PROCEEDINGS OF SCIENCE

# Analysis of EUSO-Balloon data with Offline

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EUSO-Balloon is a balloon-borne experiment, conceived as a pathfinder for JEM-EUSO experiment which is the first experiment measuring the highest energy cosmic rays from space. EUSO-Balloon is equipped with an optical system made by two Fresnel lenses and one photo detection module (PDM), representing a complete prototype for the JEM-EUSO experiment. On 24th August 2014 EUSO-Balloon was launched from Timmins Balloon base in Ontario (Canada) in collaboration with the French Space Agency CNES. The flight lasted about 5 hours with a float altitude of about 38 km, observing regions with different background light. The instrument has been also tested with laser shots emitted from an helicopter flown under the balloon for about 2 hours. A procedure to analyze these data and compare them with simulation is developed into the Offline framework. The results are reported in the following contribution.

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*Speaker.

 

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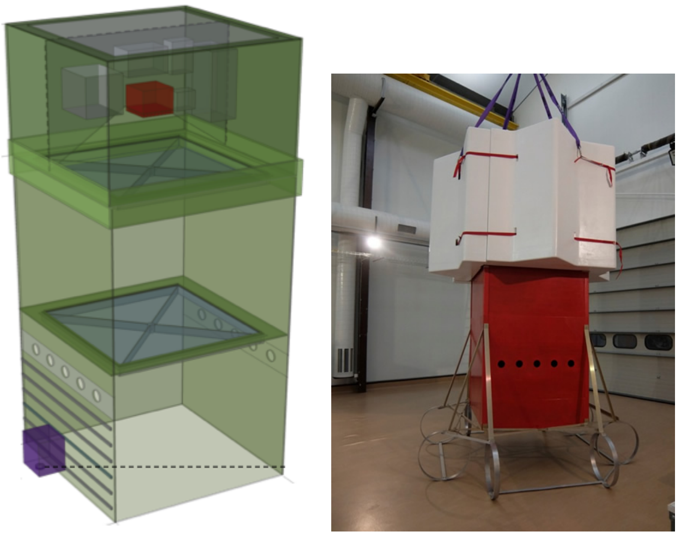


Figure 1: On the left: EUSO-Balloon schematic view. The two lenses their supports are indicated in grey, while the red box on the top represents the PDM. On the right: The gondola which contained EUSO-Balloon during its first launch.

## 1. Introduction

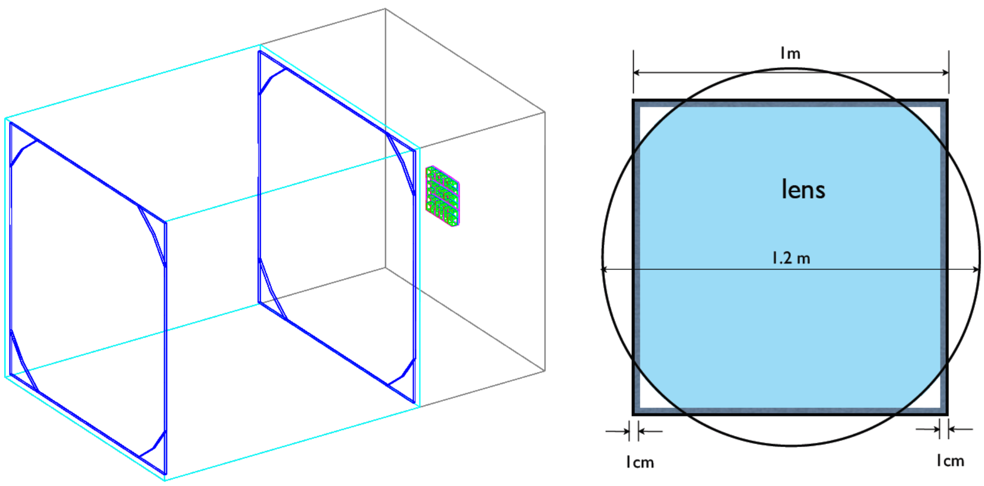
EUSO-Balloon is a pathfinder for the JEM-EUSO experiment [1], the Extreme Universe Space Observatory on the Japanese Experiment Module, a new type of observatory hosted on the International Space Station (ISS). Its main goal is the study of Ultra-High Energy Cosmic Rays (UHECRs) with an energy threshold of about $5{\cdot}10^{19}$ eV by looking downward to the Earth's atmosphere. The advantage of a space-based fluorescence telescope compared to a ground-based detector is a much larger effective area to collect more UHECR events at highest energies. The detector consists of a UV telescope to detect UV fluorescence photons with wavelengths between 300 and 430 nm that are produced along the track of the induced Extensive Air Showers (EASs) in the atmosphere. At these energies, cosmic rays are not deflected significantly by galactic magnetic field. This can lead to identify structures in the sky map that contain information about the source density and permits to test different models for the acceleration mechanisms. Further details on the JEM-EUSO mission can be found in [2, 3].
EUSO-Balloon is a balloon-borne experiment to test technologies and methods that will be used in the JEM-EUSO mission. It has been launched for the first time on the 24th August 2014 from Timmins Balloon base in Ontario (Canada); its flight is performed by the balloon division of the French Space Agency CNES.

