Characterizing and Correcting the Cross-Talk Effect on Depth Measurement in the NCT Detectors

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***Abstract*—The Nuclear Compton Telescope (NCT) is a balloon-borne soft gamma ray (0.2–10 MeV) telescope designed to study astrophysical sources of nuclear line emission and polarization. The heart of NCT is an array of 12 cross-strip germanium detectors, designed to provide 3D positions for each photon interaction with full 3D position resolution to 1.6 mm^3. The x and y positions are provided by the orthogonal strips, and the interaction depth (z position) in the detector is measured to an accuracy of 0.4 mm FWHM using the relative timing of the anode and cathode charge collection signals. The charge collection signals are affected by cross-talk when interactions occur in adjacent strips, altering the timing measurement in those interactions. We simulated this effect in our NCT detectors, and have developed a method to correct the timing information. Here we present the simulation and the correction results.**

***Index Terms*—Compton telescope, gamma-ray astronomy detectors, germanium radiation detectors.**

I. Introduction to the NCT

The Nuclear Compton Telescope (NCT) is a balloon-borne soft γ-ray (0.2–10 MeV) telescope designed to study astrophysical sources of nuclear line emission and γ-ray polarization [1]–[4]. The heart of NCT (Fig. 1) is an array of 12 cross-strip germanium detectors (GeDs), designed to provide 3D positions for tracking each photon interaction with full 3D position resolution to 1.6 mm^3. Tracking 3D positions enables Compton imaging, effectively reduces background through Compton Kinematic Discrimination (CKD) [5], and enables the measurement of polarization. NCT is designed to optimize sensitivity to nuclear line emission over the crucial 0.5–2 MeV range, and sensitivity to polarization in the 0.2–0.5 MeV range.

Each NCT detector is a 37×37 cross-strip planar detector with 15 mm thickness. The electrode strips have a 2.0 mm pitch with a 0.25 mm gap between strips to minimize the number of charge sharing events and the resulting charge loss, while maintaining the high GeD spectral resolution. The strips define an active area of 5400 mm^2. A 2 mm thick guard ring surrounds this active area on both faces of the detectors, with a 1 mm gap between the ring and the edge of the crystal. The entire set of detectors and their cryostat are enclosed inside an active BGO well, which defines an overall field of view of 3.2 sr. The instrument is mounted in a pointed, autonomous balloon platform (gondola).

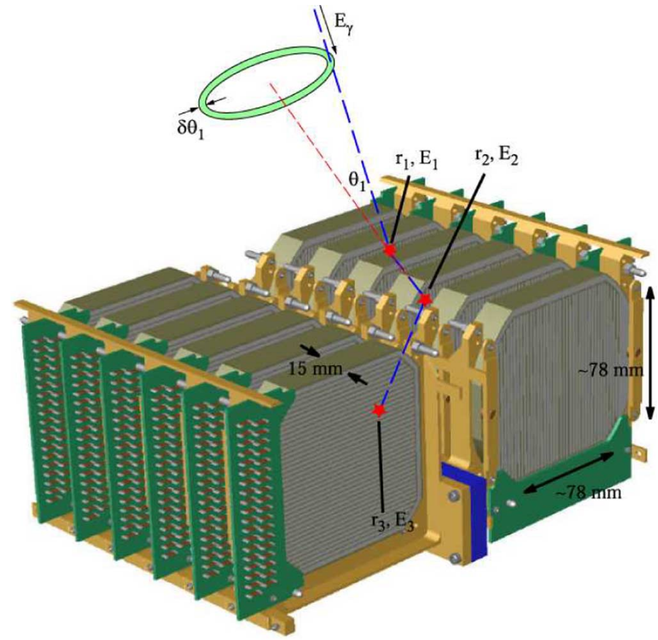

Fig. 1. The NCT utilizes 12 cross-strip GeDs with 3D position resolution, excellent spectroscopy, sensitivity to γ-ray polarization, and high efficiency. The expected performance can be found in [3].

The NCT prototype was successfully launched from Fort Sumner, New Mexico on June 1, 2005. The flight lasted 6 hours with the instrument at approximately 40 km altitude. The details of this flight can be found in [2], [6]. We are currently preparing for a $\sim$ 36-hour flight from New Mexico in Spring 2009, followed by a long duration balloon flight from Alice Springs, Australia (23.7S, 133.9E) in December 2010 [7]. The first flight will focus on observing northern hemisphere γ-ray point sources like the Crab pulsar and Cygnus X-1. The second flight will focus on observing and mapping diffuse galactic nuclear line emission.

