Pattern recognition and direction reconstruction for JEM-EUSO experiment

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Abstract: JEM-EUSO is a space based observatory, that will detect light produced by an extensive air shower (EAS) after interaction of a cosmic ray particle with atmosphere. The fluorescent and Cherenkov light produced in EAS is focused on a focal surface by a system of Fresnel lenses. The focal surface is covered by a set of multi-pixel photomultipliers. For the experiment preparation and the data analysis a dedicated software ESAF is used. ESAF is a robust simulation code which includes libraries for the EAS simulation, fluorescent and Cherenkov light production, its propagation in the atmosphere and the detector response. In order to reconstruct the direction of the primary cosmic rays we need a pattern recognition algorithm able to find EAS on the ‘image’ on the focal surface. In this work we develop algorithms of pattern recognition and angular reconstruction. The results are presented in this proceedings.

Keywords: JEM-EUSO, UHECR, angular reconstruction, pattern recognition

1 Introduction

JEM-EUSO is a space based observatory, that is aimed at observation of ultra high energy cosmic ray (UHECR). The telescope will be mounted to the International Space Station (ISS) at altitude of approximately 400 km. It will collect fluorescent and Cherenkov light produced by extensive air shower (EAS) after interaction of a primary cosmic ray particle with atmosphere [1]. To collect the light from EAS a system of three Fresnel lenses and a focal surface is used. The focal surface is covered by a set of multi-pixel photomultipliers. The description of the detector in more detail can be found in [2] and [3].

One of the main scientific goals of the JEM-EUSO mission is the identification of individual cosmic ray sources using the arrival direction of the primary particle and study acceleration mechanisms with the observed events [4]. JEM-EUSO is able to study UHECR with energies above $5 \times 10^{19}$ eV [5]. The cosmic rays of such a high energy are weakly deflected by the galactic magnetic field and they can be traced back to their origin by their measured arrival direction with accuracy better than a few degrees. Therefore precise estimation of the arrival direction of the UHECRs is among of the major scientific objectives of the mission.

One of the difficulties of arrival direction reconstruction is to distinguish the signal from the background: the atmosphere night glow and city light. In order to discriminate the signal in ESAF (Eusco Simulation and Analysis Framework) [6] several algorithms of the pattern recognition are developed. In this article we focus only one of them: the “Track finding method”.

2 Pattern recognition

2.1 Track finding method

The track finding method is an additional algorithm in ESAF that makes it possible to find a shower track on the focal plane. A track on the focal plane is a sequence of pixels ordered in time and lying along some direction. A signal track is a track corresponding to the EAS signal. This method uses the photon-count distribution on the focal plane at each time step. The time steps in which this information is kept are called gate time units (GTU). The GTU length is fixed by JEM-EUSO’s electronic response, and its nominal value is $2.5\mu s$. Thus we have a “snapshot” of the focal plane with photon-count distribution for each GTU. The task of the algorithm is to find a point that moves uniformly along a straight line on the focal plane using a sequence of snapshots. The algorithm creates a set of all possible track candidates, of which the best one is chosen. To build each track the algorithm uses the principles of Kalman filter [7].

Let us consider the technique of the algorithm in more detail. The algorithm operates sequentially with all snapshot pairs. For each snapshot the pixels with large number of counts are selected. As soon as we have a set of selected pixels the algorithm attempts to connect all possible pairs of pixels between two snapshots into track segments. Thus it tries to connect all pairs of points, which satisfy criteria of distance, duration and deviation from track line. If a point satisfies all the criteria it is added to the track. When the track contains at least two pixels it is fitted with a line on each step. The line is used in “deviation from track line” criterion.

In the Fig. 1a a rough scheme of the algorithm is shown. In the Fig. 1b three obtained tracks and selected pixels that can be added to the tracks are shown. On the next step the selection criteria are used to add new pixels to existing tracks and create new ones [10].

Track candidates are selected not only from two consecutive snapshots: the algorithm is able to look back for 5 GTU in order to find track segments.

