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Optimization of the gain factors and parameter settings for the new gamma-ray burst polarimeter, POLAR

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ABSTRACT

As a space-borne detector POLAR is designed to conduct hard X-ray polarization measurements of gamma-ray bursts on a statistically significant sample of events and with an unprecedented accuracy. During its development phase a number of tests, calibrations and verification measurements were carried out in order to validate instrument functionality and optimize operational parameters. In this article we present results on gain optimization together with verification data obtained in the course of broad laboratory and environmental tests. In particular we focus on exposures to the ^{137}Cs radioactive source and determination of the gain dependence on the high voltage for all 1600 detection channels of the polarimeter. Performance of the instrument is described in detail with respect to the dynamic range, energy resolution and temperature dependence. Gain optimization algorithms and response non-uniformity studies are also discussed. Results presented below are important for the development of the POLAR calibration and operation database.

1. Introduction

Gamma-ray bursts (GRBs) are extragalactic transient sources emitting extremely energetic packets of X- and gamma-rays. Although more than 40 years passed since the discovery, GRBs are still poorly understood. There is neither any definite description of physical processes during the burst nor any certainty on why they occur, or where such high energy release comes from. Thanks to observational contributions of the Burst and Transient Source Experiment (BATSE) onboard the Compton Gamma-Ray Observatory (CGRO) [1], BeppoSAX [2], Swift [3], Fermi [4] and several other missions, scientists were able to propose a number of competitive theoretical models aimed to explain the GRB phenomena. Different models generally give different predictions on the polarization degree of X-rays coming from the prompt GRB emission. Thus, reliable and precise polarization measurements of GRBs are very likely to play a key role in explanation of the GRB mechanisms. Several attempts to measure the X-ray polarization in GRB prompt emission have been performed with existing missions e.g. BATSE [5], the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [6–8], the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) with the Spectrometer for INTEGRAL (SPI) [9,10], and Imager on-Board the INTEGRAL (IBIS) [11,12] and the Cadmium Zinc Telluride Imager

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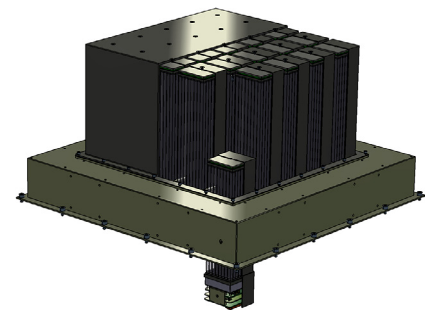
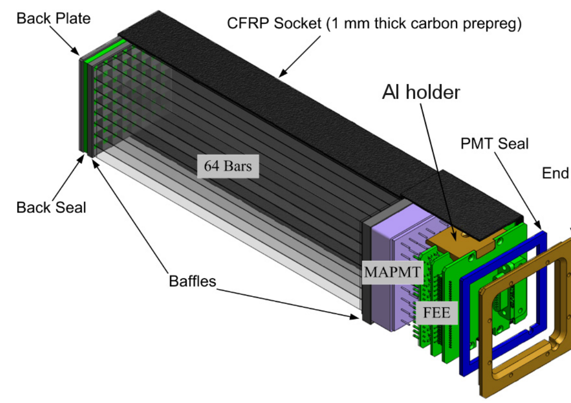
(CZTI) onboard AstroSAT [13]. However, none of the above detectors were specifically designed for polarization measurements, resulting in large uncertainties in the measured polarization levels caused by systematic effect resulting from insufficient optimizations for explicit polarization studies. New dedicated apparatus specifically optimized for polarization observations should provide rigorous measurements. Several attempts have been made to design dedicated polarimeters [14,15]. The Gamma-ray burst polarimeter (GAP) [16] was one of the first such instruments designed to observe polarization of GRBs. So far there are three meaningful results based on GAP observations [17,18]. Unfortunately, because of GAP's small effective area, the photon statistics are very low and the confidence levels are not very high.

