In-flight energy calibration of the space-borne Compton polarimeter POLAR

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Abstract

POLAR is a compact wide-field space-borne detector for precise measurements of the linear polarization of hard X-rays emitted by transient sources in the energy range from 50 keV to 500 keV. It consists of a 40×40 array of plastic scintillator bars used as a detection material. The bars are grouped in 25 detector modules. The energy range sensitivity of POLAR is optimized to match with the prompt emission photons from the gamma-ray bursts (GRBs). Measurements of the GRB polarization in the prompt emission photons would provide unique information on event mechanisms as well as on of GRB jets. POLAR can also detect hard X-rays from solar flares and be used for precise measurement of their polarization. The instrument was launched into a low Earth orbit on-board the Chinese space-lab TG-2 on September 15th, 2016. To achieve high accuracies in polarization measurements it is essential to provide already in flight a precise energy calibration. Such calibrations are performed with four low activity \textsuperscript{22}Na radioactive sources placed inside the instrument. Energy conversion factors are related to Compton edge positions from the back-to-back anni-
hilation photons from the sources. This paper presents the principle of the in-flight calibration, studies of the method with Monte Carlo simulation and its laboratory verification and finally some results based on the in-flight data analysis.

Keywords: Gamma-ray burst; Polarization; POLAR; In-flight calibration

1. Introduction

Gamma-ray bursts (GRBs) are unpredicted and non-repetitive short flashes of gamma-rays appearing in the sky at random time and position and typically lasting from few milliseconds to even several hundred seconds. In a few seconds they release a huge amount of energy in the order of \(10^{48}\) to \(10^{55}\) ergs. It is comparable to the rest energy of the sun if the energy release is isotropic. Thus, they are regarded as the most energetic events in the universe [1]. GRBs are produced at cosmological distances being possibly associated with collapses of massive stars or mergers of compact binary systems [2, 3]. Since their discovery in the 1960s, thousands of GRBs have been detected by various space-borne instruments [4, 5, 6, 7]. They have been measured in great details in timing, location and energy spectrum. Our understanding of GRBs has already enormously improved as a result of dedicated measurements and studies (see Refs. e.g. [1, 8, 9] for recent reviews). However, many key questions such as their emission mechanisms, geometric structure, magnetic properties or nature of GRB jets are not yet answered. Direct polarization measurements would provide much better understanding as well as possible answers to these questions [2, 3].

To date, tens of polarization measurements in the gamma-ray range have been reported with polarization levels from 30% to 80% (see Refs. e.g. [10, 11, 12]). Most of these measurements have limited statistical significance. Moreover, results frequently do not provide a consistent picture of the GRB polarization [13]. Thus, it is still difficult to propose firm answers to pending GRB questions. Both high-quality data and statistically significant polarization results from new, dedicated instruments are still needed to determine the true nature of the GRBs.

POLAR is a compact space-borne GRB detector for measurements of the polarization of the gamma-rays in the energy range from about 50 keV to 500 keV. The instrument was developed by an international collaboration of Switzerland, China and Poland. It was launched on September 15th, 2016 on-board the Chinese space-lab TG-2 into a low Earth orbit with an altitude...
around 380 km and an inclination of 42.79° for an up to three years long observation period.

POLAR detector uses 1600 segmented plastic scintillator (PS) bars as the gamma-ray detection material. It has both a large effective detection area of $\sim 80 \, \text{cm}^2$ and a large field view of 1/3 of the sky. Its main goal i.e. measurements of the linear polarization in GRBs is realized using Compton scattering. Distribution of the azimuthal Compton scattering angle from statistically significant number of gamma-rays contains information about their mean polarization level and direction. It is determined using positions of two scintillator bars with the maximum energy depositions left by the incoming gamma-ray. Reliable energy calibration is crucial to precisely reconstruct these energy depositions. Before the launch, the whole energy response of POLAR was carefully calibrated in a series of laboratory test campaigns. One used radioactive sources, low energy X-ray generators as well as X-ray beams from the synchrotron radiation facilities \[14, 15, 16, 17, 18\]. It should be noted that the energy response of the detector is susceptible multiple factors such as thermal drifts, high voltage (HV) variations in power supplies, ageing processes in light transmission systems and radiation effects. It implies that periodic calibrations of the detector energy response in space are necessary. For this purpose four weak $^{22}\text{Na}$ positron sources were installed inside POLAR at the innermost edges of the four corner modules. The collinear annihilation photons selected offline allow for proper calibration of the detector. This paper presents the principle of the in-flight calibration, studies of the method with Monte Carlo simulation and its laboratory verification and finally several results based on the in-flight data analysis.

2. POLAR Instrument

2.1. POLAR detector

As the low-Z materials have large Compton scattering cross-sections, plastic scintillator (EJ-248M) was chosen as gamma-ray detection target. It consists of 1600 plastic bars segmented into 25 identical modules as shown in the left panel of Fig. 1. Each module has $8 \times 8$ PS bars, a 64 channel MAPMT (Hamamatsu R10551-00-M64) and its own front-end electronics (FEE). The bar dimensions are $5.8 \times 5.8 \times 176 \, \text{mm}^3$ with both ends cut into a pyramid-like shape in order to match the size of the MAPMT pixel and to reduce optical crosstalk between neighbour bars. The surfaces of each bar were polished and wrapped in a highly reflective foil (Vikuiti Enhanced Specular Reflector Film) to increase light collection. All the bars are
Fig. 1: POLAR detector module structure (left) and full POLAR instrument (OBOX) (right). The POLAR full module consists of 25 identical modules as shown in the left panel. The coordinates used in the Monte Carlo simulations are also shown on the right panel.

