EUSO-BALLOON : a pathfinder for observing UHECR's from space


Abstract: EUSO-BALLOON is a pathfinder mission for JEM-EUSO (Extreme Universe Space Observatory on-board the Japanese Experiment Module of the International Space Station). Through a series of stratospheric balloon flights starting in 2014, performed by the French Space Agency CNES, the JEM-EUSO consortium will demonstrate the key technologies and methods featured in its future space mission. As JEM-EUSO is designed to observe Ultra-High Energy Cosmic Rays (UHECR)-induced Extensive Air Showers by detecting their ultraviolet (UV) light tracks, EUSO-BALLOON is an imaging UV telescope too. The balloon-borne pathfinder points towards the nadir from a float altitude of about 40 km. With its Fresnel Optics and Photo-Detector Module, the instrument monitors a 12x12˚ wide field of view in a wavelength range between 290 and 430 nm, at a rate of 400'000 frames/sec. The objectives of EUSO-BALLOON are to perform a full end-to-end test of a JEM-EUSO prototype consisting of all the main subsystems of the space experiment, and to demonstrate the global detection chain while improving our knowledge of the atmospheric and terrestrial UV background. The balloon pathfinder also has the potential to detect for the first time, from above, UV-light generated by atmospheric air-showers, marking a milestone in the development of UHECR science, and paving the way for any future large scale, space-based UHECR observatory.

Keywords: JEM-EUSO, UHECR, balloon instrument, fluorescence

1 The Context for EUSO-BALLOON

EUSO-BALLOON is a prototype of JEM-EUSO, the Extreme Universe Space Observatory to be hosted on-board the Japanese Experiment Module of the International Space Station (ISS). JEM-EUSO is designed to observe ultra high-energy cosmic rays (UHECRs) by looking downward to the Earth’s atmosphere from the ISS, observing the UV fluorescence light of UHECR-induced Extensive Air Showers (EAS). These proceedings contain a number of detailed articles on JEM-EUSO, notably its status [?], the science case [?], and an overview on the instruments [?]. EUSO-BALLOON is developed by the JEM-EUSO consortium as a demonstrator for the technologies and methods featured in the forthcoming space instrument. Since JEM-EUSO’s observation of UHECR-induced EAS is based on the detection of an UV light track (fluorescence emission of Nitrogen molecules excited by collisions with shower particles), EUSO-BALLOON is an imaging UV telescope as well. The balloon-borne instrument points towards the nadir from a float altitude of about 40 km. With its Fresnel Optics and Photo-Detector Module, the instrument monitors a 12x12˚ wide field of view in a wavelength range between 290 and 430 nm, at a rate of 400’000 frames/sec. The EUSO-BALLOON mission has been proposed by a collab-
oration of three French laboratories (APC, IRAP and LAL) involved in the international JEM-EUSO consortium. Balloon flights will be performed by the balloon division of the French Space Agency CNES, a first flight is scheduled for 2014.

2 Objectives of the balloon flights

EUSO-BALLOON will serve as a test-bench for the JEM-EUSO mission as well as any future mission dedicated to the observation of extensive air showers from space. The following objectives shall be attained in a series of balloon flights:

A) technology demonstrator

EUSO-BALLOON is a full scale end-to-end test of all the key technologies and instrumentation of JEM-EUSO. Crucial issues that will benefit from the balloon flights include the HV power supplies, the HV switches (HV relays commuting the HV in case a bright atmospheric event comes into the field of view and on a pixel), the Front-End Electronics (including the ASICs and FPGA), the on-board hardware and software algorithms involved in the triggering and recognition of cosmic-ray initiated air showers.

B) data acquisition and background study

Although the physics and the detection technique of EAS through ultraviolet light (UV) emission is well established and used daily in ground based detectors, their observation from space has never been performed. Since JEM-EUSO uses the Earth’s atmosphere to observe UV (300-400 nm) fluorescence tracks and Cherenkov reflections from EAS, the observations will be sensitive to the variation of the background sources in the UV range. Whereas a number of background measurements have been performed by previous missions, even from space, no focusing instruments have been employed so far and, most importantly, spatial resolutions were extremely low, i.e. the “pixel size” was much larger. Important localized background signals could have been washed out by the integration over a large surface and, likewise, possible temporal variations on small scales were not observable, and thus went unconstrained.

Measuring a representative background for JEM-EUSO has been the principal driver for determining the pixel size, and hence the global Field of View of EUSO-BALLOON. The EUSO Simulation and Analysis Framework (ESAF) has been adapted to simulate the response of the instrument to the continuous power of 225 W during 24 hours of flight (which is more than enough for a first flight that is to last only one night). The optical bench contains three Fresnel lenses made from 8 mm thick PMMA (UV transmitting polymethylmethacrylate) with a front surface of 100 cm x 100 cm each. The EUSO-BALLOON optics has been dimensioned to measure a background level comparable to the one expected for JEM-EUSO.

