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A Compton Telescope for Remote Location and Identification of Radioactive Material

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ABSTRACT

The spare detectors from NASA Compton Gamma-Ray Observatory COMPTEL instrument have been reconfigured to demonstrate the capability at ground level to remotely locate and identify sources of g radiation or the movement of material that might shield γ-ray sources. The Gamma-Ray Experimental Telescope Assembly (GRETA) employs two 28 cm diameter scintillation detectors separated by 81 cm: one 8.5 cm thick liquid scintillator detector and one 7.5 cm thick NaI(Tl) detector. The assembly electronics and real-time data acquisition system measures the energy deposits and time-of-flight for each coincident detection and compiles histograms of total energy and incident angle as computed using the kinematics of Compton scattering. The GRETA field of view is a cone with full angle approximately 120°. The sensitive energy range is 0.3 to 2.6 MeV. Energy resolution is ~10% FWHM. The angular resolution, ~19° in the simplified configuration tested, will improve to better than 5° with well-defined enhancements to the data acquisition hardware and data analysis routines. When operated in the mode that was used in space, the instrument is capable of measuring and imaging up to 30 MeV with an angular resolution of 1.5˚.

The response of the instrument was mapped in the laboratory with 14 μCi ^{22}Na source 3 m from the instrument. Later, we conducted demonstrations under two measurement scenarios. In one, the remotely located instrument observed an increase of background radiation counts at 1.4 MeV when a large amount of lead was removed from a building and a corresponding decrease when the lead was replaced. In the other scenario, the location and isotope-identifying energy spectrum of a 500 μCi ^{137}Cs source 3-5 m from the instrument with two intervening walls was determined in less than one minute. We report details of the instrument design and these measurements.

Keywords: Compton Telescope, Gamma-ray spectroscopy, Gamma-ray imaging, Remote detection

1. INTRODUCTION

1.1 Motivation

The remote detection and location of radioactive material (RAM) is a key problem facing emergency crews, cleanup teams and search and rescue teams. Dangerous undetected quantities of RAM can stall or suspend operations once discovered. Searching for γ-ray emitting sources is time consuming and hazardous. Standard equipment for searching for RAM includes hand held counters and spectrometers. Either device registers an increased count rate in the presence of RAM. The spectrometer can also identify the nature of the source, *e.g.*, whether it is ^{137}Cs or ^{60}Co. However, both devices must overcome the effect of background radiation and neither pinpoints the source other than by proximity inducing the high count rate.

1.2 Technique

A better way would be to sense the presence of RAM from a safe standoff distance. Better still would be to locate the source and identify the isotope. To do this one must have an imaging γ-ray telescope that spectroscopically analyzes the imaged source. Such a device has already been used in space to image cosmic γ-ray sources in harsh, high background environments. Compton telescopes are the instrument of choice for γ-ray sources in the 1 MeV range. Other techniques for producing γ-ray imaging exist but do not have the sensitivity of Compton telescopes.

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For example, coded aperture imaging relies on the ability of the mask to absorb the incident photons. At higher energies, this requires thicker masks that are impractical. This, coupled with the intrinsic background of the imaging system, renders coded aperture imaging less attractive at higher energies, *i.e.*, 1 MeV.

A more effective approach at higher energies takes full advantage of the Compton effect, in which a photon scatters off an electron. Compton imaging becomes effective at energies above about 500 keV. The Compton telescope concept relies on measurements of both the scattered electron and the scattered photon. This double scatter approach typically relies on two separate detectors, one designed to measure the scattered photon and the location of the scatter interaction and the other detector designed to absorb the scattered photon to record its total energy and scatter direction.

Until now, Compton telescopes have not been able to determine the precise direction of the incident photon. Rather, the direction of the incoming photon is determined to lie along a so-called "event circle," whose parameters are defined by the kinematics of the scattering process. A large number of event circles are used to generate maps of the γ-ray emission within the field-of-view. Figure 1 (right) shows the COMPTEL instrument[1] that flew in earth orbit for nine years as part of the payload on the Compton Gamma Ray Observatory (1991-2000). This instrument, operating between 750 keV and 30 MeV, achieved a moderate angular resolution (1° - 2°) over a fairly large field-of-view.

