The Nuclear Compton Telescope (NCT): a status report after 2009 balloon flight

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***Abstract*. The Nuclear Compton Telescope (NCT) is a balloon-borne gamma-ray telescope, which use an array of 3D-positioning germanium detectors (GeDs) to detect gamma-ray in the energy range of 0.2-10 MeV. Each GeD is 15-mm thick, 5400mm^2 of active area, and covered by 37×37 2-mm pitch electrode strips on the opposite faces. Then 2×6 GeDs form an array to increase aperture and chance of multiple Compton scattering. This design provides 3D position resolution <1.6 mm^3, which enable high spectral resolution, moderate angular resolution, and novel sensitivity to gamma-ray polarization. A 2 GeDs prototype was tested in 2005 balloon flight. The second flight using a upgraded detector consists of 2x5 GeDs array is launched at Fort Sumner, New Mexico May, 17, 2009 and stay at float altitude for a record breaking 39 hours. This paper describes the current status for this 2009 balloon flight.**

***Keywords*: Gamma rays, Compton scattering, Germanium detectors**

I. 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 (see, e.g., [1] - [4]). It employs a novel Compton telescope design, utilizing twelve high spectral resolution germanium detectors with the ability to record in three dimensions the location of each individual photon interaction. Figure 1 shows 10 GeD array used May 2009 flight. Tracking individual interactions serves three purposes: 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 3.2 sr. 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.

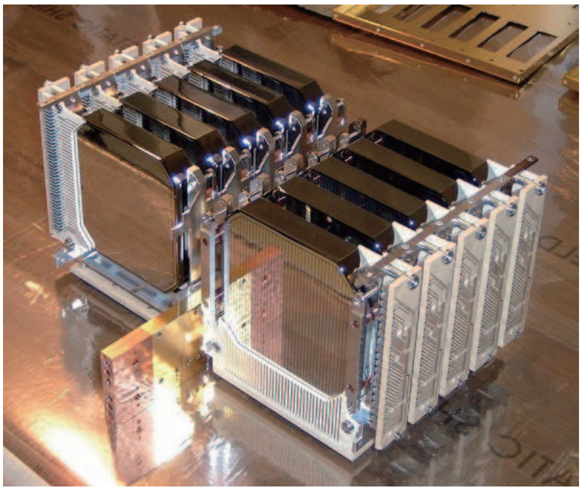

Fig. 1. The 10 GeDs flown on the NCT May 2009 flight. Notice the vertical metal electrode strips on the front face of the first GeD. These vertical strips and their horizontal counterparts on the back face allow 2D positioning of γ-ray interactions inside the GeD. Depth is obtained from the collection time difference between the two faces. Six of the 12 GeDs for the LDBF will be identical, but the other 6 will differ slightly by having a layer of amorphous Si on the cathode side (see text).

The prototype NCT flew from the National Scientific Balloon Facility (NSBF, now Columbia Scientific Balloon Facility, **CSBF**) site in Fort Sumner, New Mexico on June 1, 2005. The flight lasted 6 hours at float altitude approximately 40 km. Due to the relatively short flight and a malfunctioning of the pointing system, limited scientific data was obtained. However, with the prototype flight we were able both to demonstrate the successful integration of the flight systems and instrument and to qualify NCT for a future long duration balloon flight (LDBF). Calibrations performed on the prototype instrument include energy calibrations [5], where we showed that the NCT prototype achieved 3 keV FWHM at 662 keV, or 0.45% energy resolution, for single-site events. More details of the prototype flight can be found in [3], [6].

In 2006, a team from Taiwan joint NCT collaboration. NCT-Taiwan team consists of three university (NTHU, NCU, and NUU) and National Space Program Organization (NSPO) under a three year grants from NSPO. The main purpose is prepare for a long duration balloon flight (LDBF) with a full detector (12 GeD) system. We originally were planning for an Alice Springs, Australia flight in Spring 2009; however, due to the delay of the Alice Springs campaign until Spring 2010, we decided to first attempt a conventional flight in Spring 2009 from Fort Sumner, New Mexico. This flight focus on observing northern hemisphere γ-ray point sources like the Crab pulsar and Cygnus X-1. We had $\sim$ 38 hours at float altitude to carry out various tests and observatons. Currently, we are planning a third flight, which will be an LDBF from Alice Springs, Australia in spring of 2010 The goal of the LDBF flight is for the longest multi-day flight at Southern latitudes possible at approximately 40 km altitude. The flight will focus on observing and mapping diffuse galactic nuclear line emission.