Coupled to the MAPMT with a 0.7 mm thick optical pad which also partially absorbs vibrations protecting the MAPMT glass. The FEE consists of three stacked Printed Circuit Boards (PCBs): HV divider board, signal processing board and power supply and interfacing board. The HV divider consists of twelve 470 kΩ resistors distributing HV to the MAPMT dynodes. The signal processing board consists of an ASIC chip (IDEAS VA64) with 64 separate readout channels, an ADC, a FPGA and a temperature sensor. A special internal pulser circuit is also included in order to test the gain and the non-linearity of the electronics for each channel. The third board has a low voltage power supply circuit and interfacing connectors. The whole detector module is packed into a 1 mm thick carbon fibre socket. 25 modules are connected to a Center Task Processing Unit (CT) board. The CT manages 25 modules and it is also responsible for making trigger decision, processing data packets, managing the high and the low voltage power supplies and handling communication with the POLAR IBOX which contains the interfaces to the TG2 space-lab. All 25 modules, the CT, the power supplies were placed into an aluminium frame covered with a carbon fibre enclosure (300 × 300 × 175 mm³). The POLAR instrument (OBOX) is shown in the right panel of Fig. 1. It is mounted on the outside panel of the space-lab facing permanently to the sky. A more detailed description the POLAR detector can be found in Ref. \[19\].
2.2. POLAR OBOX data types

When ionizing radiation passes through the scintillator bars, optical photons are emitted as a result of energy deposition. The generated light pulses are converted by the MAPMT into electric signals that are subsequently shaped and integrated by the ASIC. Final amplitudes of the shaped signal are proportional to the visible energy depositions. If the amplitude of any channel is above the ASIC discriminator threshold, all 64 analogue signals of the module are hold and a trigger signal is sent to the CT starting trigger decision process. In case of trigger acceptance all analogue signals are digitized in the ADC. The digitized readout data with 64 trigger bits, the timestamp string and some auxiliary data form a module science packet transmitted to the CT. The event arrival time and the trigger status are also recorded by CT and form a trigger packet. Trigger packets are used to identify and merge science packets from different modules belonging to the same event.

Apart from packets with the physical data, another two packet types are periodically generated: pedestals and housekeeping data. The CT takes from every module one pedestal event per second. Housekeeping data such as information on OBOX operating mode, temperatures of each module and HV values is collected by CT to form a packet every two seconds.

2.3. Compton polarimetry

The principle linear polarization measurements with POLAR is based on the Compton effect. In the POLAR energy range of 50 keV to 500 keV, gamma-rays have a large probability to be Compton scattered in its PS bars. They tend to be scattered in a plane perpendicular to their electric field vector (polarization direction) according to the Klein-Nishina equation:

\[ \frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left( \frac{E'}{E_0} \right)^2 \left( \frac{E_0}{E'} + \frac{E'}{E_0} - 2 \sin^2 \theta \cos^2 \eta \right), \]  

(1)

where \( r_0 \) is the classical electron radius, \( E \) and \( E' \) are the incident photon energy and the scattered photon energy, respectively, \( \theta \) is the scattering angle of the scattered photon measured from the direction of the incident photon, and \( \eta \) is the azimuthal scattering angle between the initial polarization vector and the direction of the scattered photon. In the case of unpolarized incident photon beams the distribution of scattered photons with respect to the azimuthal angle \( \eta \) is uniform as there is no preferred electric vector direction in the incident beam. However, it is not the case for polarized
beams. According to Eq. (1), the distribution of $\eta$, also called modulation curve, follows a $\cos(2\eta)$ function and can be parameterized as:

$$f(\eta) = k \cdot \{1 + \mu \cos (2 (\eta - \eta_0) + \pi)\},$$

where $\eta_0$ is the polarization angle, $k$ is the normalization factor and $\mu$ is the modulation factor. Values of two parameters $\eta_0$ and $\mu$ can be obtained from a fit to the data.

We define the angle between $x$-axis of POLAR detector and the line connecting centres of two bars with the maximum energy depositions as the ‘azimuthal angle’ $\xi$. It is correlated with the real azimuthal angle $\eta$. The distribution of the number of photons with respect to $\xi$ is defined as the observed modulation curve $f_{\text{obs}}(\xi)$. The true modulation curve $f_{\text{true}}(\xi)$ can be obtained by correcting the geometry effect caused by the anisotropy of the detection efficiency as follows [14, 20]:

$$f_{\text{true}}(\xi) = N \cdot \frac{f_{\text{obs}}(\xi)}{f_{\text{non}}(\xi)},$$

where $N$ is the normalization factor and $f_{\text{non}}$ is the modulation curve measured for the unpolarized beam with the same incident angle and the same energy spectrum. Both $f_{\text{non}}(\xi)$ and $\mu_{100}$ are obtained with Monte Carlo simulations verified with experimental data. One uses the GRB coordinate Network (GCN) [21] for both an event position localization and spectral information. The polarization degree of the beam $p$ is equal to $p = \mu / \mu_{100}$, where $\mu_{100}$ is the modulation factor measured for the 100% polarized beam. An alternative procedure to determine the polarization is to fit the experimental modulation curve with a set of simulated modulation curves using the least squares method [10, 11].

3. In-flight calibration requirements

The main task of POLAR is to measure modulation curves for detected GRBs and provide values for their polarization degree and polarization angle. Energy calibrations are necessary to determine common energy thresholds and identify two bars with the maximum energy depositions needed to calculate the azimuthal Compton scattering angles.

