Preliminary results from the Spring 2010 balloon campaign of the Nuclear Compton Telescope

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ABSTRACT

The Nuclear Compton Telescope (NCT) is a balloon-borne telescope designed to study astrophysical sources of gamma-ray emission with high spectral resolution, moderate angular resolution, and novel sensitivity to gamma-ray polarization. The heart of NCT is a compact array of cross-strip germanium detectors allowing for wide-field imaging with excellent efficiency from 0.2-10 MeV. Before 2010, NCT had flown successfully on two conventional balloon flights in Fort Sumner, New Mexico. The third flight was attempted in Spring 2010 from Alice Springs, Australia, but there was a launch accident that caused major payload damage and prohibited a balloon flight. The same system configuration enables us to extend our current results to wider phase space with pre-flight calibrations in 2010 campaign. Here we summarize the design, the performance of instrument, the pre-flight calibrations, and preliminary results we have obtained so far.

Keywords: Gamma-ray astronomy detectors, gamma-ray imaging, Compton imaging, germanium radiation detectors

1. INTRODUCTION

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 gamma-ray polarization[1-3]. The heart of NCT is an array of 12 cross-strip germanium detectors (GeDs) (Fig. 1 left), providing high spectral resolution (~0.3-0.9% FWHM at 662 keV for most channels) and capability of tracking each photon interaction with full 3D position resolution to 2 mm[3]. The determined energy and position of interactions in NCT allow Compton imaging, which effectively reduces background and provides polarimetric sensitivity[4], at moderate angular resolution (~5° FWHM ARM) through event reconstruction[5]. The entire set of detectors and their cryostat are enclosed inside a well of anticoincidence BGO shield (Fig. 2), giving an overall field of view of ~3.2 sr. The instrument is mounted in a pointed, autonomous balloon platform (gondola).

Before 2010, NCT had flown successfully on two conventional balloon flights in Fort Sumner, New Mexico. The first was a 6-hour prototype flight with two-GeDs at float altitude (~40 km) on June 1, 2005. It succeeded in measuring the soft gamma-ray atmospheric background and the galactic anti-center region[6-8].

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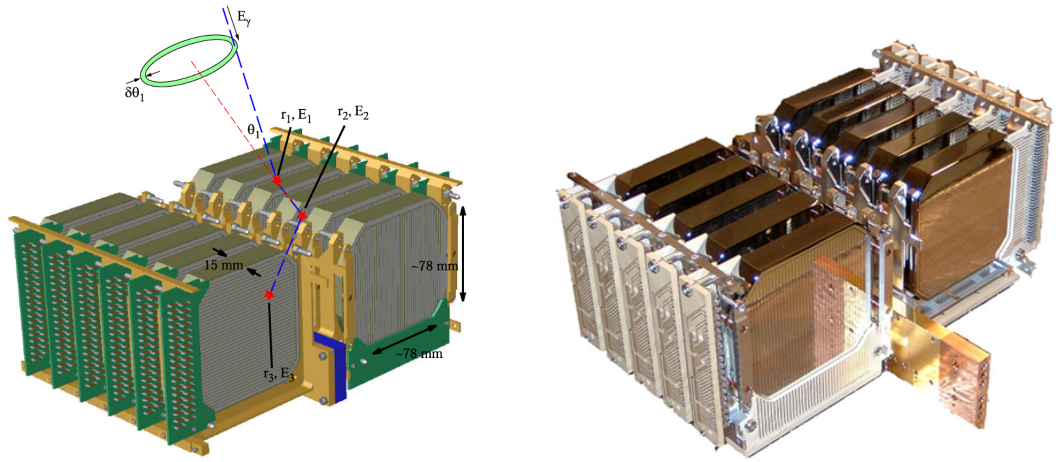


Figure 1. Left: The NCT utilizes 12 cross-strip GeDs with 3D position resolution, excellent spectroscopy, sensitivity to γ-ray polarization, and high efficiency. Right: The 10 germanium cross-strip detectors of NCT that were adopted in the 2009 and 2010 balloon campaigns.

The second flight[9] with 10-GeDs (Fig. 1 right) was launched on May 17, 2009. The total duration was ~38.5 hours with nine of the ten detectors operational for a total of 22 hours at about 35 km to 40 km altitude. The primary science goal was to observe the Crab Nebula and Pulsar. The science instrument performed well during the flight, except for anomalies from the azimuthal pointing system on the first day and from power system on the second. Minor damage of the instrument upon landing made a subsequent flight possible in a short time.