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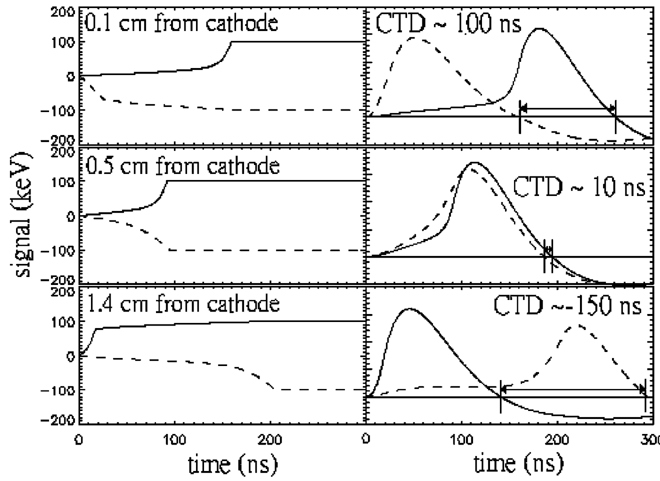

Fig. 2. [LEFT] Induced signals on anode and cathode strips of our NCT detectors, for 100 keV photon events at 0.1 cm from cathode (TOP), 0.5 cm from cathode (MIDDLE), and 1.4 cm from cathode (BOTTOM). [RIGHT] The signal after bipolar shaping . The solid line is collection for the electron, dashed line is for the hole. The timing measurement is determined by the zero-crossing of the signal. The CTD is the time difference between two zero-crossing times. These events are all from simulation.

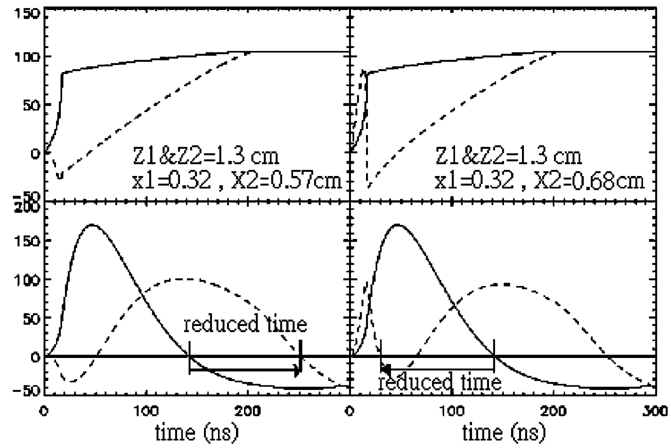

Fig. 3. [TOP] The induced signal before bipolar shaping on an anode strip, for a 106 keV event. [BOTTOM] The same 106 keV signal after bipolar shaping. The zero crossing times are indicated. Left and right panels are different events with different X2 positions. The dashed lines are signals including cross-talk for an 554 keV event on the adjacent strip. Solid lines are signals without cross-talk effect. The reduced time is defined as "the time without cross-talk effect minus the time with cross-talk effect", *i.e.*, the time by which the zero crossing time is modified by the cross-talk effect.

II. Cross-Talk Effect on Depth Measurement

There are two main keys to Compton imaging with NCT's Ge-strip detectors. The first is to accurately determine the energy deposited in the detector at each interaction. The second is successfully tracking, in all three dimensions, the γ-ray photon interactions within the detector. The full 3D position of an interaction is determined by identifying the active cross-strip pair, and by determining the depth of the interaction (the distance between the γ-ray interaction and either the anode or cathode strip). The interaction depth in the detector is measured to an accuracy of 0.4 mm FWHM using the relative timing of the anode and cathode charge collection signals. The timing channel is measured by a 200 ns shaping time bipolar shaper and stamps the waveform when the signal crosses zero (signal changes from positive to negative) with 10 ns time resolution. The time resolution is limited by a 100 MHz counting timer on the analog channel. The Collection Time Difference (CTD) is defined by the difference between two zero-crossing times (Fig. 2), and with an error of ~ 14 ns. We use Monte Carlo charge transport simulations with an electric field model of our detectors to simulate the charge signals and the CTD [8]. The CTD for an event is well defined, and is linear with depth to first order. Our technique of converting CTD to depth, or z position, is discussed in detail in [9], [10].

