# Impact of Event Quality on 3D Localization for Gamma-ray Imaging with Scene Data Fusion


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## Overview

The ability to image gamma-ray source distributions in three dimensions for arbitrary imaging domains could have an immediate impact for many applications; such as nuclear decontamination planning and safety, treaty verification, and monitoring nuclear facilities. Furthermore, the ability to localize point sources within unknown environments is a powerful tool for homeland security. A mobile gamma-ray imaging platform is under development at UC Berkeley to probe the application space for volumetric gamma-ray imaging. The ability to simultaneously reconstruct the scene while performing 3D gamma ray imaging in near real time has been demonstrated (see below). Furthermore, methods for using the scene data to improve the accuracy and speed of the imaging algorithms are also being investigated.

In this work, the tradeoff between imaging efficiency and image resolution is investigated for volumetric gamma-ray imaging. Unlike collimator-based imaging modalities, where the properties of the image (resolution, contrast, SNR) depend predominantly on the collimator properties in conjunction with the incident gamma ray energy, each Compton cone impacts the resolution of the resulting image differently. A model for event quality; i.e. the expected cone width due to the measurement uncertainties of the detection system, is presented here. This model is evaluated for accuracy, and any shortcomings of the model are identified. Finally, the output of the volumetric imaging algorithm is evaluated when event selections are made based on the event quality model. This sub-sampling procedure allows the user to govern the tradeoff between efficiency and resolution. Preliminary conclusions on the effects of this event selection procedure are presented and further steps for experimental validation identified.

## Imaging Platform and Demonstration of Volumetric Gamma-ray Imaging

**Compact Compton Imager II – (CCI-2)**

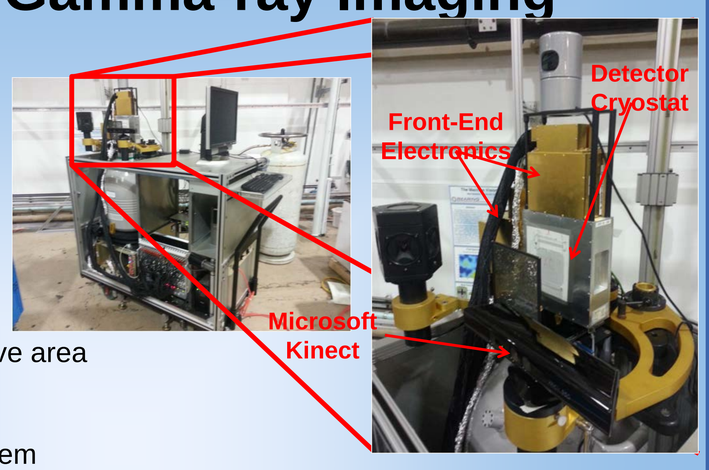
CCI-2 is a cart-based mobile imaging platform. The system hosts a variety of radiation detection and scene-sensing hardware:

**Radiation Detectors**

- 2 planar HPGe detectors with segmented strip readouts
- 15.1 mm thick, 74mm x 74mm active area
- 3D interaction position sensitivity

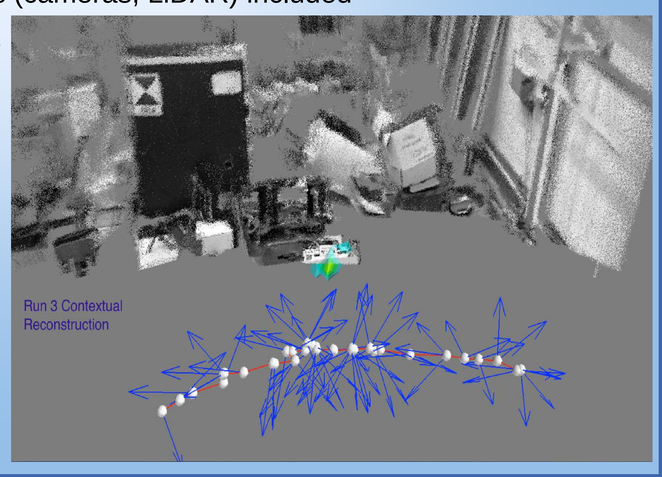
**Scene Sensing**

- Microsoft Kinect active stereo system
- SLAM algorithm for real-time scene reconstruction
- Mounts and software for other sensors (cameras, LiDAR) included




**Demonstration – Volumetric Gamma Ray Imaging**

The figure at right shows the results from a typical volumetric imaging run. The red line represents the tracked position of the detector as it moves through the scene. The point cloud is reconstructed in real-time by the SLAM algorithm. The blue and yellow surface represents the output of a 3D MLEM imaging algorithm; the hot spot it correctly reconstructed into the true source location.