According to Ref. [22], the visible energy deposited by gamma-rays in 64 bars of each POLAR module can be reconstructed by a linear transformation of the recorded energy deposition:

$$\vec{E}_{\text{dep}} = R^{-1} \vec{E}_{\text{meas}},$$

(4)
where $\vec{E}_{\text{dep}}$ and $\vec{E}_{\text{meas}}$ are two vectors representing the real and the recorded energy depositions in all 64 bars respectively, and $\mathbf{R}$ is the response matrix of the module. $\mathbf{R}$ is given by $\mathbf{R} = \mathbf{F}^T \mathbf{M}$, where $\mathbf{F} = (f_{ij})_{64 \times 64}$ is the crosstalk matrix and $\mathbf{M} = \text{Diag}(m_{0,0}, m_{1,1}, ..., m_{63,63})$ is the energy conversion matrix whose diagonal element is the recorded ADC channel per unit energy deposition in the corresponding bar. The transformation allows for energy calibration, including corrections of crosstalk and non-uniformities. Calibration of the crosstalk matrix in Eq. (4) can be easily done by measuring correlations of signals between two channels using background data as described in Refs. [14, 22, 15]. Thus, the main task of the in-flight calibration is to determine for each module its energy conversion matrix that consists of 64 energy conversion factors (in units of ADC channel/keV). A proper energy calibration in-flight is for several reasons a rather complex subject: 1) 1600 channels have to be calibrated simultaneously; 2) plastic scintillators have rather poor energy resolution; 3) background rates are high due to low threshold values and POLAR large field of view; 4) calibrations should not jeopardise polarization measurements (implying low source activity). Initial studies began with a series of Monte Carlo simulations conducted to verify several in-flight calibration options such as solar flares, the Crab Nebula and GRBs themselves. Unfortunately, none of them had clear spectral features useful for energy calibration. Therefore further studies were performed with various radioactive sources optimised for calibrations in-flight.
4. In-flight calibration method

4.1. Calibration with four $^{22}\text{Na}$ sources

Fig. 2: $^{22}\text{Na}$ calibration source positions, the numbering of calibration sources, modules and bars (POLAR channels) and coordinate system conventions as adopted in the experimental data analysis in this paper. The corners of modules with four $^{22}\text{Na}$ sources are indicated by stars.
A set of four weak $^{22}$Na $\beta^+$ sources was proposed for the in-flight calibration in a configuration optimized for using back-to-back 511 keV gamma-rays emitted during positron-electron annihilation. Multiple calibration sources allow for higher and more uniform coincidence rates for different scintillator bars. The $^{22}$Na isotope was chosen due to its relatively long half-life of 2.6 years as compared with other positron sources [23]. As shown in Fig. 2, the four sources are located at the corners of modules 7, 9, 17 and 19, and fixed outside the carbon fibre sockets at a half of the length of the bar (about 88 mm from the bar’s top surface). As shown in Fig. 3, the $^{22}$Na nucleus decays with emission of a positron with a probability of 90.3%. The positron annihilation creates two 511 keV photos flying two back-to-back. Both photons traverse through the detector having a similar probability of interacting with the scintillator bars located on opposite sides of the source. The most probably interaction process is the Compton scattering. Corresponding hits are attributed to the same event if their time interval is within the hardware coincidence time window of 110 ns. As annihilation photons are emitted back-to-back the bars hit by the photons can be accurately se-

![Fig. 3: $^{22}$Na decay scheme (taken from Ref. [23]).](image-url)
lected during offline analysis using conditions based on the event geometry, namely collinearity of two bars and the source. Compton edges in energy spectra created with above conditions provide energy conversion factors for each POLAR channel.

4.2. Coincidence hit selection algorithm

Fig. 4: Definitions of the perpendicular distance $d$, opening angle $\theta$ and angle $\varphi$ between the diagonal line of the bar and the line connecting the two bar centres, and the maximum allowed perpendicular distance $d_{\text{max}}$. $C_1$ and $C_2$ are the centres of two bars. The $^{22}$Na source is indicated by a star.

It is impossible to determine the exact locations of interactions inside of the bar. As shown in Fig. 4, two bars can only be hit simultaneously by the collinear annihilation photons when the position of the source is inside the polygon (i.e., the grey region). The perpendicular distance $d$ i.e. the distance from the source to the line connecting the two bar centres and the opening angle $\theta$ must satisfy the conditions $d < d_{\text{max}}$ and $\theta > 90$ degree, where $d_{\text{max}}$ is the maximum distance of the four vertices of one of the bars to the line connecting the two bar centres. Obviously, $d_{\text{max}} = \max(\sqrt{2}w|\sin(\varphi)|/2, \sqrt{2}w|\cos(\varphi)|/2)$, and $w/2 \leq d_{\text{max}} \leq \sqrt{2}w/2$, where $w = 5.8$ mm is the width of the PS bar and $\varphi$ is the angle between the diagonal line of the bar section on the XY plane and the line connecting centers of two bar. Therefore, coincidence hit events can be selected by imposing conditions as above. In practice, the value of $d$ is slightly increased to take into account the size of the source. An energy spectrum from the hits selected for each bar can be obtained with a sufficient amount of data. Such the spectrum shows a clear Compton edge signal observed at the energy of 340.7 keV. The identification of Compton edge positions in the energy spectra leads to the energy calibration factors. The coincidence selection condition effectively rejects most of the hits produced e.g. either by the
1.274 MeV gamma-rays from the same $^{22}\text{Na}$ sources or background events from space (e.g. diffuse cosmic x-rays, electrons and protons).

