PROCEEDINGS OF SCIENCE

Performance of the EUSO-Balloon UV Camera

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JEM-EUSO [1] is intended to be a space-borne fruorescence telescope onboard of JEM/EF (Japanese Experimental Modeul/Exposure Facility) on the International Space Station (ISS). The main goal of the JEM-EUSO project is to detect the Extensive Air Showers (EAS) produced by the Extreme Energy Cosmic Rays (EECRs) with energies above $10^{19} eV$ from the extragalactic objects. As a pathfinder, the JEM-EUSO collaboration is currently developing a balloon-borne fluorescence telescope experiment, called EUSO-Balloon, funded by CNES, the French space agency. It will perform end-to-end tests of the JEM-EUSO subsystems and instrumental concept, and measure the UV background for space-based EECR detectors. It involves several French institutes (LAL, APC and IRAP) as well as several key institutes of the JEM-EUSO collaboration. The EUSO-Balloon instrument consists of an UV telescope and an infrared camera. The UV telescope will be operated at an altitude of 40 km to observe the background and possibly signal photons in the fluorescence UV range (290-430 nm), which are emitted along shower tracks generated by ultra high energy cosmic rays with energies above $10^{18} eV$ interacting with the earth's atmosphere. The balloon experiment will be equipped with electronics and acquisition systems, as close as possible to the ones designed for the UV telescope of main JEM-EUSO instrument. The past years have been devoted to the design, the fabrication and the tests of the prototype boards of the PDM, of the digital processor, and the flight models of optics, electronics and the IR camera for EUSO-Balloon.
Here we focus on the PDM, the core element of the JEM-EUSO focal surface. We first describe all key items of the PDM, from the photodetectors to the FPGA board, the first stage of the data processing (DP). We then report on the tests carried out on the integration to assess their functionality and their suitability for a balloon mission.

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1. The EUSO-Balloon Instrument

The JEM-EUSO telescope captures the shower moving tracks by the resulting air fluorescence photons every few micro seconds to estimate the arrival direction and primary particle energy. The EUSO-Balloon instrument [2] [3] has been designed to be as close as possible to the future JEM-EUSO instrument consisting of key elements to perform complete end-to-end tests of the JEM-EUSO subsystems and instrumental concept. It will also allow us to study the UV background at 40 km altitude and its fluctuations depending on the earth geography and cloud conditions.

The EUSO-Balloon instrument is subdivided in different parts (see Fig. 1):

- The mechanical structure (the balloon gondola): It houses the other subsystems. It is watertight and allows adjustment of the two optical lenses.
- An optical system: It consists of two flat Fresnel lenses (L1 and L3) which focuses the UV photons on the focal surface.
- The Photo Detector Module (PDM): It consists of 36 64-channel Multi-Anode Photomultiplier Tubes (MAPMTs, Hamamatsu R11265-M64), the associated front-end readout (ASIC boards), the level 1 trigger electronics (PDM board) and the high voltage power supplies (HVPS).
- The data processing (DP): It contains a set of boards which produces the level 2 trigger (CCB), acquires the data (CPU), generates clocks (CLKB), performs monitoring (House Keeping, HK) and supplies low voltages (LVPS).
- An infra-red camera (IR): It is used to study the structure and condition of clouds.

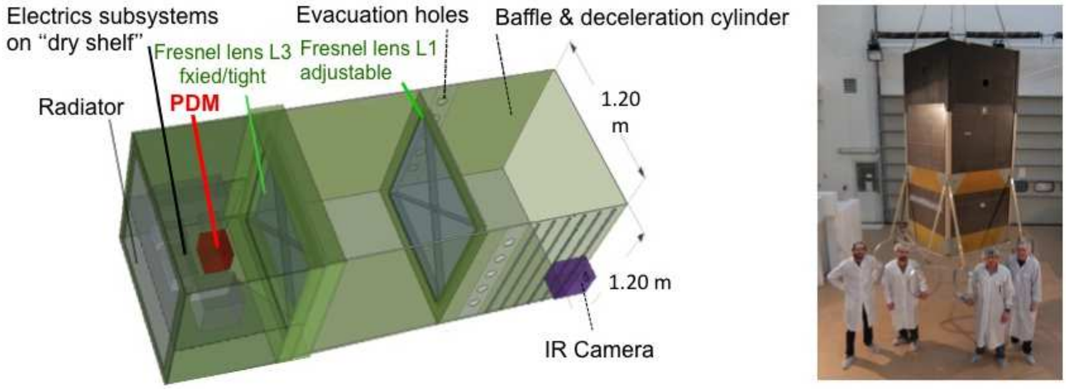

Figure 1: Left: Schematic view of EUSO-Balloon instrument in its mechanical structure. Right: Photo of instrument booth assembled at IRAP, Toulouse.