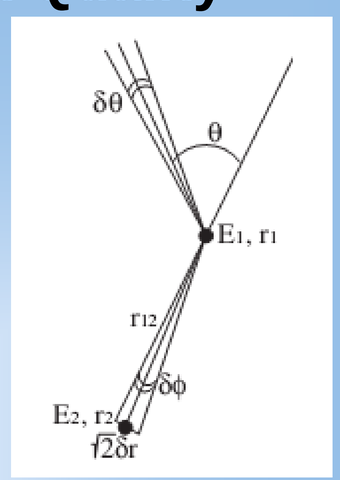



## Model for Compton Event Quality

In order to make informed event selections, there must be a model to relate the measured gamma-ray interaction parameters to the impact on the image. Some parameters of a multi-site Compton event include:

- Uncertainty in the position of the first and second interaction
- Uncertainty in the energy deposited by the gamma-ray at each interaction position
- The distance between interactions (lever-arm)

By applying the propagation of uncertainty formula to the Compton scattering equation and leveraging geometric considerations to describe position uncertainty, the model in [1] can be derived.




$$cos(\theta) = 1 + \frac{1}{A_0} - \frac{1}{A_d} \qquad A_0 = \frac{E_0}{m_e c^2} \quad A_d = \frac{E^1_{deposit}}{m_e c^2}$$

$$\delta^2 \mu_E = \frac{\sigma^2_{A_0}}{A_0^4} + \frac{\sigma^2_{A_d}}{A_d^4}$$

$$\delta^2 \mu_R = 2(1-\mu^2)\frac{\sigma_r}{\vec{r}_{12}}$$

$$\delta\mu = \sqrt{\delta^2 \mu_E + \delta^2 \mu_R}$$

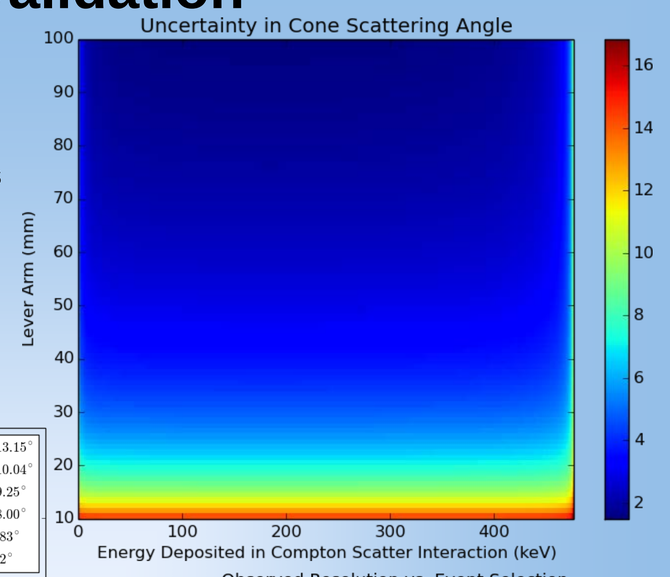
$$\delta\theta = \frac{\delta\mu}{\sqrt{1-\mu^2}} \quad [1]$$

