DATA ACQUISITION SYSTEM OF THE PoGOLite BALLOON EXPERIMENT

Session: Missions and Applications

Long Paper

H. Takahashi, M. Matsuoka, Y. Umeki, H. Yoshida, T. Tanaka, T. Mizuno, Y. Fukazawa

Hiroshima University, Higashi-Hiroshima 739–8526, Japan

T. Kamae, G. Madejski, H. Tajima

SLAC and KIPAC, Menlo Park, California 94025, USA

M. Kiss, W. Klamra, S. Larsson, C. Marini Bettolo, M. Pearce, F. Ryde, S. Rydström

Royal Institute of Technology, SE–106 91 Stockholm, Sweden

K. Kurita, Y. Kanai, M. Arimoto, M. Ueno, J. Kataoka, N. Kawai

Tokyo Institute of Technology, Meguro-ku, Tokyo 152–8550, Japan

M. Axelsson, L. Hjalmarsdotter

Stockholm University, SE–106 91 Stockholm, Sweden

G. Bogaert

Ecole Polytechnique, 91128 Palaiseau Cedex, France

S. Gunji

Yamagata University, Yamagata 990–8560, Japan

T. Takahashi

JAXA/ISAS, Sagamihara 229–8510, Japan

G. Varner

University of Hawaii, Honolulu, Hawaii 96822, USA

T. Yuasa

University of Tokyo, Bunkyo-ku, Tokyo 113–0033, Japan

E-mail: hirotaka@hep01.hepl.hiroshima-u.ac.jp, matsuoka@hep01.hepl.hiroshima-u.ac.jp, umeki@hep01.hepl.hiroshima-u.ac.jp, hyoshida@hep01.hepl.hiroshima-u.ac.jp, tanaka@hep01.hepl.hiroshima-u.ac.jp, mizuno@hep01.hepl.hiroshima-u.ac.jp, fukazawa@hep01.hepl.hiroshima-u.ac.jp, kamae@slac.stanford.edu, madejski@slac.stanford.edu, htajima@slac.stanford.edu, mozsi@kth.se, klamra@particle.kth.se, stefan@astro.su.se, cecilia@particle.kth.se, pearce@particle.kth.se, Stefan@particle.kth.se, kurita.k.aa@m.titech.ac.jp, kanai@hp.phys.titech.ac.jp, arimoto@hp.phys.titech.ac.jp, masaru@hp.phys.titech.ac.jp, kataoka@hp.phys.titech.ac.jp, nkawai@hp.phys.titech.ac.jp, magnusa@astro.su.se, nea@astro.su.se, felix@astro.su.se, bogaert@poly.in2p3.fr, gunji@sci.kj.yamagata-u.ac.jp, takahasi@astro.isas.jaxa.jp, varner@phys.hawaii.edu, yuasa@amalthea.phys.s.u-tokyo.ac.jp

ABSTRACT

The Polarized Gamma-ray Observer, PoGOLite, is a balloon experiment with the capability of detecting 10% polarization from a 200 mCrab celestial object in the energy-range 25–80 keV. During a beam test at KEK-PF in February 2008, 20 detector units were assembled, and a 50 keV X-ray beam with a polarization degree of ~90% was irradiated at the center unit. Signals from all 20 units were fed into flight-version electronics consisting of six circuit boards (four waveform digitizer boards, one digital I/O board and one router board) and one microprocessor (SpaceCube), which communicate using a SpaceWire interface. One digitizer board, which can associate up to 8 PDCs, outputs a trigger signal. The digital I/O board handles the trigger and returns a data acquisition request if there is no veto signal (upper or pulse-shape discriminators) from any detector unit. This data acquisition system worked well, and the modulation factor was successfully measured to be ~33%. These results confirmed the capabilities of the data-acquisition system for a “pathfinder” flight planned in 2010.