One advantage of Compton imaging over coded aperture imaging is that the Compton imaging treats each photon individually. This means that background rejection becomes more efficient. On COMPTEL, time-of-flight information (measuring the time between the Compton scatter interaction and the subsequent absorption of the scattered photon) was employed to dramatically reduce the background from other sources. This is especially important for astronomical applications where orbiting spacecraft are subjected to a high level of both particle and photon backgrounds. We found that capability to also be practical for terrestrial applications, *i.e.*, rejecting background γ rays from outside the intended field of view.

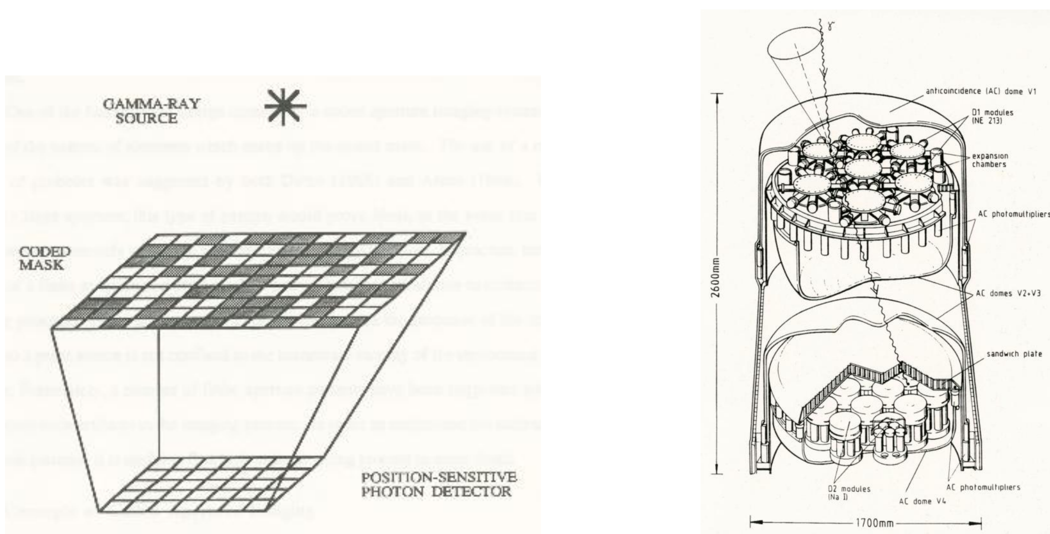

Figure 1 Coded aperture concept (left) using a coded mask with opaque elements and a position-sensitive photon detection plane that measures the resulting shadow cast by the γ-ray source. A schematic of the COMPTEL instrument (right) that was flown on the NASA Compton Gamma Ray Observatory (CGRO). The principle of measurement is shown, along with the event circle that is reconstructed from the measured kinematics. The photons incident direction is known to have come from somewhere along the mantle of an event cone.

2. INSTRUMENT DESCRIPTION

2.1 The GRETA instrument

The Gamma-Ray Experimental Telescope Assembly (GRETA) employs two rugged cylindrical scintillation detector assemblies aligned on their cylindrical axes and separated by 81 cm (Fig 2). These detector assemblies are spares from the NASA Compton Gamma-Ray Observatory COMPTEL instrument.

