Simulated Performance of the GammaTracker CdZnTe Handheld Radioisotope Identifier

Carolyn E. Seifert, *Member, IEEE*, Mitchell J. Myjak, *Member, IEEE,* and David V. Jordan

***Abstract*–The GammaTracker handheld radioisotope identifier currently under development at the Pacific Northwest National Laboratory uses a pixellated CdZnTe spectrometer array to measure the energy and incoming direction of gamma rays from 50 keV to 3 MeV. This instrument, which incorporates the Polaris technology developed at the University of Michigan, houses two 3×3 arrays of 2.25-cm^3 CdZnTe detectors. In this work, we present Geant4 simulation results of gamma-ray detection, identification, and directionality performance of the GammaTracker instrument. Estimated minimum detectable activities (MDAs) are determined to be only 20-30% higher than the MDAs predicted for a comparable-efficiency HPGe system over a reasonable energy range. The simulated imaging resolution is determined to be ~20° FWHM, and the imaging efficiency is evaluated as a function of gamma-ray energy.**

I. Introduction

GammaTracker is a hand-held radioisotope identifier capable of directional sensing. Based on the University of Michigan's Polaris technology [1], GammaTracker incorporates a large-volume (40 cm^3), high-efficiency detector array. Each detector measures 1.5 cm × 1.5 cm × 1.0 cm and has an array of 11 × 11 pixel anodes deposited on one of the square faces; a planar cathode is deposited on the opposite face. The anode pixels are bonded to a ceramic substrate, which acts as a plate-thru-via. Signals from the anodes are routed to a connecting board with a 129-channel self-triggering application-specific integrated circuit (ASIC) that performs charge integration and signal amplification for both timing and pulse height determination. The ASIC carrier board is then connected to a front-end motherboard, which holds a 3 × 3 array of detector-ASIC modules. Two such motherboards are used in the GammaTracker instrument for a total of 18 detectors and 40.5 cm^3 of active detector volume. Simultaneous gamma-ray interactions in multiple detectors are used for spectroscopy by summing energies and for directionality by measuring 3-D position coordinates and energies and performing Compton imaging.

GammaTracker uses the detectors and ASICs from the Polaris design, but has custom motherboards designed for reduced size and power consumption, and a specialized high voltage design that allows independent control of individual cathode biases while maintaining a high low-voltage to high-voltage conversion efficiency. A commercial low-power microprocessor, LCD display, and user inputs are incorporated into the system, which operates on two Li-ion batteries. More details of the GammaTracker electronics design are discussed in [2].

Presented in this work is the expected performance of GammaTracker calculated via Geant4 simulations [3]. System performance is expressed via several metrics: total peak efficiency, minimum detectable activity, imaging resolution, and imaging efficiency. Section II provides details on the simulation parameters, while Sections III and IV discuss simulated performance relative to a comparably sized high-purity germanium (HPGe) detector.

II. Simulation Parameters

The simulations performed in this study used Geant4 (ver. 4.6.1) with a low-energy physics package that includes both Rayleigh scattering and Doppler broadening. The GammaTracker array is modeled as eighteen 15 mm × 15 mm × 10 mm $Cd_{0.9}Zn_{0.1}Te_{1.0}$ crystals (density of 5.8 g/cm^3) arranged in two layers of nine detectors. The detector pitch is 22 mm laterally with a 2-cm spacing between layers to accommodate the readout electronics.

Two types of sources are modeled: point sources and area sources. The point sources are modeled as true isotropic points with no self-attenuation located 25 cm from the surface of the first array. Environmental background is modeled as an area source with 2-m radius located 25 cm from the detector. For either source, a gamma-ray energy is selected via an intensity-weighted random distribution. The initial direction of the gamma ray is sampled uniformly in 4π. The gamma ray is then transported through the system geometry. The number of gamma-ray interactions and the energies deposited in each interaction are tallied for a large number of source gamma rays (at least 100 million for each simulation).

