Exp Astron (2005) 20:387–394
DOI 10.1007/s10686-006-9051-4

ORIGINAL ARTICLE

Performance of the Nuclear Compton Telescope

Steven Boggs · Mark Bandstra · Jason Bowen · Wayne Coburn · Robert Lin · Cornelia Wunderer · Andreas Zoglauer · Mark Amman · Paul Luke · Pierre Jean · Peter von Ballmoos

Received: 24 February 2006 / Accepted: 18 May 2006

Abstract On 1 June 2005, the prototype Nuclear Compton Telescope (NCT) flew on a high altitude balloon from Fort Sumner, New Mexico. NCT is a balloon-borne soft γ-ray (0.2–10 MeV) telescope for studying astrophysical sources of nuclear line emission and γ-ray polarization. Our program is designed to develop and test technologies and analysis techniques crucial for the *Advanced Compton Telescope*; however, our detector design and configuration is also well matched to the focal plane requirements for focusing Laue lenses. The NCT prototype utilizes two, 3D imaging germanium detectors (GeDs) in a novel, ultra-compact design optimized for nuclear line emission in the 0.5–2 MeV range. Our prototype flight provides a critical test of the novel detector technologies, analysis techniques, and background rejection procedures developed for high resolution Compton telescopes.

Keywords Compton telescopes · Gamma-ray spectroscopy · Gamma-ray astronomy · Balloon payloads

1. Introduction

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 (Boggs et al. 2003, 2004). It employs a novel Compton telescope design, utilizing *twelve* high spectral resolution germanium detectors (GeDs) with the ability to track the location of each photon interaction in three dimensions (Fig. 1). Tracking serves three purposes:

S. E. Boggs (✉) · M. E. Bandstra · J. D. Bowen · W. Coburn · R. P. Lin · C. Wunderer · A. Zoglauer
Space Science Laboratory, University of California, Berkeley, CA 94720 USA

M. S. Amman · P. N. Luke
Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

P. Jean · P. von Ballmoos
Centre d'Etude Spatiale des Rayonnements, UPS-CNRS, Toulouse, France

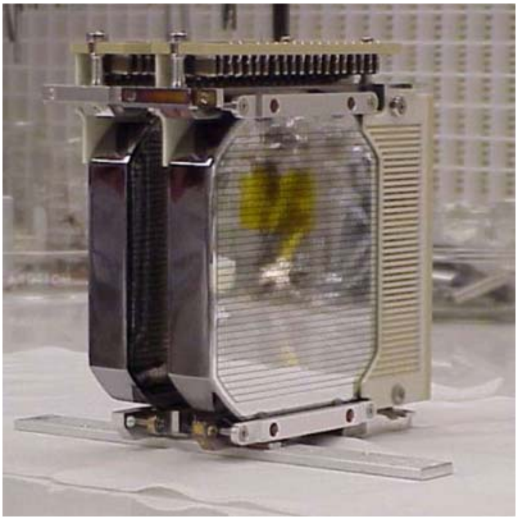

Fig. 1 The NCT two-detector prototype GeD array, consisting of 15-mm thick cross strip detectors of active area 54 cm^2. Each detector has 37 × 37 2-mm pitch strips, resolving the active volume into over 4×10^4 individual elements of volume $< 2\,\text{mm}^3$.

imaging the sky using Compton imaging techniques, measuring polarization, and very effectively reducing background.

The entire set of detectors and their cryostat are enclosed inside an active BGO well (Fig. 2), giving an overall field of view of >25% of the sky. The instrument is mounted in a pointed, autonomous balloon platform and is capable of long duration (>20 day) balloon flights. 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. The guiding principle of NCT is that high efficiency and excellent background reduction are critical for advances in soft γ-ray sensitivity.

NCT will explore a new phase space of nuclear γ-ray observations. Some of the long term goals of NCT include mapping both ^{26}Al and ^{60}Fe in the plane and bulge of our galaxy, measuring the amount of ^{44}Ti contained in recent core collapse supernova remnants, measuring with high resolution the spectra of AGN and searching for γ-ray polarization, looking for polarization in the emission from pulsars and associated plerions, and searching for redshifted deuterium lines from the surfaces of neutron stars.

