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The ESAF Reconstruction Framework of UHECR Events for the JEM-EUSO Mission

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Abstract: JEM-EUSO is a space based UV detector that will be mounted on the International Space Station (ISS) to monitor the earth's atmosphere searching for UHECR induced extended air showers (EAS). By evaluating the fluorescence and Cherenkov signal on the focal surface of the instrument the arrival direction, energy and nature of the primary can be determined. Due to the instantaneous aperture of 10^5 km^2 sr JEM-EUSO will be able to measure several hundreds of events at energies higher than 5*10^{19} eV. ESAF is a software for the simulation of space based UHECR detectors. It is configured to cover the specific aspects of the JEM-EUSO mission and to estimate its expected performance. ESAF can simulate every step of the generation and observation of an EAS - from the fluorescence track formation, the light transport in the atmosphere and through the instrument to the telemetry stage. The reconstruction chain covers the discrimination of the recorded track from background as well as the estimation of energy, arrival direction and Xmax for the determination of the UHECR species. In this paper we present strategies and algorithms implemented to estimate the spatial and energy resolution of JEM-EUSO as well as a selection of examples demonstrating the expected performance.

Keywords: JEM-EUSO, ESAF, Reconstruction, UHECR Events.

1 Introduction

The JEM-EUSO detector is a space based UHECR detector designed to be mounted on the Japanese Experiment Module "Kibo" on board the ISS [1]. It will monitor the earth's atmosphere from above to search for extended air showers generated by of cosmic rays in the energy range of 10^{19} eV to 10^{21} eV and possibly beyond. JEM-EUSO will reach an instantaneous aperture of approximately 10^5 km^2 sr [2] allowing a high statistics of events compared to ground based observations. Thus, JEM-EUSO is a key mission to explore the realms of extremely high energy cosmic rays far beyond the capabilities of any ground based UHECR observatory. More details can be found in [3].

ESAF - the EUSO Simulation & Analysis Framework, is a ROOT [4] based, modular software designed to simulate space based UHECR detectors. It has been developed in the context of the former EUSO mission [5]. Its modular structure allows to simulate any EUSO-like[1] instrument. The simulation comprises all physical processes relevant to UHECR measurement. Among these are the development of the resulting air shower, the production of fluorescence and Cherenkov light as well as propagation of photons towards the detector. Inside the instrument, simulations involve the propagation of photons through the optics, the response of the photomultiplier and electronics and the event reconstruction eventually. In this article we explain the reconstruction algorithms implemented in ESAF and present some results to demonstrate their achievement potentials.

2 The Reconstruction Framework

Cosmic ray induced EAS emit fluorescence light isotropically in all directions plus a beamed Cherenkov component. Parts of that light go directly to the telescope. Other com-

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[1] We define EUSO-like a space borne detector for the measurement of UHECR by the measurement of the fluorescence and/or Cherenkov light of EAS.

ponents are reflected diffusely from ground or scattered towards JEM-EUSO. The UV photons reaching the entrance pupil of the instrument propagate through the optics and activate the photomultiplier tubes arranged on the focal surface. When the readout electronics recognizes certain patterns a trigger is issued. Now the signal is processed and transmitted to earth for analysis and reconstruction. More details on the observation technique can be found in [2].

In ESAF different modules are dedicated to the single stages during the evaluation of the signal. First of all, the signal has to be disentangled from noise. Following that direction and energy reconstruction algorithms can be applied.

2.1 Pattern Recognition

The fluorescence signal will appear as a faint moving spot of the instruments focal surface embedded in the background generated by night glow, city lights, weather phenomena and other sources. The extraction of the signal track and the determination of its spatio-temporal behavior remains crucial for any further analysis aiming at reconstructing the arrival direction or energy of the primary. There are two possible algorithms for the pattern recognition:

- *Clustering* of data points in space and time to disentangle causally related data points from those distributed randomly.
- *Hough Transform*, developed to identify prefixed shapes within noise by transforming the relevant parameters to the so called Hough space and back.

Both are in principle capable to perform the required operation and have been implemented in ESAF.

2.2 Clustering

The approach of the cluster technique is to arrange data points into causal patterns by analyzing their minimum spanning tree (MST) which is in this case made of the Euclidean distance between them (fig. 1). A group of activated pixel is then identified as a cluster if their distance is less than a certain pre-adjusted threshold ξ. If this cluster is regarded as significant (large with respect to others) a line fit is performed to estimate its geometrical parameters [6].