C) pioneering mission for JEM-EUSO

A “bonus objective” for EUSO-BALLOON is the actual detection of one or several EAS by looking downward from the edge of space. Since detecting these obviously rare events is unlikely during a first short balloon flight (threshold \( \simeq 10^{18} \text{eV} \), see the paragraph on performance below), xenon-flashes and LASER-induced events will provide a proof of principle and a way to calibrate the threshold / sensitivity.

3 Payload Overview

The general layout of EUSO-BALLOON is shown in Figure ??, its main components are the optical bench and the instrument booth. An electronic block diagram of the entire instrument is shown in Figure 2. The development of all components and sub-assemblies[?] is based on similar JEM-EUSO components and sub-assemblies. The total mass of the payload is about 320 kg; the battery packs will maintain constant power of 225 W during 24 hours of flight (which is more than enough for a first flight that is to last only one night). The optical bench contains three Fresnel lenses made from 8 mm thick PMMA (UV transmitting polymethylmethacrylate) with a front surface of 100 cm x 100 cm each. The EUSO-BALLOON optics has been designed to resemble the JEM-EUSO optics (i.e. three Fresnel lenses) : it is dimensioned to produce an RMS spot size smaller than the pixel size of the detector (i.e. 2.85 mm) and keep the background rate per pixel comparable to the one anticipated for JEM-EUSO (i.e. roughly 2 \( \pm 1 \) photoelectrons per pixel in a 2.5\( \mu \text{sec} \) frame). Whereas L1 and L3 are aspherical Fresnel Lenses with focal lengths of 258.56 cm and 60.02 cm, respectively, L2 is a diffractive lens with focal of 385.69 cm (focal lengths are reference values only, single lenses are not producing stigmatic images). Within the optical

<table>
<thead>
<tr>
<th>Number of PDMs</th>
<th>JEM-EUSO</th>
<th>BALLOON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Altitude [km]</td>
<td>420</td>
<td>40</td>
</tr>
<tr>
<td>Diameter of Optics [km]</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Field of View / PDM</td>
<td>3.8 ( \pm 1 )</td>
<td>12</td>
</tr>
<tr>
<td>PDM@ground [km]</td>
<td>28.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Field of View / pixel</td>
<td>0.08 ( \pm 0.05 )</td>
<td>0.25 ( \pm 0.05 )</td>
</tr>
<tr>
<td>Pixel@ground [km]</td>
<td>0.580</td>
<td>0.175</td>
</tr>
<tr>
<td>Signal w/r JEM-EUSO</td>
<td>1</td>
<td>17.6</td>
</tr>
<tr>
<td>BG w/r JEM-EUSO</td>
<td>1</td>
<td>0.9-1.8</td>
</tr>
<tr>
<td>S/\sqrt{N} w/r to JEM-EUSO</td>
<td>1</td>
<td>20-10</td>
</tr>
<tr>
<td>Threshold Energy [eV]</td>
<td>3.10(^{19})</td>
<td>1.5-3.10(^{18})</td>
</tr>
</tbody>
</table>

Table 1: Comparison of the principle characteristics between JEM-EUSO and EUSO-BALLOON. The field of view of EUSO-BALLOON - and hence its pixel size - has been dimensioned to measure a background level comparable to the one expected for JEM-EUSO.
The EUSO-BALLOON pathfinder

The Photo-Detector Module (PDM)

UV light collected by the telescope is focused onto - and detected by - the PDM, which is composed of 36 MAPMT (Hamamatsu M64 multi-anode photomultipliers) containing 64 anodes each. Testing and sorting of the photomultipliers is detailed in [3]. The PDM is organized in 3x3 Elementary Cells (EC) which in turn are composed of 2x2 MAPMTs. A UV color glass filter is bonded to the window of the MAPMTs, collecting the signals from their anodes and transmitting them to the ASIC for processing.

