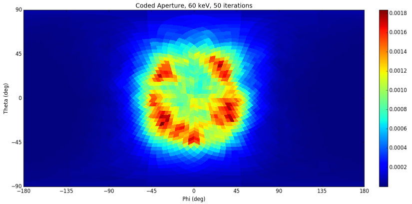
Fully populated mask, 2-interaction sequences



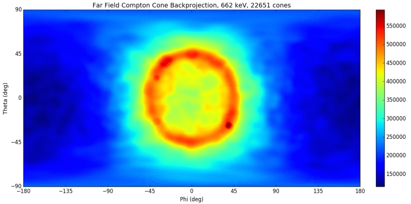
	200 keV	662 keV
50 cones		
2000 cones		

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).

[2] C. Wahl, Ph.D. Thesis, University of Michigan (2011).

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