1. INTRODUCTION

The Polarized Gamma-ray Observer (PoGOLite) is a balloon-borne astronomical soft gamma-ray polarimeter optimized for point-like sources [1]. It measures polarization in the energy range 25–80 keV from sources with flux levels as low as 200 mCrab by using the azimuthal angle anisotropy of Compton-scattered photons. As shown in Figure 1 and 2, it measures coincident Compton scattering and photoabsorption for gamma-ray events in an array of 217 well-type phoswich detector cells (PDCs), each comprising a fast plastic scintillator (detection part), a slow plastic scintillator collimator and a BGO crystal (shield), which are viewed by a single photo-multiplier tube (PMT). The 217 PDCs are surrounded by a side anti-coincidence shield (SAS) made of 54 segments of BGO crystals. The instrument is currently under construction and an engineering flight of a 61-unit ‘‘pathfinder” instrument is planned for 2010 from the Esrange facility in the North of Sweden.

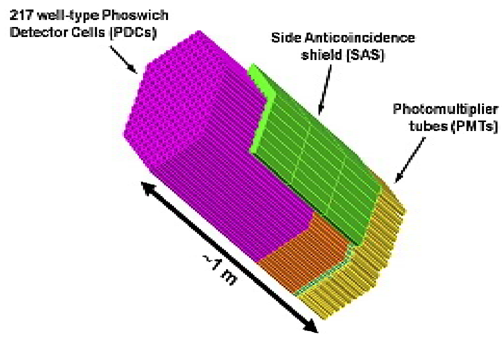

Figure 1. Schematic view of the PoGOLite detector array, consisting of 217 PDCs and 54 SAS units, giving 271 PMT output signals in total.

The in-flight background due to cosmic-rays, charged particles, atmospheric gamma-rays and neutrons is extremely high, typically a few hundred Hz in each unit. The data acquisition (DAQ) system of PoGOLite is required to handle weak signals from astrophysical objects (200mCrab, 2–4 counts per second in the energy range of the instrument) under such a severe environment.

In section 2, we describe the PoGOLite DAQ system. Section 3 details the beam test results obtained at KEK-PF in February 2008, which demonstrate the performance of the detector units and the flight-version DAQ system with the SpaceWire interface.

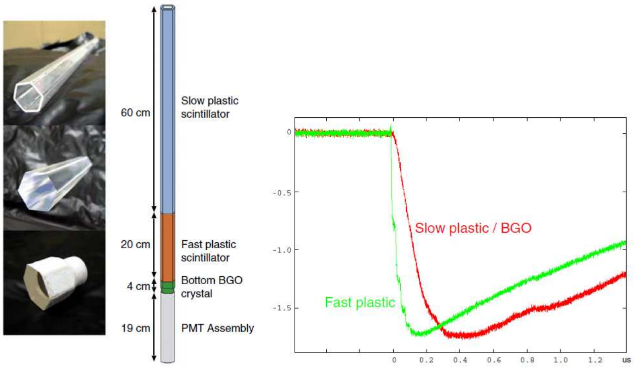

Figure 2. (Left) Structure of the PDC. Fast, slow and BGO scintillators are viewed by one PMT. (Right) An example of waveforms of the PoGOLite CSA output. The decay time of the fast scintillator (τ~2 ns) is distinguishable from that of the slow scintillator/BGO (τ~300 ns) (Pulse- Shape Discrimination).

2. DATA ACQUISITION SYSTEM OF POGOLITE

2.1. GAMMA-RAY MEASUREMENT BY PDC UNITS

The PoGOLite DAQ system consists of six parts: front-end electronics, waveform digitizer, trigger logic, global event logic, microprocessor and storage system. These parts are undertaken by four electronic components: waveform digitizer board, digital I/O board, SpaceCube [2] and router board. The first three functions are implemented on the waveform digitizer board, the fourth logic on the digital I/O board, the last two in the SpaceCube, and all the electronics are inter-connected through the router board. Figures 3 and 4 show pictures of the SpaceWire boards and a block diagram of the DAQ system, respectively.

