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The LANL Prototype Compton Gamma-Ray Imager: Design and Image Reconstruction Techniques

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R. Marc Kippen, Andrew S. Hoover, John P. Sullivan, Mohini Rawool-Sullivan, William Baird, and Eric B. Sorensen

ABSTRACT

Compton imaging, which reconstructs the direction of incident photons based on the kinematics of Compton scattering, is of interest in the fields of astrophysics, medical imaging, and nuclear nonproliferation. To explore the capabilities of this approach for detecting and imaging spatially extended radiation sources at relatively close distances, we are developing a prototype system using commercially available detector technologies. In the LANL prototype system the Compton scatter takes place in one of three layers of thin silicon pixel detectors and the secondary photon is measured in an array of CsI(Tl)/PIN diode detectors. Construction of the prototype is about to be completed. In this paper we discuss the design of prototype device along with computer simulations of the expected performance, and techniques for imaging analysis. In the future, data from this device will be used to explore design options for large operational Compton imaging systems.

1. Introduction

Development of improved passive gamma-ray detection techniques for sensing radiation from radioactive nuclear materials is important for many fields, including homeland security, astrophysics, and medical imaging. Current systems are severely limited in sensitivity (and therefore detection range) due to background confusion, and they typically cannot precisely localize sources when detected. At Los Alamos National Laboratory (LANL) we are investigating the use of Compton gamma-ray imaging to address these needs. Our goal is to first demonstrate a small prototype system using available detector technology to show the ability of a Compton imaging device to overcome limitations of current sensing systems. Next, we plan to develop optimized, scalable technologies that will lead to large operational systems for wide-area nuclear material sensing and tracking. Below, we discuss the design of our prototype Compton imager, and techniques that we plan to use on resulting data.

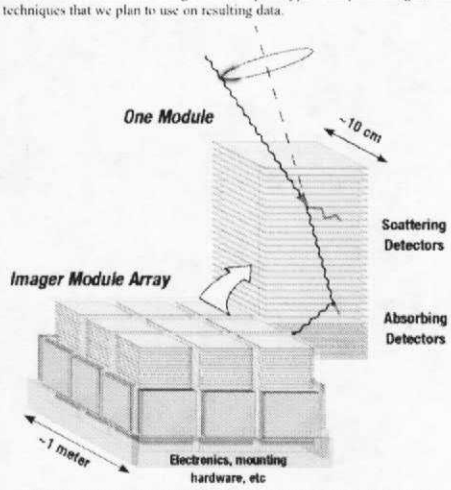


Fig. 1. *Concept for a large operational Compton gamma-ray imager system using solid-state planar detectors.*

2. Compton Imager Concept

The Compton imaging technique is based on the fact that the known kinematics of the Compton scattering process can be used to reconstruct the direction of incident photons if all the scattering by-products are measured. Figure 1 illustrates how a series of multiple, position-sensitive detectors (a scatterer and an absorber) could be used to make the required measurements: directions and energies of the scattered photon and scattered electron. In practice, position and energy measurement uncertainties, combined with intrinsic quantum atomic binding effects ("Doppler broadening" [1]) lead to non-ideal angular blur. Furthermore, measuring the scattered electron direction is problematic—without it the photon direction is only constrained to a cone. In any case, statistical superposition of many photons is required to create meaningful images from the measurements.

