SIMULATED PERFORMANCE OF A GERMANIUM COMPTON TELESCOPE

Steven E. Boggs[1,2] and Pierre Jean[3]

[1]Space Radiation Laboratory, California Institute of Technology, MC 220-47, Pasadena, CA 91125 USA
[2]Department of Physics, University of California, Berkeley, CA 94720 USA
[3]Centre d'Etude Spatiale des Rayonnements, UPS-CNRS, Toulouse, France

ABSTRACT

To build upon the goals of the upcoming INTEGRAL mission, the next generation soft γ-ray (0.2-20 MeV) observatory will require improved sensitivity to nuclear line emission while maintaining high spectral resolution. We present the simulated performance of a germanium Compton telescope (GCT) design, which will allow a factor of ten improvement in sensitivity over INTEGRAL/SPI. We also discuss a number of issues concerning reconstruction techniques and event cuts, and demonstrate how these affect the overall performance of the telescope.

Key words: gamma-ray astronomy; nuclear astrophysics; gamma-ray spectroscopy; gamma-ray telescopes.

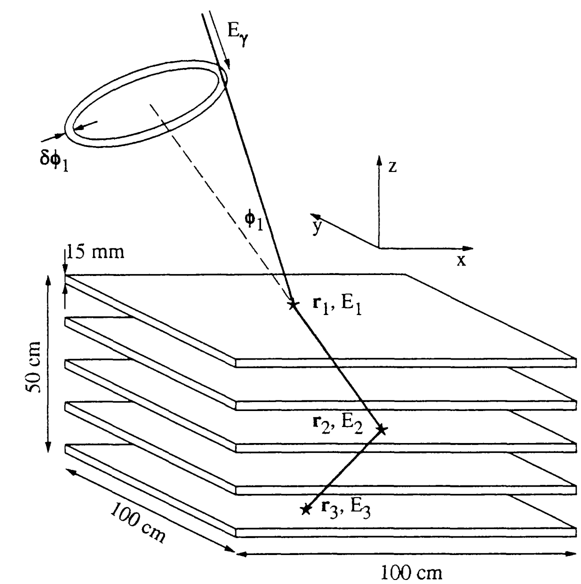

Figure 1. Germanium Compton telescope configuration analyzed in this work.

1. INTRODUCTION

Combining the success of COMPTEL/CGRO and the spectral resolution of INTEGRAL/SPI, a number of researchers (Johnson et al. 1996; Jean et al. 1996; Boggs 1998) have discussed the merits of a germanium Compton telescope (GCT). Compton telescopes work on a well-known principle: by measuring the positions and energies of the photon interactions the initial photon direction can be reconstructed to within an annulus on the sky using the Compton scatter formula (Figure 1). The uncertainty, or width, of this annulus depends on the spatial and spectral resolution of the detectors, but also has a fundamental limit set by Doppler broadening due to Compton scattering off of bound electrons. Reconstruction of the event annulus requires that the first and second photon interaction locations in the instrument are spatially resolved, and their order properly determined.

Germanium detectors pose two major complications for Compton telescope designs. Photons above ~0.5 MeV predominantly scatter multiple times in germanium before being photoabsorbed. Also, the expected event timing resolution in germanium detectors (>10 ns) is not adequate to determine the interaction order for reasonable GCT configurations.

In a previous paper (Boggs & Jean 2000), hereafter Paper I, we introduced two *reconstruction techniques* to accurately determine the photon interaction order in GCTs. The first technique, Compton Kinematic Discrimination (CKD), takes advantage of redundant information for photons which interact three or more times in the instrument (3+ site events) to determine the most probable interaction order. CKD additionally allows efficient rejection of background events, including photons which scatter out of the instrument before fully depositing their energy (Compton continuum photons), non-localized β^--decays, β^+-decays, and pair-production events. The second reconstruction technique, Single Scatter Discrimination (SSD), allows good determination of the interaction order in 2-site events, but without the

Proceedings of the 4th INTEGRAL Workshop 'Exploring the Gamma-Ray Universe', Alicante, Spain, 4-8 September 2000 (ESA SP-459, September 2001)