However, the charge collection signals are affected by cross-talk when interactions occur in adjacent strips, altering the timing measurement in those interactions. We use custom charge transport simulations model to investigate the cross-talk effect on the timing measurement. Fig. 3 shows how the cross-talk affects the collection time. Fig. 4 is a diagram of a two-site adjacent-strip event. The transient induced charge from the adjacent strip changes the waveform of the main strip, thus altering the time of the zero-crossing. The "reduced time" on the main strip is defined as the time difference between the zero crossing time with and without the cross-talk effect.

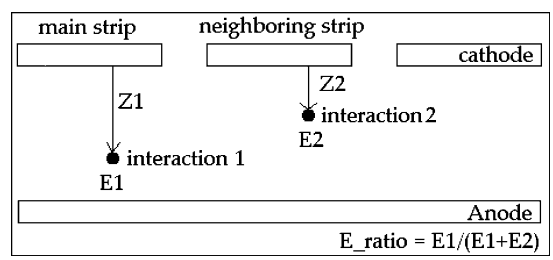

Fig. 4. Diagram of two-site adjacent-strip event. Two interactions occur in the adjacent strips. The timing measurement on the main strip would be affected by cross-talk from neighboring strip.

The reduced time varies with different energy ratios between adjacent strips and different 3D positions. But it is independent of the total deposited energy $(E1 + E2)$. An example of the variation of reduced time is also shown in Fig. 3. There are two adjacent-strip events with the same positions on the main strip (X1, near the edge of the strip, the center of the strip is in 0.4 cm for main strip, 0.6 cm for neighboring strip), and the same energy ratio between strips, but different positions (X2) on the neighboring strip. The difference of interaction position results in a different drift path of the charge carriers. The charge carriers passing through positions with different weighting fields cause the different waveforms of transient induced charge. The different waveforms of transient induced charge from the neighboring strip result in the difference of the timing measurement, although the signals on the main strip are the same.

Fig. 5 is the timing diagrams with fixed energy ratio and fixed depth of interaction at the neighboring strip from simulation results. It shows the relationship between the timing with and without the cross-talk effect. The CTD without cross-talk effect (Y-axis in the Fig. 5) is related to the interaction depth on the main strip (Z1). The cross-talk effect causes the reduced time, changing the zero-crossing time on one side, and moving the

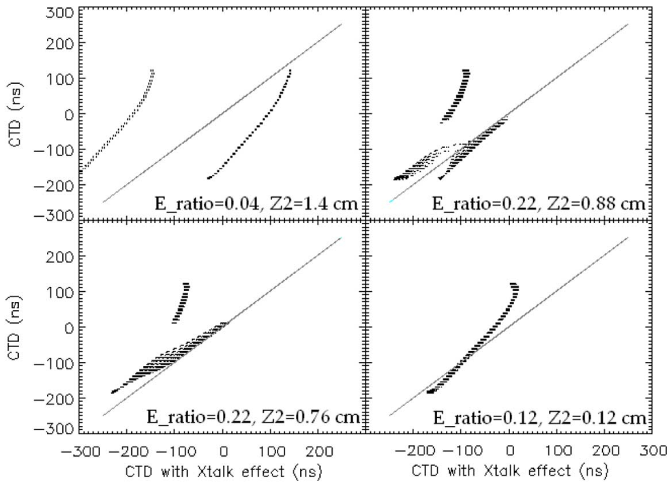

Fig. 5. Timing relationships for the ideal CTD vs. the CTD as altered by cross-talk. Each plot is for a fixed energy ratio between the strips, and a depth of interaction Z on the neighboring strip (Z2). The ideal CTD varies as a function of interaction depth in the main strip (Z1), and the scatter and/or multiple branches of the distributions are due to sampling the range of x and y positions across the main and neighboring strips. The distributions would fall on the gray line if there were no cross-talk effect.

CTD away from the gray line in Fig. 5. An interaction occurring on the edge or center of a strip would cause a large difference in the timing measurement (Fig. 3). This difference causes the branching and discontinuities in the measured CTD, *i.e.*, the CTD with cross-talk effect, as seen in Fig. 5. For example, if the shaped signal from the transient induced charge is above the threshold, then it makes the first zero-crossing from positive to negative come earlier (Fig. 3 RIGHT), and makes the measured time shorter than it should be. If the transient induced charge doesn't make an early zero-crossing, but makes the zero-crossing later, it makes the measured time longer. Those are the two branches in the TOP LEFT of the Fig. 5. The energy ratio between two strips is another factor which would cause different reduced time. Larger charge deposited on the neighboring strip would give higher transient induced charge on the main strip, changing the timing measurement more significantly. This effect would lead large error to the depth measurement for the adjacent-strip event. It is difficult to find a relationship to correct the CTD with the cross-talk effect directly, due to the variations caused by different x or y positions in the same strip.