## 2. EUSO-Balloon

EUSO-Balloon is an imaging UV telescope designed to detect the fluorescence emission of Nitrogen molecules excited by collisions with shower particles in the atmosphere. It is equipped with a Photo-Detector Module (PDM) and Fresnel optics. The PDM is the base model planned for JEM-EUSO. EUSO-Balloon monitors a 12°x12° field of view in a wavelength range between 290 and 430 nm, at a rate of 400000 frames/sec [4]. A schematic view of the apparatus is in Fig. 1. The external container (or gondola) is shown on the right panel of the same figure. The PDM is contained in a waterproof instrument booth that also houses the telemetry system, CNES specific instrumentation, and two battery-packs. Since the atmospheric fluorescence emission of interest for JEM-EUSO includes the three Nitrogen lines (337nm, 357nm, 391nm), the front surface of each photomultiplier is covered with a UV transmitting glass filter, with the band-pass of 330-400 nm. MAPMT signals are digitized and processed by the Front-End Electronics that perform data acquisition and readout within a defined time slot called a Gate Time Unit (GTU = 2.5 $\mu$s).

## 3. Payload Simulation

The simulation for the JEM-EUSO experiment was performed in the Offline software framework which supports both simulation and reconstruction of events [5]. The experimental configuration is performed using Geant4, a free toolkit based on C++ which accurately simulates the passage of particles through matter [6, 7]. The object-oriented design is especially suitable for JEM-EUSO and its pathfinders, because its modular architecture allows the user to load and use only components needed by a particular payload.




(a) (b)

Figure 2: (a) Simulated configuration of the payload optics and PDM, as implemented in the simulation code. (b) Drawing of the lens design.

The payload simulation has been performed starting from the definition design as shown in Fig.2a. The setup is represented in Geant4 as a structure of geometrical volumes and the color legend for the elements shown in the Fig.2a is the following.

- Grey: indicates the entire payload of EUSO-Balloon;
- Cyan: indicates the optics module which contains the two Fresnel lenses;
- Blue: indicates the two lenses as inserted into the previous volume;

