# Reconstruction of Extreme Energy Cosmic Ray Events Observed by JEM-EUSO in the ESAF Framework

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***Abstract*. The JEM-EUSO (Extreme Universe Space Observatory onboard the ISS Japanese Experiment Module) aims at measuring the extreme energy component of cosmic rays up to the decade of $10^{20}$ eV. When striking the earth's atmosphere, protons, nuclei and neutrinos interacting with air initiate extensive air showers (EAS). By observing from space the fluorescence and Cherenkov light emitted by the EAS, the species, energy and direction of the primary particle can be effectively determined. Due to the altitude of approximately 430 km the instantaneous aperture of JEM-EUSO will be in the order of $10^5$ km$^2$ sr. This allows us to observe the entire shower development with relatively small light absorption. The ESAF (EUSO Simulation and Analysis Framework) software package has been designed to simulate space-based observation of EAS, taking into account all necessary steps from EAS generation, propagation of light in atmosphere, detector response and eventually reconstruction. In this paper we will give an overview on the algorithms used for track analysis, geometrical reconstruction and energy measurement. We will illustrate step by step the reconstruction chain and describe how it has been updated to meet JEM-EUSO specification.**

***Keywords*: ESAF, Reconstruction, JEM-EUSO**

## I. Introduction

The JEM-EUSO mission has been designed to observe cosmic rays with an energy above $10^{19}$ eV from space. Due to the low flux of particles with energies of this order [1] monitoring a huge target mass is required to detect a statistics of more than 1000 events [2]. JEM-EUSO uses the UV light emitted by EAS to evaluate the energy, indent direction and type of the primary particle.

ESAF is a ROOT-based software package, written in an object oriented aproach with C++ and partly FORTRAN code. It has been developed for the former (ESA) EUSO mission to provide an End-To-End framework, able to simulate the whole chain of events. All relevant physical processes are taken into account: simulation of primary particle and air shower development, propagation of light in atmosphere, detector response and finally reconstruction of the event [3].

Currently, ESAF is upgraded to meet the requirements and features of the JEM-EUSO mission.

This paper focuses on the reconstruction techniques used in ESAF as first described in [5], [4] and [6]. First we describe how pattern recognition is applied to distinguish signals from background and to estimate their geometrical parameters on the focal surface. Then we give a brief introduction to the direction and energy reconstruction algorithms. In the end we summarize the recent developments of the ESAF framework.

## II. Pattern Recognition

The JEM-EUSO instrument detects the fluorescence signal of the EAS as a track on the focal surface whose geometry, intensity and timing allows to reconstruct the direction and maximum of the shower and therefore the energy and incoming direction of the primary particle. ESAF provides two possibilities to disentangle signal from background and to estimate the geometrical properties of the signal track on each projection plane of the focal surface: Cluster Analysis (CA) and Hough Transform (HT).

### A. Cluster Analysis

This method attempts to organize patterns into groups. Active pixel are regarded as randomly scatterded data points interlinked by a minimum spanning tree (MST) (Fig 1). The weight of each edge of the MST is in our case the Euclidean distance. A cluster track can be identified by all those pixel whose distances are less than a certain threshold $\xi$. It will be regarded as significant, once the number of active pixel contained exceeds a

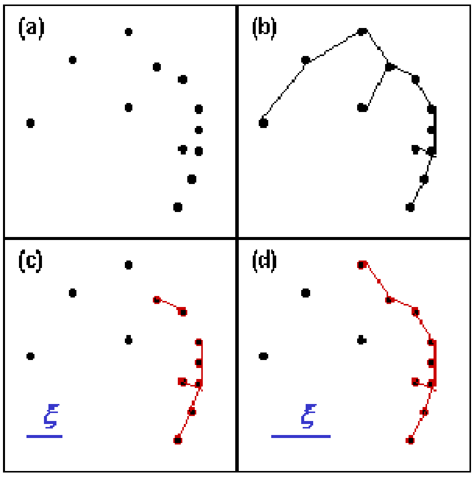


Fig. 1. (a) data points interlinked by a minimum spanning tree (b). Clustersize depends on $\xi$ (c,d), [4]

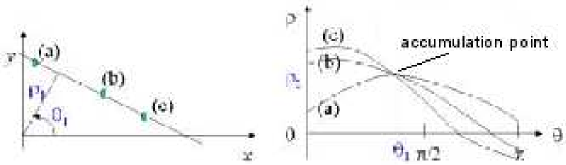


Fig. 2. Image points (a),(b),(c) are mapped into parameter space, [5]

certain value. After clustering, a line fit is performed to estimate the parameters of the shape in each projection plane [4].