In post processing, the data are then "pixellated" using the array geometry; the exact lateral position is replaced by the coordinates of the center of the pixel face, and the depth coordinate is blurred according to a 1-mm FWHM Gaussian distribution. Multiple events that occur under one pixel are modified by summing the event energies, averaging the depth coordinates, and treating them as a single event. Then, the energies are blurred according to a Gaussian distribution whose FWHM is 1% at 662 keV and follows a $\sqrt{(k_1+k_2E)}$ relation. In this way, the Geant4 simulated data are transformed to reflect realistic energy and position resolutions.

For sensitivity comparisons to known portable spectrometers, a Ø 5 cm × 3 cm closed-ended coaxial high-

Manuscript received November 21, 2007. This work was supported by the NNSA Office of Defense Nuclear Nonproliferation, Office of Nonproliferation Research and Development.

C. E. Seifert, M. J. Myjak, and D. V. Jordan are with the Pacific Northwest National Laboratory (telephone: 509-376-3915, e-mail: carolyn.seifert@pnl.gov). PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

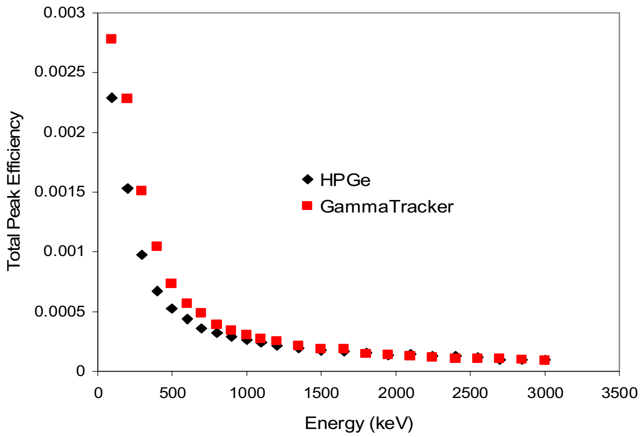

Fig. 1. Absolute peak efficiency for GammaTracker and a comparable HPGe spectrometer.

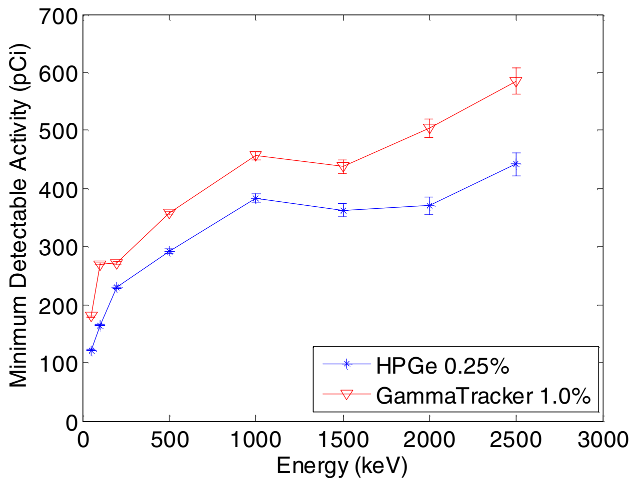

Fig. 2. Minimum detectable activities for 1-minute acquisition for GammaTracker and a comparable efficiency HPGe detector for simulated monoenergetic gamma-ray sources.

purity germanium (HPGe) detector was also modeled. Again, energy resolution was incorporated using a Gaussian distribution with 0.25% FWHM at 662 keV.

III. Efficiency and Minimum Detectable Activity

Monoenergetic point sources with energies from 100 keV to 3 MeV were modeled independently, and detected count rates were simulated. The resulting absolute peak efficiencies are shown in Fig. 1. Also shown are simulated peak efficiencies for a 5 cm × 3 cm closed-ended coaxial HPGe detector. These two systems have nearly equivalent efficiencies throughout the simulated energy range, with GammaTracker showing higher efficiency at low energies. At 1332 keV, both detectors exhibit a relative efficiency of 20% compared to a standard 3” × 3” NaI(Tl) detector. Both detector systems also have an effective detection area of 20 cm^2.