5. Monte Carlo simulations

5.1. The simulation package

A complete Monte Carlo simulation package was built based on the GEANT4 suite [24] developed by CERN. Physical processes are described by the ‘emlivermore_polar’ physics model, which has a high accuracy of electron, hadron and ion tracking. Incident particle definitions use either the General Particle Source toolkit (GPS) from GEANT4 or particle generators implemented in the POLAR simulation package (e.g. back-to-back photons and $^{22}\text{Na}$ events). Several parameters are recorded for each simulated event including the incident particle type, its energy, position, momentum and direction as well as visible energy depositions and positions of each interaction in the scintillator bars. Simulation outputs are saved using the ROOT file format [25]. Extensive set of Monte Carlo simulations has been started already during the R&D phase of the in-flight calibration method.

5.2. Simulations of $^{22}\text{Na}$ calibration sources

The $^{22}\text{Na}$ sources emit gamma-rays of 1274 keV with 100% probability and back-to-back gamma-rays of 511 keV from the beta decay with 90.3% probability. Beta emission spectrum of emitted positrons has the end-point energy of 543 keV. Positrons travel some distances before annihilating with encountered electrons. The distance depends on the base material of the source. The minimum thickness needed to stop positrons was estimated for various materials with the help of Monte Carlo simulations. As an example, Fig. 5 shows simulated distributions of positron traversing distances (i.e. the distances between their initial position and the places of the annihilation) in copper, aluminium and carbon fibre. The positron initial kinetic energy was sampled from the beta emission spectrum. Mean distances for three materials listed above are equal to 40 $\mu$m, 150 $\mu$m and 300 $\mu$m respectively. For example, a few hundred $\mu$m thick copper plate can stop all positrons. Moreover, all values of the stopping lengths are much smaller than the lower limit of $d_{\text{max}}$, which is $w/2 = 2.9$ mm. Therefore, for the coincidence hit selection the travelling distances of positrons in the source can be ignored. In the following simulations the $^{22}\text{Na}$ sources are simplified to be point-like.
Fig. 5: Distributions of $^{22}\text{Na}$ positron traversing distances in large blocks of copper, aluminium and carbon fibre. The mean transverse distances are 0.04 mm, 0.15 mm, and 0.3 mm respectively.

5.3. Gamma-ray detection efficiencies

Fig. 6: Detection efficiencies for gamma-rays of 511 keV and 1274 keV in 40 diagonal bars aligned with the source No. 1. Gamma-rays were shot isotropically and detection threshold values were equal to 5 keV.

Five simulation runs (see Table 1 for details) were performed to study efficiency of POLAR for detection of gamma-rays at different energies. For
Table 1: Simulation runs performed to study gamma-ray detection efficiency and coincidence probability

| Run # | Particle source | Particle energy (keV) | Position      | Direction |
|-------|-----------------|-----------------------|---------------|-----------|
| 1     | γ               | 1274                  | Source 1      | isotropic |
| 2     | γ               | 511                   | Source 1      | isotropic |
| 3     | back-to-back γ  | 2 × 511               | Source 1      | isotropic |
| 4     | $^{22}$Na       | 1274 or with 2 × 511  | Source 1      | isotropic |
| 5     | γ               | 511                   | top surface   | -z        |

The first two runs, gamma-rays with energies of 511 keV and 1274 keV were isotropically generated at the source 1 position. For the third and fourth runs, two annihilation photons from the $^{22}$Na decay were generated back-to-back at the same source position. For the last run, gamma-rays with the energy of 511 keV were randomly generated towards scintillator bars (-z) from the top surface of OBOX. Each simulation run got one million generated events. Fig. 6 shows detection efficiencies of 40 diagonal bars computed for gamma-rays with energies of 511 keV and 1274 keV as in the first two simulation runs. A hit event was counted if its energy deposition in any bar was larger than 5 keV. Fig. 7 shows detection efficiencies of the full detector for five different threshold values ranging from 5 keV to 40 keV. An event is considered as detected (i.e. $n_{\text{hits}} > 1$) if in at least one bar the deposited energy is above a given threshold value. It can be seen that 33% gamma-rays of 1274 keV and about 43% of 511 keV are detected. The detection probabilities of back-to-back photon events and a $^{22}$Na event are $\sim 67\%$ and $\sim 74\%$, respectively. As the four calibration sources are placed symmetrically inside POLAR, the detection efficiencies of the full detector are similar if the gamma-rays are generated at the positions of the other sources.
5.4. Coincidence selection

In order to study efficiency of events selection for energy calibration purposes, all coincidences with energy depositions higher than 5 keV were selected. The data from previously described five simulation runs were used with selection conditions described in Section 4.2. As mentioned before one million events was simulated for each run and the size of the source was not included in the model. The percentages of events with coincidence hit pairs $N_{cid}$ as well as the number of detected events $N_{det}$ are shown in Table 2. As can be seen, the percentage of events with coincidence pairs selected for the back-to-back gamma-ray simulation run is equal to 17.7%. It is slightly smaller than 19.4% which is the probability to detect both annihilation gamma-rays as calculated from the detection efficiency of one single 511 keV gamma-ray. It is due to the fact that the events can not be selected if the two back-to-back gamma-rays deposit energies lower than the threshold during their first interaction; however, both of them can still be detected if the scattered gamma-rays deposit energy higher than the threshold in other i.e. not aligned bars.

The percentage of selected events with coincidence hit pairs from the $^{22}$Na run is equal to 17.4%. The back-to-back gamma-rays are generated in 90.6% of all $^{22}$Na decays and 17.7% of them are found with the valid coincidence pattern. Thus the absolute percentage of selected coincidence events should be equal to 16.0% assuming an absence of gamma-rays from the decay channel with energy of 1274 keV. Thus, about 8% of all coincidence
events selected from $^{22}$Na decays, i.e. 1.4% of total events, are due to extra coincidences between gamma-rays with energies of 511 keV and 1274 keV. We also see in Table 2 that only 0.4%, 1.0% and 0.3% of events from runs 1, 2 and 5 respectively are coincidences with a multiple scattering. Thus, the introduced coincidence selection method is able to effectively select hits with a back-to-back pattern coming from the $^{22}$Na decay while and other events i.e. without the pattern are rejected.