### B. *Hough Transform*

The Hough Transform is an algorithm for the detection of certain objects in images and estimation of their parameters. To speed up the process in order to save computer power we need a small number of parametrized objects - in our case we are searching for straight signal tracks. Originally designed to identify shapes in bubble chambers, it converts the initial problem (find a straight track on each projection plane of the focal surface) from the image space into a parameter space. (See Fig.2) For each 'feature point' in our image space we can think of many straight lines passing through it. In polar coordinates each line can be parametrized by two parameters: distance to origin $\rho$ and $\theta$, the angle between the normal of the length $\rho$ to the origin of the coordinate system and the x-axis. When this is mapped to parameter space each data point is represented by a sinusoidal curve in parameter space.

$$\rho = xcos\theta + ysin\theta$$

The point where the sinusoidals intersect transformed back to image space corresponds to a line passing through all data points. The identification of the track's geometrical parameters can be performed by a line fit [5].

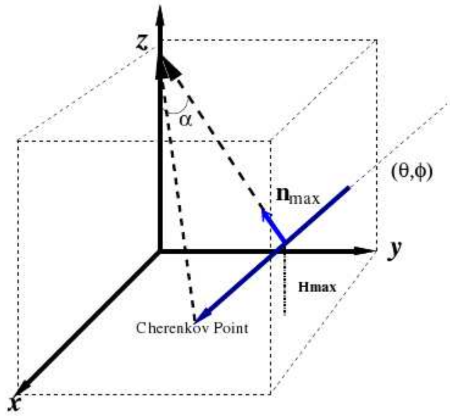


Fig. 3. Shower in atmosphere with Cherenkov point, [6]

## III. Direction Reconstruction

The module devoted to the reconstruction of the shower direction inherits the points found by pattern recogniton (CA or HT) as described in the previous paragraph and then finds the plane that contains the track and the detector plane (TDP) by a further HT and a linear fit of the x-t, y-t projections of these points on the plane. Then the shower direction is reconstructed by numerical and analytical methods where the angular velocity of the incoming light to the detector is taken into account. After upgrading ESAF to JEM-EUSO configuration, some changes in the fitting procedures and careful selection of angular reconstruction methods have been inevitable. Currently thorough testing of angular reconstruction capabilities with ESAF is in progress.

## IV. Reconstruction of Shower Maximum and Energy

Apart from the knowledge of the origin of the particles, it is important to measure the energy. This is directly linked to the reconstruction of the altitude of the shower maximum $H_{max}$. It is our key parameter for the fitting procedure, neccessary to estimate the energy. Besides that, the shower depth in atmosphere $X_{max}$ can be retrieved relatively easy from $H_{max}$, which is important for the identification of the type of the primary particle. In general there are two possibilities in ESAF to be used for the reconstruction of the shower maximum.

### A. *The Cherenkov Technique*

For events with an inclination angle $< 70°$ usually a Cherenkov reflection mark on the earth's surface can be observed. Using the time delay between arrival of the photons from direct fluorescence and reflected Cherenkov light, the altitude of the maximum can be reconstructed [6] (Fig. 3). This method could be applied for less inclined showers with great precision. However, identification of the Cherenkov stamp belonging to a certain flourescence track on the focal plane is not an easy task, because geometrically it is not always obvious that fluorescence track and Cherenkov stamp belong

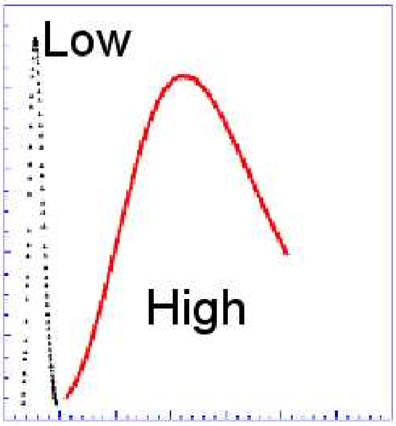


Fig. 4. The number of photons arriving to JEM-EUSO for two horizontal EAS at different altitudes. [6]

together. Here the timing information is being used. In principle ESAF is able to handle the application of this tool for the estimation of the shower maximum, nevertheless at this stage it is relying on the $H_{max}$ by shape method only.

### B. The $H_{max}$ by Shape Method

Duration and brightness of a showertrack strongly depends on the density of the atmosphere traversed. The number of photons produced in the shower and thus the amount of photons arriving at the detector is proportional to the shower lenght [6]. However, shower length decreases with air density (Fig. 4). Therefore, knowing air density at the maximum enables us to calculate the altitude of the maximum $H_{max}$.