The GammaTracker handheld radioisotope identifier is intended for detection (as well as localization and identification) of radiation sources in the environment. Although it has a similar efficiency to common portable HPGe systems, a more suggestive metric of the detection performance of the device is minimum detectable activity (MDA). An instrument with lower MDAs performs better and can detect and identify radionuclides more quickly in the environment. Fig. 2 shows the calculated minimum activities detectable in 1-minute acquisitions for both GammaTracker and the HPGe system, assuming a continuum terrestrial background emitted at a rate of 2 $\gamma/cm^2/s$. The MDAs of the GammaTracker system are only 20-30% higher than those achievable with the HPGe detector at gamma-ray energies above 300 keV. This is significantly better performance than would be expected from a naïve calculation relying only on changes in energy resolution.

GammaTracker is competitive with the HPGe system because it has a high peak-to-total ratio. Gamma rays associated with the environmental background have a higher probability of undergoing a photoabsorption in CdZnTe than HPGe for equivalent efficiency detectors.

To assess the effect of peak-to-total ratio on the detectability of gamma-ray sources, the HPGe data was artificially modified to match the energy resolution of the CdZnTe detectors used in GammaTracker, namely 1% at 662 keV. The resulting MDAs are shown in Fig. 3. Despite having equivalent efficiencies, detector areas, and energy resolutions, the GammaTracker system outperforms the HPGe system at energies below 2 MeV by as much as 28%.

Of interest in GammaTracker development is the energy resolution of CdZnTe that would be required to match the MDA performance of high-quality HPGe detectors at 0.25% FWHM energy resolution. We determined that 0.5% FWHM energy resolution in GammaTracker would yield equivalent MDAs over most of the energy range of interest, as in Fig. 4 below.

The preceding analysis is predicated on the concept of detecting radiation sources and identifying radioisotopes based on isolated individual gamma-ray peaks. To do any sophisticated spectral unfolding of overlapping gamma-ray

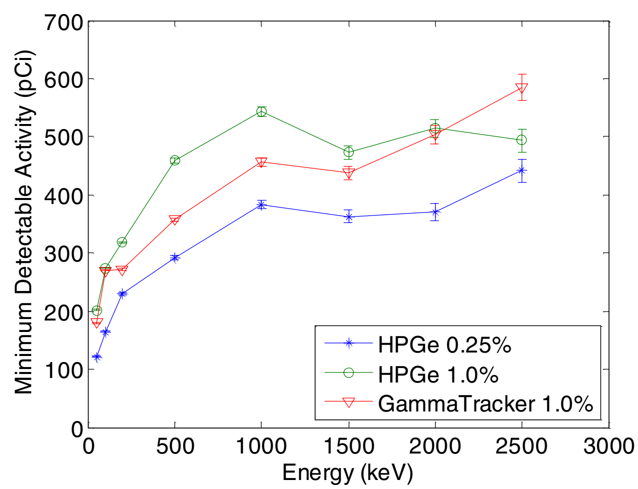

Fig. 3. Minimum detectable activities for 1-minute acquisition of GammaTracker and a comparable-efficiency HPGe detector with energy resolution artificially blurred to 1% FWHM at 662 keV. At the same efficiency and energy resolution, GammaTracker outperforms its HPGe counterpart at most energies due to higher photoabsorption probability.

