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The boresight alignment of the DArk Matter Particle Explorer

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Abstract The DArk Matter Particle Explorer (DAMPE) can measure γ-rays in the energy range from a few GeV to about 10 TeV. The direction of each γ-ray photon is reconstructed in the DAMPE payload reference system. To convert this to celestial coordinates, we require the celestial orientation of the payload system, which, however, may slightly deviate from that of the satellite system provided by the star-tracker. In this paper, we adopt a maximum likelihood method and use the γ-rays centered around several bright point-like sources to measure and correct the angular deviations between the DAMPE payload and satellite system, the so-called "boresight alignment". We also check our method of boresight alignment for some sets of simulation data with artificial orientations and obtain consistent results. The time-dependent boresight alignment analysis does not show evidence for significant variation of the parameters.

Key words: instrumentation: detectors — gamma rays: general — methods: data

1 INTRODUCTION

The DArk Matter Particle Explorer (DAMPE) is a satellite mission which has been operating stably in a solar synchronous orbit since it was launched on 2015 December 17 from Jiuquan, China. The payload is designed to detect high energy cosmic rays and γ-rays with high energy and spatial resolutions. The detector consists of four subdetectors (Chang 2014; Chang et al. 2017), from top to bottom, a Plastic Scintillator Detector (PSD) (Yu et al. 2017; Ding et al. 2019), a Silicon Tungsten tracKer-convertor (STK) (Azzarello et al. 2016), a BGO calorimeter (BGO) (Zhang et al. 2016), and a NeUtron Detector (NUD) (He et al. 2016). DAMPE collects about five million high energy galactic cosmic ray (GCR) events, mostly cosmic-ray protons, and a number of cosmic-ray helium nuclei, various heavier nuclei, electrons, and γ-rays. The on-orbit calibration with these data proves that DAMPE is fully operational as expected and all sub-detectors perform well. One important part of the on-orbit calibration is the payload internal alignment (DAMPE Collaboration 2019). Details on alignments of the STK and PSD with the on-orbit data have already been published (Tykhonova et al. 2018; Ma et al. 2018). In this work we focus on the alignment between the payload and the satellite platform.

For each incident high energy GCR particle, the direction is first reconstructed with respect to the reference system of the DAMPE payload. To convert this to celestial coordinates, we require the celestial orientation of the payload. The DAMPE satellite orientation is provided by the GPS and star-trackers. The GPS gives the parameters of current position and velocity of the satellite. The star-trackers are used to determine the attitude of the satellite as the satellite stays in 3-axis stabilization so that the z-axis always points to the Earth center and the y-axis is always perpendicular to the plane formed by the z-axis and the vector of velocity, and it points toward the Sun. Accordingly, the direction of the x-axis, given by the outer product of the z- and y-axis, is close to the velocity.

The payload system is normally the same as the satellite system. But as a result of uncertainty in the ground alignment process, thermal variations, acoustic vibrations, relaxation in zero gravity, and STK and BGO alignment process, small deviations between the payload system and the satellite system are expected. Such a mismatch will cause a systematic shift between the observed deirection and the real one of each detected particle. In order to ef-

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fectively correct such a bias, we take the GeV γ-ray data centered around a few brightest point-like sources detected by DAMPE to measure the angular deviations between the payload system and the satellite system. Such a process is called "boresight alignment" of the DAMPE payload. In this work we introduce the method, result, and verification of our boresight alignment in detail.