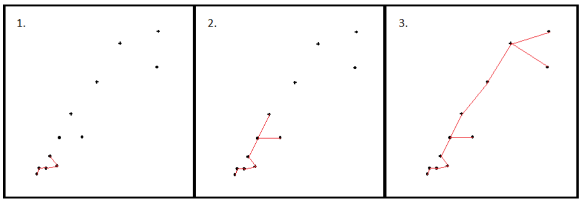

Figure 1: Clustering of data points: the size of the cluster depends on a threshold

2.3 Hough Transform

Initially designed for the detection of patterns in bubble chambers, the HT is an algorithm for the discrimination of certain shapes (even incomplete ones) from others, e.g. noise [7]. Here the item sought-after is a longish pattern that can be abstracted as a straight line. For each data point the HT assumes a number of lines passing through it. These lines can be parametrized by their distance from the origin of the coordinate system ρ and the angle θ between its normal and the x-axis (fig. 2, left). Transformed into the Hough space, a two dimensional parameter space spanned by ρ and ξ each data point represents a sinusoidal curve (fig. 2, right). The intersection points of the many sinusoidals are summed up in an accumulator. The intersection point that drews in most of the counts is then transformed back into the image space, where it corresponds to a straight line passing through as many data points as possible. Hence, when the signal track is identified a line fit estimates its parameters. This information is handed over to the direction reconstruction module.

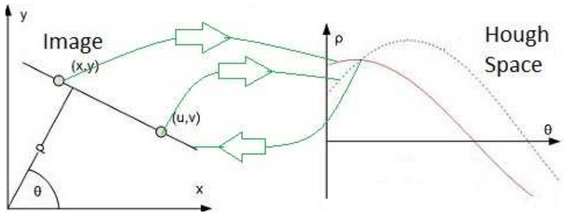

Figure 2: Simple example of a Hough transform for two data points.

2.4 Pulse Finder

Performances of pattern recognition algorithms can be further improved introducing a preliminary pulse finding step over each single camera pixel defining the associated time window validity. In each pixel, pedestal, variance and peaks of the recorded signal as a function of time are evaluated. Starting from a first guess time window defined around peaks, start and stop positions of signal are identified maximizing the signal to noise ratio. The procedure allows to make a pre-rejection of the noise and strongly reduces the probability to misleadingly identify a noisy pattern as a track.

3 Direction Reconstruction

From the geometrical properties of the signal track on the focal surface the arrival direction of the primary can be computed by a variety of methods implemented in ESAF as described in more detail in [8] and [9]. Fig. 3 shows the system of the EAS and the detector. In the current configuration there are 5 different algorithms implemented in ESAF. Two of them yield the most promising performance:

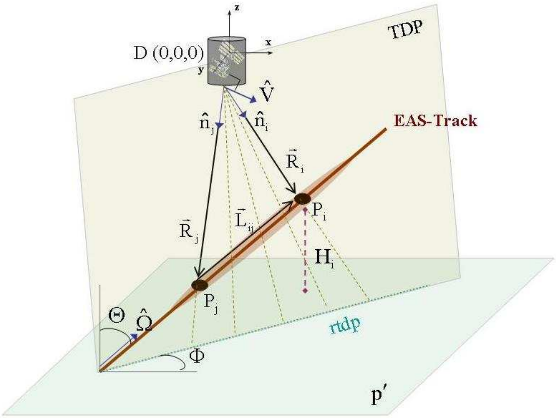

Figure 3: EAS observed with JEM-EUSO: Within the track-detector-plane (TDP), photons emitted at different times t$_j > t_i$ reach the detector from certain directions $\hat{n}_i$, $\hat{n}_j$ after traversing R$_i$, R$_j$ in atmosphere. From the timing information and arrival angle of the shower photons, the direction of the primary $\hat{\Omega}(\Theta, \Phi)$ can be determined.

- *Analytical Approximate 1*: angular velocities of the signal track int the x(t) and y(t) planes are linearly fitted. The arrival angle of the primary is derived by geometrical estimations.
- *Numerical Exact 2*: a χ^2 minimization is performed between the activation times of pixel induced by the actual signal to those induced by a signal track theoretically computed.

3.1 Energy Reconstruction

The ESAF package has an extensive module dedicated to the reconstruction of the energy of the primary as further described in [10].

Moreover, an alternative energy reconstruction module have been implemented by the Tübingen group. Starting from the reconstructed signal profile inherited from the pattern recognition we successively correct for the instrumental losses such as optical absorption in the lens system or inefficiency of the photomultipliers in order to get the photon's curve at the level of the entrance pupil of the optics (fig. 4). A parameterization both for the photomultipliers and for the optics response is required at this step. Using the reconstructed primary arrival direction and, if present, the timing of the Cherenkov mark we then reconstruct the position of the shower at each time. Using this information we can now correct the atmospheric effects and the geometrical loss which dim the signal. Several methods to reconstruct the geometry of the shower [2] have been implemented. Some of them use the timing of the Cherenkov mark, other make assumptions on the particle type or infer the position of the maximum from the shower width. Once the photon distribution within the shower has been reconstructed, assuming a certain fluorescence yield we can compute the number of charged particles in the shower. After that, the backscattered Cherenkov component is calculated and then subtracted from the contaminated electron curve. Eventually, a fit with a parameterization for the shower profile is performed. Having already calculated the Xmax (at the level of the electron curve reconstruction) - energy is the only remaining free parameter. Performing the fit therefore allows to give an estimate of the energy of the primary.