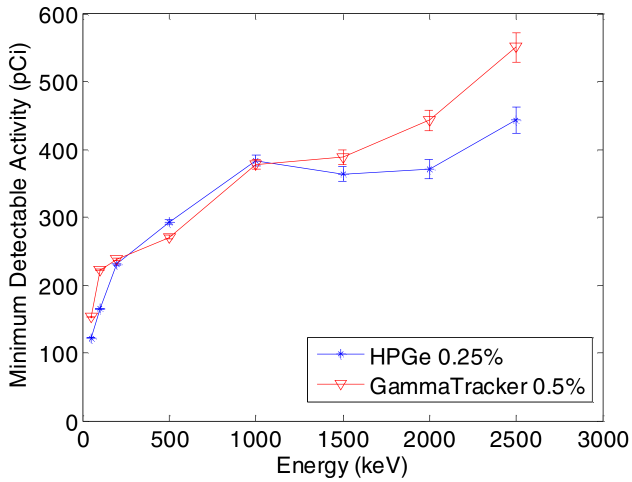

Fig. 4. Minimum detectable activities for 1-minute acquisition of GammaTracker at 0.5% FWHM energy resolution and a comparable-efficiency HPGe detector. At this efficiency and energy resolution, GammaTracker performs comparably with the HPGe system.

lines, it is always preferable to have higher energy resolution, regardless of the peak-to-total ratio of the instrument. Thus, for spectrometry an HPGe spectrometer is always preferred.

IV. Imaging Resolution and Efficiency

GammaTracker is a localization instrument; that is, it is intended to provide pointing directions to the sources of radiation, rather than displaying the actual radiation image maps. Nonetheless, imaging methods are used to determine the direction to the gamma-ray source, and that imaging performance will be presented here.

GammaTracker uses common Compton imaging techniques to localize gamma-ray sources with medium to high energies. Traditional Compton imaging methods involve intersecting a backprojection cone with a given image surface (in this case a sphere surrounding the detector). We developed improved algorithms for implementation on FPGAs (discussed in detail in [5]) in which the imaging process involves intersecting two backprojection cones with the image sphere. The two intersection points are tallied for GammaTracker directionality determinations, and for the purposes of this work are plotted on a 2-D image. Furthermore, only pairs of backprojection cones with similar energies (<5% different) are included in the intersections. In this way, the imaging algorithm naturally discriminates various sources and reduces the amount of image clutter due to the presence of multiple sources in the field of view. A more detailed discussion of the algorithms is given in [5].

Fig. 5 shows the point source response of the GammaTracker system. A slice through the maximum point in the distribution demonstrates an angular resolution of 20° FWHM after fitting with a Gaussian function. The typical non-Gaussian backprojection tails are also observed in the figure, and the spatial extent of the point source response is evident out to ±45° from the true source position.

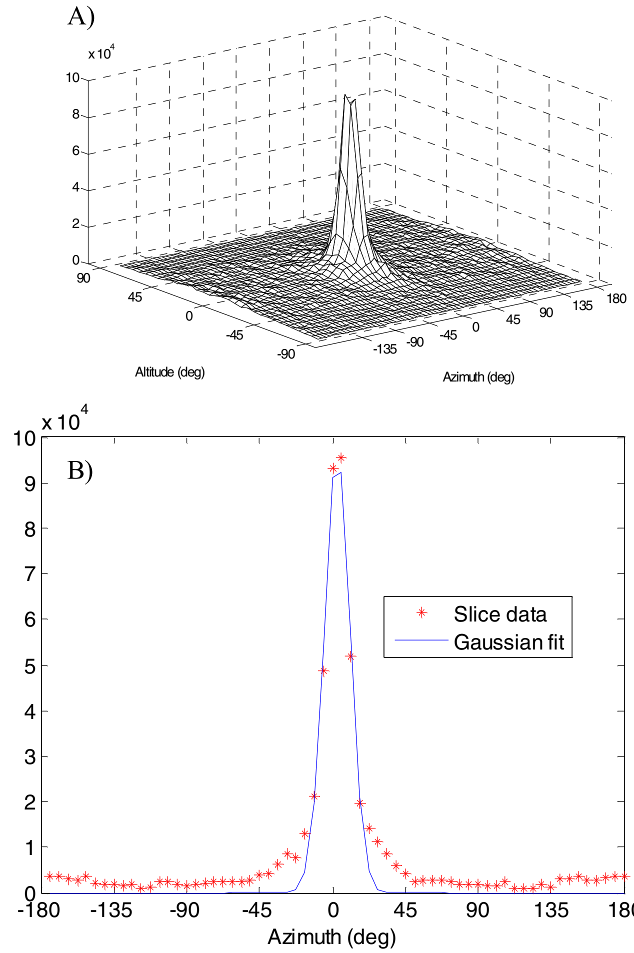

Fig. 5. A) Image of 662-keV point source with no background. B) A slice through the image demonstrates an angular resolution of 20° FWHM.