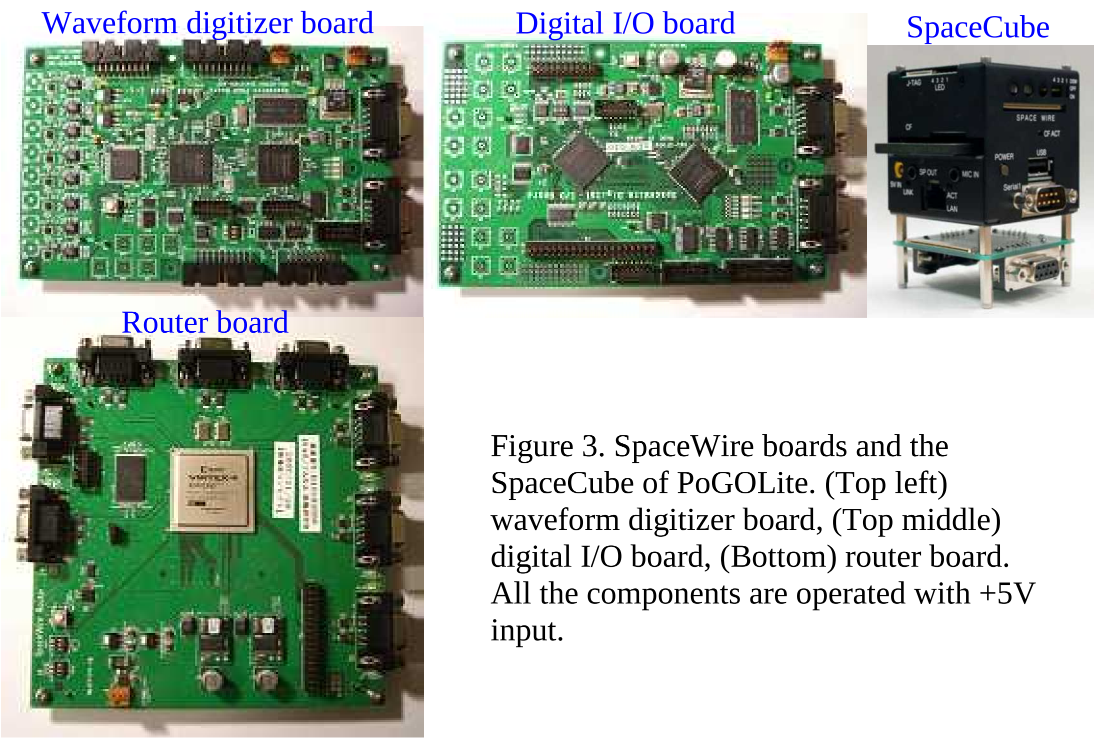

Figure 3. SpaceWire boards and the SpaceCube of PoGOLite. (Top left) waveform digitizer board, (Top middle) digital I/O board, (Bottom) router board. All the components are operated with +5V input.

Signals from the last dynodes of all PDC and SAS PMTs are fed to individual flash ADCs (FADC) and digitized to 12 bit accuracy at a 36 MHz sampling rate in waveform digitizer boards, where one digitizer board can associate up to 8 PDCs. FPGAs on the digitizer boards continuously monitor the waveforms and issue a Level-0 (L0) trigger, when a transient signal compatible with a clean hit in the fast plastic scintillator is detected above the lower discrimination level ~15 keV. A veto signal is issued when the FPGA detects a transient signal above the upper discrimination level (UD veto) or one compatible with a slow rise-time corresponding to that expected from the slow plastic scintillator or BGO (Pulse-Shape Discrimination veto, PSD veto; also see Figure 2 right).