The new GRB polarimeter POLAR, which has just been launched on-board the Chinese space station TianGong-2 (TG-2) on September 15, 2016 is dedicated for high precision polarization measurements of prompt hard X-ray GRB emission. It is based on the Compton scattering principle [19]. POLAR has advantages of both large effective area (80 cm^2 [20]) and high sensitivity (μ_{100} = 40%@140 keV [21]). With its wide field of view it covers a third of the sky. It was optimized for the hard X-ray spectra in the energy range from 50 keV to about 500 keV. Mission goals require the low energy threshold to be set at $\sim$ 5 keV. POLAR consists of 25 modules arranged in a 5 × 5 array. Each module is composed of 64 plastic scintillator bars made of EJ-248M, a H8500 multi-anode photomultiplier tube (MAPMT) and a front-end electronics (FEE). Each bar has a square cross section of $5.85 \times 5.85\mathrm{mm}^2$, a length of 176 mm and is wrapped with the high reflectivity Vikuiti$^{\mathrm{TM}}$ Enhanced Specular Reflector (ESR) foil. Its ends are formed as cut-off pyramids to reduce crosstalk between nearby channels. All components of the module are enclosed in a mechanical construction consisting of a carbon-fiber baffle protecting the scintillators and an Aluminum-made holder keeping MAPMT and FEE (see Fig. 1(b)). The drawings of the whole POLAR instrument and one of its modules are presented in Fig. 1. During GRB detection, X-ray and γ-ray photons will interact with electrons in the plastic scintillator giving them some part of their energy during the scattering process. The energy deposited in the plastic scintillator bar will be converted into scintillation light photons and then, as the walls of each plastic bar are wrapped in a highly reflective screen, a fraction of these photons will reach the entrance window of the MAPMT. The MAPMT photo-cathode will convert them into photoelectrons. The initial photoelectrons will be multiplied on subsequent dynodes of the MAPMT. Finally the FEE will read the resulting current pulses from the MAPMT outputs and perform further signal processing as described in [22]. The event readout sequence starts only if at least one pulse has its amplitude higher than the hardware threshold of the FEE ASIC. There is one common threshold for all channels in the module apart from limited range trimmers [23]. Detailed description about determination of polarization from POLAR's data can be found in Refs. [24,25].

Each of the 64 anodes in the 25 MAPMTs is coupled to 64 scintillator bars giving 1600 independent detection channels for the whole polarimeter. All channels in a module use the same high voltage value (HV). Because of differences in the fluorescence efficiency, variations in light attenuation and collection as well as unequal gain levels of individual MAPMT anodes, the final signal amplitudes within the same module may be quite different. Therefore the whole POLAR instrument will reveal some level of input signal non-uniformity requiring careful characterization, calibration and periodic re-checks. In addition, optimization of the appropriate HV values is needed to balance different mean gain factors between the modules and control linearity of the system. Both signal non-uniformity and HV optimization were intensively studied during 2015 and 2016. The instrument performance was characterized using different radioactive sources covering the whole energy range of POLAR. For the purpose of this work we concentrate on the results obtained with the $^{137}\mathrm{Cs}$ calibration source. This source with the activity of 4×10^5 Bq was used to calibrate values of the HV and trigger thresholds of the POLAR Flight Model (FM). Firstly, we investigated the relationship between gain factors and HV values for all 1600 channels of POLAR FM, followed by the discussion about energy resolution and influence of FEE temperature and random vibration on the gain factors. In the next step the non-uniformity measurements were performed for several HV settings. Finally a dedicated HV optimization procedure was introduced and tested. In addition to aspects discussed above the aim was to meet and verify the basic scientific requirements of the POLAR mission with respect to the maximizing the sensitivity and optimizing the Minimum Detectable Polarization (MDP) [19]. A summary of major calibration tests is given in Table 1. Other results e.g. the low energy response linearity [26] or threshold fine tuning [27] are presented elsewhere.



(a)



(b)

Fig. 1. *Left*: POLAR consists of 5 × 5 modules; each one with 64 plastic scintillators coupled with the MAPMT; *Right*: expanded view of one module.

2. Gain and high voltage relationship

2.1. Theoretical considerations

According to the PMT operation principle, the following equation describes the relationship between the gain factor and the HV value for an unequally-distributed voltage divider (pages 46–47 in [29]):

$$G = \left(a \cdot V_i^k\right)^n = a^n\left(c_1 V \cdot c_2 V \cdot \dots \cdot c_n V\right)^{kn} = A \cdot V^{kn}, \quad (1)$$

where G is the gain factor of the PMT defined as the product of the collection efficiency and secondary emission ratio of all dynodes, V is the HV value, a is a constant, k is a coefficient determined by the structure and material of the dynode, $V_i = c_i V$ is the interstage dynode voltage, n is the number of dynode stages, $A = a^n\left(c_1 c_2 \dots c_n\right)^{kn} = a^n c^{kn}, c = c_1 c_2 \dots c_n$. Obviously, c is a constant independent of V and G. One can rewrite the equation above as follows:

$$\ln G = p_0 + p_1 \ln V, \quad (2)$$