Air density can be derived from the ratio of photons arriving to JEM-EUSO from the shower maximum $N_{max}$ and in total $N_{tot}$.

$$N_{max}/N_{tot} \sim \rho(h) \quad (1)$$

The number of photons per shower length interval arriving at the detector is

$$dN = \frac{\Delta\Omega}{4\pi} Y \eta N_e(t) dL \quad (2)$$

where $\Delta\Omega$ is the JEM-EUSO solid angle, $\eta$ the atmospheric transmittance, $Y$ the fluorescent yield and

$$N_e(t) = \frac{E}{E_1} e^{f(t)}$$

represents the number of electrons and positrons in the shower according to the GIL parametrization that approximates the longitudinal shower profile analytically [7]. E is the energy of the incident particle, $E_1$=1.45 GeV, $f(t) = t - t_{max} - 2t(ln(s))$, with $t = \frac{x}{x_0}$, where $x$ is the atmospheric depth measured in g/$cm^2$, $x_0$=37.15 g/$cm^2$ the air radiation length. At $t_{max}$ the

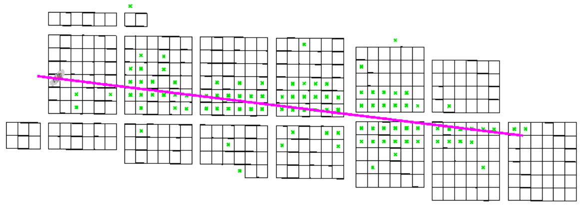

Fig. 5. Signal track on a part of the focal surface with line fit. Primary particle: proton with energy of $10^{20}$ eV, $\theta$=60°

shower reaches the maximum, $s$ stands for the shower age.

This allows us to calculate the number of photons from the shower maximum, but also the total number of shower photons by computing the integral of (2).
The ratio of $N_{max}$ and $N_{tot}$ can be approximated by

$$N_{max}/N_{tot} = \frac{\rho(h_{max})\Delta L}{x_0\sqrt{\pi t_{max}}(Erf_{left} + Erf_{right})} \quad (3)$$

where Erf stands for the error function on the left and right part of the shower. For a more detailed derivation of the formulas, refer to [6]. Knowing the air density at $H_{max}$ finding $X_{max}$ is straightforward. All we need to know is the density profile of the atmosphere. $X_{max}$ will provide us with the possibillity to distinguish between incoming neutrinos and nuclei.

### C. Estimation of the Energy

From the signal track on the focal surface (Fig.5) a histogram (Fig.6), showing the distribution of counts per time is extracted. To enable the fitting routine for the estimation of the energy, some corrections need to be applied. First the deadtime of the photomultipliers which suppresses a fraction of the counts is considered. After considering the background noise and quantum efficiency, the optics response is taken into account. The efficiency of the optics plays an important role, as well as the dependency on the incoming angle of the light on detector pupil. Due to the dead spaces between the single photomultiplier tubes there are some gaps in the counts curve - they are systematically corrected as well. After considering these various effects, a Gaussian fit is performed that recovers -using the GIL parametrization- the energy.

## V. Upgrades to JEM-EUSO Configuration

Due to the several improvements that have been made to adapt ESAF to the new JEM-EUSO detector including trigger algorithms, new optics and new focal surface layout an upgrade of the pixel-anglemap has been inevitable. This assignment table is necessary to relate each pixel on the focal surface to a certain angle in the field of view of the detector. It is generated by a ray tracing code and its precision is of utmost importance for the correct reconstruction of the information of interest.

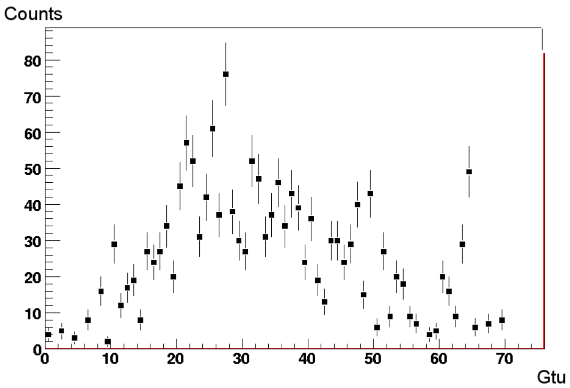


Fig. 6. Count distribution vs time (in Gtu, 1 Gtu=2.5 $\mu$s). Primary particle: proton with energy of $10^{20}$ eV $\theta$=60°

## VI. Conclusions

ESAF is a strong tool for the simulation and reconstruction of EHECR. The software has been upgraded to JEM-EUSO configuration. A preliminary version is now running. Our ESAF approach provides an independent and parallel assessment of the JEM-EUSO performance. A complete End-To-End simulation and analysis of a larger number of events including studies about angular and energy resolution will be carried out in the near future.

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