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The Euso Simulation and Analysis Framework

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ESAF is the simulation and analysis software framework developed for the EUSO experiment. ESAF's scope is the whole process of data simulations and data-analysis, from the primary particle interaction in atmosphere to the reconstruction of the event. Based on the ROOT package and designed using Object Oriented technology, ESAF is organized in two main programs: the full montecarlo simulation and the reconstruction framework. The former includes all the relevant physical contributions, shower development in atmosphere, light transport to the detector pupil and detector response, while the latter comprises basic data cleaning, track direction, shower profile and energy reconstruction algorithms. Here we describe the software architecture and its main features.

1. Introduction

The experiments aiming to study Extensive Air Showers (EAS) generated in the atmosphere by Ultra High Energy Cosmic Radiation with energy above 10^{19} eV require detectors with huge target.

In order to achieve a larger geometrical aperture an alternative and complementary approach to ground based experiment has been proposed for the first time by John Linsley more than 20 years ago. An EAS can be detected by observing the fluorescence light emitted by atmospheric nitrogen. In fact, instead of looking at this UV light from ground, the same signal can be watched from above, using a space-borne telescope on orbit around the earth. The fluorescence light is produced isotropically and, at any depth in the shower, is proportional to the number of charged particles.

The "Extreme Universe Space Observatory - EUSO" [1] was proposed as free-flier satellite in winter 1999. EUSO was accepted for an Accommodation Study on the ISS (end 2000) and then approved for Phase A (study report and conceptual design), successfully completed in summer 2004.

ESAF, the EUSO Simulation and Analysis Framework, has been developed during the EUSO Phase A study as the full End-to-end simulation and analysis chain, from the simulation of the primary particle interaction in atmosphere, to the transport of light to the EUSO optical pupil, to the detector response simulation and finally to the reconstruction and the physical analysis. We designed ESAF so that each one of the above steps could be run individually and independently from the other ones. With this approach it is possible to run the same reconstruction and analysis code for the real data and for the simulated ones. Moreover, it is also possible to run single parts of this chain and check quantitatively the differences between different configurations of the detector or different approximations for the physical processes involved. Therefore ESAF is easily adaptable to any space-borne detector design.

ESAF consists of a simulation package and a reconstruction package, is written in C++ and based on the ROOT

[3] framework. ESAF is designed following the general guidelines of the Object Oriented programming, that provide the required degree of flexibility and modularity.

The simulation has been structured in two main subsystems, the light generation, encapsulating all the physical phenomena occurring outside EUSO that can produce photons on the entrance of the detector, and the detector, where the photons are traced through the telescope and the electronics response is simulated.

The ROOT file format has been chosen for the output of the simulation. Each event in the ROOT file contains detailed information of each simulated effect along with the detector configuration used. To inspect the results a set of detailed event viewers for every step in the simulation chain have been implemented (fig:1). The ROOT file acts also as interface between the simulation and the reconstruction.

The reconstruction is designed as framework and a set of modules that will reconstruct the event. Each module has a specific task, that can actually be picked by the user and included in the reconstruction chain build by the framework.

2. The light generation

The detected shower signal depends critically on the atmospheric parameters. The monitored volume of atmosphere is continuously and rapidly changing, it spans many degrees in latitude and characterized by strongly variable weather conditions. Clouds may affect and distort or even enhance the shower signal. Also, many different kind of backgrounds are expected, including night-glow, man-made lights, lightnings, reflected moonlight.

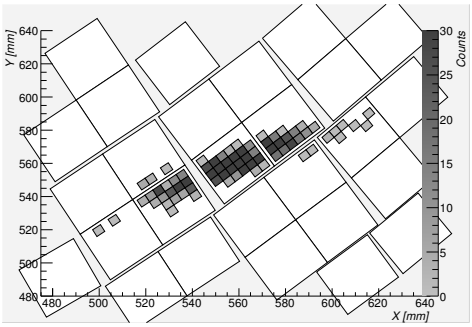


Figure 1. Front-end counts, generated by a 1.5×10^{20} eV proton shower developing in clear sky atmosphere, on the EUSO focal surface. The night glow background hits are not shown.

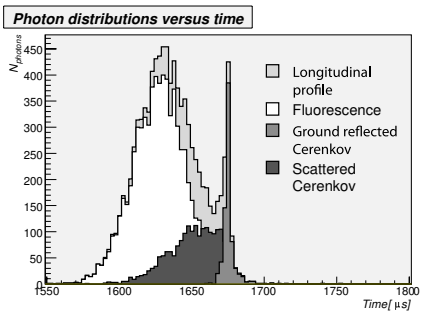
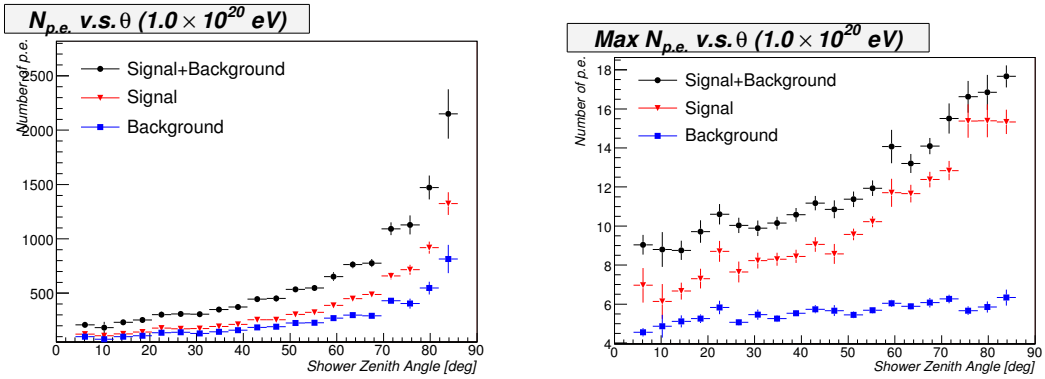