To demonstrate the performance of the GammaTracker algorithms, we reconstructed simulated data from a 662 keV point source on an environmental background in three different ways: using traditional Compton backprojection, using intersecting cones method, and using the intersecting cones method with energy discrimination. In these images, one gamma ray from the point source is emitted for every seven gamma rays from the background. The resulting images are shown in Fig. 6. The point source is not distinct in the traditional image, but can be seen using the GammaTracker imaging methods.

Imaging efficiency is a complex metric for Compton imagers. To be imaged, a sequence must consist of at least two events. In GammaTracker, only 2- or 3-pixel sequences are imaged; the 4+-pixel sequences comprise less than 1% of all detected sequences in the detector array. To be correctly imaged, a sequence must also correspond to a full energy deposition by the gamma ray, and the order of events must be determined correctly. Finally, at high energies, the sequence must not consist of a pair production event, for which the Compton scattering equation does not apply.

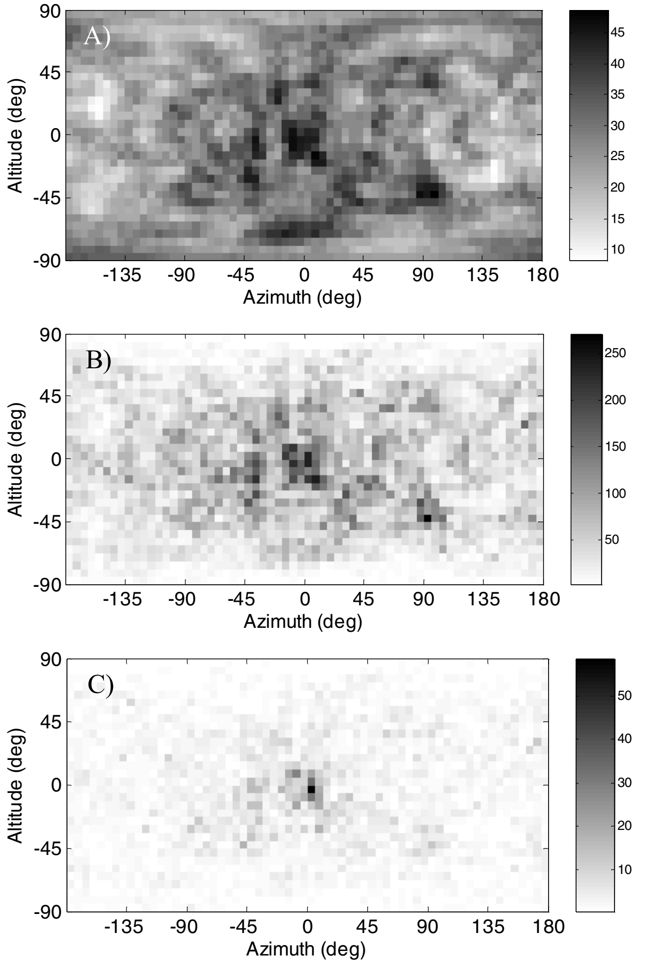

Fig. 6. Image of 662 keV point source on environmental background using A) traditional Compton backprojection, B) intersection of cones method, and C) intersection of cones method with energy discrimination.

Imaging efficiency for GammaTracker and other Compton imagers cannot be directly measured. In measurements, it is not possible to know on a sequence-by-sequence basis if the full gamma-ray energy is deposited, if the correct event order is selected, or if a pair production event has occurred. In simulations, however, it is possible to tally the fraction of gamma-ray sequences that are imaged correctly. We use the terms "imaging efficiency" and "peak imaging efficiency" to mean the fraction of detected sequences and the fraction of detected full-energy sequences, respectively, that are correctly reconstructed (i.e. contribute to useful data in the image).