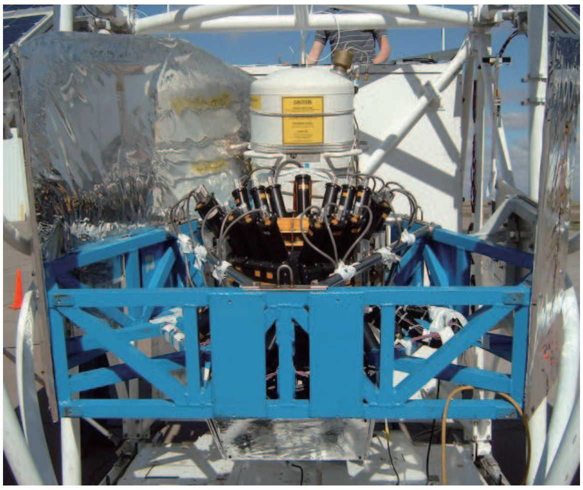

Fig. 2. The cryostat as it was situated in the balloon gondola. The view is from above and in front of the detectors. Note the white LN2 dewar behind the cryostat and the active BGO shielding surrounding the sides and bottom of the cryostat. For the LDBF, the size of the signal cables (visible here) will be greatly reduced. An active collimator will also be added around the cryostat, constraining the field of view further.

II. Detectors and Instrumentation

The NCT detectors are custom 15 mm-thick cross-strip GeDs of active area 5400 mm^2 each. orthogonal 37×37 2 mm pitch electrode strips on the opposite faces, combined with signal timing, provide full 3D position resolution to 1.6 mm^3 The two GeDs used in the prototype flight are shown in Fig. 1.

The NCT 3D-GeDs operate as fully depleted p-i-n junctions, using amorphous Ge contact technologies pioneered by LBNL [7]. The 10 NCT GeDs are housed in a single cryostat that successfully flew on the prototype flight (see Fig. 2). The cryostat is attached to a single 50-liter liquid nitrogen dewar which cools the GeDs to 85 K for approximately 7 days. The dewar is vented through a 5 psi valve keeping the liquid nitrogen under pressure at float. Each GeD is mounted in its own carrier bracket that mounts on a central copper coldplate. The entire assembly is enclosed in a thin IR radiation shield.

NCT uses conventional GeD-quality signal processing electronics [8]. Each detector strip has a compact, low power signal processing chain. Detector signal extraction is accomplished with a unique charge-sensitive preamplifier, then followed by a much-simplified pulse-shaping amplifier, with both a fast and a slow channel. The slow channel, with a 6 μs time-to-peak unipolar shaper, is followed by a peak detect and stretch function. The fast channel uses a bipolar shaper to time stamp each waveform at the signal zero-crossing.

One 10-channel signal processing cluster resides on a single printed circuit card, with both the fast and slow analog signal processing electronics. Eight of these “analog boards” are required for each GeD. Each set of eight 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 therefore shielded for noise. Each analog board has one ACTEL Field-Programmable Gate Array (FPGA). This ACTEL keeps track of trigger rates, and coordinates logic between the different channels. A single Altera NIOS embedded processor board interfaces with each set of eight analog boards to coordinate the logic between the eight ACTELs, compresses event data from the ACTELs, and communicates with the main flight computer via an ethernet link.

The GeD cryostat is surrounded by a 5-cm thick bismuth germanate (BGO) scintillator arranged in a hexagonal well surrounding the sides and bottom of the cryostat, read out by 32 individual PMTs. With a threshold of 80 keV, the BGO shields significantly reduce the instrumental background even before the Compton imaging and the spectral signature techniques are applied. During the prototype flight, typical shield rates were 12,000 cts/s, dominating the instrument dead-time of 8%.

III. Improvements over last flight in 2005

Since the prototype flight in 2005, the NCT team has upgraded the full system in many parts to suit the needs of LDBFs[9]. The primary goals are lower power, lower noise, and more compact size . These improvements are listed below.