The algorithm does not distinguish between the signal and background pixels. However, the background pixels are distributed randomly and the probability of these pixels to be connected into a single track decreases vastly with the track length. In addition, occasionally a background pixel can be added to the signal track, thereby spoiling it. In this case the problem is solved by copying the track before point addition. Thus we have two tracks: one of them does not
have a bad point and another has. This provides a way of continuing track reconstruction even after the addition of an improperly aligned pixel.

In the end of the procedure we have a large set of tracks. Nearly the entire set is composed of short tracks, which are occasioned by the accidental coincidence of background pixels as well as the fragments of the signal track, that are “spoiled” by addition of background pixels. The signal track is selected as a track with maximal summary number of counts: it corresponds to the longest found straight track with highest signal and containing no time leaps. In the Fig. a result of algorithm application to a MC event is shown.

Further, one can define the selection criteria that are used in the algorithm in more detail:

**Pixel selection** The number of selected pixels on each step is an adaptive quantity: the number of selected pixels with same number of counts on each snapshot should be less than 32. In the Fig. the average distribution of p. e. counts for signal and background pixels for events with energies $7 \times 10^{19}$ and $3 \times 10^{20}$ eV and incident angles $30^\circ$ and $75^\circ$ are shown. One can see that the chosen cut on number of counts selects a big portion of background pixels in addition to signal ones: the main purpose of this cut is to limit the number of track candidates in memory.

**Distance** In the beginning of the procedure the maximal distance between two connected pixels is equal to 2 pixel diagonals. If track average velocity exceeds one pixel diagonal per GTU the additional cut on distance is applied: the distance to the new pixel divided by delta GTU should be less than doubled track velocity.

**Duration** The duration between two connected pixels should be less than 5 GTU. This number is based on the geometry of the focal plane and velocity of the track: the gap between photomultipliers is not large enough to produce a delay in signal of more than 5 GTU.

![Figure 1: The scheme of track finding method.](image1)

Figure 1: The scheme of track finding method. Figure 1a represents three already found tracks (dashed lines) with their pixels (black dots) and a fitted line for the track containing more than 2 pixels. Selected pixels which will be added to the tracks on next iterations are drawn with circles (+1 GTU) and triangles (+2 GTU). Figure 1b represents the same set of data, but after the addition of new pixels: two more short tracks are found, one track is extended and one pixel is ignored since it’s not matched to any track.

**Deviation from the track line** A distance between the pixel and the fitted line should be less than 2 pixels in size.

The constants for this algorithms are chosen based on geometrical estimations and in the future can be tuned based on simulation results. Currently the algorithm was tested on the MC simulation and reconstructs proper tracks for all the triggered events.

3 Angular Reconstruction.

After the signal discrimination basic information about the track on the focal plane is available. For each pixel on the focal surface that is determined as ‘signal’ the number of
produced photo-electrons $N_{p.e.}^i$, their timing information $t_i$ and photons arrival direction $\vec{n}_i$ are known.

The first step of the angular reconstruction is the estimation of the Track Detector Plane (TDP). It is the plane that contains the shower track and the detector itself.

### 3.1 TDP determination algorithm

Based on $\vec{n}_i$ the unit vector pointing on the shower maximum $\vec{n}_{\text{max}}$ can be obtained and the TDP can be computed in the following way. The TDP is determined by it's normal $\vec{V}$. It can be made up of two unit vectors $\vec{n}_{\text{max}}$ (pointing to the shower maximum) and $\vec{n}_i$ (Fig. 4):

$$\vec{V}_i = \vec{n}_i \times \vec{n}_{\text{max}} / \sin(\alpha_i)$$  \hspace{1cm} (1)

where $\alpha_i$ is angle between $\vec{n}_{\text{max}}$ and $\vec{n}_i$. The normal $\vec{V}(\theta_V, \phi_V)$ describing TDP is found by maximizing the sum of scalar products of $\vec{V}$ and $\vec{V}_i$: $C = \sum \langle \vec{V}_i \vec{V} \rangle$. All $\vec{V}_i$ are chosen to point in the same half-sphere, so all scalars have the same sign. This can be done analytically by requiring first derivatives of $C$ by $\theta_V$ and $\phi_V$ to be zero. Thus the TDB is given by the following equations:

$$\theta_V = \arctan \left( \frac{\sum \sin \theta_i}{\sum \cos \theta_i} \right), \quad \phi_V = \arctan \left( \frac{\sum \sin \phi_i}{\sum \cos \phi_i} \right)$$  \hspace{1cm} (2)