Table 2: Percentages of detected events $N_{\text{det}}$ and events with coincidence hit pairs $N_{\text{cid}}$ for five simulation runs. The simulation conditions are shown in Table 1.

| Run# | $N_{\text{det}}$ (%) | $N_{\text{cid}}$ (%) |
|------|------------------|------------------|
| 1    | 34.1             | 0.4              |
| 2    | 44.2             | 1.0              |
| 3    | 70.1             | 17.7             |
| 4    | 75.8             | 17.4             |
| 5    | 50.8             | 0.3              |

Fig. 8 shows the distributions of the opening angles $\theta$ and the perpendicular distances $d$ in the coincidence hits from the $^{22}$Na simulation run (i.e. run 4). It can be seen that the opening angles $\theta$ are close to 180° while $d$ is less than the upper limit of $d_{\text{max}}$ (i.e., 4.1 mm) as expected. The distribution of the distances between the selected hits and the source 1 (i.e. $d_{\text{bar1}}$ and $d_{\text{bar2}}$) is shown in the right panel of Fig. 15 in the next chapter. According to the simulation, 96% of the selected hits have distances smaller than 200 mm. Thus, a cut of the distance at the value of 200 mm can be further
applied for the coincidence hit selection. It will further reduce a contamination with e.g. accidental coincidences for cases in which the background rate is very high.

5.5. Energy spectra

A new $^{22}$Na run with 10 million incident events was performed in order to have enough statistics for energy spectra studies. An example of detected spectra for three typical bars is given in the left panel of Fig. 9. The energy spectra were smeared using the formula for energy resolution $R(E) = \sigma_E/E$ as given by [26]

$$R(E) = \sqrt{r_0^2 + a/E},$$

where $E$ is deposited energy in units of keV, $a$ and $r_0$ are two constants. The first term in Eq. (5) represents contributions for material inhomogeneities and imperfect light coupling; whereas the second term is attributed to the statistical effects. Note that the noise from the electronics and the detector response non-proportionality considered in Ref. [26] are ignored in Eq. (5). The two free parameters $a$ and $r_0$ were estimated using the ground calibration results described in Refs. [17] and [15]. Typical energy resolution values in POLAR channels are about 15% for 662 keV gamma-rays and about 45% for 80 keV gamma-rays. The deposited energy spectra for three selected bars modified using the energy resolution formula are shown in the right panel of Fig. 9. The Compton edges at the value of 340.7 keV are still clearly seen for all the bars. The counts on the right side of Compton edges are due to multiple scattering of gamma-rays inside the bars or extra coincidences between gamma-rays of 511 keV and 1274 keV. They can be reduced by applying a high energy cut in the hit selection procedure. The energy conversion factors can be obtained by fitting the Compton edges with a step-like function described in Ref. [14].
5.6. Space backgrounds

According to simulations described in Ref. [27], the main sources of the POLAR background in space apart the South Atlantic Anomaly (SAA) are diffuse cosmic X-rays, electrons and positrons. Other sources such as neutrons and primary cosmic rays are either negligible or easily rejected by the trigger system. Our simulations showed that positrons can not contaminate Compton edges in calibration spectra as most of them are stopped by the POLAR enclosure and the energy spectrum after their annihilation is roughly the same as from calibration sources. Thus, simulations of the other two background sources, i.e. diffuse cosmic X-ray and electrons were performed. Energy spectra for both backgrounds were taken from Ref. [27]. Incoming particles were generated on the surface of a sphere with a radius of 30 cm. The coincidence hit selection method as described above was applied to the simulated data. Fig. 10 shows the number of coincidences per second in POLAR diagonal bars obtained for: the 200 Bq strong $^{22}$Na source placed at the Source 1 position, the diffuse cosmic x-ray background and the electron background. The threshold values for hit selection were equal to 5 keV. It can be seen that the coincidence hit rates of the background are much lower than for the calibration signals. Furthermore, most of the coincidence hits selected from the background events have rather low energy depositions. Only the hits with energy depositions larger than about 200 keV could contaminate the Compton edges. The signal to noise ratio of each bar can be improved even further if higher threshold values are applied.
5.7. Activity of calibration sources

Duration of POLAR mission extends up to three years. Activities of the calibration sources after 3 years will be reduced to 45% of their initial values. According to Fig. 10, the coincidence hit rates from calibration sources will be above the background rates if the source activity is higher than about 20 Bq. Obviously, in order to obtain similar statistical uncertainties much longer calibration time periods will be required. Using sources with higher activity shortens the calibration time but also increases dead time and real background rates by worsening the signal to noise ratio of the GRB polarization measurement. The sources of higher activities will also need larger data bandwidth from the space-lab. Based on above considerations, the source activity of 100 – 250 Bq was proposed. Simulations showed that statistical errors in the energy conversion factors for the outermost bars obtained using 100 Bq strong calibration sources are of the order of 1% for 24 hours long data taking.

6. Laboratory verification of the method

The first experimental test of the in-flight calibration method was carried out with the POLAR flight model spare (FMS). Four small $^{22}$Na sources with a total activity of about 1000 Bq were prepared for the experiment. The dimensions of each source were approximately $3 \times 3 \times 0.3$ mm$^3$. Each
source was glued to a L-shape plastic support. Finally the supports with their sources were glued to outer edges of four POLAR corner modules as shown Fig. 2. The data acquisition was started when the temperature of POLAR after switching its power on was stable. The high voltage values for all the modules were set to 650 V. The average total trigger rate per module was around 70 Hz. In order to cross-check the results, another run was performed with a 10 \( \mu \text{Ci} \) \(^{137}\text{Cs}\) source placed at a distance of 40 cm from the top surface of the POLAR FMS.