Figure 2. Number of photons reaching the EUSO pupil versus time. The different contributions are shown.

The simulation of light toward the detector has been divided in three steps: the physics event generation, the production of light and the transport of light through the atmosphere. These steps are independent, allowing the user to test and compare different shower models, or fluorescence emission in the same structure.

1. Several shower generators have been implemented, both as integrated part of ESAF (UNISIM [4]) or as interfaces to well established stand-alone generators (SLAST[5] and Corsika[6]). Lightnings and Meteors generators are foreseen.

2. The description of the physical event is given to the light source module to be converted into photons. Shower's fluorescence and Čerenkov signal spectra are simulated according the local atmosphere and electrons distributions. Nitrogen fluorescence yield data by Kakimoto[7] and Nagano[8] are used.
3. Eventually the photons are propagated from the creation point to the pupil of the detector by the radiative transfer module. Nitrogen fluorescence and Čerenkov radiation are treated separately. The former, isotropic, is transmitted directly to the detector, the latter, strongly forward beamed, is scattered in the air and diffusely reflected by the earth surface or clouds at the impact point (fig.2). Transmission coefficients are computed for each wavelength as a function of the local atmosphere using the LOWTRAN[9] package. The radiative transfer module supports several atmospheric models (US Standard, Lowtran, Corsika) and MSISE. The MSISE models, that depends on geodetic position (Lat. and Longitude), is particularly important for an earth-orbiting detector studies. The reflection of Čerenkov light on simple uniform cloud layers has been implemented.



(a) (b)

Figure 3. (a) Number of counts on the EUSO focal surface generated by 10^{20} eV showers as a function of the shower zenith angle. (b) Number of counts in the most populated pixel on EUSO focal surface as a function of shower zenith angle. EUSO Redbook requirements configuration was used. Background counts are limited to the pixel with signal.

3. The detector

The instrument must collect as many photons as possible, in order to be able to detect the faint signal from the less energetic EAS and to discriminate it from the background. All the components must be carefully assembled to minimize any possible signal loss. Dead areas on the focal surface, optics design, fluctuations in photo detectors response, background rate dependence on the position on the focal surface affect the performances of the instrument if not correctly taken into account. The role of the detector's simulation is twofold:

1. Support a full Monte Carlo simulation of the advanced instrument design. Currently, EUSO Phase A configuration has been successfully implemented: Large field of view Fresnel optical system, modular focal surface design, photo sensors assembled in 2x2 elementary cells (fig. 1). All sensors are supplied with an UV bandpass optical filter and each elementary cell is connected to its own front-end chip. Elementary cells are grouped into logical triggering units (macrocells) and several first level trigger patterns based on the space-time coherence of the shower signal has been included.

2. Provide a fast and reliable tool to simulate a parameterized detector. The possibility to test the response as a function of optics field of view, optics transmittance, point spread function, photo detector pixel size and many other parameters is fundamental for any feasibility study of future space-borne UHECR detectors.

4. Reconstruction

Because of the small number of detected photons (fig. 3a and 3b), the reconstruction of the features EAS and then the primary particle parameters is very tricky, especially at the lower energies (10^{19} eV). The shower image on the focal plane must be located according to the trigger information, cleaned up from the background and then analyzed. The core of the reconstruction is the modular framework. Every task of the reconstruction chain is a module. Many tasks have been implemented using different algorithms to find the most suitable and robust one.

Pattern recognition : Disentangling of the signal from the incoherent background is committed to the Hough transform and clustering algorithms.

Track finding : The EAS develops in the atmosphere at the speed of light. Using this information, its direction in space can be computed from the 2-dim. image on the focal surface. Several robust numerical and analytical approaches have been implemented.

Energy : The primary particle energy is, in principle, proportional to the number of detected photo electrons. Nevertheless many effects can lead to a wrong estimation, if not taken into account. The energy module uses the information on atmosphere optical depth, detector's optics and focal surface dead areas to recover the shower longitudinal profile and then extrapolate the initial energy.

5. Conclusions

ESAF is a stable, powerful and flexible simulation and reconstruction tool for UHECR space-based UV telescopes. Thanks to its flexibility, it will also play a key role in feasibility studies for future experiment proposals within the ESA Cosmic Vision 2015-2025 program.

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