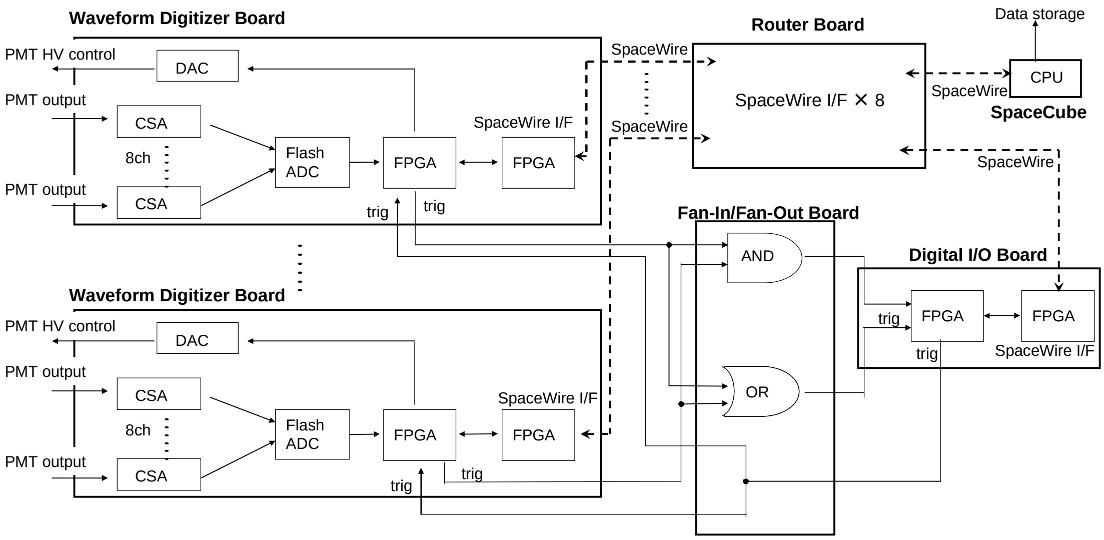

Figure 4. Block diagram of the PoGOLite DAQ system. All waveform digitizer boards and digital I/O boards are controlled and read by the SpaceCube through the router board. The reference voltage to operate each PMT (around +5V) is set by accessing the digitizer board through the SpaceWire connection.

The global event logic on-board the digital I/O board collects all L0 triggers and vetoes, and issues an acquisition request (L1 trigger) if there is no UD nor PSD veto from any PDC. When the waveform digitizer receives an L1 signal from the global event logic, it moves 15 pre-trigger and 35 post-trigger samples from each FADC to a FIFO after zero-suppression. The pre-trigger samples are used to correct for possible baseline shift due to preceding signals. Signals from SAS BGO modules are also stored when an L1 trigger is received. The only difference between the PDC and SAS digitizer boards is the programming of the FPGA. In the final step, the microprocessor in the SpaceCube records all waveforms in the storage system. Figure 5 shows waveforms for a Compton scattering and a photoabsorption, caused by a gamma-ray.

For the 217-PDC PoGOLite, the L0 trigger, the UD rate and the PSD veto rates are estimated to be about 13 kHz, 6 kHz and 12 kHz, respectively. We expect the L1 rate to be ~0.5 kHz, with a dead time fraction of ~0.6%. The validity of the UD and PSD vetoes were tested in a proton beam test at the Research Center for Nuclear Physics (RCNP) in Osaka University, which confirmed the performance of the current system for proton rates of up to ~5 kHz, which is more than an order of magnitude higher than that expected for one PDC unit in flight.

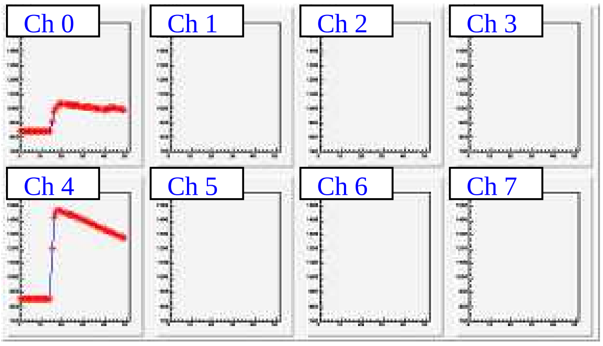

Figure 5. An example of waveforms from a gamma-ray. One photon has Compton-scattered in channel 0 (top left) and subsequently been photo-absorbed in channel 4 (bottom left) of the same waveform digitizer board. Signals from the remaining six channels were not stored due to the zero-suppression setting.