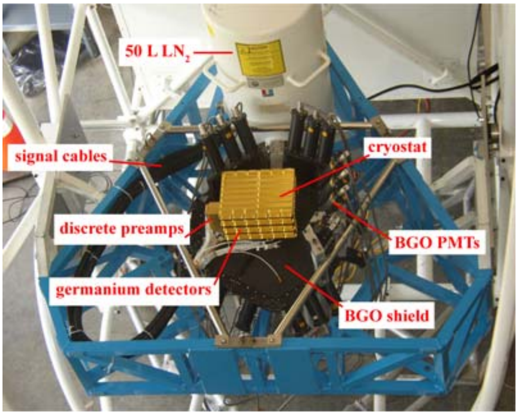

Fig. 2 NCT flight cryostat during integration with the BGO shields into the instrument cradle. The cradle assembly, including shields and dewar, can pivot to allow pointing at an arbitrary positive elevation. The on-axis direction (perpendicular to the face of the detectors) is shown.

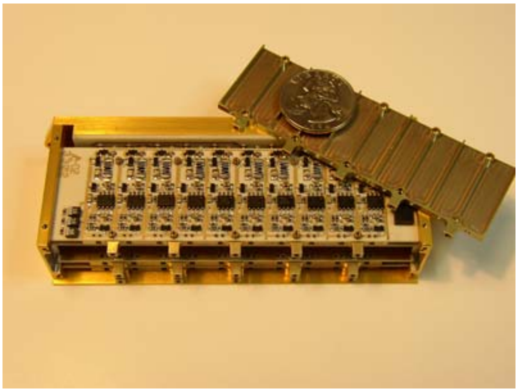

Fig. 3 NCT flight preamps in their shielded housing, with 10 compact preamps per board, four boards per GeD face. (The top cover has been removed and flipped to show how each preamp is electrically shielded for low noise.)

The NCT prototype is a scaled down, two detector version of NCT. The NCT prototype flew on a high altitude balloon from Fort Sumner, New Mexico on 1 June 2005. The duration of the flight was approximately nine hours. The NCT prototype balloon flight had two primary goals, to qualify the gondola for a future, Long Duration Balloon Flight (LDBF) from Alice Springs, Australia, and to measure our instrumental background at balloon altitudes. Our secondary goal was to obtain images and spectra of the Crab Nebula/Pulsar and possibly the transient X-ray pulsar A 0535 + 262. The analysis of the flight data is ongoing, with results in preparation.

2. Instrumentation

At the heart of the NCT prototype are two large volume, 3D positioning cross strip GeDs, fabricated at LBNL using their amorphous Ge contact technology (Luke et al. 1992). Each GeD is a 37 × 37 strip, 15 mm thick, p-type planar detector. Orthogonal strips were deposited on both faces of the GeD, with a strip pitch of 2 mm and a 0.2 mm gap between strips. A 2-mm thick guard ring surrounds this active area on both faces of the detector, with a 1 mm gap between the ring and the edge of the crystal. We instrumented the strips on both the ground (DC coupled, anode) and HV (AC coupled, cathode) sides with custom low power, low noise preamplifiers.

NCT uses custom GeD quality signal processing electronics (Coburn et al. 2004). Each detector strip has a compact, low power signal processing chain made predominantly of conventional surface mount components. Detector signal extraction is accomplished with a unique charge sensitive preamplifier (Fig. 3), in which excellent spectroscopic performance is achieved in a small footprint and at modest cost and low power, without sacrificing signal bandwidth (Fabris et al. 2004). A much-simplified pulse-shaping amplifier, with both a fast and a slow channel, follows each preamplifier. The slow channel, with a 3 μs peaking time, is followed by a peak detect and stretch function. The fast channel uses a small delay line constant fraction discriminator to time stamp each waveform at 50% of its maximum amplitude, generating a low time walk signal. Demonstrated resolutions for these large flight detectors are 2.2 keV FWHM at 122 keV, and 0.4 mm FWHM depth determination for all interactions that deposit ≥40 keV. Spectroscopy signals uniquely match the fast-signal pairs for multiple interactions in the same GeD.

One 16-channel signal-processing cluster resides on a single printed circuit card, with both the fast and slow analog signal processing electronics (Coburn et al. 2004). Five of these "analog boards" are required for each GeD. Each set of five analog boards connects to a common back plane, which supplies bi-directional housekeeping communication, power, and event data channels. Low level input signals connect to the front panel, well away from the back plane, and are shielded for noise. Each analog board has two *ACTEL* Field Programmable Gate Arrays (FPGA). One ACTEL keeps track of the LLD, ULD and fast trigger rates in each strip, while the second coordinates the logic between the slow and fast channels, as well as the shield veto signals. A single Altera *NIOS* embedded processor board interfaces with each set of five analog boards, and communicates with the main flight computer via an ethernet link. The total power per channel is currently 210 mW, although lower power options are currently being developed for the next flight.