III. Correction Method

Even though the timing on adjacent strips is changed by cross-talk, we still can use the relative timing from the orthogonal strips on the other side of the detector if they are separated. The measured time on a single strip is not related to the depth directly due to the unknown time of the trigger start. However, the Relative Time *Difference* (RTD) between strips on the same side is related to the Relative Depth Difference (RDD) between those two interactions. For any two given interactions in the same detector, where the depths of the interactions are unknown, the RDD can be corrected by using this RTD technique.

There are several issues that would affect the RTD measurement: the difference of occurring time between two interactions, the trigger start time, the charge collection time of each interaction, and the time delay on the electronics. The mean free path for a high energy photon in the germanium is a few centimeters, the time interval between two interactions in the same detector for each event is less than 1 ns. Because of NCT's time resolution of 10 ns, we can consider those two interactions occurring simultaneously. We use the same trigger start time for those interactions occurring in the same detector for each event. The unknown trigger start time would be eliminated when we take the time difference between those two interactions in the same detector. The time delay from the electronics would be calibrated via the calibration method. The relationship between charge collection time and ideal measured time can be found through simulations.

The first step of this correction method is finding a conversion curve to convert the RTD between strips on the same side to the RDD between those two interactions. We use a custom charge transport simulations model [8] to create a grid of interactions with different x, y and z positions. To get the timing of each interaction, we simulate the NCT bipolar shaper response for those interactions, and calculate the zero-crossing time as our ideal timing measurement. We can calculate the RTD and RDD between any two interactions, and get the relationship between RTD and RDD. Because of the 10 ns time resolution of analog channels on NCT's electronics, we average the RDD for each 10 ns. Fig. 6 shows the relationships between RTD and RDD on both sides from the simulations. The standard deviation of each bin is also shown. The gray line from 5th order polynomial fit is the conversion curve that we use to convert RDD. The error of this RTD technique is defined as the absolute depth difference minus the depth difference after correction. The root mean square values of those errors are 1.4 mm for the anode side, and 0.9 mm for the cathode side. The error of this technique can be reduced when we know one of the interaction depths. This conversion curve only use for ideal timing measurement, for measured data from detectors, we should calibrate it first. The calibration method for time difference can be found in [10].

The second step of this correction method is using the time difference between nonadjacent strips on the same side of the detector for the adjacent-strip events. Depending on the position of the fired strip, we select an appropriate conversion method to avoid using the timing with the cross-talk effect. For any single pixel interaction, the CTD can be converted to depth with 0.4 mm FWHM depth resolution. For adjacent-strip events, the absolute depth can be derived by using RDD from this RTD technique and the depth from any other single pixel interaction in the same detector, *i.e.*, the absolute depth of one of those two adjacent-strip interactions is the depth of the third single pixel interaction plus the depth difference between the third interaction and the target interaction. For a multiple site event with adjacent strips on one side of the same detector, without a single pixel interaction for absolute depth calculation, *e.g.*, only two interactions occur on adjacent strips in one detector, we still use the relative depth difference for event reconstruction and imaging if there were no other interactions in the other detectors. This method cannot correct events with only two interactions on adjacent-strip in one detector, and with other interactions in the other detectors, because there is no correlation between the

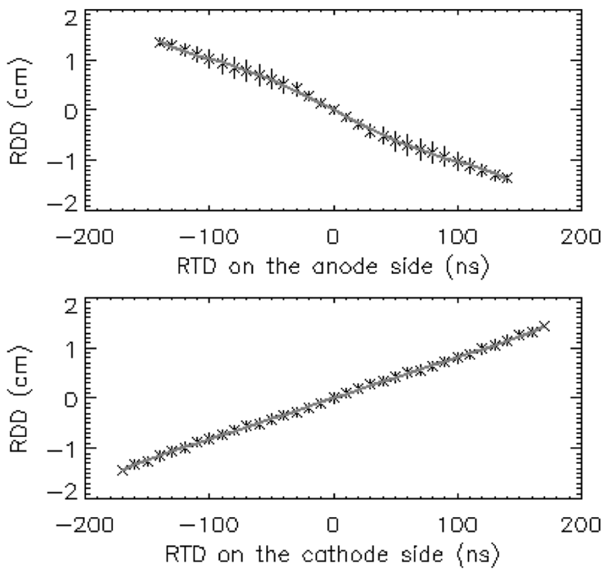

Fig. 6. The relationship between time difference, on nonadjacent anode strips (TOP) and the cathode strips (BOTTOM), and the actual depth difference. The data points on those plots are the averages of depth differences, which are calculated from different 3D positions within each 10 ns bin. The standard deviation of each bin is indicated by vertical bars.