Each of the 2304 pixels (anodes) in the PDM is sensitive to single photons, and features a dynamic range of 6 orders of magnitude thanks to an adaptive gain. The dynodes are driven by Cockroft Walton High-Voltage generators. In order to protect the photodetectors against highly luminous events (lightnings, etc.), custom made High-Voltage switches are capable of reducing the gain in a few microseconds. The analogue signal from the MAPMTs anodes is continuously digitized and processed by the Front-End Electronics based on the "SPACIROC" ASIC (Spatial Photomultiplier Array Counting and Integrating Readout Chip, see [3]). The ASIC features a single photo-electron mode (SPE) as well a charge integration mode (KI - i.e. charge to time conversion permitting to measure the intensity of the photon flux). Data acquisition and readout are performed within a defined time slot called Gate Time Unit (GTU=2.5 µs). This is fast enough to observe the speed-of-light phenomena in EAS. The output signals from the four ASICs of an EC unit are transmitted to the PDM board which can handle all 9 EC units. The hardware of the PDM board electronics includes an FPGA (Field Programmable Gate Array, the present baseline is the Virtex XC6VLX240T), which performs a first-level trigger algorithm (persistence track trigger). A shower candidate is triggered if there is an excess of signal above expected background fluctuations in a box of 3x3 pixels for few consecutive GTUs. The parameters will be adapted in flight as a function of the average background level.

The Digital Processor (DP)

The different sub-assemblies of the DP collect the PDM data, process them (trigger, time- and position-tagging), handle their on-board storage, and send a subset to the telemetry system. The DP also includes the housekeeping system. The CCB (Control Cluster Board) is developed around a Xilinx Virtex-4 FX-60, it collects the data from the PDM board, processes and classifies the received data, and performs a second level trigger filtering [3]. The DP then tags the events with their arrival time (UTC) and payload position (GPS). It also manages the Mass Memory for data storage, measures the operating- and dead-time of the instrument, provides signals for time synchronization of the event, performs housekeeping monitoring, and handles the interface with the telecommand/telemetry system.

An event selected by the two trigger levels represents roughly 330 kB of data. Since only a limited data rate can be transmitted to the ground through CNES' new NOSICA telemetry system, all data will be systematically stored on board. The mass storage is composed of two Solid-State Drives (SSD), each one with 1 TB capacity operating in fault-tolerant mode RAID-1 disks (Redundant Array of Independent Disks). The on-line and off-line data analysis is described in [3].

Balloon operation

During a first flight the payload will operate in nadir pointing mode, the spin rate will be determined by the natural azimuthal oscillations of the flight train. For later flights, the inclination of the pointing axis will be controlled between 0° and 30° with respect to the nadir and an azimuth motor will provide the possibility to perform revolutions with a spin rate of up to 3 rpm. Performing azimuthal revolutions will simulate a groundspeed comparable to the ~7 km/s of the space-station, permitting a full scale test of the HV-switches : i.e. switching MAPMT voltages on/off within a few microseconds, as artificial and other light sources cross the field of view of the instrument. As the first balloon flight shall take place from a new CNES launch base in Timmins, Canada (lat 48.5° N) a number of different groundcovers will be overflown, including various types of groundcovers.
soil and vegetation, water, urban and industrial areas, and - very likely - clouds. EUSO-BALLOON should therefore be able to measure a representative variety of background conditions.

**Performance**

While the detection of Extensive Air Showers was not amongst the initial objectives for EUSO-BALLOON, the simulation showed that the instrument was able to detect and image Extensive Air Showers with energies above $10^{18}$ eV. This threshold energy arises from the background estimate reported in [1]. A first analysis indicates that 0.2-0.3 event ($E > 2 \cdot 10^{18}$ eV) are expected to be observable during a night-flight of 10 hours. The uncertainty in the estimation assumes also the presence of a moderate cloud fraction. A clear detection will require long duration balloon flights - this is foreseen for subsequent launches and has become a further objective (C-level) for EUSO-BALLOON while the objective of the first flight is to focus on the A- and B-level objectives (see section 2).

In order to monitor the actual cloud covers, a co-aligned IR camera will observe the field of view of the main instrument (similar to the one used on JEM-EUSO, see [2], [3]).

4 Project Organization and Status

EUSO-BALLOON is a mission of the French Space Agency CNES, led under the responsibility of the French team, which acts in coordination with the JEM-EUSO management. The instrument is designed and built entirely within the JEM-EUSO collaboration. As its pathfinder, EUSO-BALLOON is identical (PDM, triggers etc.) or similar (optics) to the main mission. All relevant institutions and international partners within the JEM-EUSO collaboration contribute to the instrument according to their corresponding tasks and responsibilities within JEM-EUSO. A ground-based prototype, very similar to EUSO-BALLOON, has recently been integrated at RIKEN, Japan and installed on the Black Rock Mesa site of Telescope Array (TA), Utah. It is designed to cross calibrate the instrument with the TA Fluorescence Detectors through noise background comparison and during Lidar or electron beam shots. As this article is submitted, the Critical Design Review at CNES has been held, a qualification model of the entire electronics chain has shown to operate, and the Fresnel optics is under fabrication: the EUSO-BALLOON project is on track for its first balloon flight in 2014!

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