The third flight with the same ten-detector instrument was attempted in Spring 2010 from Alice Springs, Australia as NCT's first southern-hemisphere flight to conduct observations of the Galactic Center Region. However, there was a launch accident that caused major payload damage and prohibited a balloon flight[10].

Data analysis for the flight as well as ground calibrations[11-12] from the 2009 campaign is ongoing against improving data-processing pipeline. The same system configuration enables us to extend our current results to wider phase space with pre-flight calibrations in 2010 campaign.

In this article, we will summarize the design, the performance of instrument, the pre-flight calibrations, and preliminary results we have obtained so far.

2. DETECTORS AND INSTRUMENTATION

NCT employs ten high-purity germanium cross-strip detectors (Fig. 1 right) that measure both the position and energy of gamma-ray interactions in 2009 and 2010 balloon campaigns. The crystals were fabricated by ORTEC and processed at Lawrence Berkeley National Laboratory (LBNL) using amorphous germanium contact technology[13, 14] for the ten GeDs, of which three were coated with amorphous silicon on the cathode side to increase the stability of detectors through temperature cycles[15]. Each GeD is a 37 × 37 cross-strip planar detector, measuring 8 × 8 × 1.5 cm. A gap of 0.25 mm between the strips for the 2.0 mm pitch has been demonstrated by LBNL to minimize the number of charge sharing events and the resulting charge loss, while maintaining the high GeD spectral resolution. There is a 2-mm thick guard ring surrounding this active area on both faces of the detector, with a 1-mm gap between the ring and the edge of the crystal, to provide anticoincidence signals for rejection of events with interactions in these regions.

The 2D position of each interaction is determined by the orthogonally-oriented strips on each GeD, while the difference in charge collection time between two faces infers the third-dimension (depth) information inside the detector.[14, 16, 17] The full 3D position resolution is approximately 2 mm^3.

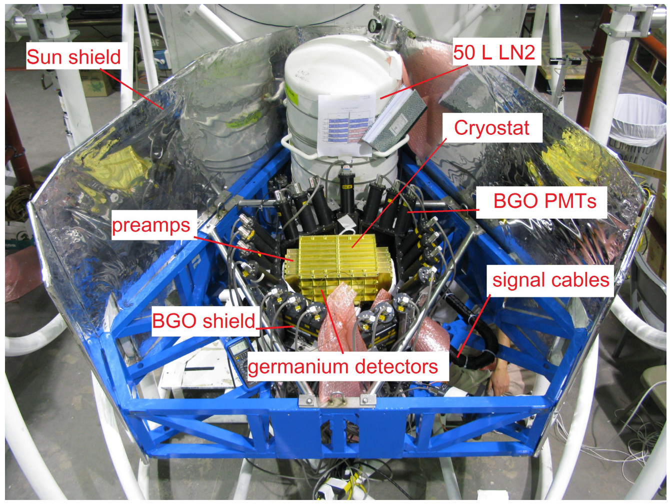


Figure 2. The configuration of NCT instrument in the cradle. The cradle is mounted in a pointed, autonomous balloon platform (gondola).

The NCT detector array is housed in a cryostat, which is attached to a 50-liter liquid nitrogen dewar (Fig. 2) to cool the GeDs to ~ 85 K for about 7 days. Each GeD is mounted in its own carrier bracket that mounts on a central copper coldfinger. The entire assembly is enclosed in a thin IR radiation shield.

NCT uses conventional GeD-quality signal processing electronics.[18] There are two low-power charge-sensitive preamplifier modules[19] attached to each GeD. Signals from a detector are transmitted from the preamps by compact coaxial ribbon cables to a "card cage" enclosure which contains all the data-acquisition electronics needed to instrument that GeD.

Each card cage includes eight analog boards of ten channels each. The channels have a pulse-shaping amplifier with fast and slow channels to digitize timing and energy signals from the strips. Each analog board has one ACTEL Field-Programmable Gate Array (FPGA) to keep track of trigger rates and to coordinate logic between different channels. A single "DSP board" with an Altera NIOS embedded processor then coordinates the logic among eight ACTELs, compresses event data from the ACTELs, and communicates with the main flight computer via an Ethernet link.[20]

3. GONDOLA SYSTEMS

The NCT balloon gondola, which was originally used by the HIREGS LDBF payload, contains systems to provide power, telemetry, aspect measurement, and autonomous pointing for the telescope. Figure 3 shows the gondola used in the 2010 flight with major components labeled. The cryostat, LN2 dewar, and BGO shields rest in a movable cradle (Fig. 2) protected by roll bars in the front of the gondola. The signal cables are harnessed together and pass into an enclosed and thermally insulated electronics bay (Fig. 4) at the back of the gondola. Inside this electronics bay are the card cages, flight computer, batteries, and other devices. Attached on the bottom of the gondola is the CSBF SIP, which is responsible for ground commanding and telemetry. More details can be found in [21] besides the summaries below.