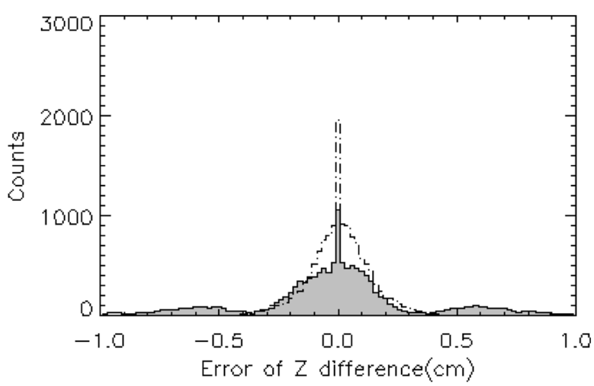

Fig. 7. The error of the relative depth difference, solid line is before correction, and dashed line is after correction. The error is defined by absolute depth minus the depth from the conversion.

depth difference in one detector and the absolute depth in the other detector.

IV. Correction Result

We use the MGEANT simulation tools [11] with NCT mass model to produce a list of interaction positions and energies for events from a 662 keV source with a 70 degree elevation angle. We then took two-site adjacent-strip events in the same detector to test our correction method. An assumed 2.4 keV FWHM noise for energy measurement and an assumed 10 ns FWHM electronics noise for the timing measurement are added in the simulations.

Fig. 7 shows the error of the depth difference before and after application of our correction technique. The error of time difference can be reduced by this method. The events with error larger than 0.35 cm are about 31%, 2%, before and after this

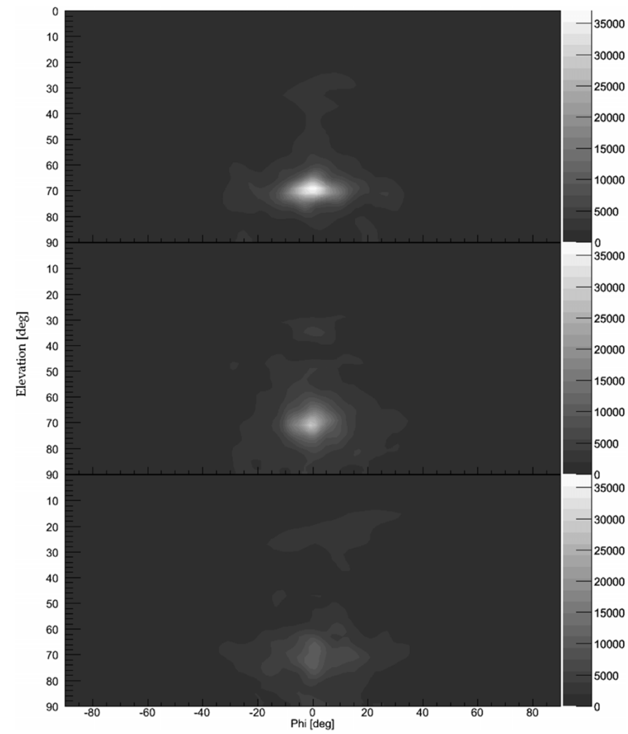

Fig. 8. The imaging of the same events (only two-site adjacent-strip interactions in a single detector, 662 keV), but using different depth calculations. TOP uses absolute depth from MGEANT simulation, BOTTOM uses CTD conversion method without our correction, MIDDLE uses our correction technique. The performance of imaging is significantly improved after our correction.

correction, respectively. The root mean square values of the errors improve from 0.34 cm to 0.13 cm. The FWHM of the angular resolution improves from ~ 27 degree (before correction) to ~ 19 degree (after correction). Fig. 8 shows the imaging of those two-site adjacent-strip events. The software tool used for event reconstruction and imaging is MEGAlib [12], a comprehensive software package designed for Compton Telescopes. The imaging performance is limited by short-distance interactions where the uncertainty of x and y positions is relatively large. Comparing the imaging using different depth calculations, the performance is significantly improved after our correction technique.