Once TDP is found the task of finding 3-dimensional shower direction vector $\vec{\Omega}$ is reduced to the 2-dimensional case with a single parameter $\beta'$. As one can see from Fig. 4 the $\beta'$ is the plane angle between vector that points to shower maximum $\vec{R}_{\text{max}}$ and shower direction $\vec{\Omega}$. The shower direction vector $\vec{\Omega} = -\left( \sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta \right)$ can be found by rotating $\vec{n}_{\text{max}}$ around the calculated $\vec{V}(\theta_V, \phi_V)$ on the angle $\beta' = \pi$.

### 3.2 Direction reconstruction algorithm

As soon as the TDP is found the expected value of $\vec{n}_i = \frac{\vec{R}_i}{|\vec{R}_i|}$ can be obtained:

$$\vec{R}_i' = \vec{R}_{\text{max}} + \vec{\Omega} \cdot L_i$$  \hspace{1cm} (3)

where the $L_i$ is the distance which shower passes during time $\Delta t = t_i - t_{\text{max}}$. $L_i$ is given by eq.:

$$L_i = c \Delta t + R_{\text{max}} - \vec{R}_i'$$  \hspace{1cm} (4)

The length of the expected vector $\vec{R}_i'$ then can be found by taking the square of eq. (3). Thus $\vec{R}_i'$ is given by the following equation:

$$\vec{R}_i' = \frac{\left( \vec{R}_{\text{max}} + \vec{\Omega} (c \Delta t + R_{\text{max}}) \right)^2}{2 \left( \vec{R}_{\text{max}} \cdot \vec{\Omega} + c \Delta t + R_{\text{max}} \right)}$$  \hspace{1cm} (5)

The distance $R_{\text{max}}$ between the detector and shower maximum can be obtained using equation in which the altitude of the EAS maximum $H_{\text{max}}$ is computed using relation between the time width of the signal on the focal plane $\sigma$ and air density $\rho(\bar{E}_{\text{max}})$ in the atmosphere at.

Figure 3: The integrated signal on the focal surface from EAS with $E = 1 \cdot 10^{20}$ eV and $\theta = 60^\circ$. The pixels selected by the algorithm are marked with black circles. The dotted red line represent the obtained track line. Pixels color corresponds to the p. e. count.

Figure 4: The scheme of angular reconstruction algorithm.
which EAS develops \([6]\). \(R_{\text{earth}}\) and \(H_{\text{ISS}}\) denotes the earth radius and altitude of the ISS, respectively. The angle \(\theta_{\text{max}}\) corresponds to the angle between two unit vectors \(\hat{n}_{\text{max}}\) and vector pointing from ISS to the center of Earth.

\[
R_{\text{max}} = (R_{\text{earth}} + H_{\text{ISS}}) \cdot \cos \theta_{\text{max}} - \\
\sqrt{(R_{\text{earth}} + H_{\text{max}})^2 - ((R_{\text{earth}} + H_{\text{ISS}}) \cdot \sin \theta_{\text{max}})^2}
\]

(6)

Equations [7] and [8] were obtained using the GIL parametrization for the longitudinal development of the number of charged particles. \(\xi_{\text{max}}\) is a dimensionless parameter, \(E\) is the energy of the primary particle, \(A\) — its atomic number, \(X_0 = 37.15\ \text{g/cm}^2\) — air radiation length, \(E_c = 81\ \text{MeV}\) (critical energy), \(a = 1.7, b = 0.76\). These values are chosen based on CORSIKA-QGSJET-II results [8].

\[
\sigma = \sqrt{2 \max_{n \text{mix}} \left(\frac{X_0(1 + \max_{\text{max}} \Delta)}{\rho(H_{\text{max}})}\right)}
\]

(7)

\[
\xi_{\text{max}} = a + b \ln \left(\frac{E}{E_c - \ln A}\right)
\]

(8)

Considering that parameter \(\xi_{\text{max}}\) depends on UHECR energy logarithmically, it can be taken into account in an iterative procedure or the energy can be set to a mean expected value. The \(\sigma\) can be estimated from the information about the signal or can be assumed as a minimization parameter.