1) Preamps: We have redesigned the preamplifiers for lower operating voltages, dropping their overall power requirements from 138 mW/channel to 26 mW/channel and reduce their noise by 40% [10].
2) Readout Electronics: We have redesigned our analog readout electronics for lower power and more compact design [10].

3) Cabling: We have converted the signal cabling to flexible coaxial ribbon cable.
4) BGO shields Recalibration: The new calibration is temperature dependent, so we have a more accurate determination of the threshold as a function of temperature.
5) Solar power system: In 2005 flight, a lead-acid battery array were used. For LDBF, we add an independent solar power system, which contains 2x3 solar panels, two 150 AH Lithium ion battery arrays, and a power control unit. This system builds in double redundancy in all major components, which include solar panels, charger, and battery. The chargers responsible for maximum power point tracking of solar panels and manage charging/discharging of battery. Two chargers, switching circuit board, and monitoring circuit board are all inside a Power Control Unit (PCU) box. To prevent RF interference, PCU uses RF feed-throughs to connect to solar panels, battery arrays, and system load [11].
6) New Flight Computer: Upgrading to a 1.4 GHz processor, converting the flight software to Linux.
7) Adding a differential GPS for altitude determination.

IV. CALIBRATIONS

All of the redesigned electronics boards were tested at SSL. We performed end-to-end tests of the boards using a double-sided cross-strip GeD similar to the flight detectors. The output from the GeD's preamps (not the redesigned flight preamps) was connected to the electronics boards using test cabling. The output from the boards was sent over ethernet to a PC running our Linux-based Ground Support Equipment (GSE) software. The GSE allowed realtime diagnostics of the board performance, including the accumulation of strip data (spectra, timing) and the monitoring of housekeeping data. Further examination of the data was done offline.

We obtained energy spectra for ^{241}Am and ^{57}Co lab sources using the redesigned boards to test the slow (energy) channel performance. Energy was calibrated for each strip using a simple quadratic calibration curve fitted to the three source lines at 59.5 keV (^{241}Am), 122 keV, and 136 keV (both ^{57}Co). We used only single-site events, meaning that in each event there was exactly one strip active on each side of the detector. The resulting spectrum is shown in Fig. 3.

We also checked the redesigned fast (timing) channels by examining the Collection Time Difference of γ-ray events. The Collection Time Difference (CTD) is the difference between the electron collection time and the hole collection time, which serves as a proxy for the depth of the interaction, [12], [13], [14], [15]. One of NCT's fast channels measures collection times by using the zero-crossing of the bipolar shaper, with a time resolution of 10 ns. We accumulated CTD histograms for each of the 100 pixels, or strip crossings (we tested 10 channels on each side of the detector, hence 10×10 = 100 crossings). Both the 59.5 keV and 122 keV CTD histograms turned out as expected, see Fig. 3.

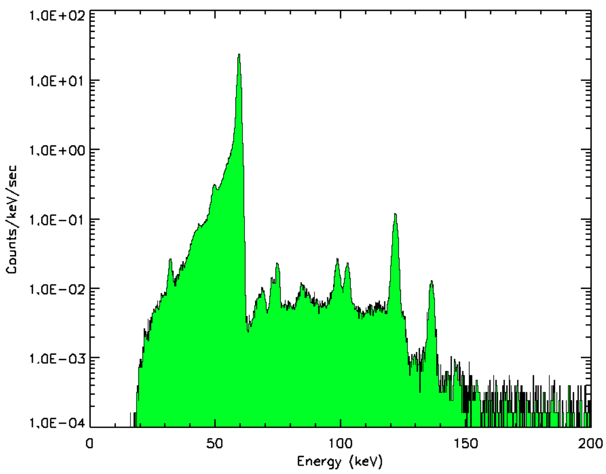

Fig. 3. Energy spectrum obtained during the end-to-end test of the electronics boards. Data shown are for single-site events (i.e., the event contains only two strips – one from each side of the detector. Clearly seen are the ^{241}Am 59.5 keV line and the ^{57}Co lines at 122 keV and 136 keV. Other weaker lines are mostly from ^{241}Am.