2 LIKELIHOOD ANALYSIS

The deviations between the payload system and the satellite system that needs to be calibrated can be described as a rotation in the payload system. Therefore, with a rotation matrix the vectors in the payload coordinate and the satellite coordinate systems can be directly related. The rotation of a vector in the satellite coordinate system can be described by three Euler angles that are generally called roll ($\boldsymbol{\psi}$), pitch ($\boldsymbol{\theta}$) and yaw ($\boldsymbol{\phi}$), which represent the rotation angles along x, y and z axes respectively. The rotation matrix in terms of these variables reads

$$\boldsymbol{R}(\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi}) \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\boldsymbol{\psi} & -\sin\boldsymbol{\psi} \\ 0 & \sin\boldsymbol{\psi} & \cos\boldsymbol{\psi} \end{bmatrix} \begin{bmatrix} \cos\boldsymbol{\theta} & 0 & \sin\boldsymbol{\theta} \\ 0 & 1 & 0 \\ -\sin\boldsymbol{\theta} & 0 & \cos\boldsymbol{\theta} \end{bmatrix} \begin{bmatrix} \cos\boldsymbol{\phi} & -\sin\boldsymbol{\phi} & 0 \\ \sin\boldsymbol{\phi} & \cos\boldsymbol{\phi} & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{1}$$

Thus, the column vector $\boldsymbol{r}$ of the track in the payload coordinate system can be expressed as

$$\boldsymbol{r} = \boldsymbol{R}(\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi})\boldsymbol{r}', \tag{2}$$

where $\boldsymbol{r}'$ is the track constructed in the payload coordinate system before the boresight alignment.

The rotation transforms the position of the incident particles in the payload coordinate, and subsequently modifies direction in the corresponding celestial coordinate. Based on the housekeeping data provided by the navigation system and star trackers, the transformation at time $\boldsymbol{t}$ from the payload coordinate to the celestial coordinate can be computed as a matrix $\boldsymbol{R}_{\rm sky}(\boldsymbol{t})$. The correction of a vector $\boldsymbol{p}$ in celestial coordinates due to boresight alignment ($\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi}$) can be expressed as

$$\boldsymbol{p}(\boldsymbol{t},\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi}) = \boldsymbol{R}_{\rm sky}(\boldsymbol{t})\boldsymbol{R}(\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi})\boldsymbol{r}'. \tag{3}$$

Some bright GeV sources, such as Vela, Geminga and Crab, have been measured well in the radio and optical bands, and their positions in the celestial coordinate system are known with a precision of ~ 0.01 arcsec (Fey et al. 2004). So, we can use the brightest γ-ray sources to carry out the boresight alignment. A set of software packages (DmpST), which incorporate the instrument response functions (IRFs) and the science tools, has been developed to analyze the γ-rays detected by DAMPE (Duan et al. 2019). In this work, DmpST is adopted to achieve our purpose. The point spread function (PSF) is a function of an incident photon's primary energy and incident angle. It means the probability distribution of the reconstructed direction for a γ-ray event, especially with a large variance at low energies and large incident angles (e.g., 68.3% of the counts will be within $\sim 0.8^\circ$ at 1 GeV and 50° (Duan et al. 2019)). Therefore, the counts within a region around a point-like source have to be included when we analyze the source. We call that region the "region of interest (ROI)".

In order to determine the boresight alignment parameters with the on-orbit data, a likelihood maximization analysis of some bright γ-ray point-like sources has been preformed. For a given source in an ROI, we have implemented a point-like γ-ray source model with a background component. To evaluate the background, we consider all the other point-like sources in the ROI, Galactic diffuse emission, extragalactic emission and some residual cosmic-ray background in the ROI, which, for the sake of simplicity, is modeled as a uniform template with a power-law spectrum (Fermi-LAT Collaboration 2012; Roth 2012). After this model is multiplied by the exposure and convolved with the PSF of DAMPE, we get the expectation of the Poisson distributed variable observed by the γ-rays in the ROI. We ignore the effect of misalignment in the exposure since the angular deviation is expected to be very small and the exposure changes smoothly in the ROI. In the DmpST, we model the PSF by two King functions (Duan et al. 2019) and it is consistent with the GEANT4 simulation for DAMPE, so we apply it to describe the angular distribution of the selected γ-ray sample. Thus, the unbinned Poisson likelihood (Cash 1979) of the reconstructed γ-ray directions to estimate the best fit parameters of the boresight alignment($\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi}$) is given as