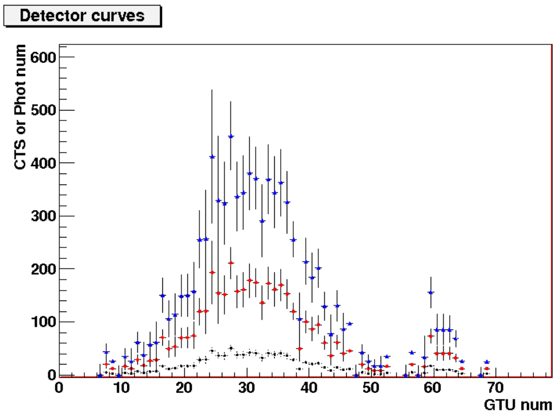

Figure 4: Energy reconstruction: Count distribution (black) is obtained by smoothing the clustering data. Focal surface light curve (red) and entrance pupil light curve (blue) are computed by taking into account the instruments efficiency.

energy	$7 * 10^{19}$ eV, $1 * 10^{20}$ eV, $3 * 10^{20}$ eV
primary	proton
inclination Θ	30°, 45°, 60°, 75°
right ascension Φ	0° - 360°
statistics	1000 events each E/ Θ config.

Table 1: Configuration of study.

4 Some Examples

Currently the ESAF code is being updated to the most recent JEM-EUSO configuration. This includes improvements in the optical system as well as latest trigger algorithms (see [11]). Here we present a few examples of ESAF's reconstruction performance. For the angular resolution study only a certain subclass of events is considered as seen in tab. 1. For the energy resolution we limited outselves to standard events (E=1 $*$ 10^{20} eV, Θ=60°) All simulations have been carried out assuming an ISS altitude of 430 km. The the recently introduced PulseFinder has not been used in this particular study. Thus the examples presented here are rather conservative and may be regarded as preliminary.

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[2] Geometry means the position of the shower in the FOV at each time.

4.1 Spatial Resolution

γ^{68} is a measure of the angular resolution. 68% of all events have separation angle less than γ^{68}. Here we show the separation angle as function of E and Θ.

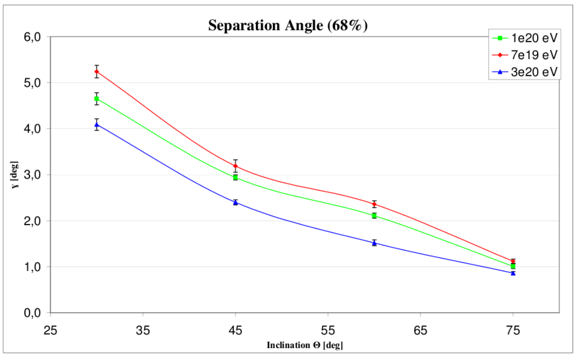

Figure 5: Angular resolution for different E ($7 * 10^{19}$,$1 * 10^{20}$, $3 * 10^{20}$ eV) and Θ (30°, 45°, 60°, 75°).

4.2 Energy Reconstruction

In fig. 6 we show the relative energy resolution for standard events (proton, E=10^{20} eV, Θ=60°). For details see [12].

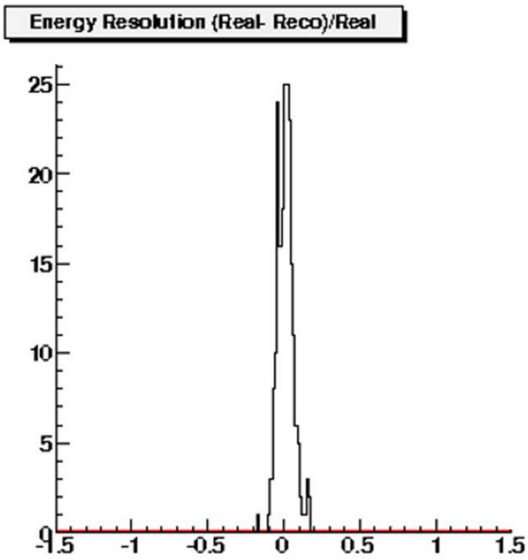

Figure 6: Energy resolution: $\frac{(E_{real}-E_{reco})}{E_{real}}$

5 Conclusion

ESAF is a powerful software and the tool of choice for the simulation and reconstruction of UHECR measuremnts with space-based detectors. ESAF 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 different primaries and changing atmospheric conditions such as cloud coverage is in progress (see [13]). Due to relatively recently introduced improvements such as the PulseFinder technique, we expect significant improvements of the spatial and energy resolution in the near future.

Acknowledgements

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