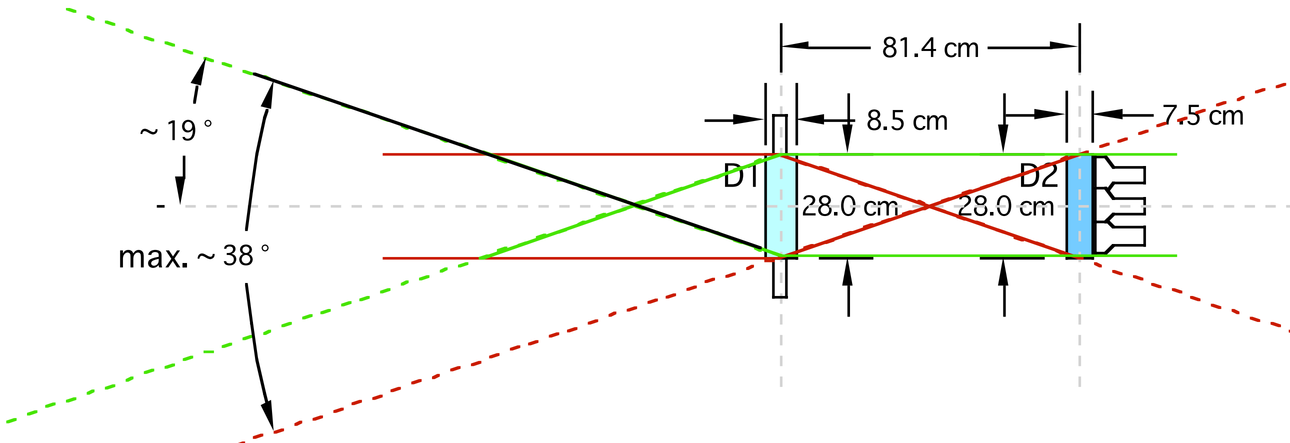

Fig. 2. Geometrical configuration of the Compton telescope formed with GRETA's D1 and D2 detectors

The front detector (D1, Fig 3) is an aluminum tank containing approximately 5.6 l of liquid scintillator NE213A. The liquid scintillator tank features low-density aluminum honeycomb front and back cover plates, eight quartz glass windows distributed evenly around the circumference, an integrated metal bellows expansion reservoir and redundant seals to safely contain the liquid. Eight 51 mm diameter fast bialkali photomultiplier tubes (PMT), optically coupled to the eight windows view the interior volume. The interior walls are coated with bright, white, diffuse, reflector paint. The active liquid scintillator volume for D1 is 8.5 cm thick and 28 cm in diameter.

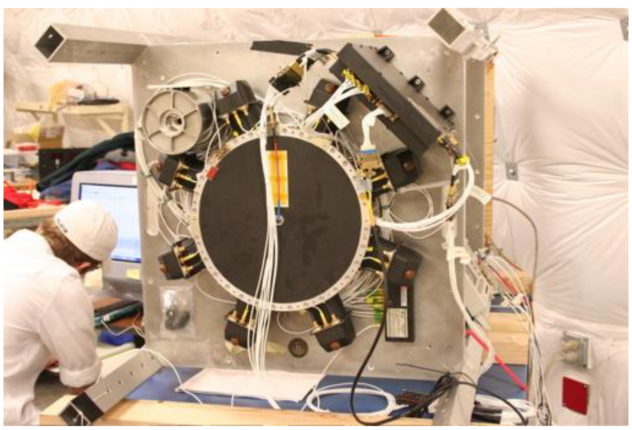

Fig. 3. D1 detector. 28 cm diameter, 8.5 ck thick liquid scintillator tank viewed radially by eight 51 mm PMTs.

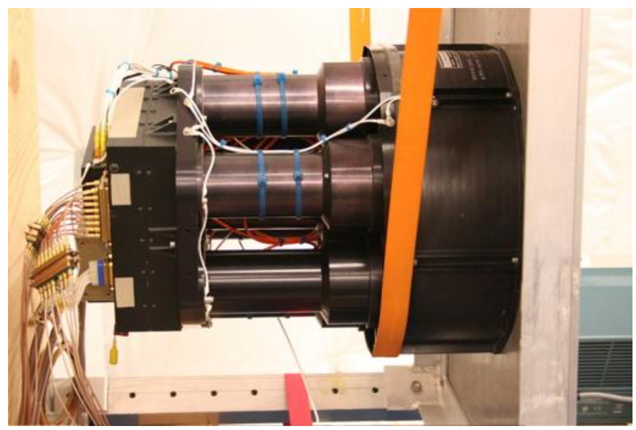

Fig. 4. D2 detector. 28 cm diameter, 7.5 ck thick NaI(Tl) scintillator viewed by seven 76 mm PMTs.

