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In-orbit instrument performance study and calibration for POLAR polarization measurements

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ABSTRACT

POLAR is a compact space-borne detector designed to perform reliable measurements of the polarization for transient sources like Gamma-Ray Bursts in the energy range 50–500 keV. The instrument works based on the Compton Scattering principle with the plastic scintillators as the main detection material along with the multi-anode photomultiplier tube. POLAR has been launched successfully onboard the Chinese space laboratory TG-2 on 15th September, 2016. In order to reliably reconstruct the polarization information a highly detailed understanding of the instrument is required for both data analysis and Monte Carlo studies. For this purpose a full study of the in-orbit performance was performed in order to obtain the instrument calibration parameters such as noise, pedestal, gain nonlinearity of the electronics, threshold, crosstalk and gain, as well as the effect of temperature on the above parameters. Furthermore the relationship between gain and high voltage of the multi-anode photomultiplier tube has been studied and the errors on all measurement values are presented. Finally the typical systematic error on polarization measurements of Gamma-Ray Bursts due to the measurement error of the calibration parameters are estimated using Monte Carlo simulations.

1. Introduction

Gamma Ray Bursts (GRBs) are short flashes of gamma-rays that appear in the sky at unpredicted times and from unpredictable directions. Since their discovery in the 1960s their exact nature is still not fully understood despite the properties of the prompt emission, like energy, time and direction having been measured in great detail by many other instruments [1]. The polarization of the prompt emission is another important dimension that can help us understand the emission mechanisms of GRBs and the possible magnetic and geometric structure of the source [2–4]. Measuring the polarization will allow to constrain different theoretical emission models. There have already been several attempts to measure the polarization of the high energy emission from GRBs by instruments such as the BATSE instrument onboard CGRO [5], RHESSI [6,7] and the IBIS and SPI instruments onboard INTEGRAL [8,9]. All these instruments are however primarily designed for spectroscopy, timing and imaging, and therefore unoptimized for polarization studies. As a result their polarization measurements have large systematic and statistical errors. The small scale GAP detector onboard the IKAROS solar sail was the first dedicated GRB polarimeter which reported polarization measurements of three bright GRBs [10,11].

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However in order to constrain emission models a larger sample of GRB polarization measurements with higher precision is required.

POLAR [12,13] is a compact space-borne detector with a wide field of view which is specially designed and optimized to measure the polarization of hard X-rays for transient sources like GRBs in the 50–500 keV energy range. The POLAR experiment was proposed with the scientific goal to give a reliable polarization measurement of a large sample of GRBs [14].

When the polarized photons interact with the detection materials through the Compton scattering process, the differential cross-section follows the Klein–Nishina equation (1).

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E}+\frac{E}{E'}-2\sin^2\theta\cos^2\phi\right)\\ &= \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E}+\frac{E}{E'}-\sin^2\theta+\sin^2\theta\cos\left(2\left(\phi+\frac{\pi}{2}\right)\right)\right)\end{aligned} \tag{1}$$

where r_0 is the classical electron radius, E and E' are the energies of the photon before and after the scattering process respectively, θ is the polar scattering angle and ϕ is the azimuthal scattering angle. After integration of θ, the distribution of ϕ follows a distribution described by Eq. (2)

$$f(\phi,E) = A(E) + B(E)\cdot\cos\left(2\left((\phi-\phi_0)+\frac{\pi}{2}\right)\right) \tag{2}$$

where ϕ_0 is the azimuthal scattering angle correlated to the polarization direction. The azimuthal scattering angle distribution of the scattered photons described by this function is called the modulation curve, and the ratio of B over A is called the modulation factor as presented by Eq. (3)

$$\mu(E) = \frac{B(E)}{A(E)} = \frac{f_{max}-f_{min}}{f_{max}+f_{min}}. \tag{3}$$

When the incident photons are 100% linearly polarized μ, for at a specific initial energy E, is defined as μ_{100}. For partially polarized photons, the corresponding μ is in the range $0-\mu_{100}$ and has a linear relationship with the polarization degree, then the polarization degree can be determined by $\Pi = \mu/\mu_{100}$. Based on this theory, the information of polarization including polarization degree and polarization direction can be directly measured by the distribution of the azimuthal scattering angle ϕ of the photons interacting through the Compton scattering process.