The data size of each waveform is currently 110 bytes, which includes a 10-byte header as well as the 50-clock waveform (15 pre-samples and 35 post-samples). Each one-clock waveform consists of a 12-bit pulse height and a 4-bit dummy column for a total of 16 bits (2 bytes). The header includes a sequential number, the logical address of the waveform digitizer board, an 8-channel hit-pattern for the board, presences of UD and PSD vetoes, and a 32-bit time counter (one count is 0.427 μs). During data acquisition, measured waveforms are first stored in the FPGA of each digitizer board. They are then read out by the SpaceCube through the SpaceWire connection when more than 32 waveforms are stored in one board. This reduces the required number of the read-out accesses by the SpaceCube and increases the data-acquisition rate, since the current rate is limited by the relatively long overhead of the SpaceWire access from the SpaceCube. With this configuration, we have at present obtained a maximum data-acquisition rate of about 400 waveforms per second, corresponding to ~340 Kbps. This rate is sufficient for the 61-unit pathfinder flight planned in 2010.

To support waveform sampling technique described above, the digital I/O board additionally outputs a pseudo-trigger every second if it is not occupied with data acquisition. Once the pseudo-trigger is issued, every waveform digitizer board receives this signal and simultaneously stores a pseudo event, from which we can synchronize the on-board time counters among the SpaceWire boards and estimate the dead time (from the number of the discarded events) in off-line analyses.

2.2. Background Monitoring by SAS Units

As well as storing hit-pattern information for background events coincident with the L1 trigger (see section 2.1), the waveform digitizer board for the SAS continuously records a Pulse Height Analysis (PHA) histogram with a 12-bit resolution, where the exposure of the histogram is changeable. This histogram can be used to study the in-flight background environment, which strongly relates the background contribution. To obtain an accurate energy spectrum from the PHA, we have implemented a base-line subtraction logic in the FPGA of the SAS digitizer board.

As shown in Figure 6 (left), the FPGA subtracts a “delayed” waveform from the original one and issues a trigger when the differential pulse-height exceeds a given threshold. It then subtracts the base-line (pre-trigger pulse height) and records the “corrected” pulse height in a PHA histogram. This logic allows us to measure the pulse-height (photon energy) correctly, even if a signal occurs during the undershoot of a large pulse caused e.g. by charged particles. To verify the performance of this logic, we obtained spectra of low-intensity gamma-rays from ^{241}Am (59.5 keV) in a high-intensity background from 662 keV gamma-rays from ^{137}Cs, which simulates gamma-ray background. The result shown in Figure 6 (right) confirms the validity of the logic and demonstrates that the SAS unit can reject gamma-rays down to ~50 keV.

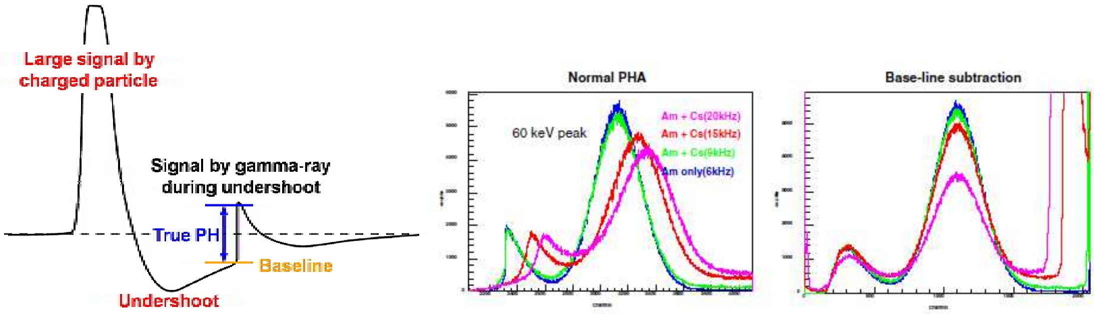

Figure 6. (Left) Base-line subtraction in the SAS PHA monitoring. (Right) Spectra of low-intensity gamma-rays from ^{241}Am (59.5 keV), recorded under irradiation of high-intensity gamma-rays from ^{137}Cs (662 keV). The peak in the left spectrum (without base-line subtraction) is shifted due to the gamma-rays from ^{137}Cs, but in the right spectrum, the peak position remains constant thanks to the base-line subtraction.