The rear detector (D2, Fig 4) employs a 7.5 cm thick 28 cm diameter NaI(Tl) scintillator and seven 76 mm diameter fast bialkali PMTs that view the interior volume from the rear face. The D2 assembly features a low-density entrance window of honeycomb aluminum construction and a rugged hermetically sealed housing to protect the scintillator crystal and PMTs. The D1 and D2 detector materials and dimensions were selected to optimize detection via the Compton scattering process in the energy range > 300 keV. The GRETA electronics were more simply configured to ensure adequate response in the limited energy range of 0.4 to 3 MeV, the important range for RAM. However, active interrogation of high explosives need an energy range extending to at least 10 MeV, requiring flight-like electronics.

The front-end electronics for D1 and D2 are located on the detector assemblies. An aluminum frame aligns and supports the detector assemblies. The Compton telescope rests atop a rolling cart that also supports the power supplies and data acquisition electronics (Fig. 5). This configuration facilitated the field measurements reported here.

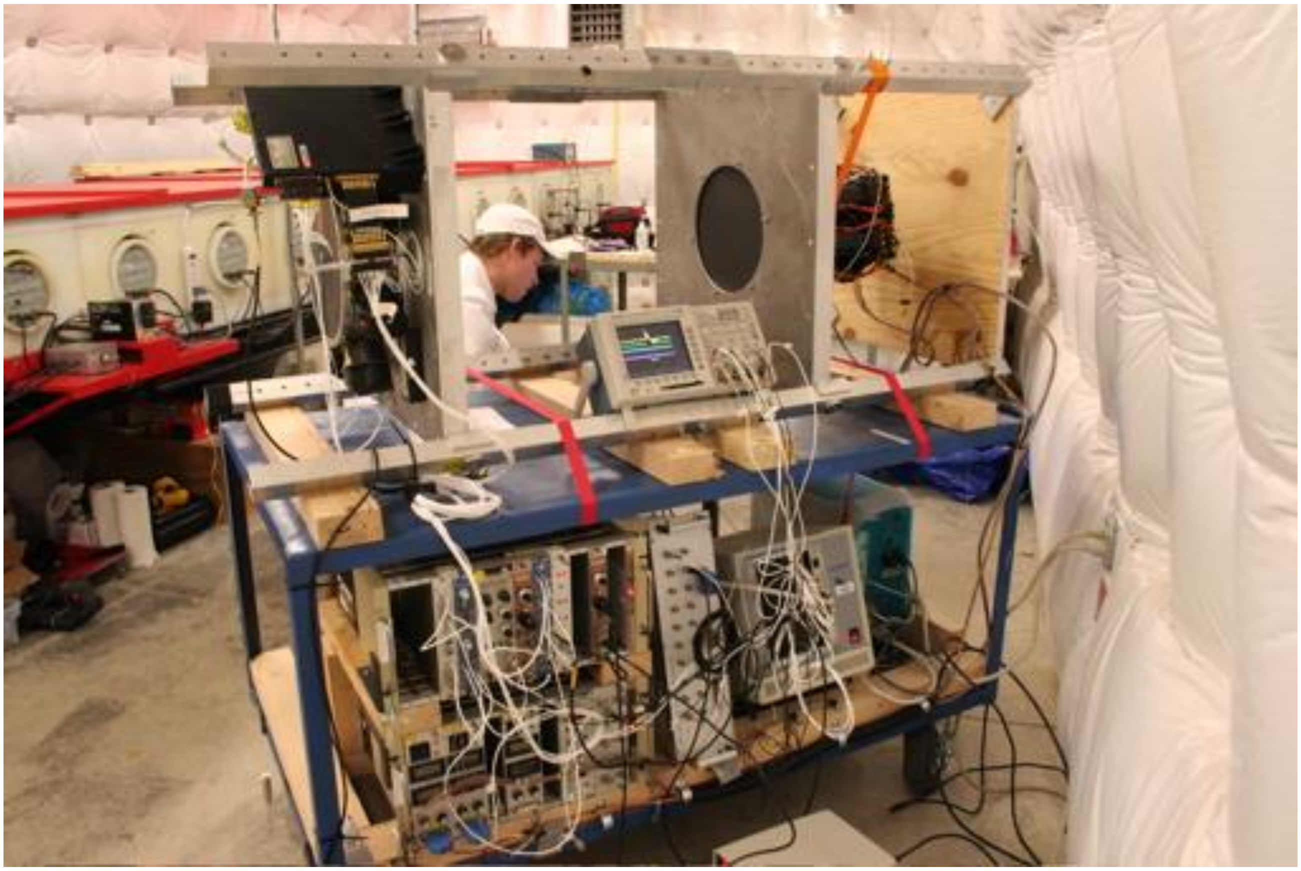

Fig. 5.GRETA. The Compton telescope rests atop a cart carrying the supporting electronics and data acquisition system.