![Histogram of energy spectra](image)

**Fig. 11:** Experimental energy spectra in the channel 3 of module 25 taken using \(^{22}\text{Na}\) and \(^{137}\text{Cs}\) sources. The black line represents the spectrum of the coincidence hits selected for the internal \(^{22}\text{Na}\) calibration sources. The grey line shows the spectrum measured with the external \(^{137}\text{Cs}\) source. Fits of the Compton edges are also shown.

The data taken from the above runs was processed in several steps. Firstly, the was decoded and re-written using the ROOT file format [25]. Pedestal events taken periodically during data acquisition were pre-selected to calculate the pedestal positions for each input channel. Subsequently, for each detected event the pedestal values were subtracted. In the next step also the common noise values (i.e., common shifts of baseline) were subtracted from amplitudes of detected events. Finally, the hits belonging to the same physical event were merged using hit pattern information from trigger packets and timestamps values from the module science packet. After the merging, coincidence hits were selected by using the method as described in Section 4.2. The value of \( d_{\text{max}} \) calculated for each hit pair was increased by 3 mm in order to take into account the size of the sources. Moreover, the
events with large common mode noise values were excluded. As an example, Fig. 11 shows the energy spectrum of the selected coincidence hits for channel 3. The energy spectrum measured with the external $^{137}$Cs source is also shown. The Compton edge positions given in units of ADC channel were found by fits with the step-like function given in Refs. \cite{14, 22}. Theoretical Compton edge positions for gamma-rays with energies of 511 keV and 662 keV are equal to 340.7 keV and 477.7 keV respectively. Corresponding two energy conversion factors were obtained by dividing the Compton edge positions given in units of ADC channel by equivalent theoretical values expressed in keV. The same procedure was applied for all channels. Fig. 12 shows a comparison of two energy conversion factors for all channels in module 25. A generally good agreement can be seen for energy conversion factor values determined with two different sources.

Fig. 12: Comparison between energy conversion factors of module 25 obtained with an internal $^{22}$Na source and an external $^{137}$Cs source.

7. In-flight Calibration of POLAR

7.1. Calibration sources and calibration runs

Four newly produced $^{22}$Na sources were prepared for the POLAR flight model (FM). Each of them was glued between two L-shape copper foils with a 0.5 mm thickness each. The foils as well as the glue prevented positrons from escaping. The total activity of all sources according to the measurement in January 2016 using the germanium detector was equal to 520 ± 10% Bq. Activities of single sources were between 100 Bq and 200 Bq. The foils with the sources were installed inside of POLAR FM at the very last
moment before shipment to the launch site. They were glued to the edges of
the four corner modules. Positions of the sources are a few mm away from
the module edges pointing direction to the instrument center as shown in
Fig. 2. Some more details on the source fabrication and their exact positions
in FM are given in Ref. [19].

![Graph showing HV values for FM calibration](image)

**Fig. 13:** Two settings with HV values used for FM in space. Basic in-flight calibration
settings are represented by squares. Full circles show settings used for optimized GRB
observations.

Shortly before the launch several HV and threshold settings were pre-
pared and optimized for the purpose of the in-flight calibration. The opti-
mization method for the settings as well as laboratory test procedures can
be found in Ref. [28]. HV values for the basic in-flight calibration setting
are shown in Fig. 13. Using them assures that Compton edges for all the
channels would be seen in the spectra of the coincidence hits. During PO-
LAR operation in space several in-flight calibration runs with above settings
have already been performed.

### 7.2. Calibration data processing chain

A dedicated data centre was established at Paul Scherrer Institute in
order to store and process all POLAR space data. The raw datasets arriv-
ing at the data centre are firstly preprocessed, decoded and converted into
the level 0 data using the ROOT file format. Data coming from different
POLAR modules as well as housekeeping packets are stored separately. In
order to form the level 1 data set all pedestals and common mode noise
values are subtracted for each physical event. In the next step of data processing all hits belonging to the same physical event recorded at different modules are merged. Additionally the merged events contain attached all relevant housekeeping data such as e.g. module temperatures and HV values. They are written to the new data files making the level 2 dataset. After data merging, the coincidence algorithm is applied to the level 2 dataset to extract the in-flight calibration events. The maximum allowed perpendicular distance \( d_{\text{max}} \) for each hit pair is increased by 3 mm to include the size of the sources and the uncertainties of the source centres. Events with energy depositions above the ADC range or with too many channels triggered, e.g. caused by cosmic-rays, are excluded. Moreover, all hits for which the neighbouring bars have higher energy depositions are excluded as well to filter out excessive crosstalk or small-angle Compton scatterings. All events selected with the help of above criteria are written to new data files assigned as level 2B.

Compared to the level 2 data, all events in the 2B dataset contain some extra information such as e.g. positions of two selected bars, their distances to the calibration sources, the perpendicular distance and the opening angle. The selection steps leading to the 2B dataset and described above are performed using an automated data processing chain running at the PSI POLAR data centre. Further description of the POLAR data centre is given in Ref. [29].

7.3. Event selection

![Fig. 14: 2D map of coincidence hit rates with the in-flight calibration data (left) and the total coincidence event rate for each calibration source (right).](image)
The left panel in Fig. 14 shows the 2D map with coincidence rates constructed using the in-flight calibration data taken on November 19th, 2016. The rate values attributed to each calibration source are shown in the right panel of Fig. 14. The total event rate for the in-flight calibration data taking was equal to 80 Hz corresponding to the total activity of $^{22}\text{Na}$ sources equal to 460 Bq. Based on measurements from January of 2016 the remaining activity of the sources was equal to $420 \pm 40$ Bq. The calculated number of detected $^{22}\text{Na}$ events was equal to 73 Hz computed with selection criteria for coincidence hit pairs as described in section 5.4. Thus, the calculated and measured event rates for the in-flight calibration runs are in very good agreement.