2.1. 3D Positioning

There are two main keys to Compton imaging with this system. The first is to accurately determine the energy deposited in the detector for each interaction. The second is successfully tracking, in all three dimensions, the γ-ray interactions within the detector. By segmenting the anode into strips, and the cathode into orthogonal strips, 2-D positioning is achieved directly through identification of the active anode and cathode strips. Interactions are matched on the two faces of the detectors by performing spectroscopy on both anode and cathodes strips. Before matching interactions we must first account for potential charge-sharing events on neighboring strips, or multiple interactions on the same strip. Optimization and performance of these event reconstruction techniques are still in progress.

Measuring the "depth", or "z position", of the interaction in the detector (the distance between the γ-ray interaction and either the anode or cathode strip), is achieved by measuring the difference between electron and hole collection times on opposite faces of the detector. The Collection Time Difference (CTD) for an event is well defined, and has been shown to be linear with depth to first order (Amman & Luke 2000, Amrose et al. 2001). The drift time across a 15-mm thick GeD at our operating bias of -800 V is on the order of 200 ns and 250 ns for electrons and holes, respectively.

To measure the time when the signal on each channel reaches 50% of its maximum amplitude, we use a simple analog constant fraction discriminator built into each channel's electronics chain (Coburn et al. 2004). These "fast channels" give us an 0.4 mm FWHM spatial resolution at 60 keV. This is comparable to what get by digitizing the preamp signals, but with a much smaller, simpler, lower power system.

The calibration of the interaction depth in terms of the CTD poses a unique problem since we cannot send in events of known depth. We can, however, send in events with a known depth distribution. Our technique of converting CTDs to depth, or z position, is discussed in detail in Amrose et al. (2003).

2.2. Spectral performance

The spectral resolutions of each of the anode channels taken with the flight electronics are quite good. On average, the resolutions obtained with the flight electronics are identical to what we get using benchtop electronics. The variation of values obtained with the flight electronics ($\pm$12%) is also similar to the range seen with lab equipment ($\pm$8%). Charge loss for events shared between strips remains minimal, and can be corrected (Coburn et al. 2002). Overall spectroscopy of multiple-site Compton events remains excellent (Fig. 4), though we are still in the process of optimizing the cross calibration of strips.

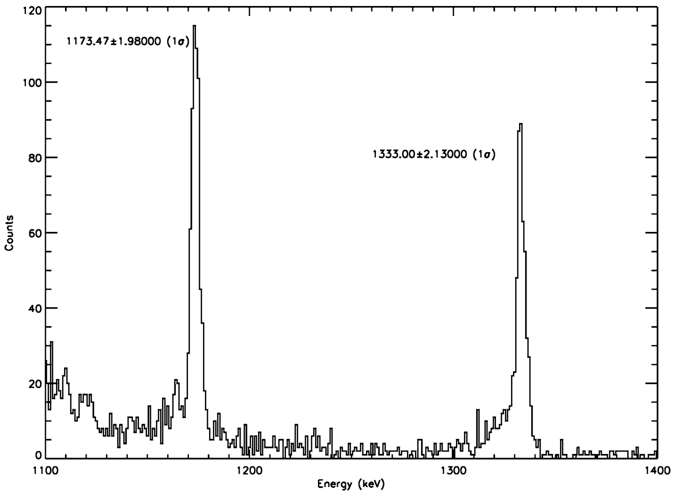

Fig. 4 Preliminary ^{60}Co (1173, 1333 keV) spectrum of all Compton-scatter events for the two-GeD prototype array. Resolutions of ~4 keV FWHM are currently achieved, with ~3 keV expected as cross-calibration between the strips improves. The low-energy tailing on these lines is partially due to our finite thresholds (~ 15 keV), and partially due to charge loss between strips, which is largely correctable. Optimizing these spectra is work in progress.

2.3. Imaging

With well calibrated positioning and spectroscopy, NCT can image wide γ-ray source fields with moderate angular resolution. In Fig. 5 we show the results of a calibration run of the NCT prototype with a ^{60}Co (1.173 MeV) source placed ~60° above the instrument pointing axis. The source is obviously evident in the image and is well localized, demonstrating the wide FoV Compton imaging capabilities of NCT.