We also studied changes in the SAS PHA histogram caused by large signals from charged particles at RCNP. In these tests, SAS PHA spectra of 662 keV gamma-rays from ^{137}Cs were obtained in a background from 392MeV protons. The spectra of ^{137}Cs are shown in Figure 7, where the 662 keV peak was unaffected even with a proton intensity of up to 6.5 kHz. This rate is significantly higher than that expected for one SAS unit in flight (~1 kHz), confirming the performance of the SAS PHA at float altitude (~40 km).

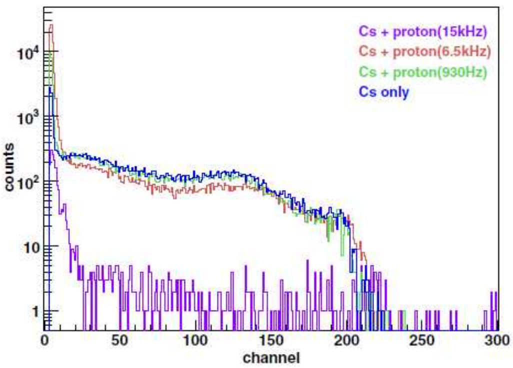

Figure 7. SAS PHA spectra of ^{137}Cs (662keV) measured under irradiation with 392 MeV proton beams with various intensities.

3. RESULTS OF KEK BEAM TEST WITH 19 PDCS AND ONE SAS UNIT

The performance of the detector units and the flight-version DAQ system was verified in a beam test, carried out at KEK-PF in February 2008. In this test, a prototype instrument, comprising 19 PDCs and one SAS unit, was irradiated by a 50 keV X-ray beam (polarization degree ~90%). As shown in Figure 8, signals from all 20 units were fed to 4 waveform digitizer boards (three for the 19 PDCs and one for the SAS).

The DAQ was constructed as described in section 2.1 with a digital I/O board, a SpaceCube and a router board. This setup is identical to that of the 61-unit pathfinder instrument, apart from the number of the waveform digitizer boards. Once the procedure is established, it is straight-forward to expand the DAQ system.