V. Summary

NCT uses an array of twelve cross-strip germanium detectors to perform Compton imaging and spectroscopy. The depth of an interaction within a Ge-strip detector is measured by using the CTD conversion technique. In adjacent-strip events, the cross-talk from a neighboring strip would affect the timing measurement on the main strip. Using the RTD technique, one can correct the cross-talk effect in the adjacent-strip events, and consequently significantly improve interaction localization and ultimately imaging performance.

References

[1] S. E. Boggs, W. Coburn, D. M. Smith, J. D. Bowen, P. Jean, J. M. Kregenow, R. P. Lin, and P. von Ballmoos, "Overview of the Nuclear Compton Telescope," *New Astron. Rev.*, vol. 48, pp. 251–255, Feb. 2004.

[2] S. Boggs, M. Bandstra, J. Bowen, W. Coburn, R. Lin, C. Wunderer, A. Zoglauer, M. Amman, P. Luke, P. Jean, and P. von Ballmoos, "Performance of the Nuclear Compton Telescope," *Experiment. Astron.*, pp. 25–32, Sep. 2006.

[3] H.-K. Chang, S. Boggs, and Y.-H. Chang, "The Nuclear Compton Telescope (NCT): scientific goals and expected sensitivity," *Adv. Space Res.*, vol. 40, pp. 1281–1287, 2007.

[4] E. C. Bellm, S. E. Boggs, M. S. Bandstra, J. D. Bowen, D. Perez-Becker, C. B. Wunderer, A. Zoglauer, M. Amman, P. N. Luke, H.-K. Chang, J.-L. Chiu, J.-S. Liang, Y.-H. Chang, Z.-K. Liu, W.-C. Hung, C.-H. Lin, M. A. Huamg, and P. Jean, "Overview of the Nuclear Compton Telescope," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 3, Jun. 2009.

[5] S. E. Boggs and P. Jean, "Event reconstruction in high resolution Compton Telescope," *Astron. Astrophys. Suppl. Ser.*, vol. 145, pp. 311–321, 2000.

[6] W. Coburn, S. E. Boggs, J. D. Bowen, M. E. Bandstra, M. S. Amman, M. T. Burks, W. Craig, P. Jean, R. P. Lin, P. N. Luke, N. W. Madden, D. M. Smith, and P. von Ballmoos, O. H. W. Siegmund, Ed., "First results from the balloon flight of the NCT prototype," in *UV, X-Ray and Gamma-Ray Space Instrumentation for Astronomy XIV*, Aug. 2005, vol. 5898, pp. 13–21.

[7] M. E. Bandstra, E. Bellm, S. E. Boggs, J. D. Bowen, D. Perez-Becker, C. B. Wunderer, A. Zoglauer, M. Amman, P. N. Luke, H.-K. Chang, J.-L. Chiu, J.-S. Liang, Y.-H. Chang, Z.-K. Liu, C.-H. Lin, M. A. Huang, and P. Jean, "The upcoming long duration balloon flight of the Nuclear Compton Telescope," in *Proc. Nuclear Science Symp. Conf. Rec.*, 2007, vol. 4, pp. 2532–2537.

[8] S. Amrose, S. E. Boggs, W. Coburn, G. Holland, R. P. Lin, and D. M. Smith, "Numerical simulations of 3D positioning in cross-strip Ge detector," in *Proc. Nucl. Sci. Symp. Conf. Rec.*, 2001, vol. 1, pp. 230–233.

[9] S. Amrose, S. E. Boggs, W. Coburn, R. P. Lin, and D. M. Smith, "Calibration of 3D position in a Ge cross-strip detector," *Nucl. Instrum. Meth. Phys. Res. A*, vol. 505, pp. 170–173, 2003.

[10] M. E. Bandstra, J. D. Bowen, A. Zoglauer, S. E. Boggs, W. Coburn, C. B. Wunderer, M. Amman, and P. N. Luke, "Position calibrations and preliminary angular resolution of the prototype Nuclear Compton Telescope," in *Proc. Nucl. Sci. Symp. Conf. Rec.*, 2006, vol. 2, pp. 770–777.

[11] S. J. Sturner, H. Seifert, C. Shrader, and B. J. Teegarden, "MGEANT—A GEANT-based multi-purpose simulation package for gamma-ray astronomy missions," in *Proc. AIP Conf.*, 2000, vol. 510, pp. 814–818.

[12] A. Zoglauer, R. Andritschke, and F. Schopper, "MEGAlib the medium energy gamma-ray astronomy library," *New Astron. Rev.*, vol. 50, pp. 629–632, 2006.