$$\ln\mathcal{L}(\lambda,\boldsymbol{\psi},\boldsymbol{\theta},\boldsymbol{\phi}) = -\iiint_{\rm ROI}\sum_{j=1}^{n_{\rm sources}} r_j\left(E',\boldsymbol{p};t',\boldsymbol{\lambda}_j\right) + \sum_{i=1}^{n_{\rm events}} \ln\left(\sum_{j=1}^{n_{\rm sources}} r_j\left(E'_i,\boldsymbol{p}'_i(\boldsymbol{\psi},\theta,\phi);t',\boldsymbol{\lambda}_j\right)\right), \tag{4}$$

Table 1 Preset Boresight Parameters and Statistics of the Fitted Results for Simulation Samples

	Preset Parameters			Fitted Means and RMSs		
Group	$\psi(^\circ)$	$\theta(^\circ)$	$\phi(^\circ)$	$\psi(^\circ)$	$\theta(^\circ)$	$\phi(^\circ)$
1	–0.3083	–0.4682	–1.7161	–0.3068 $\pm$ 0.00246	–0.4605 $\pm$ 0.00302	–0.3046 $\pm$ 0.00434
2	–0.7615	–0.6123	0.3076	–0.7613 $\pm$ 0.00236	–0.6134 $\pm$ 0.00317	–0.3078 $\pm$ 0.00401
3	–1.1194	–0.8551	–0.0436	–1.1195 $\pm$ 0.00262	–0.8562 $\pm$ 0.00275	–0.0450 $\pm$ 0.00477
4	–1.7765	1.2667	0.3106	–1.7743 $\pm$ 0.00275	1.2600 $\pm$ 0.00310	0.3084 $\pm$ 0.00492
5	0.8902	–1.1783	–0.5767	0.8913 $\pm$ 0.00261	–1.1771 $\pm$ 0.00292	–0.5746 $\pm$ 0.00406
6	0.1250	0.0211	–0.1436	0.1242 $\pm$ 0.00247	0.0222 $\pm$ 0.00313	–0.1428 $\pm$ 0.00438