Requirements for scattering detectors:

- Large area to maximize sensitivity to weak signals
- Low-Z, low-density material to minimize Doppler broadening effects and minimize multiple scattering of scattered electron
- Total thickness sufficient to ensure large probability of Compton scatter somewhere in the active detector volume
- 3D spatial resolution ~1 mm (depending on detector geometry)
- Energy resolution ~few % such that angular resolution is dominated by Doppler broadening

Requirements for absorbing detectors:

- Large area commensurate with size of scattering detector
- High-Z, high-density material to ensure good photo-electric absorption efficiency
- Total thickness sufficient for complete energy absorption over desired energy range
- 3D spatial resolution ~1 mm (depending on detector geometry)
- Energy resolution ~few % such that angular resolution is dominated by Doppler broadening

Ideally, all detectors and their readout electronics should be compact, reasonably low power, mechanically robust, and require minimal cooling. Note that in principle, full energy absorption is not a strict requirement if multiple (2+) Compton scatters can be uniquely identified and properly sequenced. In this case, the incident photon energy can be derived from the scattering kinematics [2]. The design of our prototype is meant to explore several of these options with reasonable cost.

3. LANL Prototype System Design

The design of the LANL prototype was driven by the desire to demonstrate the concept of a compact, scalable system without significant new detector development. Flexibility is also important to study different approaches, such as single scatter imaging, electron tracking, and multiple-scatter reconstruction.

Fig. 2. *Detectors used on prototype imager: silicon pixel detector (left), silicon detectors with front-end electronics (center), and CsI/PIN diode array (right).*

The prototype system includes a scattering detector consisting of three separated layers of planar silicon pixel detectors, designed and fabricated at Brookhaven National Laboratory. Each plane is 300 microns thick, and consists of a 16×20 array of 3×3 mm^2 readout pads, resulting in an active area of 28.8 cm^2 (see Figure 2). The absorbing detector consists of a close-packed 6×7 array of CsI(Tl) scintillators built by St. Gobain/BICRON. Each 12×14×10 mm^3 scintillator crystal is coupled to a 10×10 mm^2 silicon PIN photodiode (Hamamatsu model S3590-1) which measures the scintillation light signal. The total area of the array is ~72 cm^2, including crystal packing material. The silicon and CsI detectors are mounted in a mechanical assembly that allows changing the spacing between layers, since optimum spacing depends on the question being investigated.

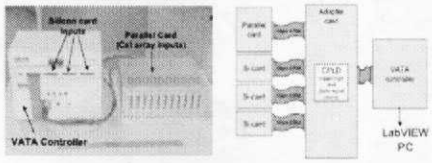


Fig. 3. *Integrated readout electronics and data acquisition system.*

Readout electronics for the system were custom designed and built by IDEAS. It consists of discrete preamp/shaping/peak-detect components on each CsI/PIN diode channel, and ASIC pulse-processing for the silicon pixel detectors based on the VA/TA preamp/trigger ASIC chip combination. The system is computer controlled using the IDEAS VA-DAQ interface system. This system also includes a flexible variety of coincidence options for triggering between the four detector layers.

While we have evaluated the detectors individually, the full readout system was only recently completed, and we have yet to test the integrated system.

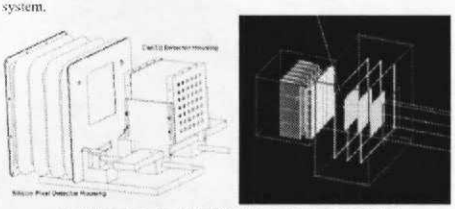


Fig. 4. *Mechanical system (left) and GEANT4 simulation mass model (right).*

4. Simulation and Image Reconstruction

Before testing the experimental system we developed a computer simulation using the GEANT4 Monte Carlo simulation toolkit. This toolkit is augmented by the G4LECS [3] package, which simulates detailed atomic binding effects such as Doppler broadening. Performance of the simulation was verified against data from individual silicon and CsI detectors with good results. The simulation will eventually be verified against data from the full prototype imager, and used as a tool to design larger imagers. First, however, we used the simulation to develop image reconstruction techniques that will be used for analyzing data from the prototype.

