The Peak and Window Searching Technique for the EUSO Simulation and Analysis Framework: Impact on the Angular Reconstruction of EAS.

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Abstract.
With the forthcoming of space borne observatories devoted to research Ultra High Energy Cosmic Rays (UHECR) in the decade of 10^{20}eV, new challenges are posed to the experimental techniques. Mounted on the International Space Station, the Extreme Universe Space Observatory on board the Japanese Experimental Module (JEM-EUSO) will rely on the well established fluorescence technique to observe Extensive Air Showers (EAS) propagating in the atmosphere from space. The EUSO Simulation and Analysis Framework (ESAF) has been developed in this context to provide a full end-to-end simulation frame. Within ESAF the angular reconstruction modules rely on an a priori knowledge of the photoelectrons that were produced by an EAS and were also detected by the focal surface. Therefore, there is the need for a tool that discriminates between EAS-photoelectrons and background. In this paper we discuss the Peak and Window Searching (PWISE) technique, which we have implemented inside ESAF as a module to perform the discrimination of the EAS photoelectrons. This is essential since the angular reconstruction modules rely on the knowledge of the EAS-photoelectrons. We also present some first results of the angular reconstruction using this module within ESAF.

1. Introduction
JEM-EUSO is a space telescope devoted to the observation of UHECRs showers in the Earth’s atmosphere [1]. This Fresnel-optics refractive telescope will fly on board of the International Space Station (ISS) at an altitude of 278-400 km. Due to the larger exposure, JEM-EUSO will study of UHECR with unprecedented statistics, allowing it to study the sources and their spectra with high precision[4].
The EUSO Simulation & Analysis Framework (ESAF)[2] is a modular software built upon the ROOT1 framework. It is designed to simulate space based Ultra High Energy Cosmic Ray

1 root.cern.ch/
(UHECR) detectors. Although currently ESAF is being developed in the context of the JEM-EUSO mission[1], its modular structure allows ESAF to simulate any JEM-EUSO-like detector. The simulations account for the physical processes that take place during the development of an Extensive Air Shower (EAS). Each simulation covers the whole chain, the longitudinal development of the EAS itself, the fluorescence and cherenkov light produced at the shower site, the atmospheric propagation of photons, as well as the processes within the detector, i.e. the propagation of photons through the optics, the response of the electronics, and the triggering algorithms. ESAF also provide the tools for reconstructing the simulated events based of the saved information of the detector’s response.

One of the main scientific goals of the JEM-EUSO mission is the identification of individual sources by a high-statistics arrival direction analysis. This could also allow measurements of the energy spectra of such sources. Therefore the assessment of the incoming direction of the UHECR will be one of the key elements in the scientific outcome of the mission[4].

2. Direction reconstruction within ESAF

2.1. Overview

ESAF was developed for space borne UHECR detectors which detect and record the fluorescence and cherenkov light of an EAS as it transverses the atmosphere. On the focal surface of such a detector, this will translate into a moving signal within the pixels of the detector. This moving signal will be used to define an “EAS-track”. In the case of energies in the excess of $10^{19.7}$, the particle’s trajectory is slightly deflected by the galactic magnetic field therefore the EAS’s track will point to the astrophysical source of the UHECR[5].

Within ESAF the information of the position on the Focal Surface (FS), the timing, and intensity of the signal are used to approximate the geometrical characteristics of the EAS-track namely the impact point at the Earth’s surface (if any), the azimuthal angle $\phi$, and zenithal angle $\theta$ (see Figure 1). Once the geometrical characteristics of the EAS are calculated, the other reconstruction modules can use them to calculate the energy of the primary, the slant depth at EAS’s maximum($X_{max}$), height of the first interaction, etc.

Of particular importance is to disentangle the background noise from the signal coming from the EAS. To address this issue the JEM-EUSO instrument has a dedicated trigger technology [3] that filters the relevant information from the whole of the focal surface. Thus, transmitting only the information from the pixels that are most likely to contain an EAS signal.

Nevertheless, once the information from the selected pixels are transmitted a second more stringent algorithm must separate signal from background. To this effect we have implemented the Peak and WIndow SEarching (PWISE) technique.