Shown in Fig. 7 is the imaging efficiency as a function of energy. Simulated efficiencies range from 10-20% over the energy range from 200-2500 keV. Thus, for a total count rate of 100 counts per second at 1 MeV, approximately 14 sequences per second will be reconstructed correctly. At low energies, the low event multiplicity dominates the efficiency curve; most gamma-ray sequences consist of a single event. At high energies, the efficiency is dominated by the probability of full energy deposition. Fig. 8 shows the peak imaging efficiencies as a function of gamma-ray energy. At high energies, the peak imaging efficiency approaches 60%.

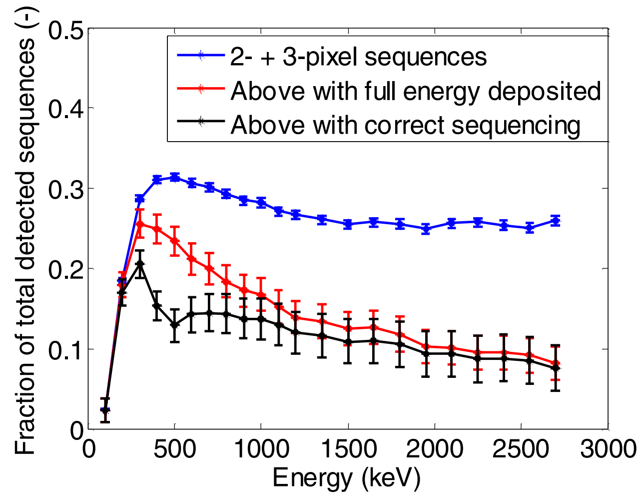

Fig. 7. Fraction of total detected sequences with two or three interactions (blue curve), with full energy deposition (red curve), and with correct sequence ordering (black curve). The black curve represents the imaging efficiency.

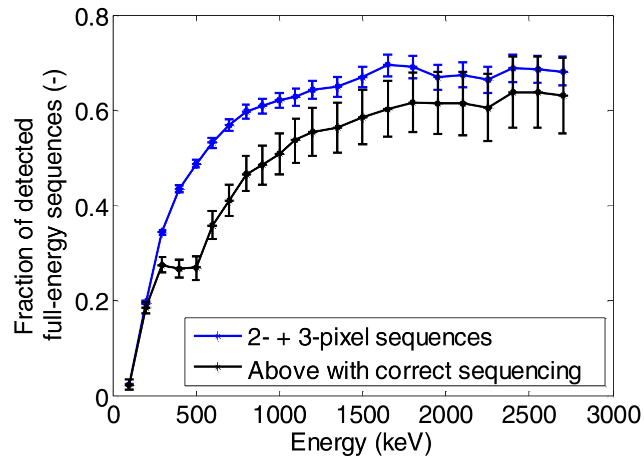

Fig. 8. Fraction of detected full-energy sequences with two or three interactions (blue curve) and with correct sequence ordering (black curve). The black curve represents the peak imaging efficiency.

V. Summary

The GammaTracker handheld radioisotope identifier will be competitive with modern mechanically-cooled HPGe spectrometers. The relative efficiency of the CdZnTe array used in GammaTracker is approximately 20%, a value on par with that of other high-efficiency handheld devices and much higher than other CdZnTe-based spectrometers. With a nominal 1% FWHM energy resolution, the MDAs achievable with GammaTracker are only 20-30% higher than for a comparably efficiency HPGe system.

GammaTracker uses imaging techniques to determine the direction to gamma-ray sources. The predicted imaging resolution is ~20º FWHM, with a total imaging efficiency between 10-20% of all detected events. Once completed, GammaTracker will be a high performance handheld instrument for radioactive source search, survey, and characterization.

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