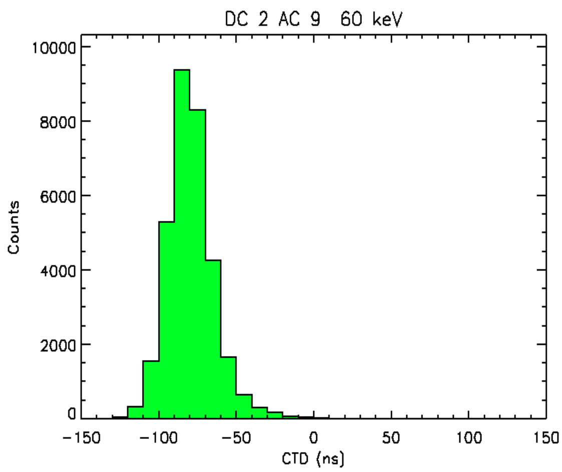

Fig. 4. More data from the test setup: CTD histogram of a single pixel (AC 9, DC 2), showing events that are energy-selected to be photoabsorptions of 59.5 keV photons. Since the CTD is a proxy for depth in the detector, we see the expected result that the 59.5 keV photons do not penetrate far into the detector (the incident detector surface is at approximately -100 ns, the far side is at approximately +100 ns).

V. ANALYSIS PROGRESS

The primary software tool used for NCT is MEGAlib [16], a comprehensive software package designed for Compton telescopes. MEGAlib has been updated to perform Bayesian Compton event reconstruction [17], which significantly outperforms conventional methods. Recent investigation [18] has shown neural network Compton event reconstruction to be promising as well, and it requires many fewer simulated events to achieve similar performance.

Finally, the data from the prototype flight is being analyzed to determine the γ-ray background as a function of atmospheric column depth [20]. So far, the measurements agree well with detailed simulations of the different background components.

For the 2009 flight, we had simulated field of view of NCT detectors and calibrated with radioactive source at various points and distances [19].

VI. Flight Program and Preliminary Results

Since NCT is sensitive to γ-rays in the range 0.2-10 MeV, which covers the crucial 0.5-2 MeV range where most nuclear lines are located, the project's main goals are observing nuclear lines from various astrophysical phenomena. For May 2009 flight, we will focus on observing northern hemisphere point sources such as the Crab (a pulsar), Cygnus X-1 (a black hole candidate), and Cassiopeia A (a supernova remnant). Figure 5 is a plot of the elevation angles of different γ-ray sources during a 24 hour period at Fort Sumner, New Mexico

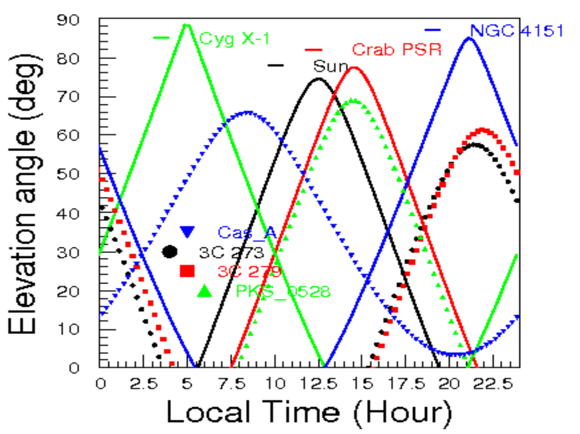

Fig. 5. Plot of elevation angles of different sources for one 24-hour period from Fort Sumner, New Mexico in May 2009. Primary targets are Crab during day time and Cyg X-1 during night time, with transition period looking at 3C273 & 3C279, and Cas_A

VII. Summary

Our preliminary conclusions about the flight are that the science instrument worked perfectly during the entire flight, producing 22 hours of science data. Most of the new flight systems also worked flawlessly during the flight. We experienced two intermittent technical challenges during the flight, an instability in the automated pointing system, and incomplete battery charging with the solar power/battery system. These systems will be investigated and repaired as soon as the system returns to Berkeley. The gondola had a relatively benign cutdown, landing upright in the Arizona desert. Recovery of the payload is currently in progress, but we anticipate only minor repairs. Thus, NCT is in excellent position to make the Spring 2009 campaign from Alice Springs, Australia.

VIII. Acknowledgment

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