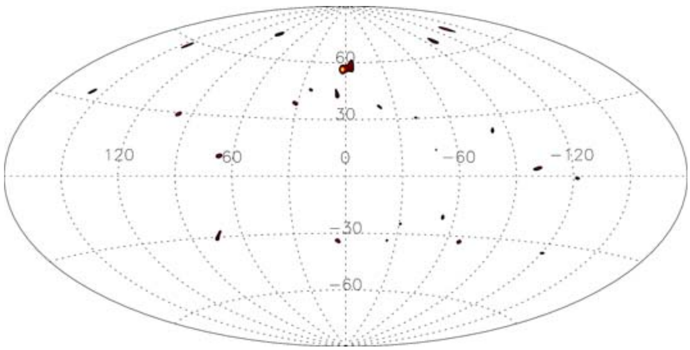

Fig. 5 "All-sky" ^{60}Co (1173-keV) image of a lab point source taken with the NCT balloon payload, processed using a simple event list, maximum entropy technique Wilderman et al. (1998). These are specifically two-site interaction which scatter between the detectors, more detailed analysis is still in progress. The source is ~60° off axis, demonstrating the wide FoV capabilities of NCT.

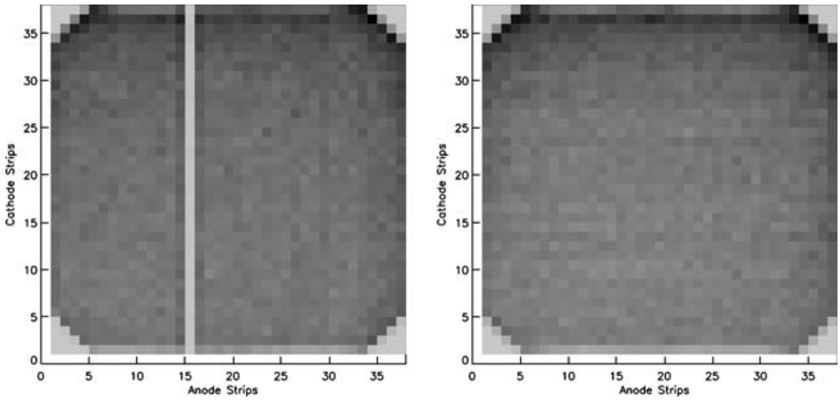

Fig. 6 Flat fields of the the front detector (left) and rear detector (right) from float during the 2005 balloon flight. The data has been binned as pixels, meaning each event uniquely triggered a single crossed pair of strips. With the exception of strip 15 on the front detector, which was not functioning prior to the flight, the flat-field detector response is very uniform. The curved corners of the detectors can also be seen in these images.

2.4. Detector uniformity

Since our Compton imaging and background rejection techniques (Boggs & Jean 2000, 2001) rely on reconstructing multiple photon interactions across different strips and even detectors, the uniformity between strips and detectors of both the spectral and positioning resolutions is very important. The instrument response has to take into account all of the slight variations between strips, and that is part of our ongoing analysis of the calibration and flight data from the last flight, Fig. 6. Since the detectors are formed from a single germanium crystal, uniformity is high (Coburn et al. 2002).

3. Prototype flight

The NCT prototype payload was launched on a 39.5 Mft^3 high altitude balloon from Fort Sumner, New Mexico on 1 June 2005 (Fig. 7). The balloon reached a float altitude of $\sim$133 kft at approximately 20:30 GMT, and was at float for approximately 5.5 h before termination. Details of the gondola systems and the flight profile are presented elsewhere Coburn et al. (2005).

We had two main goals for this flight. First, we wanted to qualify our gondola for a future LDBF. Second, we wanted to measure the instrumental background, telemetry rates, data vault needs, etc., at float. For the 2005 flight the instrument and associated electronics performed flawlessly, and we achieved both of these goals. Detail analysis results are in preparation, currently focused on detailed calibration and detector backgrounds at float.