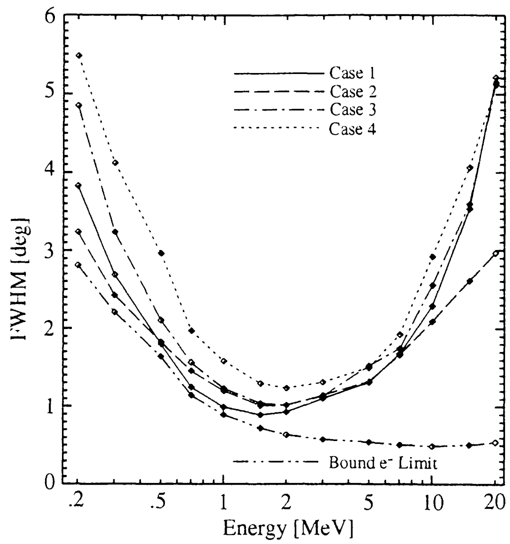

Figure 2. Angular resolution for on-axis sources as a function of photon energy. Also shown is the limit set by Doppler broadening of bound electrons.

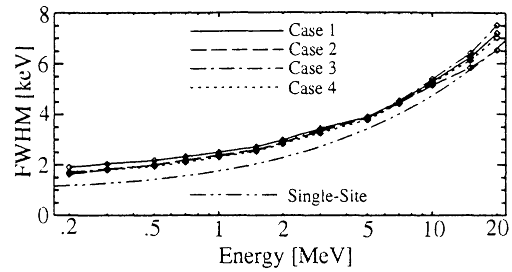

Figure 3. Photopeak spectral resolutions, which show little dependence on the reconstruction technique or event cuts. For comparison is shown the assumed single-site resolution.

benefit of background rejection. (Also in Paper I we summarized additional techniques for rejecting β^--decays, β^+-decays, and pair-production events.) In addition to CKD and SSD, other reconstruction techniques can be imagined. As we discussed in Paper I, for a given GCT configuration the performance will depend on the reconstruction techniques employed.

Telescope performance will also depend on *event cuts*, which can be made on the initial direction of the photon scatter, the number of interaction sites, and the minimum separation between the first and second interaction sites (*minimum lever arm*). The trade-offs are generally higher efficiency at the expense of degraded angular resolution, and hence increased background. First, the uncertainty in the Compton scatter angle (angular resolution) is smaller for forward scatter events than backscatter events (Paper I, Equation 4). Second, events with only 2 interaction sites (2-site) do not permit CKD background rejection, and also have a larger fraction of backscatter events that 3+ site events. Finally, a larger minimum lever arm will minimize the effects of spatial uncertainty in the detectors, improving angular resolution and hence background, but at the expense of lower efficiency.

Here we present detailed simulations of a GCT configuration in an effort to determine the optimized sensitivity to nuclear line emission, as well as demonstrate the variation in performance for several different combinations of reconstruction techniques and event cuts. Our selections range from utilizing most of the event information to physically reconstruct the event (Case 1, with CKD), to using a purely empirical, but highly efficient approach (Case 4), and should fairly represent the range of performance characteristics possible within a GCT.

2. TELESCOPE SIMULATION

The telescope configuration modeled in this study is presented in Figure 1. The instrument consists of five planar arrays of 15 mm thick germanium, each of area 100 *cm* × 100 *cm*. In reality each array would consist of separate smaller detectors (~ 5 *cm* × 5 *cm*) tiled to form the entire plane; however, the simulation performed here modeled each plane as a solid detector for simplicity. The five planar arrays are vertically spaced 12.5 cm apart center-to-center.

The instrument was simulated using CERN's GEANT Monte Carlo code, modified to include Doppler broadening of bound electrons[1]. Photon interactions are randomly modified to reflect the assumed energy resolution (shown in Figure 3), and ~1-mm spatial resolution. (These uncertainties were described in detail in Appendix A of Paper I.) Unresolved interactions are combined, and a detector threshold of 10 keV is assumed.

Components inducing soft γ-ray background in spaceborne instruments are the cosmic diffuse background (CDB) and the cosmic-ray protons that either promptly release their energy in the detector (CR prompt), or create radioactive nuclei in the instrument materials (CR delayed). The spacecraft is also a source of background events since under CR or CDB irradiation, it generates secondary particles (p^+, n, γ) able to reach the instrument. Therefore, a numerical model of a spacecraft has been added underneath the telescope presented in figure 1 in order to estimate a more realistic background. We simulate the irradiation of the GCT and the spacecraft by cosmic-ray fluxes in high earth orbit (HEO) condition using the GEANT/GCALOR code. The CDB input spectrum is based on the recent measurements by COMPTEL (Weidenspointner 1999) and SMM (Watanabe et al. 1997). The solar maximum CR spectrum (Webber & Lezniak 1974) has been used to simulate the CR components. The yields of radioac-