The distribution of distances between the source 1 centre and corresponding centres of the bars with the selected coincidence hits (i.e. $d_{\text{bar1}}$ and $d_{\text{bar2}}$ - see in Fig. 4) is shown in Fig. 15. It presents a good agreement with simulation results which are also shown in the same figure. Fig. 16 shows the raw energy spectrum and the spectrum of the coincidence hits for the POLAR channel No. 2. This channel is placed in the outermost layer. Note that the ADC channel values in the data packets were scaled by a factor of four in order to reduce the packet size. As can be seen in Fig. 16 there is no Compton edge feature in the raw energy spectrum. However, it can be clearly seen in the spectrum of the coincidence hits. It shows great improvement in the signal to noise ratio obtained after applying the coincidence selection criteria.
Fig. 16: Raw and coincidence hits energy spectra from POLAR channel No. 2 measured during calibration runs on November 19th, 2016. For the selected coincidence spectrum a fit of the Compton edge is also shown. ADC channel values of space data were scaled by a factor of four in order to reduce the packet size.

7.4. Energy conversion factors

Fig. 17: Energy conversion factors for all 1600 POLAR channels obtained using data taken in the period from September 30th to October 4th, 2016. The HV settings are shown in Fig. 13.
In-flight calibration data taken between September 30th and October 4th, 2016 were selected to study the energy conversion factors. All coincidence hits in the above time window were used to prepare the calibration energy spectra. For each bar the Compton edge position in its energy spectrum was fitted with the step-like function as given in Ref. [14]. The energy conversion factors for all 1600 POLAR channels were calculated using fit results and are shown in Fig. 17. The mean conversion factor for all POLAR channels is equal to 7.1 ADC-channel/keV. Mean temperatures of each module measured during calibration runs are shown in Fig. 18. Temperature variations during calibrations expressed as standard deviations range from 0.5 to 2.3°C.

Energy conversion factors from the in-flight calibrations can be compared with the laboratory results obtained with the same HV and threshold settings. For this purpose we analysed the data from calibration runs performed at the launch site in July 2016. The laboratory data was processed using the same procedures and methods as for data from space. The mean temperature of POLAR modules during on-ground calibrations was just about 5°C higher than in space. Fig. 19 shows both the laboratory $c_g$ and the in-flight energy conversion factors $c_s$ of the first 200 POLAR channels presented without temperature effect corrections. The distribution of the relative differences of the conversion factors, i.e. $2 \cdot (c_s - c_g)/(c_s + c_g)$, for all 1600 channels is plotted in Fig. 20. The mean in-flight calibration factor is just about 5.5% larger than the one measured on the ground factors. The difference is mostly due to temperature effects. More detailed studies of
temperature effects are presented in the next section. After applying temperature corrections the individual differences are also very small i.e. within 7% (standard deviation). Based on above results it can be seen that the detector responses did not change significantly after the launch.

![Graph](image1.png)

**Fig. 19:** Comparison of the on-ground and in-flight energy conversion factors for the first 200 POLAR channels.

![Graph](image2.png)

**Fig. 20:** Distribution of relative differences between on-ground and in-flight energy conversion factors for all 1600 channels. The mean and the standard deviation values are equal to 5.5% and 6.7% respectively.
Fig. 21: An example of the temperature of module 25 as a function of time (left) and the distribution of temperature of this module for the first six months in space (right).

As can be seen in the left panel of Fig. 21, the module temperature varies a few degrees along the spacecraft orbit largely due to differences in its illumination by the sun. To study temperature dependence of energy conversion factors, we again used the same calibration data taken between September 30th and October 4th, 2016. The study was performed for each channel of POLAR. All coincidence events in the level 2B datasets were divided into four groups using the temperature cuts from $22 - 2i \degree C$ to $22 + 2i \degree C$ ($i = 0, 1, 3, ..., 9$). Corresponding energy spectra were prepared using events belonging to the selected temperature range groups. For each group the same procedure was used to determine the energy conversion factors. The left panel of Fig. 22 shows an example of the energy conversion factors as a function of temperature. Since each POLAR module has only one temperature sensor, we assumed the same temperature values for all channels in the module. As expected the coefficient of the temperature vs. energy conversion factor has a negative dependence. Its value was fitted for each channel using a linear function. The relative temperature coefficient $\alpha_T$, i.e. the relative change of energy conversion factor per degree, was obtained with the formula $\alpha_T = p_1/\bar{c}$, where $p_1$ is the slope from the linear fit and $\bar{c}$ is the mean value of the energy conversion factor. The distribution of the temperature coefficients for about 1100 channels is shown in the right panel of Fig. 22. The mean coefficient from the fit is $-1.06\%$ per degree. The coefficients of other channels were excluded due to lack of statistics. More data from further calibration runs will be used to determine coefficients for all remaining channels. For the first six months of the POLAR operation in space a typical temperature variation for a single module was equal to
about 10°C as shown in the right panel of Fig. 21. Thus, typical drifts of the gain value due to temperature effects are about 10%.

![Graph showing energy conversion factors as a function of temperature for the POLAR channel 12 (left) and distribution of temperature coefficients together with a Gaussian fit (right).]

**Fig. 22:** Energy conversion factors as a function of temperature for the POLAR channel 12 (left) and distribution of temperature coefficients together with a Gaussian fit (right).