As soon as we calculate \(\rho(H_{\text{max}})\) the altitude of the EAS maximum becomes known. This method of the altitude shower maximum reconstruction is correct for any kind of particle.

Thus we have two minimization parameters \(\beta'\) which along with TDP determines \(\Omega\) and \(\rho(H_{\text{max}})\) which determines \(H_{\text{max}}\).

Since the expected value of the photons arrival direction \(\vec{n}(\vec{\theta}_{\text{expected}}, \vec{\gamma}_{\text{expected}})\) is computed, we can minimize the \(\chi\) function, that is defined as:

\[
\chi = \sum_{i=1}^{n_{\text{pix}}} \left(\frac{\vec{n}_i - \vec{n}_{\text{expected}}}{\sigma_\theta} \right)^2 N^\text{p.e.} \cdot \left(\frac{\sigma_\gamma}{\sigma_\gamma}\right),
\]

where \(\sigma_\theta = |\vec{n}_{i+1} - \vec{n}_i| = \sqrt{2(1 - \cos \gamma)}\) is calculated as variation of \(\vec{n}_i\) within time of 1 GTU, where \(\gamma\) is angle between \(\vec{n}_{i+1}\) and \(\vec{n}_i\), \(\sigma_\gamma = \sqrt{2(1 - \cos \gamma)}\) is calculated as variation of \(\vec{n}_i\) inside a single pixel field of view \(\Omega_{F_{\gamma}}^{\max}\), where \(\gamma\) is the cone angle that one can calculate using following equation \(\gamma \approx \sqrt{4 \Omega_{F_{\gamma}}^{\max}}\). Both assumptions overestimate the real error and will be improved in future.

To estimate the expected angular resolution of JEM-EUSO the angle \(\gamma\) between the injected shower axis and the reconstructed one is compared. We define \(\gamma_{68}\) as the value at which the cumulative distribution of \(\gamma\) reaches 0.68. The systematic errors and statistical fluctuations are included within the definition of \(\gamma_{68}\). This parameter is used to see the overall performance of our reconstruction capabilities. The expected angular resolution without any selection cuts for different energies and EAS zenith angles \(\theta\) is presented in the Fig. 5. The azimuth shower angle \(\varphi\) is simulated randomly.

4 Conclusions

Currently the pattern recognition algorithm was tested on the MC simulation and reconstructs proper tracks for all the triggered events. The pattern recognition parameters will be fine-tuned in order to increase performance and minimize memory footprint.

The direction reconstruction accuracy satisfies the experiment requirements: \(\gamma_{68} < 2.5^\circ\) for \(\theta = 60^\circ\). The results are comparable with other direction reconstruction algorithms used in ESAF. The errors used in \(\chi^2\) calculation are to be updated.

Acknowledgment: This work was partially supported by Basic Science Interdisciplinary Research Projects of RIKEN and JSPS KAKENHI Grant (22340063, 23340081, and 24244042), by the Italian Ministry of Foreign Affairs, General Direction for the Cultural Promotion and Cooperation, by the ‘Helmholtz Alliance for Astroparticle Physics HAP’ funded by the Initiative and Networking Fund of the Helmholtz Association, Germany, and by Slovak Academy of Sciences MVTS JEM-EUSO as well as VEGA grant agency project 2/0081/10. The Spanish Consortium involved in the JEM-EUSO Space Mission is funded by MICINN under projects AYA2009-06037-E/ESP, AYA-ESP 2010-19082, AYA2011-29489-C03-01, AYA2012-39115-C03-01, CSD2009-00064 (Consolider MULTIDARK) and by Comunidad de Madrid (CAM) under project S2009/ESP-1496. The work was partially supported by JINR grant No. 13-902-07.

References


Figure 5: \(\gamma_{68}\) for different energies and \(\theta\) configurations.