The onboard flight computer controls the operations of all the gondola systems, stores and telemeters science and housekeeping data, interfaces with the CSBF command uplink, and executes the automated pointing plan. Data was archived in flight to two redundant flash solid-state drives with capacities of 64 GB. The flight computer also interfaced with the CSBF Support Instrument Package (SIP) system, which provided telemetry and remote commanding during the flight.

Because of NCT's large field of view, its pointing requirements are relatively modest at about 2º pointing accuracy. A rotor assembly allows pointing in azimuth, and a three-axis magnetometer is used to orient the gondola relative to the local magnetic field.

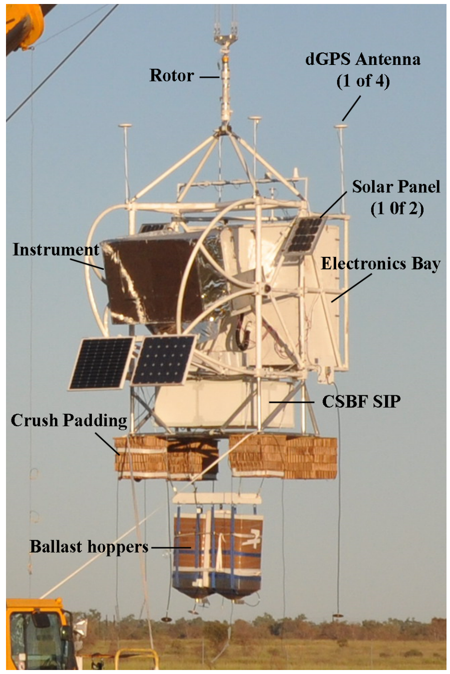


Figure 3. The NCT gondola with major components labeled.

Since the prototype flight, we have added a Magellan ADU5 differential GPS. This dGPS system provided an accurate full aspect solution in real time during the flight. The dGPS aspect solution was stored in housekeeping and telemetered. Additionally, the flight computer used the dGPS aspect to correct for any slowly-varying biases in the magnetometer-based pointing. An aspect magnetometer and accelerometer were also retained for redundancy. The instrument's ~5-10º angular resolution[15] means that aspect reconstruction is needed to only 0.5º or better.

4. ANALYSIS TOOLS

The software analysis tools for NCT are built using the Medium Energy Gamma-ray Astronomy library (MEGAlib) [22, 23]. MEGAlib provides utilities for simulations, geometry modeling, event reconstruction, and imaging reconstruction, in addition to tools for building a custom analysis pipeline considering.

Using MEGAlib, images can be obtained based on certain event selections to allow us to compare the result with our setup. Besides, a "detector effects engine" has also been developed to convert the precise energy and position information output by the GEANT4[24] simulations to the strip hits and energy channel data that NCT's detectors return. The engine includes charge sharing, charge loss, as well as current depth and energy calibrations. Thus, the Compton event reconstruction methods are applied identically to equivalent data from both simulation and calibration.

5. 2010 BALLOON CAMPAIGN

Minor damages upon landing from last flight made it easy to repair our instrument soon and supplied us an advantage to extend our efforts against similar performance of mostly the same instrument. Only minor modifications were carried out within the short preparation window between 2009 and 2010 campaigns.

A faulty strain gauge, which was attached to the main torque shaft, resulted in poor feedback behavior and necessitated manual pointing during the first day of the 2009 flight. This rotor malfunction was repaired after installing a new gauge, so the gondola pointing was then reliably accurate and steady. The expected 1-4 day conventional flight[22] in