The D1 and D2 front-end electronics processes all PMT signals. Output signals are as follows.

- Pulse height signals, (0.5 μs shaping) for each PMT; 8 for D1, 7 for D2
- Sum pulse height signal (0.5 μs shaping)
- Constant fraction discriminator (CFD) timing signal; one each for D1 and D2
- Pulse shape discrimination (PSD) signal for D1 only; neutron-gamma discrimination

While the GRETA detectors and front-end electronics are custom engineered, the data acquisition system (DAQ) employs commercial laboratory equipment consisting of NIM and CAMAC modules and a Macintosh computer running Kmax software. Key elements are a fast logic module to recognize coincident D1 and D2 CFD timing signals, a time-to-amplitude converter (TAC) to measure the time-of-flight (ToF) between the two detectors and peak sensing ADCs to convert the pulse heights, PSD and ToF for each registered coincidence. In the present DAQ configuration, only the sum pulse height signals from D1 and D2 as well as the PSD and ToF are converted and recorded. This means that we know only that the photons interacted somewhere within the 28 cm diameter D1 and D2 volumes. This limits the angular resolution to approximately 19° (Fig 2). Finer angular resolution (~1.5°) can be achieved if all 15 (8 D1 +7 D2) PMT signals are converted and recorded so that, with appropriate additional calibration and algorithms, finer location of each photon interaction within the D1 and D2 scintillators can be determined. This, in fact, is how COMPTEL operated in orbit.

Other than pointing the instrument, there is no adjustment to make. Adjustments are made *ex post facto* in data analysis. The main data selection to make (adjustment) is a selection on the scatter angle. Because the position location hardware and software is not enabled in GRETA, all events are assumed to occur at the center of the modules, D1 and D2. Thus, the scatter angle is the polar angle of the incident γ direction. To narrow the field of view of the instrument, one selects energy deposits in D1 and D2 that correspond to small angle scattering, *i.e.*, selecting small values for the energy deposit in D1 with respect to that in D2 according to the Compton kinematic formula. Conversely, one can widen the field of view by selecting events with larger deposits in D1, again with respect to that in D2. Because this is done in data analysis, all possible field-of-view configurations are acquired concurrently and sorted afterward.

3. PERFORMANCE DEMONSTRATION

Fig. 6. Field measurement before the installation of ~10^3 kg of lead in a neutron monitor.

Fig. 7. Field measurement after the installation of the lead in a neutron monitor.

The sensitivity of the instrument to detect changes in background was measured during the assembly of a neutron monitor system at the University of New Hampshire. In the process of assembling the monitor (Fig. 6) significant amounts of lead were moved into the field of view of the GRETA instrument. Background spectra were accumulated before the installation of the lead and after the full complement of lead and neutron detector equipment was in place. Figs. 6 and 7 show the measurement configuration, before and after the installation of the lead. Approximately 1 metric ton of lead was positioned approximately 3 m from the aperture of GRETA. The field of view was selected to encompass the neutron monitor and little else.

The spectra obtained from these two runs are shown in Fig. 8. The major effect of the lead as can be seen in the figure is the attenuation of background lines, *e.g.*, the U decay chain line at 2.6 MeV and ^{40}K at 1.46 MeV. Although the overall count rate does not greatly decrease, the effect can be seen in the spectrum, in particular below 1 MeV where the lead is expected to attenuate the γ intensity significantly. The signal in Fig. 8 was cleaned up in the data analysis by only selecting γ events where the scattering angle was consistent with the position of the neutron monitor (lead). This enhanced the features seen in the figure.