[1]The authors are grateful to R. M. Kippen for providing his modifications to the GEANT3 software package, which include the effects of scattering off of bound electrons. These modifications are available on-line. `http://gammaray.msfc.nasa.gov/actsim/`

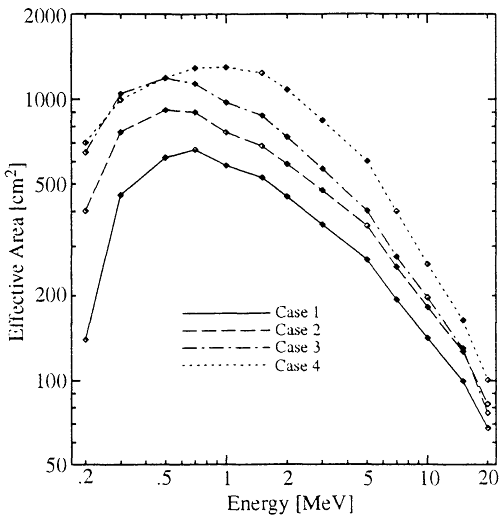

Figure 4. On-axis photopeak effective areas, which show a strong dependence on the reconstruction technique and event cuts.

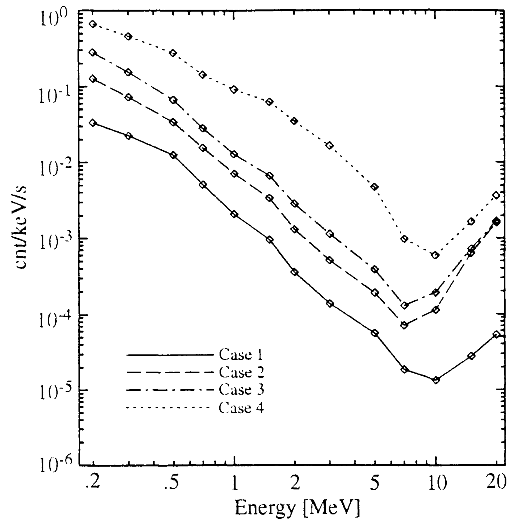

Figure 5. Background events consistent with the 78% error circle of an on-axis point source.

tive nuclei induced by CRs (and their secondaries) in the Ge have been used to calculate the decay rates after one year in orbit. Using these rates and the ENSDF database, the radioactive decays have been simulated with GEANT.

3. RECONSTRUCTION TECHNIQUES & EVENT CUTS

While CKD offers a powerful technique for background rejection, it also rejects a large fraction of signal photons which fully deposit their energy in the instrument but, for example, have two or more interaction sites not spatially resolved.

As an alternative to CKD and SSD, more empirical reconstruction techniques to determine the interaction order can be imagined. For example, the Monte Carlo simulations show that for 1 MeV photons, the majority of events have their largest energy deposit in the first (70.2%) or second (22.7%) interaction site. This information allows us to devise a different reconstruction technique. First we define a source position on the sky. Then we assume that the largest energy deposit for a given event is either the first or second interaction site, for a photon of energy equal to the total energy deposited in the instrument. Then we test each other interaction site in combination with this largest energy deposit to determine if any pair is consistent with the first and second interactions of a photon originating from the defined source position. Events which are not consistent with this source position are rejected. This empirical reconstruction technique dramatically increases the effective area relative to CKD, but also increases the background and Compton continuum components.

Table 1. Reconstruction techniques and event cuts presented.

Case	Ordering Technique	# Sites	Back-scatters	Minimum Lever Arm
1	CKD	3+	no	10 cm
2	CKD/SSD	2+	yes	10 cm
3	CKD/SSD	2+	yes	1 cm
4	Empirical	2+	yes	1 cm

The four (4) combinations of reconstruction techniques and event cuts presented here are summarized in Table 1. These cases are roughly ordered from highest angular resolution and lowest background (Case 1), to highest effective area (Case 4). In addition to CKD in Cases 1-3, we have included in all four cases the additional background rejection techniques discussed in Paper I (e.g., rejection of events with β^--signatures, positron signatures, 8+ site events). Case 4 uses the empirical reconstruction technique discussed above. The 10-cm minimum lever arm in Cases 1 & 2 almost always requires the first and second interactions to be in separate detector planes, while the 1-cm in Cases 3 & 4 allows these interactions in the same plane to increase efficiency, but at the cost of degraded angular resolution and higher background.