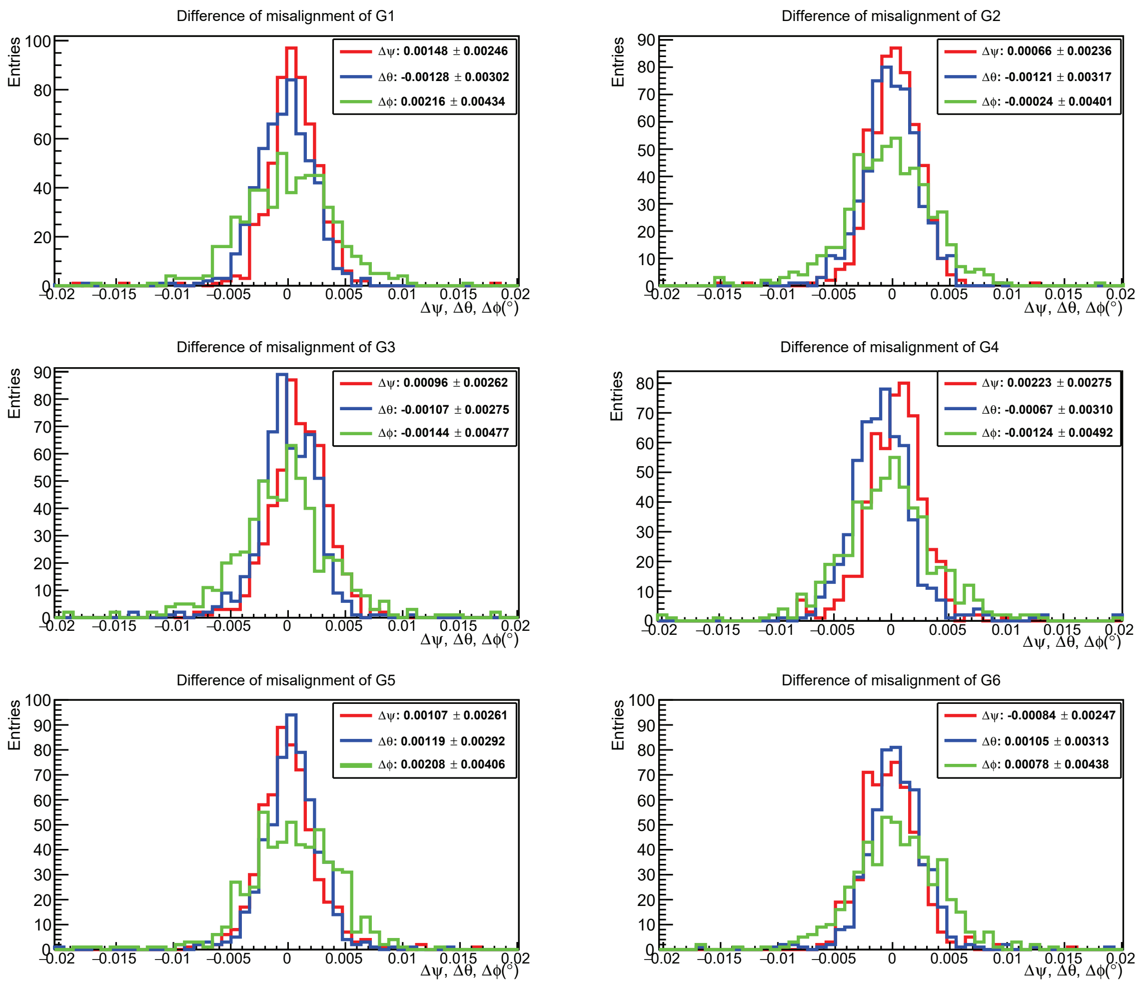

Fig. 1 The difference between the preset alignment parameters and the best-fitted results of the simulation data. The tiny amounts of deviation for all tests validate our boresight alignment method.

where $\lambda(E, \boldsymbol{p})$ is the expected contribution from the point-like source and background to the γ-rays with energy E and direction $\boldsymbol{p}$ in the celestial coordinate system, $\boldsymbol{p}'_i$ is the direction of the i-th photon after boresight alignment and t_i is the time when the j-th photon is recorded by the detector. The `MINUIT`[1] algorithm is adopted to perform the optimization (James & Roos 1975) and the three boresight alignment parameters are derived.

3 VALIDATION

Besides the DmpIRFs and the analysis tools, DmpST contains a simulation module which is utilized to simulate photons from astrophysical sources and process those photons according to the DmpIRFs during the on-orbit operation of DAMPE.

This simulation is cross-validated by the analysis tools in DmpST (Duan et al. 2019) which are used to fit the parameters of the classified γ-ray sources. To validate the alignment method, we manually import a misalignment de-

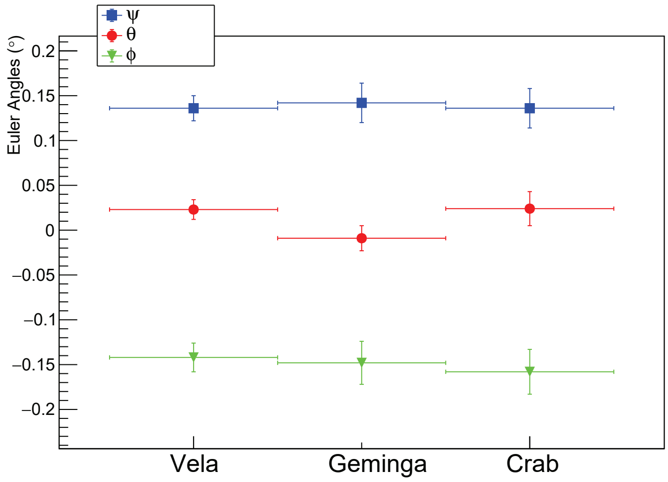

Fig. 2 The derived boresight alignment parameters for Vela, Geminga and Crab pulsars.