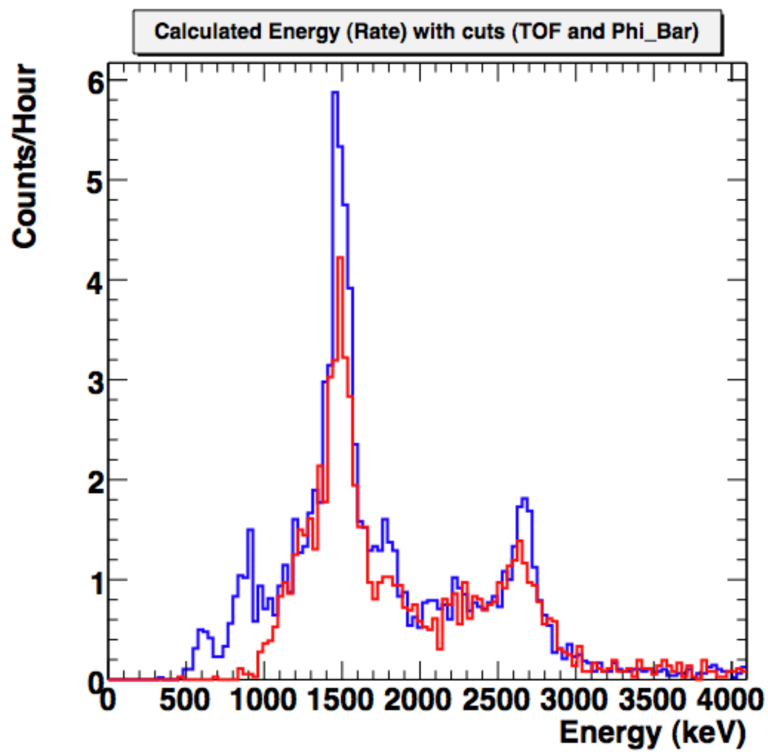

Fig. 8. Spectra of natural background radiation before (lower curve) and after (upper) introducing lead shielding into the GRETA field of view.

A second demonstration was conducted inside Morse Hall at the University of New Hampshire. The objective was to see if GRETA could detect the presence of a ^{137}Cs source on the far side of two interior walls at a rough distance of 10 m. The source was moved in and out of the instrument field of view, out of the view of the instrument operator.

The instrument was operated in a normal fashion, *i.e.*, data were collected and sorted into different fields of view. With a dynamic field of view, it is possible to observe a source enter a particular field of view and leave it on the other side. Shown in Fig. 9 are plots of the spectra obtained of a ^{22}Na source when positioned at 20˚ off the axis of the instrument, on the far side of two interior walls. In Fig. 10 is the same plot, but the source was moved to 35˚ off axis. One should compare the relative signal strengths in the 20˚ and 60˚ fields of view for the two source locations. With the source far off axis, *i.e.*, 35˚, there is little signal in the 20˚ field of view spectrum, whereas when positioned at 20˚, the 20˚ field of view signal is strong. For both cases the 60˚ field of view encompasses the source location and exhibits similar behavior.