POLAR measures the Compton scattering angles using plastic scintillator (PS) bars with the type EJ-248M [15]. This material was chosen for the reason of its low-z characteristic which contributes to a higher Compton scattering cross-section in the energy range of POLAR, as well as its higher temperature resilience. As shown in Fig. 1, 64 PS bars of dimension $5.8\times5.8\times176$ mm are grouped together as an 8×8 array and a 64-anodes photomultiplier tube (MAPMT) from Hamamatsu with its corresponding front-end electronics (FEE) connected to this PS array is used to readout and process the signals. Each PS bar is separated by a piece of thin highly reflective film of the type Vikuiti Enhanced Specular Reflector Film (ESR) [16] to increase the fluorescence photons collection and reduce the optical crosstalk. This structure with some other components such as the outer Carbon Fiber Reinforced Polymer (CFRP) shell forms a standalone module and 25 such modules are installed in an aluminum frame as a 5×5 array. Such a PS detection plane with 40×40 pixels enables POLAR to precisely measure the projection of the azimuthal scattering angle distribution. The 25 modules are connected by a central trigger (CT) system installed inside the aluminum frame which is responsible for implementing the overall trigger logic, collecting and packaging event data, etc. A more detailed description of the design and construction of the POLAR flight model is provided in Ref. [13].

POLAR was launched onboard the Chinese space laboratory TG-2 on 15th September in 2016 and successfully switched on afterwards. More than 50 GRBs have been detected by POLAR and confirmed by other satellites such as Fermi GBM, Swift, etc. during the first 6 months of operation [17]. POLAR also detected strong signals from the Crab Pulsar [18] and Solar Flares. Before the polarization analysis of these detected GRBs and other sources, a full study of the instrument performance during in-orbit operation is required and all the related in-orbit calibration parameters of the instrument itself should be provided. These in-orbit calibration parameters include pedestal and noise levels of the FEE, the nonlinearity function of the gain in the electronics, the ADC threshold of each channel, the crosstalk matrix of each module and the gain of each channel. All these calibration parameters are not only necessary in the analysis pipeline to reconstruct the deposited energy of each bar and reduce the systematic effects from the instrument, but also work as the input parameters for the Monte Carlo simulations [19] that simulate the digitization process of the PMTs and FEEs and handle the event response, which is another important procedure of the polarization analysis by comparing the modulation curves between the measured data and the simulated data. Therefore, the methods to calculate all these calibration parameters using in-orbit data and their typical values are firstly discussed and presented. It is found in the in-orbit data of POLAR that there is a certain percentage of fake events that are generated by FEEs possibly induced by the background high energy charged particles. Because the contamination of those fake events will affect the calibration, a method to filter those fake events is also provided.

Unlike the on-ground experiment, the space environment, including temperature, different density of charged particles etc. is complicated and always varies over time while POLAR arrives at different positions in-orbit. During the first 6 months of operation, the instrument settings were also changed several times for different purposes. The most important change is the high voltage (HV) setting for the purpose of gain–HV relation measurement. Therefore, both the effect of temperature change on all calibration parameters were carefully checked and studied as well as the relationship between gain and high voltage. The relations between gain and high voltage were studied using in-orbit data for the purpose of calculating the gain parameter corresponding to the high voltage setting for the normal scientific data acquisition. Finally, as all the calibration parameters have measurement errors, and they will result in a systematic error on the final modulation curves, the typical level of the calibration parameter induced systematic error on the polarization measurement of GRBs was studied and evaluated by Monte Carlo simulation.

2. Methods to measure the calibration parameters

The analysis chain for the in-orbit data of POLAR can be described in general by: subtraction of pedestal and common noise ⇒ data filtering ⇒ gain nonlinearity correction ⇒ threshold calculation ⇒ crosstalk correction ⇒ energy calibration. The details and the methods to measure all the calibration parameters that are needed by each step of this analysis chain will be discussed in this section. Firstly, a short description of the DAQ process and the trigger logic of POLAR will be given which is needed for better understanding the discussion of the methods to measure all the calibration parameters. Then the methods to measure different calibration parameters will be discussed subsequently in different subsections.

2.1. DAQ process and trigger logic

Fig. 2 shows a more detailed geometric structure of the bottom part of two adjacent modules. For hard X-rays there is a high possibility for Compton scattering to occur in one PS bar followed by one or several interactions in other different bars, these bars can be in different modules. The deposited energy of each bar will be firstly converted to fluorescent optical photons then collected at the bottom of the bar. Even though the shape of the end of each bar is made pyramid-like and there is the baffle placed between two adjacent bars as shown in Fig. 2, the photon crosstalk between different bars can still happen in the area of