![Image 1](image_url)

**Figure 1.** Image on the focal surface of the selected pixels (see text) and the consecutive cleansing of the signal.
Within ESAF’s modular approach, basically there are 3 reconstruction modules: Pattern Recognition, Angular Reconstruction and Energy Reconstruction. Nevertheless for the scope of this work we shall only focus on the first two:

- **Pattern Recognition.** This module is in charge of tagging the detected photons as photons generated by the EAS. Disentangling them from parasitic background photons induced by the atmospheric night glow or by weather phenomena. In this work we present the PWISE technique as an example of this module.

- **Angular Reconstruction.** This module calculates the most probable geometrical configuration that produced the photons labeled as EAS. This is done by properly interpreting the time of arrival of each photon and its position in the focal surface.

2.2. *The Peak and Window Searching Technique (PWISE).*

This module was developed by the authors to provide another option within the pattern recognition modules already available in ESAF. The virtue of this module is that it selects not only photons coming from the EAS, but it also filters the multiple-scattered ones that provide a “fuzzy” image of the track due to their shifted time of arrival. Its principle of operation is straightforward: for each pixel selected by the trigger, PWISE will only consider pixels whose highest photon count (peak) is above a certain threshold. Next PWISE will only select the photon counts within an specified time window centered on the aforesaid pixel’s maximum peak. To specify the time window the signal-to-noise ratio (SNR) must be higher than another given SNR-threshold. In our case the SNR as a function of the time window’s width ($\Delta \tau$) is defined by:

$$SNR = \left( \frac{1}{\Delta \tau \cdot RMS} \right) \sum_{\Delta \tau} pe(t)$$

In this last expression $pe(t)$ stands for the number of photoelectron counts as a function of time, and RMS the root-mean square of the pixel’s photoelectron counts.

2.3. *LTT-PreClustering*

The Linear Tracking Trigger (LTT) Pre-Clustering technique is an algorithm which can further enhance the performance of the angular reconstruction when applied preceding the actual pattern recognition. It selects the pixels on the focal surface containing the highest number of counts. Then it searches for the track that maximizes counts by moving an integration box along a predefined set of directions intersecting this point. Pixels outside this track are ignored by the following pattern recognition. It eliminates the vast majority of pixels that could potentially being mistaken as signal pixels by the pattern recognition.

3. **Results**

Let us name $\gamma$ the angle between the simulated-EAS’s arrival direction and the reconstructed-EAS’s arrival direction. We define $\gamma_{68}$ as the minimum value that fulfills that 68% of $\gamma$’s are less than $\gamma_{68}$. We use this parameter as a measurement of the overall performance of our study’s reconstruction capabilities. It is worth mentioning that both systematic errors and statistical fluctuations are included in the definition of $\gamma_{68}$.

As a first rough approach to assess ESAF’s current angular reconstruction capability, we simulated a set of proton initiated EAS and then compared the angle between the simulated incoming direction and the reconstructed one. This set of EASs consisted of EASs with energies of $7 \times 10^{19}$ eV, $10^{20}$ eV, and $3 \times 10^{20}$ eV. For each one of these energies we simulated $\approx 1000$ EAS at 4 fixed zenith angles ($\theta$), namely, 30°, 45°, 60°, and 75°; while the azimuthal angle
Figure 2. Preliminary results for JEM-EUSO’s angular reconstruction error $\gamma_{68}$ (see text) as a function of the zenith angle.

was randomly taken between 0° and 360°. The results of this preliminary study can be seen in Figure 2.

Since JEM-EUSO is observing the EAS’s track from above, the more vertical the EAS is, the harder it will be to reconstruct it (e.g. $\theta \leq 45^\circ$). This complication arises since these EASs are seen by relatively less pixels than EAS more parallel to the ground (more inclined showers).

4. Conclusion
We have conducted a high statistics study on the angular reconstruction capabilities of the JEM-EUSO mission. While there is still room to improve, we can conclude that the present preliminary status already satisfies the scientific requirements of the mission. We are working towards more refined selection mechanisms and the same goes for angular reconstruction algorithms. We are confident that in the nearby future, we will be able to improve these results. As an extra outcome of the study presented here, we have tested the robustness of the ESAF framework for simulating space borne detectors.

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