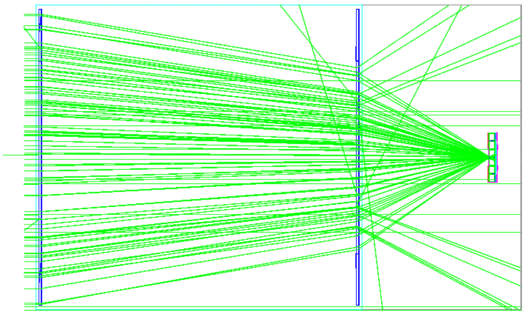
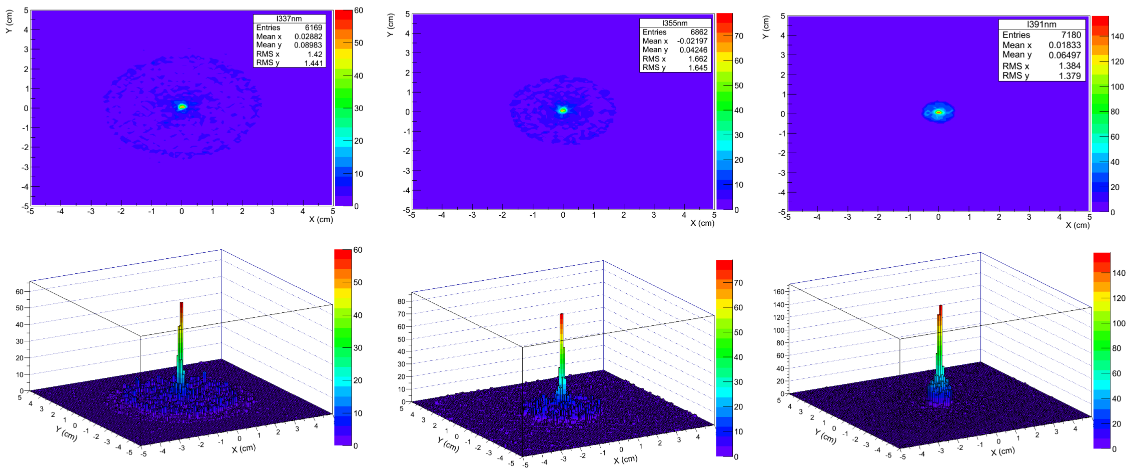


Figure 3: A working example of the lenses to test the optics focusing.



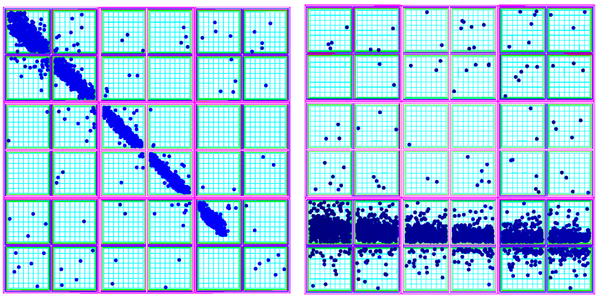
(a) (b) (c)

Figure 4: Ideal focal surface to check the optics performance with three different wavelengths: (a) 337 nm, (b) 355 nm and (c) 391 nm.

- Multicolor box: indicates the PDM box including the PMTs, Filters and anodes.

The optical bench contains two 8 mm thick Fresnel lenses made of PMMA which is a UV transmitting polymethylmethacrylate. The front surface of each lens is 100x100 cm. The shape is indicated by the sky blue in Fig. 2b. The Photo-Detector Module (PDM) consists of 36 multi-anode photomultipliers (MAPMT) each equipped with 64 anodes. The PDM is organised in 3x3 Elementary Cell (EC), where 2x2 MAPMTs comprise an EC. The EC is the electronic reference for the power supply and the signal collection and transmission for processing. To simulate the performance of the optical system a parallel beam of photons is sent on the xz plane and recoiled on an ideal Focal Surface fixed on the PMTs. The result is shown in Fig. 3. Schott BG3 absorption filters have been used for EUSO-Balloon. Tests to evaluate the lens focusing and the filter transmittance have been done using photons of three wavelengths, 337, 355 and 391 nm. The results are reported in Fig. 4.

The Offline framework can be used to analyze simulated and real events. Two simulated event sources are available: the shower generator and the single-particle generator. These are used to test



(a) (b)

Figure 5: Example of simulated events on the EUSO-Balloon PDM respectively due to an event induced by a laser pulse with 3 mJ energy and 355 nm wavelength (a) and to a shower with energy E = $10^{20}$ eV (b) in the atmosphere.

the code and the efficiency of single particle beam. In Fig. 5 two simulated events are reported as they appear on the PDM. The event shown in Fig. 5a is generated by a laser pulse with 3 mJ energy and a wavelength of 355 nm.