4. PERFORMANCES

Angular resolution in Compton telescopes is often described in terms of the *angular resolution measure* (ARM), defined as the difference between the initial photon scatter angle in the instrument and the scatter angle reconstructed from the Compton

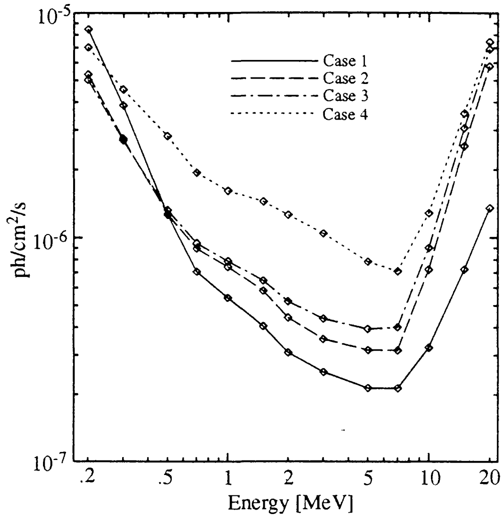

Figure 6. The narrow-line sensitivity (3σ,10^6 sec), for an on-axis point source.

scatter formula. The ARM distributions are highly non-Gaussian, with sharp central peaks and broad wings. The FWHM of the on-axis ARM distribution as a function of energy is shown in Figure 2, as well as the limits imposed by Doppler broadening of bound electrons, which dominates the angular resolution below ~2 MeV. At higher energies, the angular resolution is dominated by the degradation in the spatial resolution due to the increased recoil-electron range. The overall degradation at 1 MeV is 58% between Cases 1 and 4 (0.96° to 1.52°).

The photopeak FWHM energy resolution is broader than the single-site resolution due to the addition in quadrature of electronic noise for multiple interaction sites. The photopeak energy resolution is shown in Figure 3, with the assumed single-site resolution shown for comparison. The photopeak resolution is nearly identical in Cases 1-4. At 1 MeV, the photopeak FWHM corresponds to a ~33% broadening over the single-site resolution (1.77 keV to 2.36 keV).

The on-axis photopeak effective area as a function of energy is shown in Figure 4, determined by integrating over the ARM distribution. The effective area peaks around 0.5-1.0 MeV, with considerable area between 0.2 and 20 MeV, and is sensitive to the reconstruction technique and event cuts. Between Cases 1 and 4, the overall increase in effective area at 1 MeV is 125% (590 cm^2 to 1330 cm^2).

The total background for an on-axis point source observation is shown in Figure 5. This background is defined as all events whose event circles are consistent with a photon originating from within the 78% error circle (*effective FWHM*) of the energy-dependent ARM distribution for each particular case. At 1 MeV, the background is a factor of 40 higher in Case 4 than in Case 1. This large variation is due to the increased effective area and degraded angular resolution, as well as the minimal background rejection, in Case 4. The corresponding narrow-line sensitivities (3σ,10^6sec) are shown in Figure 6. At 1 MeV, Case 1 has the highest sensitivity at 5.1×10^{-7} ph/cm^2/s, degrading to 15.0×10^{-7} ph/cm^2/s in Case 4. We have not accounted for instrument deadtimes when processing photon or charged-particle events; however, we estimate that deadtime will affect the sensitivity by $\ll 5\%$.

5. DISCUSSION

GCTs offer an attractive option for a soft γ-ray observatory following INTEGRAL. The GCT presented here will allow a factor of 10 improvement in nuclear line sensitivity over INTEGRAL, which is required for new scientific goals such as the systematic study of Type Ia SNe, as well as improved imaging of the positron annihilation line, ^{26}Al, ^{60}Fe, and ^{44}Ti. We have also demonstrated how a judicious choice of reconstruction techniques (CKD) and event cuts (3+ site events, forward scatters) results in a 3-fold improvement in sensitivity near 1 MeV, while maintaining angular resolution near the Doppler-broadening limit. Our next goal is to study the performance of several different GCTs configurations, varying the detector-plane spacings, to determine how the geometry affects performance.

ACKNOWLEDGMENTS

S. Boggs acknowledges the Caltech Millikan Fellowship Program and NASA Grant NAT5-5285 for support. Thanks to R. M. Kippen for providing useful information on bound-electron Doppler broadening.

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