2. EUSO-Balloon Focal Surface

The EUSO-Balloon focal surface consists of one PDM (2,304 pixels in total) in a scale of 167 mm $\times$ 167 mm while the one for the JEM-EUSO telescope consists of 137 PDMs ($\sim$300,000 pixels) arranged in a curved surface structure of 2.35 m in diameter. A PDM consists of an array of 3$\times$3 Elementary Cells (ECs), each of which is composed of 2$\times$2 64-channel MAPMTs. (See Fig.2). An Elementary Cell unit (EC_unit) consists of four 64-channel MAPMTs and three types of boards placed backside of the MAPMTs (See Fig.2):

- One EC_dynode board: distributes the 14 high voltages (HV) to the four MPAMTs
- Four EC_anode boards: collect the analog signals and transmit them to the ASIC boards
- One EC_HV: interfaces the HVPS with the EC_dynode transmitting the 14 HVs.

For the severe conditions of pressure (3 mbar at 40 km of altitude), the whole EC_unit electronics are potted with resin to protect them against destructive sparking, induced possibly by the HV.

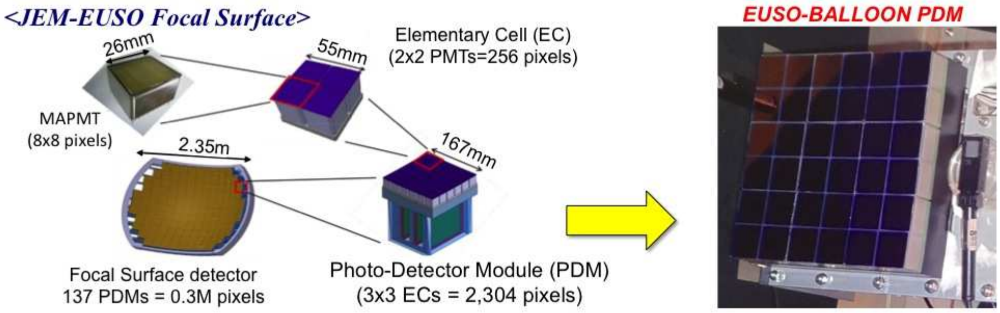

Figure 2: Left: schematic view of the JEM-EUSO focal surface detector modules. Right: photo of the EUSO-Balloon PDM assembled on mechanical frame of the EUSO-Balloon focal surfce.

3. The ASIC board

In the JEM-EUSO/EUSO-Balloon DAQ chain, an MAPMT captures single photons, converts them in its photocathode into photoelectrons (PEs) and induces pulses from the charges on their anodes and dynode output. Then the front-end ASIC transforms the charges from MAPMTs into digital numbers to be processed in the next stages of digital electronics. Similarly the trigger stages process digitally those charges which have been previously converted into numbers.

Bottom view Top view EC-ASIC mechanical frame

Figure 3: Photos of the ASIC boards (EC_ASIC). Left: bottom view, middle: top view, right: EC_ASIC housed in the EC_ASIC/PDM mechanical frame.

The analog signals coming from MAPMTs are collected by 6 ASIC boards (EC_ASIC) fixed perpendicularly to the mechanical frame that houses the 9 EC_units. As shown in the Fig.3, an EC_ASIC board is composed of 6 (3 on each side) SPACIROC ASICs packages in CQFP160, 6 68-pin connectors toward the EC_units and one 120-pin connector toward the PDM board. Each of paired ASIC board read 3 halves of EC_units. In terms of functionality, our front-end ASIC must be able to deal with different types of anode signals. The anode pulses of the MAPMT will be in discrete mode (Photon Counting) and also in charge integration mode for the wide range of signals originated by the different types of event which could be observed by JEM-EUSO. Both Photon Counting and charge integration functions are the basis of the analog part of the ASIC. The digital part is also implemented for the analog-to-digital conversion for each acquisition window, called the Gate Time Unit (GTU=2.5μs). SPACIROC, a 0.35 μm SiGe BiCMOS ASIC, has features to meet the requirements for 5 years operation of JEM-EUSO as following:

- Low power consumption: $<$1 mW/ch
- 100% trigger efficiency in Photon Counting at 50 fC ($\sim$1/3 PEs at a PMT gain of 10^6)
- Dynamic range in charge measurement 1.5 to 150 PEs/GTU/pixel or a sensitivity of factor 100
- Linearity in Photon Counting: $\geq$ 30 PEs/GTU
- Double pulse resolution: $\leq$ 30 ns

4. Integration tests

In the past years, detailed calibration tests of EC_ASIC and EC_unit as well as integration tests of key electronics such as the connection between EC_ASIC and PDM board, and between PDM board and DP have been successfully carried out. In March 2014, PDM, CPU, CCB, LVPS, HK were examined in launch conditions. 3 mbar at 0 °C and 40 °C are achieved by the CNES thermostatic vacuum chamber (SIMEON). The communication process was confirmed in all conditions. In May 2014, we performed end-to-end test and confirmed the full DAQ chain performance: we measured the width of the point spread function of the optics as a function of z (distance L3-PDM) as well as the overall efficiency for the photons of a wavelength of 375 nm, tested the DAQ chain with pulsed LED light which is externally triggered and synchronized with GPS for the flasher measurements under-flight, and successfully performed SIREN (CNES telemetry) tests.

S-curves and efficiency map

For the detection of signal photons by our UV camera, one of the most important aspects is the trigger efficiency of Photon Counting. Typically it is done by scanning the threshold (DAC) for a given injected charge. The resulting plot is known as S-curves which is in fact the cumulative distribution function of the probability to generate a trigger. Fig.4 shows the S-curves (left and middle) showing averaged photon counts per GTU as a function of DAC values, and relative efficiency map at a threshold of DAC 195 (right), indicated by a red line in each S-curve plots, which corresponds to roughly 1/3 PEs level obtained during the integration tests. The left panel shows the S-curves of four MAPMTs of the EC_unit6 (EC6), one of the 9 EC_units of PDM shown in the middle panel. Each plots contain 64 S-curves for the pixels of corresponding MAPMT. It shows the typical response of an EC_unit. Despite the good performance of the system, we recognize a few of the EC_units such as part of EC1 or EC8 show some noise contamination in their S-curves. We considered that it was related to the groundings and cable connections, and mostly solved before the flight in August 2014.

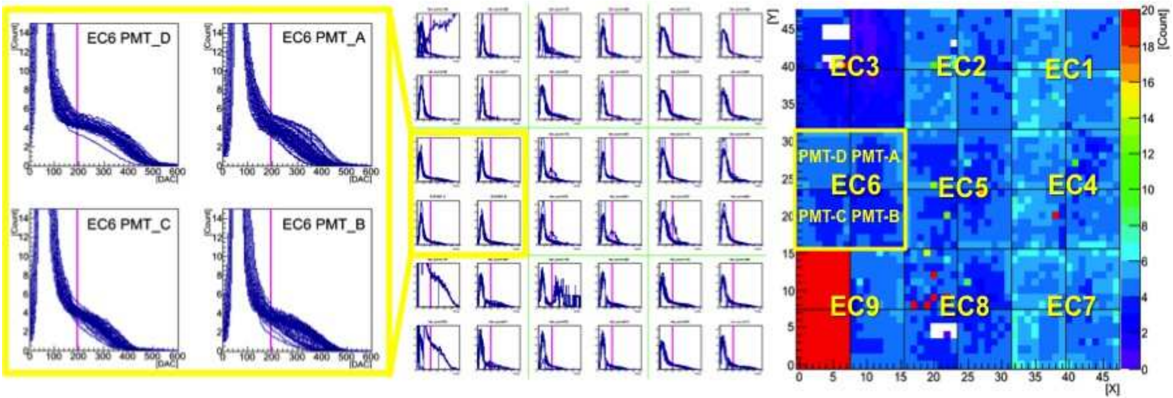

Figure 4: Left: Enlarged S-curves of EC_unit6 (EC6), middle: S-curves of all 9 EC_units, right: relative efficiency map at a threshold of DAC 195, indicated by red lines in the S-curve plots.

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