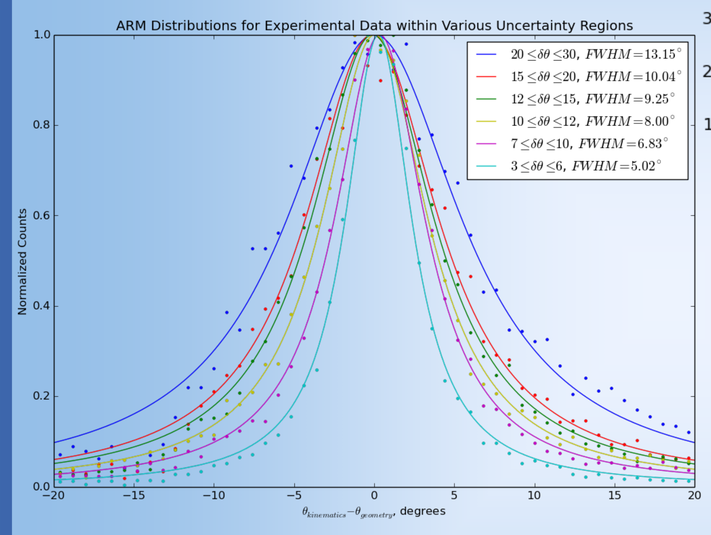
**Model Shortcomings**

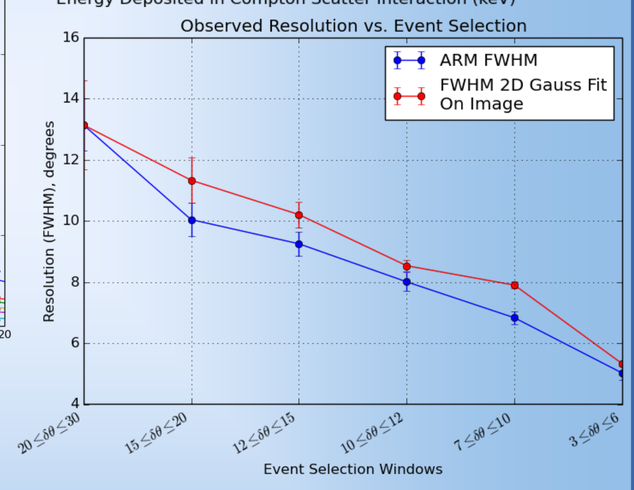
- Assumes energy of incident gamma-ray is known
- Assymetric position error not explicitly handled
- Small angle assumption not valid for events with small lever-arms
- Uncertainty in position of Compton scatter not accounted for
- Doppler broadening not accounted for

## Model Validation

The figure at right displays the application of the model in [1] to 662 keV gamma-rays for varying lever-arms and energy depositions in the Compton scatter interaction. The position error is assumed to be equal to the strip pitch. The energy uncertainties are given by the detector resolution at the displayed energies. No correction for Doppler broadening is made. The colorbar represents δθ in degrees.




The two figures above display the results when the uncertainty model is applied to Compton events collected with the CCI-2 system for a static imaging scenario. The data was collected using a 1mCi Cs-137 source at 4.5m standoff, resulting in over 170,000 cones that passed the minimum event selection thresholds. For the resolution study, the 170,000 events were broken up into groups according to the calculated uncertainty model parameter. 10,000 randomly sampled events are taken from each group for the resolution study.

The general trend of improving resolution (measured both with ARM plots and filtered back-projection images) with decreasing δθ is evident. The measured resolution however is significantly better than what is predicted for the event selection model. This could be a result of both model insufficiency and a disconnect between the δθ from the model and the angular resolution measurement methodology.

## Volumetric Imaging Results

Despite the disagreement between the event quality model and the resulting image resolution, the general trend of improving resolution as the event quality threshold is lowered can still be used. The model is applied to Compton cones acquired during a volumetric imaging run. A mCi Cs-137 source was used while the cart was pushed parallel to the source table. A total of 846 Compton cones were collected during the volumetric acquisition, which was 75 seconds long. In each case, the volumetric reconstruction is achieved by a 3D MLEM in which the reconstruction has been constrained to the voxels occupied by the scene model.

**Figure 1**: Image created using all 846 two-site photopeak gamma-ray events. The density of Compton cone axes can be seen along the detector track. The blue-yellow surface contour represents the result of the image reconstruction after 10 iterations.

**Figure 2**: Image created using events with δθ < 40°, yielding 637 events used for imaging. The decreased density of Compton cones is evident along the detector track. Note that contour surface from the reconstruction is more concentrated. The precision and accuracy of the reconstruction result is improved, despite the use of fewer Compton cones. The same number of iterations were used to create this image.

**Figure 3**: Image created using events with δθ < 10°, yielding 217 events used for imaging. Again, the decreased density of Compton cones is clearly evident along the detector track. Moderate improvements in precision and accuracy over previous images results can be seen despite the use of fewer Compton cones. The same number of iterations were used to create this image.

## Conclusions

The 3D imaging results clearly demonstrate the merits of accounting for Compton cone event quality. While the event selection procedure reduces the number of events used in imaging, the image quality (accuracy and image resolution) can be improved. These results indicate the Compton event quality model merits further study.

**Future Work**

- **Modification of event quality model** – Need to add the capability to handle assymetric position resolution. Doppler broadening correction also needed to more accurately capture interaction physics. Simulation studies are likely required to assist in validation of the event quality model
- **Systematic volumetric imaging study** – Develop a method for assessing image quality, particularly 3D resolution and noise. Investigate detector pose uncertainty effects on 3D image.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