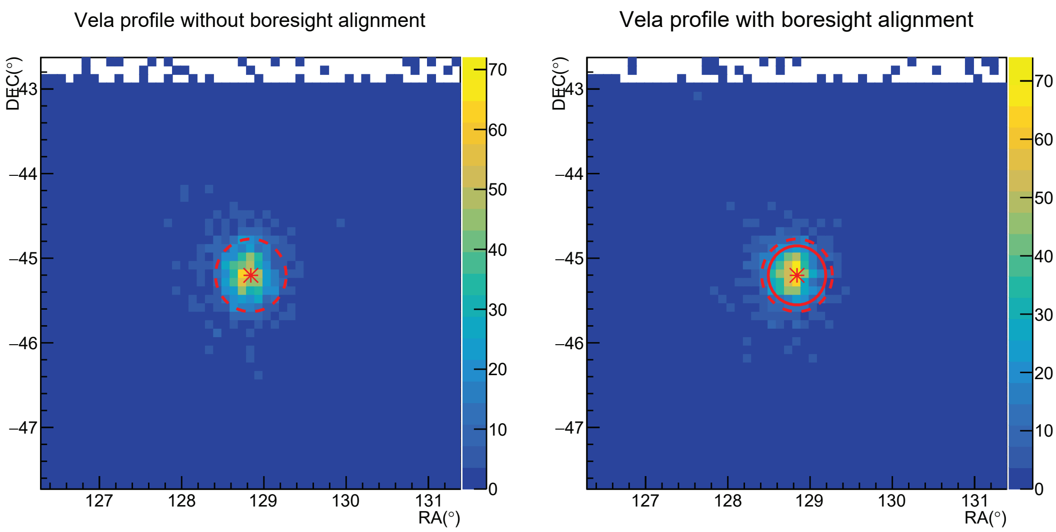

Fig. 3 The distribution of the celestial coordinates of all detected photons between 3GeV and 100GeV around the Vela pulsar. The picture on the left is the result without boresight alignment while on the right is the result after alignment. The *red contours* encircle regions in which 68.3% of the events are from the fitted point-like source. The *dotted* and *solid lines* present the fitted result without and with boresight alignment respectively. The angular radius of the 68.3% contour decreases $\sim 0.08^\circ$ after boresight alignment.

fined by Equation (3) to simulate a sample of γ-ray events, then the same alignment approach is applied to the misaligned sample.

In this test, we randomly select six groups of boresight parameters in the range between -2° to 2°, as summarized in Table 1.

For each group of preset boresight alignment parameters, we simulate observations to the Vela pulsar spanning 3 years for 600 times. We then analyze these γ-ray data with DmpST and carry out the boresight alignment analysis with the procedure introduced in Section 2. As shown in Table 1 and Figure 1, the differences between the preset alignment parameters and the best fitted ones are very small (the root mean square (RMS) is less than 0.005°). Such results demonstrate that the boresight alignment method is reliable.