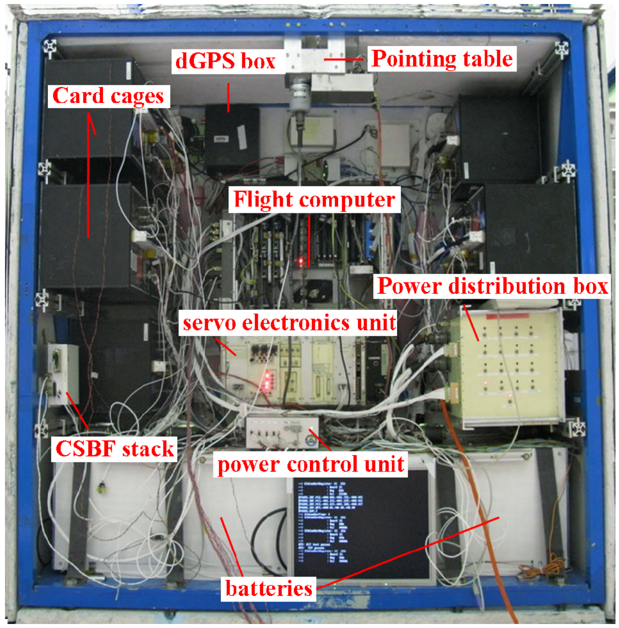


Figure 4. The gondola electronics bay in NCT 2010 balloon campaign. Visible are the 9 card cages (black anodized aluminum boxes mounted on the sides of the bay), each of which contains the readout electronics for one detector (80 channels). Also visible is the gondola control unit (GCU; the brown box in the middle of the bay consisting of the flight computer and pointing system) and disposable battery boxes are the large white boxes on the floor of the bay, and the test power control unit is the smaller white box sitting atop them. The flatscreen monitor and keyboard were removed before flight.

Australia allowed us to power the instrument entirely on disposable batteries and to test small new solar-panel modules instead of two large ones we flew in 2009 flight.

Most of the NCT instrument as well as support equipments were shipped from the US in January 2010, while the cryostat, which required persistent cooling via dewar, was shipped by air to Sydney in late February and then transported by truck to Alice Springs.

The primary science target for the 2010 Alice Springs campaign was the Galactic Center Region. Goals included detection of the 511 keV positron annihilation line and the 1.809 MeV ^{26}Al emission. Secondary science targets included the Vela region, the Crab Nebula and pulsar, the blazar 3C 454.3 with extraordinary outburst then, and the AGN PKS 0208-512.

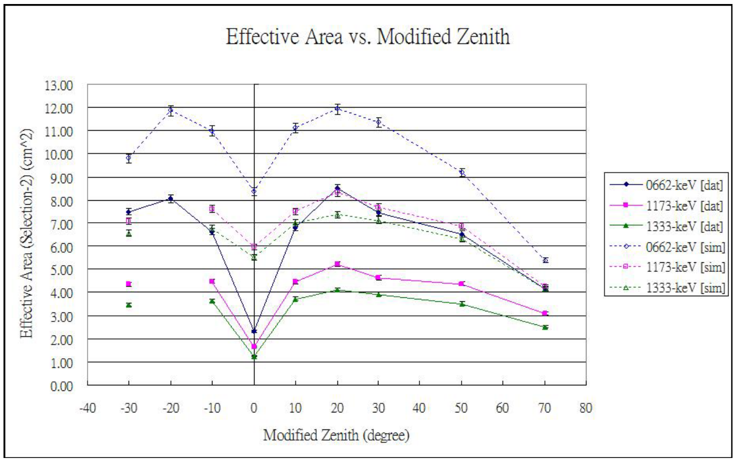
All NCT equipments arrived in Alice Springs in the beginning of March, and it took us about a month to integrate the instrument, to test the performance, and to carry out pre-flight calibrations. Poor weather delayed the launch opportunities for about two weeks. On April 29, NCT had its fourth launch attempt. However, a launch accident occurred causing major payload damage and prohibiting a balloon flight[10].

6. CURRENT RESULTS

Analysis for both flight and calibration data from the 2009 campaign is ongoing, as the analysis tools being improved with more realistic considerations. Current results in NCT are summarized below:

Detection of Crab Nebula is being confirmed quantitatively, while the measured spectra are being checked with simulation results.

We have performed energy calibrations, which achieved the average energy resolution for the different detectors ranging from 1.8-3.0 keV FWHM at 60 keV to 2.7-6.3 keV FWHM at 1333 keV, and the full-reconstructed spectral



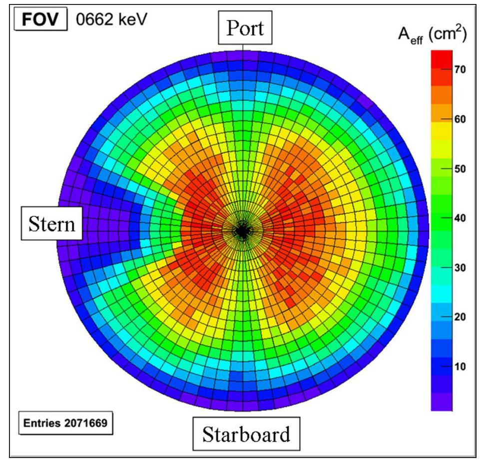


Figure 5. Left: Measured (solid) and simulated (dotted) NCT on-axis effective area at 662 keV (blue), 1173 keV (magenta), and 1333 keV (green). Errors are 90% C.L. Right: The simulated FOV of NCT in detector coordinate. On the left is the stern of cradle where Dewar is.

resolution at 662 keV was about 5.9 keV after cross-talk correction. A simulation-intensive technique has been developed for calibrating the depth of interactions in our planar germanium cross-strip detectors adequately.