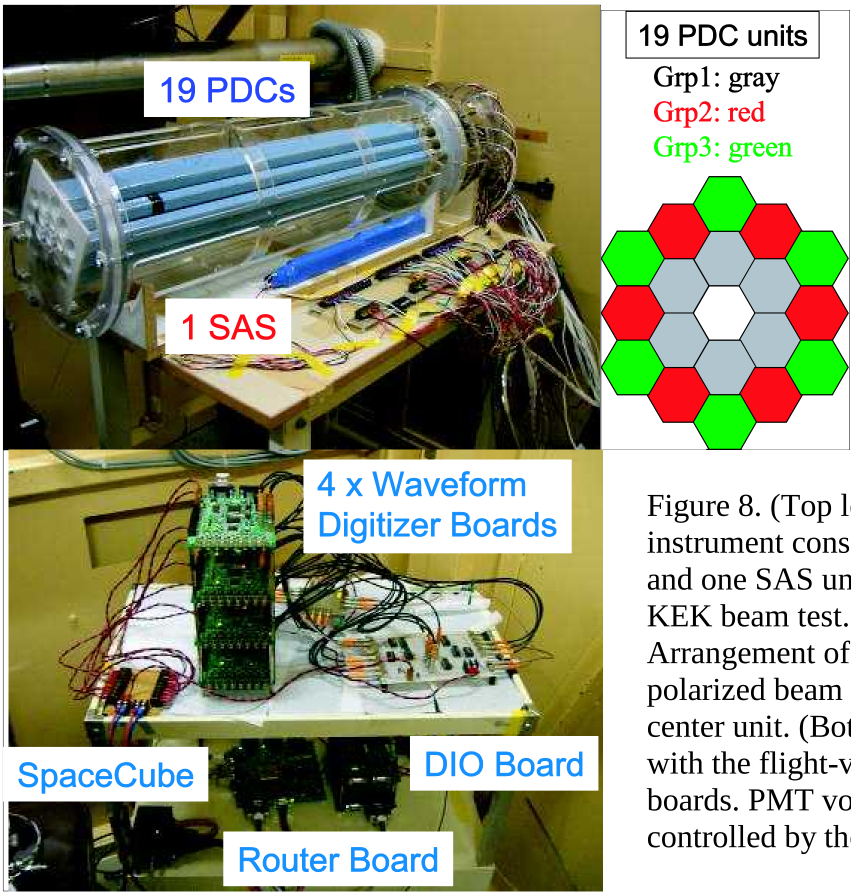

Figure 8. (Top left) Prototype instrument consisting of 19 PDCs and one SAS unit, used in the KEK beam test. (Top right) Arrangement of the 19 PDCs. A polarized beam is irradiated at the center unit. (Bottom) DAQ Setup with the flight-version SpaceWire boards. PMT voltages are also controlled by the digitizer boards.

Candidates of X-ray events with both a Compton scattering and a photoabsorption were selected from the recorded PDC waveforms in off-line analyses. The pulse-height thresholds were achieved as 0.3 photo-electron (~0.5 keV) and 15 keV for the Compton and photoabsorption events, respectively. Between successive measurements, the instrument was rotated in 30-degree steps until a full revolution had been completed. We then determined the azimuthal angle of scattering for each event, corrected it for the rotation of the detector, and derived the modulation curve. Figure 9 shows the measured modulation curve, where distributions of valid Compton events along the azimuth angle are drawn separately for three PDC groups, Grp 1, Grp 2 and Grp3 (see Figure 8 top right). The modulation depends on the distance between the Compton-scattering site and the photoabsorption site. Obtained modulation factors for the 90% polarized beam are (31.3 ± 0.4)%, (37.9 ± 0.7)% and (40.2 ± 0.8)% for Grp1, 2 and 3, respectively. These results are consistent with those predicted by our GEANT4-based simulation within ~5%.

We have evaluated the performance of the PoGOLite DAQ system and confirmed the capability to operate the 61-unit pathfinder launched in 2010. In the near future, we will test the new SpaceWire I/F developed by Shimafuji Electric which increases the read-out speed, and the new waveform digitizer board which samples waveforms with an almost doubled-clock rate (70 MHz). These improvements will allow us to increase the data-acquisition rate, and more clearly distinguish waveforms of background neutrons from those of caused by gamma-ray events, respectively.

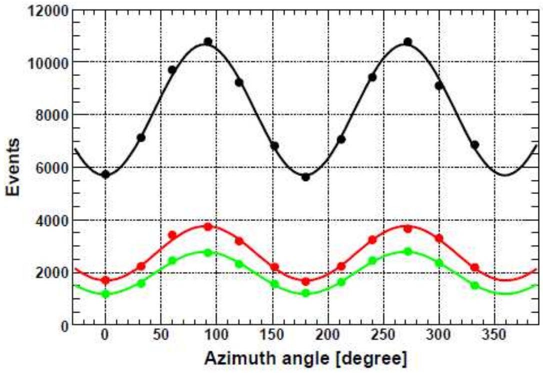

Figure 9. Measured modulations of a ~90% polarized beam with an energy of 50 keV. The curves are obtained from the three PDC sets, Grp1 (black), Grp2 (red), and Grp3 (green), shown in the top right side of Figure 8.

ACKNOWLEDGMENTS

The SpaceWire-based I/O and boards were developed in JAXA's program "Research and Development for Future Innovative Satellite."

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