4 BORESIGHT ALIGNMENT OF FLIGHT DATA

During the first 3 years of on-orbit operation, DAMPE successfully observed some bright GeV γ-rays sources (Xu et al. 2018; Liang et al. 2017). A few sources with accurate location information are bright enough for our purpose of boresight alignment. The sources considered in our following analysis are Vela, Crab and Geminga (Fermi-LAT Collaboration 2012). The data detected from 2016 January 1 to 2019 January 1 are used in the analysis. We selec-

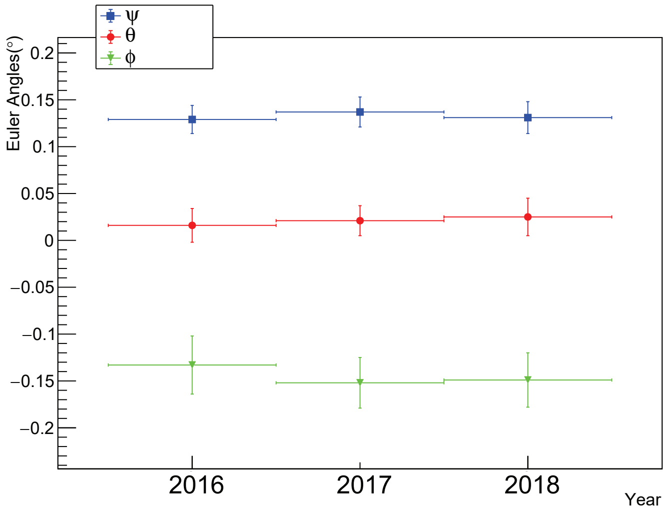

Fig. 4 The boresight alignment parameters of the Vela pulsar for each year. There is no evidence for variation.

t the photons within 4° from the targets and restrict the energy between 3 GeV and 100 GeV (Duan et al. 2019). We fix the spectral parameters of the target sources to the values from the Third Fermi-LAT Catalog of High-Energy Sources (Fermi-LAT Collaboration 2012) and optimize the rotation angles as well as the spectral parameters of the background employing the maximum likelihood method. The resulting boresight alignment parameters for these three sources are consistent with each other (see Fig. 2), as expected. In practice, the parameters which are applied for γ-ray analyses mainly come from the contribution of the Vela pulsar, which are

$$\begin{aligned} \psi &= \ 0.136^\circ \pm 0.014^\circ, \\ \theta &= \ 0.023^\circ \pm 0.012^\circ, \\ \phi &= -0.142^\circ \pm 0.018^\circ. \end{aligned} \tag{5}$$

Because the number of photons collected by DAMPE around the Vela pulsar is at least several times larger than that of any other brightest γ-ray source, the boresight alignment result of the Vela is mainly applied to actual data processing while the other results act as validations and supplements. The uncertainties consist of two independent parts: the statistical errors fitted by MINUIT and the measurement errors of $\sim 0.01^\circ$ to each parameter provided by the engineering parameters of the satellite.

After applying these boresight alignments, the position profile of the target source is improved (see Fig. 3 for illustration). We have also studied the stability of the boresight alignment parameters by evaluating the parameters each year. As depicted in Figure 4, there are no significant variations in the boresight alignment parameters.

5 CONCLUSIONS

The DAMPE payload consists of four sub-detectors and the directions of incident particles are reconstructed with the STK and BGO data in the payload reference system. To convert this to celestial coordinates, we require the celestial orientation of the payload system, which may slightly deviate from the satellite system whose celestial orientation is provided by the GPS and star-trackers. We introduce in this work a calibration of the mismatch between the DAMPE payload and satellite system, the so-called boresight alignment. For such a purpose we have developed a maximum likelihood method. Our approach has been verified with the simulation data provided by DmpST. We then take the 3-year γ-ray data of Vela, Geminga, and Crab pulsars measured by DAMPE to estimate the boresight alignment parameters. The fitted results of the Vela pulsar demonstrate that there is a primary offset between the orientation of payload and satellite platform of $\sim 0.15^\circ$, which is consistent with the other brightest γ-ray point-like sources. We have also examined the variation of these parameters over time and do not find any evidence for their evolution, which provides additional support to the stability of the sub-detectors of DAMPE in space, as found in the on-orbit calibration of the whole payload. With the boresight alignment corrections, the accuracy of the direction measurements of the incident particles are improved.

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