On-axis effective area calibrations have been carried out and analyzed. The measured profile but a steeper dip from Zenith is consistent with simulated one (Fig. 5 left). Improvement for detector effects and event selections is ongoing to obtain consistent simulation results with data and then to yield efficiencies throughout NCT's FOV (Fig. 5 right).

Imaging capabilities enables us to localize a ^{137}Cs source within 1° precision and to distinguish ^{137}Cs sources ~6° away, even though the angular resolution is ~9°.

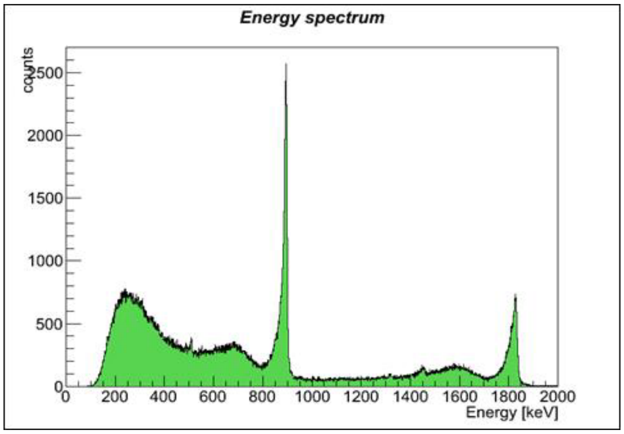
Although there was no flight in 2010 campaign, the pre-flight calibrations were still good sources to verify the instrument performance. Comparison with data from 2009 campaign is also expectable, since almost all the system configuration is the same. Furthermore, new data taken with other radioactive sources, such as ^{88}Y (0.898 and 1.836 MeV) and ^{133}Ba (81, 303, and 356 keV) (Fig. 6), will help us to extend our current results to wider phase space, once the data analysis of 2009 campaign is finalized to show good consistence between data and simulation results.

7. FUTURE PROSPECTS

The NCT instrument is on the way being shipped back to the US. Subsequent tests will be carried out to determine the state of the GeDs, the BGO shields, and the readout electronics. Hopefully, next flight opportunity will be possible in just about 2-3 years.

NCT's capabilities can be improved by some upgrades: (1) Thinner strip pitch would allow finer spatial localization of events to provide better angular resolution; (2) Converting the readout electronics to an ASIC would be necessary with the finer strip pitch and would pave the way for an eventual satellite instrument; (3) Cryocooler instead of an LN2 dewar would allow for arbitrarily long flights, including 100-day ultra-long duration balloon flights on forthcoming super-pressure balloons.

Although a launch accident prohibited the NCT 2010 balloon campaign, the efforts people have made so far will continue to present more scientific potential during next flight.



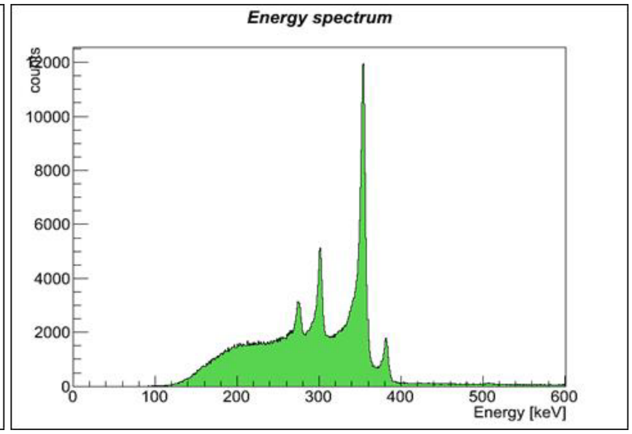


Figure 6. Spectra of two effective-area calibrations obtained from 2010 campaign. Left: ^{88}Y (0.898 and 1.836 MeV); Right: ^{133}Ba (81, 303, and 356 keV) at zenith 20° on-axis.

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