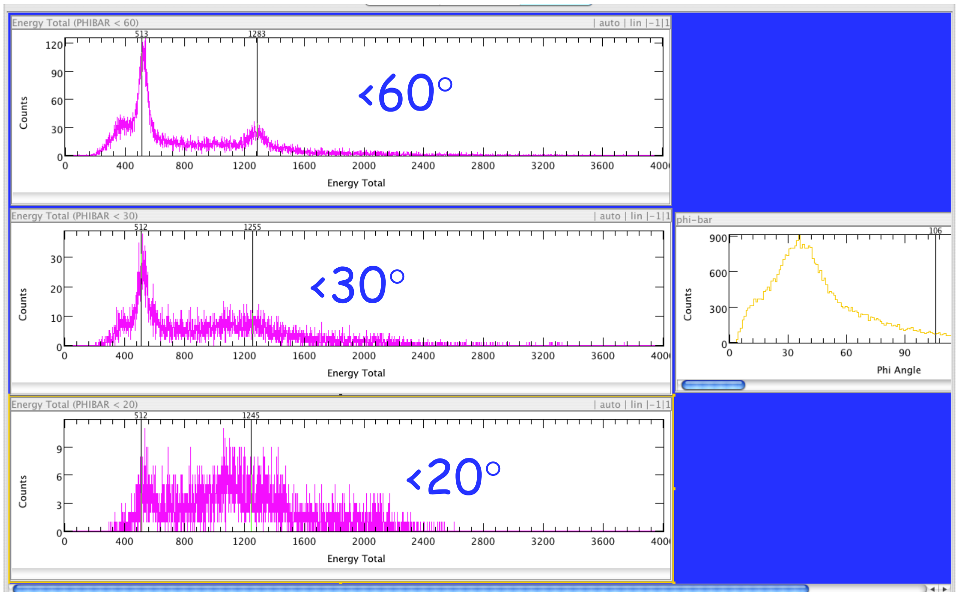

Fig. 9. Operator's display: Spectra within view cones as defined by the Compton scatter kinematics, ^{22}Na source located approximately 35° of axis.

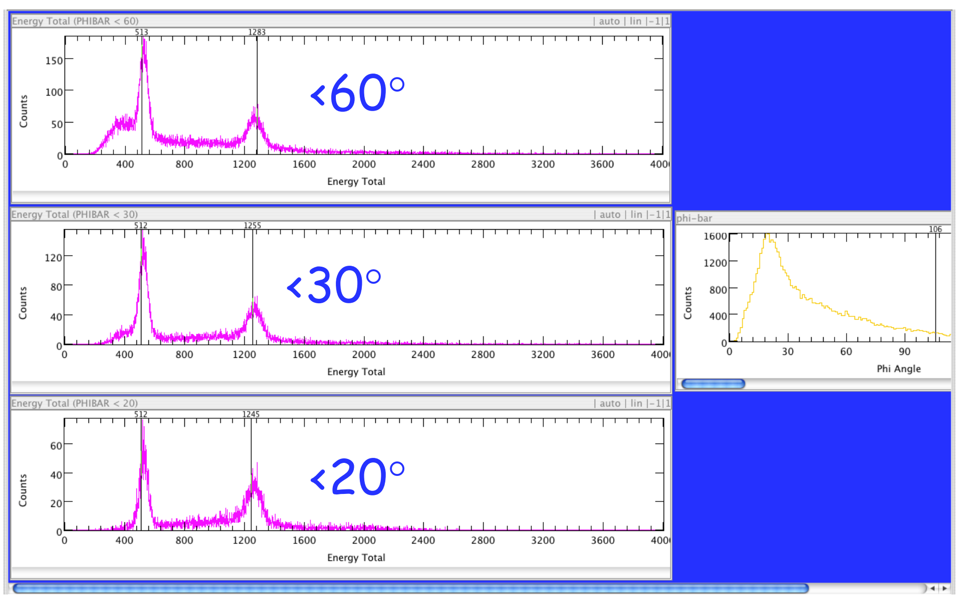

Fig. 10. Operator's display: Spectra within view cones as defined by the Compton scatter kinematics, ^{22}Na source located approximately 20° of axis.

In all cases, the nature of the source is clear. The two ^{22}Na peaks are plainly visible when the source is in that particular field of view.

A scan of the detector response as a ^{137}Cs source was moved from within the field of view, on axis, to outside the field of view is shown in Fig. 11. The source was between 3 and 5 m from the instrument with two intervening interior walls. Presented are the count rates of double-scatter events as compared to single scatter events. The single scatter events are intended to simulate the performance of an omni-directional, perhaps hand held, instrument. The singles rate shows no significant modulation across the field of view, whereas the double-scatter rate in the 662 keV photopeak with a preset field of view of 60˚ degrees shows significant modulation as the source reaches the edge of the field of view. At the location of GRETA, the singles count rate is dominated by background and there is little change in the rate as the source is moved. However, the imaging properties of GRETA reveal the location of the source with respect to the instrument axis. The energy count spectrum of the ^{137}Cs source is shown in Fig. 12. Although undetectable in the singles mode of the instrument, in the double-scatter mode, the source reveals itself.