Our secondary goal was the observation of two science targets, the Crab Nebula/Pulsar and the transient accreting pulsar A 0535 + 262. Both pulsars are spatially close on the sky, separated by $\sim 4^\circ$, and therefore simultaneously fell with within the NCT field of view. The Crab was chosen as a standard calibration source, as well as being an excellent candidate for polarization measurements. The pulsar A 0535 + 262 is transient, and we were fortunate enough that it was in a rare outburst state during our flight. In addition to being able to image

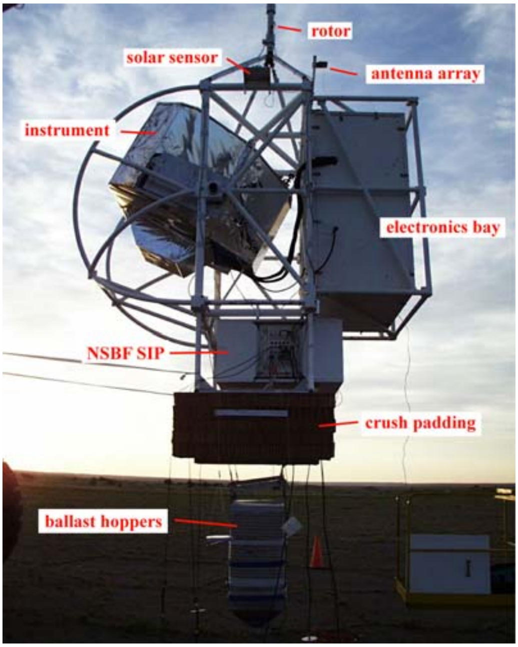

Fig. 7 The NCT gondola on the flight line, showing the relative positions of the instrument, electronics bay, SIP, and ballast hoppers.

two bright point sources, A 0535 + 262 provided the opportunity to search for hard X-ray cyclotron absorption features with unprecedented spectral resolution.

The gondola pointing system was set up to keep the instrument at a fixed elevation, but to actively point in azimuth to keep the Crab centered in the field of view. Unfortunately, shortly after launch the azimuthal pointing system failed, seriously compromising our exposure to our sources and adding an extra level of complexity to the data analysis. The instrument aspect is known at all times, it just was not controllable during the flight. Fortunately, with NCT's wide FoV we hope to recover some of the source data.

Our balloon gondola frame suffered some minor and mostly cosmetic damage during impact, but is otherwise fine. The NSBF parachute termination package worked flawlessly, releasing the parachute from the gondola right after landing. Since the flight, the entire detector and data system has been powered up in the laboratory and is working fine. Neither the detectors, cryostat, nor electronics suffered any damage during the flight, landing, or recovery.

The most important result of the flight, however, was the fact that the instrument and associated electronics functioned flawlessly for the duration. Overall the system logged more than 2.3 million events while at float. The detectors and shields worked well, our detector electronics had no problems handing the incoming data, and all strips and channels performed as expected. So, although there was a failure in the pointing system and the data analysis is still ongoing, we are confident that this flight will be a critical step in demonstrating the viability of the NCT concept for future space missions such as the *Advanced Compton Telescope*.

4. Future work

Our next step is to prepare the instrument and gondola for a long duration balloon flight from Alice Springs, Australia in December 2007. For the next flight, we are currently fabricating four more GeDs for integration into our existing cryostat for two stacks of detectors, three layers deep, bringing our total number of detectors to six. The gondola needs some minor mechanical work, but overall is in excellent shape. We are planning a redesign of our azimuthal pointing system, both to fix the failure and to incorporate differential GPS for positioning.

We are currently redesigning our entire electronics system for the LDBF, as well as in anticipation of future satellite applications. There are three primary goals for redesigning the electronics. First, we are redesigning the preamplifiers for lower operating voltages, dropping their overall power requirements by factors of 5–6, low enough for direct application on satellite missions. Second, we are redesigning our analog readout electronics to be compatible with conversion to an ASIC design for future applications, which primarily requires a redesign of the fast (timing) circuit on each strip. Finally, we are redesigning the signal cabling to very low mass, flexible coaxial ribbon cable, ideal for satellite requirement.

5. Focal plane technologies

The Compton technologies and techniques developed for NCT are directly applicable to focusing Laue lens telescopes. The Compton tracking will allow identification of the first scatter site in the focal plane, with millimeter spatial resolutions consistent with the lens requirements. The Compton scatter information will allow superior background rejection and Compton continuum rejection, similar to those developed for the pure Compton telescope applications (Boggs & Jean 2000, 2001). Our current generation of GeDs provide excellent spectral resolution, high spatial resolution, and good stopping power to match the novel lens capabilities. Technologies we are developing for NCT that are directly applicable to satellite focal plane applications include the GeD design, detector mounting and fabrication, cryogenic design, low power preamplifiers, and low mass cabling. Our redesigned analog electronics will be optimized for straight-forward conversion to ASICs. Finally, NCT background measurements should provide a direct check of focusing telescope backgrounds.

Acknowledgements Thanks to C. Wunderer for presenting this work at Gamma Wave 2005.

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