## 4. Data analysis

During its first launch the payload operated in nadir mode. The flight lasted about 5 hours with a float altitude of 38 km and a field of view on the ground of $\sim$250 km$^2$. A helicopter equipped with a UV Laser and a UV flasher flew under the balloon at an altitude of $\sim$2.3 km for 2.5 hours. The energy laser alternated between 9-16 mJ, equivalent to an EAS of $\sim 10^{20}$ eV.
The analysis of events is divided into two steps:

1. the identification of tracks corresponding to real laser events;
2. the reconstruction of the event direction.

### 4.1 Event selection

To select the laser signal from the nightglow background, it is possible to use two different module sequences based on two different algorithms: the Trigger Sequence or the Selection Sequence. An application of these algorithms is reported in Fig. 6 for a real laser event selected from EUSO-Balloon data. In Fig. 6a the pixel counts summed for all 128 GTUs are reported, while in Fig. 6b only counts related to GTUs selected by the trigger are reported.
An analysis to check the efficiency of both algorithms obtains the similar results.

**The Trigger Sequence**

This is the first level trigger developed for EUSO-Balloon [8]. It is based on the analysis of the event topology. For each box composed of 3x3 pixels identified on the PDM, the counts of pixels, that exceed a chosen limit, have been summed. The trigger is issued if the summation is greater than a threshold calculated by averaging over the 128 GTUs.