7.6. **Energy calibration with the high HV settings**

The mean threshold values with the basic HV setting range from about 20 keV to 50 keV. The discriminator threshold voltage (vthr) could not be set to lower values because of the electronic noise of the readout system. Lower energy thresholds corresponding to higher values of HV are needed to accumulate more events especially from weaker GRBs and to improve the signal to background ratio for GRB detection. For higher values of HV it is however impossible to conduct direct calibrations for channels with Compton edge positions outside of the ADC range. Therefore, the energy calibration for these channels relies on the indirect method described in Refs. [15] and [17]. The principle of the method is briefly introduced as below.

The MAPMTs of POLAR operate using an equally distributed voltage divider. Their gain factor in function of the applied HV $V$ is given by the following equation:

$$G = a^n \left( \frac{V}{n+1} \right)^{kn},$$

where $a$ is a constant, $n$ is the number of dynode stages and $k$ is a constant determined by the structure and material of the PMT. The typical value of $k$ is equal to 0.7 [30]. In the case of POLAR, $n$ is equal to 12. According to Eq. (6), the gain $G$ is proportional to the $kn$-th power of the HV value. It is reasonable to assume that the energy response of POLAR detector close to its typical operating condition is linear. Therefore the energy conversion
The energy conversion factor $c$ (in units of ADC channel / keV) can be given by

$$c(V) = \frac{E_{\text{meas}}}{E_{\text{vis}}} = bG = \alpha \left( \frac{V}{n + 1} \right)^{kn},$$  \hspace{1cm} (7)

where $b$ is a constant, $V$ is the HV value, $\alpha$ is equal to $ba^n$, $E_{\text{vis}}$ is the energy deposition (in units of keV) and $E_{\text{meas}}$ is the recorded energy deposition (in units of ADC channel). Again, for POLAR, $n$ is equal to 12. Eq. (7) can be parameterized using calibration data taken with several HV settings. Thus, the energy conversion factors for settings with higher values of HV can be determined using the parameterized function in the extrapolated range.

![Graph showing the fit of energy conversion factors vs. HV values for POLAR channel no. 0. A data fit with Eq. (7) together with the confidence intervals (at 95% C.L.) are also shown. The fit parameters $k$ and $\alpha$ from the fit are 0.693 and $3.47 \times 10^{-14}$ respectively.]

![Graph showing the mean temperatures of POLAR module No. 1 during calibration runs.]

**Fig. 23:** Left: Fit of the energy conversion factors vs. HV values for the POLAR channel no. 0. A data fit with Eq. (7) together with the confidence intervals (at 95% C.L.) are also shown. The fit parameters $k$ and $\alpha$ from the fit are 0.693 and $3.47 \times 10^{-14}$ respectively. Right: Mean temperatures of POLAR module No. 1 during calibration runs.
Another four HV settings were prepared to improve extended calibrations and for further studies of the energy conversion factors dependence on the HV values. The HV values differed by -21 V, -14 V, -7 V and +6 V relative to the basic calibration settings. Several in-flight calibration runs have been performed using above settings to date. The left panel of Fig. 23 shows an example of the energy conversion factors as a function of HV values with extended calibration data taken in November 2016. The fit to the data done using Eq. (7) together with the confidence intervals (at 95% C.L.) are also shown in the figure. Temperature corrections were not applied as the differences between the mean temperatures of the modules were negligible during all calibration runs. As an example, the mean temperature of module No. 1 is plotted in the right panel of Fig. 23.
Most of the time during its first six months in space POLAR operated with very high HV settings. The high voltage values are shown in Fig. 13. The energy conversion factors were obtained from the data taken in November 2016 using procedures as described above. The distribution of the energy conversion factors for all 1600 channels calculated according to Eq. (7) is shown in Fig. 24. Note that the final calibration data for each detected GRB have to be corrected for temperature effects and long-term drifts in the detector performances verified with periodic calibrations. The final calibration data applied for detected GRBs will be presented in the future papers.

In order to estimate values of the low energy thresholds, we constructed for each POLAR channel the energy spectra with all triggered hits. A sharp cut-off on the left side of the spectrum is related with the low energy threshold. Its value (in units of ADC channel) was chosen to be given by the position of the half-maximum of the cut-off. Fig. 25 shows the distribution of the threshold values for the high HV setting obtained using the energy conversion factors. Neither quenching effects nor crosstalk corrections was taken into account yet as final refinement of the calibration data for each detected GRB is still ongoing.

8. Conclusion

POLAR is a compact, wide-field of view, space-borne detector devoted for precise measurements of the linear polarization of hard X-rays. The instrument is optimized for X-ray detection from GRBs and solar flares in the energy range from 50 keV to 500 keV. Polarization measurements are based
on the Compton scattering occurring in its 1600 plastic scintillator bars. They utilize distribution of azimuthal scattering angle of incoming X-rays interacting in at least two POLAR channels. Energy calibrations of POLAR in space are performed with four low activity $^{22}$Na calibration sources. The method relies on the Compton edge measurements in the energy spectra of the selected back-to-back annihilation 511 keV photon pairs taken with pre-defined basic HV and threshold settings. The energy conversion factors applied at the HV settings optimized for the GRB detection are determined using extrapolations based on the extended calibration dataset from calibration runs at different HV values. Additional correction factors for temperature effects were also determined and found to be on a few percent level only. Comparison of calibration results between laboratory measurements before the instrument launch and in-space showed only very minor changes in the energy conversion factors. Studies of the in-flight calibration method using Monte Carlo simulations as well as verification of method based on laboratory measurements are also presented. The results consistently shows good agreement with the data taken during several in-flight calibration runs performed to date.

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