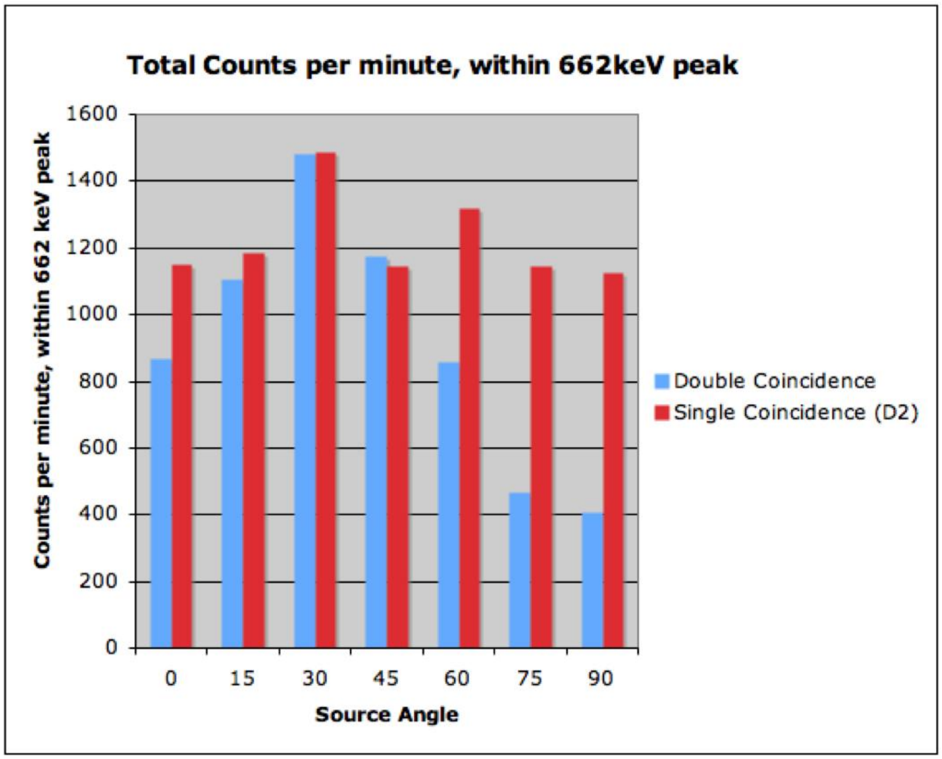

Fig. 11. The instrument count rates in the double-scatter mode and the single mode showing the sensitivity of the instrument to weak sources compared to background.

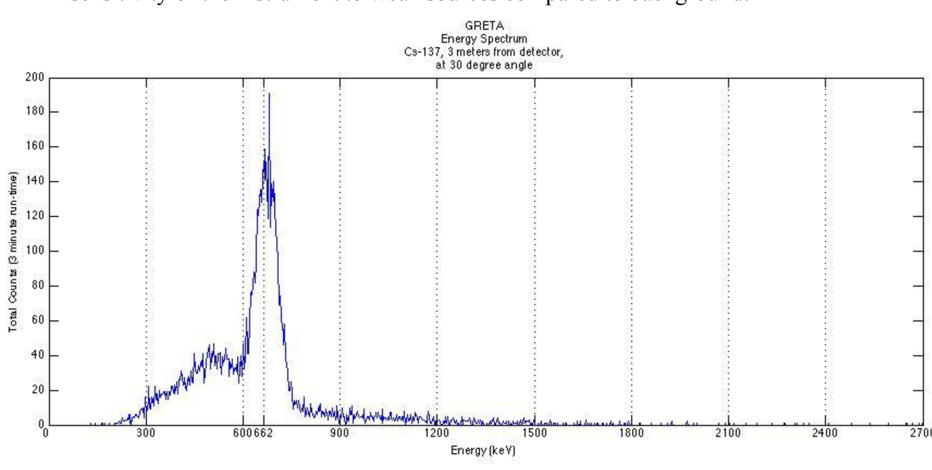

Fig. 12. The energy count spectrum of a 137Cs source through two interior walls obtained with GRETA in the double-scatter mode.

REFERENCES

[1] Schönfelder et al., "Instrument description and performance of the Imaging Gamma-Ray Telescope COMPTEL aboard the Compton Gamma-Ray Observatory," Astrophysical Journal Supplement Series, 86, 657-692 (1993).