**The Selection Sequence**

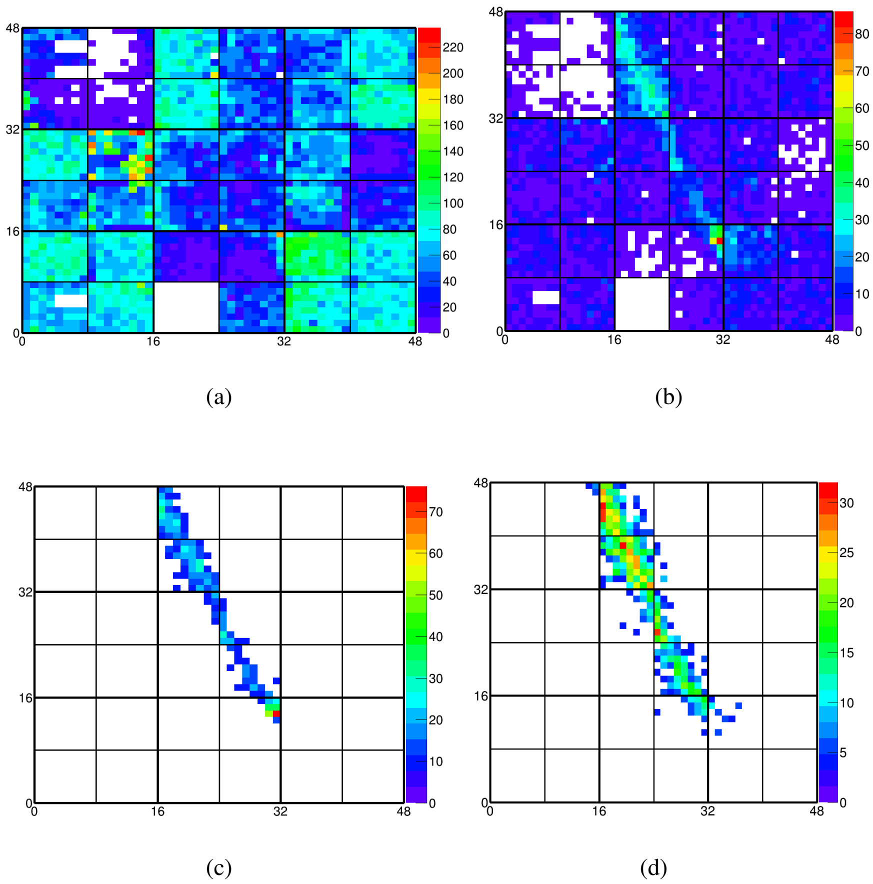



Figure 6: An event generated by a laser and measured by EUSO-Balloon during its flight. The event selection sequence identifies out a signal in the packet represented in the plot (a) where the integral of 128 GTUs are shown; the plot (b) is the pixels sum only for the GTUs involved in the trigger sequence. In the plot (c) only pixels with a given contents are selected as belonging to the track. The track region is improved (plot d) by adding other pixels to perform the event reconstruction.

This is a selection based on a series of constraints on the pixel counting. It uses a sequence of three modules: (1) SelectEvents, (2) PixelCalibrator, (3) SelectTracks. The SelectEvents module makes a first selection based only on pixel counting, to cancel noisy pixels, due for example to electronic problems. The PixelCalibrator module calibrates raw data. The SelectTracks module identifies laser spots GTU by GTU, saving data related only to the pixels involved in the triggered event. During the EUSO-Balloon flight, an UV LED flasher precedes the laser. SelectTracks module can search for GTUs containing flasher spots, identify them and remove them from the final track. This is done by splitting the collection of pixels belonging to the track into two separate spots by performing a linear fit on the pixel positions. The result of the SelectTracks module is reported in Fig. 6c.

**Non laser events**

SelectEvents module can search for these events splitting the collection of pixels belonging to the track into two separate spots by a linear fit on the pixel positions. Since the typical GTU window containing the laser event is around 10 GTUs in duration, the analysis of the total number of GTUs for each spot permits to discriminate the events. To filter non laser events two checks are implemented. First a threshold on the distance of the pixel from the centroid calculated on the integrated track is done. Secondly, the central line of the integrated track is defined and a limit on the RMS value of the distance of pixels to that line is set. For a laser track, the typical RMS value is $\sim$1, while for noise this value is 2.

### 4.2 Reconstruction

The second step is to reconstruct the event direction, through the determination of its Shower Detector Plane (SDP). The module sequence is: (1) AddCoordinates, (2) SDPFinder and (3) AxisFinder. The first module, AddCoordinates, adds pixels to the track to improve the determination of the SDP, by calculating the average of background counts and considering only pixels with a content greater than $3\sigma$ respect to that average within a given radius from the centroid of the track. The result is reported in Fig. 6d. The SPDFinder module defines the SPD by two vectors $(U,V)$, where $U$ is a vector in the plane and $V$ is an orthogonal vector obtained by the cross product of viewing directions of pixels involved in the selected track

$$V = \sum_{i,j} w_i w_j \, \mathbf{n}_i \times \mathbf{n}_j, \tag{4.1}$$

being $n$, $w$ respectively the viewing direction and the content by GTU for each pixel in the track.

Finally, AxisFinder is the laser/shower angular reconstruction module, where the laser axis can be reconstructed by fitting the arrival time of photons on the PDM. The expected arrival time is given by

$$t_i^{exp} = t_0 + \frac{R_0}{c}\tan\left(\frac{\pi}{4} + \frac{\alpha_0 - \alpha_i}{2}\right), \tag{4.2}$$

where $t_0$, $R_0$ and $\alpha_0$ are the time, the distance and the azimuthal angle of the closest point on the axis to the SDP, and $\alpha_i = acos(\mathbf{U} \cdot \mathbf{n}_i)$ is the azimuthal angle of the viewing direction $\mathbf{n}_i$ in the SDP. The laser axis can be reconstructed by minimizing the following $\chi^2$ function

$$\chi^2 = \sum \left(\frac{t_i - t_i^{expc}}{\Delta t}\right)^2, \tag{4.3}$$

where $\Delta t \sim 0.5$ GTU is the time error.

## 5. Conclusions

The framework developed for the analysis of data collected during the first launch of EUSO-Balloon has been described. The simulated data induced by laser events or EASs developed in the atmosphere is also reported.

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