Dealing with the complexities of Compton image reconstruction, as opposed to hardware technology, is now arguably the critical problem t addressed en route to achieving the full potential offered by Com imagers. Several methods have been developed, but there is as ye general analytic solution to the problem. The most commonly used technique is simple back projection of individual photon cones onto an image plane, but this approach yields little quantitative information and is easily confused by background. Recently, iterative optimization techniques have been applied in the form of Expectation Maximization (EM) algorithms, but these, too, have proven difficult to yield quantitative information in a practical manner. Because of the desire for quantitative imaging, we investigated the Maximum Likelihood Ratio (MLR) technique that was successfully used to analyze astronomical data from the COMPTEL space-borne Compton gamma-ray telescope [4].

The MLR technique is essentially an extension of forward-folding hypothesis testing. It tests two hypotheses simultaneously: background only and point source plus background. Models of the source point spread function (PSF) and background (B) are compared to measured Compton scatter parameters in a binned multi-dimensional "data space." For initial studies we concentrated on a three-dimensional data space consisting of the photon scatter direction projected onto an image plane (x,y) and the photon scatter angle φ derived from the measured energy deposits. This concept is schematically illustrated in Figure 5, which also shows the cone-shaped simulated 3D PSF for a 662 keV point source 0.2 m from the first silicon detector. In practice, we decompose the PSF into a part that depends only on geometry, and the remainder which describes the complex scattering physics.

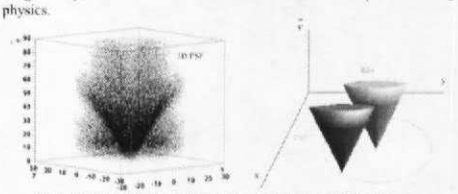


Fig. 5. *Simulated 3D point spread function for a monoenergetic 662 keV point source.*

Statistical comparison between model-predicted response and measured data is made through the log likelihood ratio test statistic λ, assuming Poisson noise in each data space bin. Source and background model parameters, such as source position and intensity, are varied in a controlled search for values that maximize λ. An example MLR map comparing simulated data and background to simulated PSF and background models is shown in Figure 6.

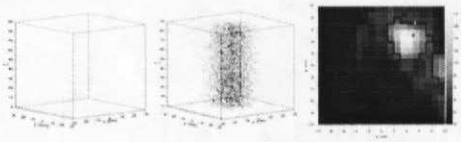


Fig. 6. *Simulated data space for 662 keV photons containing 500 source events (left), and 500 source plus 10,000 background events (center). At right is shown the MLR log likelihood ratio (λ) map computed from the same data (source position marked by cross).*

The great power of the MLR technique lies in its ability to distinguish weak sources embedded in background, and to yield quantitative information about model parameters. Assuming the source and background models are reasonable, the behavior of the log likelihood ratio is governed by the chi-square distribution function. The absolute value and deviations of λ thus yield quantitative statistical constraints on the model parameters, such as source position, source intensity, and detection significance. To test the validity of this theory, we evaluated the behavior of λ as a function of signal to noise ratio (SNR) and obtained a close match with the theoretical expectation (see Fig 7).

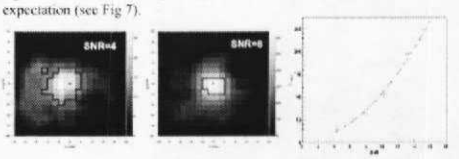
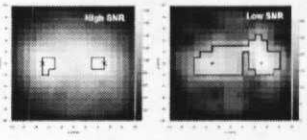


Fig. 7. *MLR maps for different SNR compared with theoretical prediction (dashed line, right). Heavy solid lines indicate 5σ confidence constraints on the source location.*

Below: MLR maps for fields containing two point sources.



5. Conclusion

We are constructing a prototype system to demonstrate the feasibility of Compton imaging for ground-based nuclear material detection applications. The hardware system is nearing completion, and we have used Monte Carlo simulation to model its performance and to develop preliminary data analysis techniques. We have shown that the MLR imaging technique, previously used only for astronomical imaging, can be used effectively to provide quantitative information for nearby sources. Next, we plan to extend the technique for three-dimensional characterization of sources at close range.

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