Detailed description of EUSO-BALLOON instrument

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Abstract: EUSO-Balloon is a pathfinder prefiguring the future fluorescence space telescope JEM-EUSO that should be installed on-board of the Internal Space Station before the end of this decade. This telescope will be the payload of a stratospheric balloon operated by CNES, starting its flight campaign in 2014. Current technical development for JEM-EUSO are a challenge for a space project, have been implemented in EUSO-Balloon. In this poster, the complete design of this instrument will be presented. It consists of an advanced modular telescope structure including a set of three Fresnel lenses having an excellent focusing capability onto its pixelized focal surface of its UV Camera. This camera is very sensitive to single photons, with 6 orders of magnitude dynamic range thanks to an adaptive gain, and fast enough to observe speed-of-light phenomena. The camera is an array of multianodes photomultipliers, which dynodes are driven by Crockoft Walton HV generators capable of switching down the gain in few microseconds to protect the photodetectors against strongly luminous events. The analog signals at anodes are digitised continuously each time window (2.5 microsecond) by an ASIC, performing two kinds of signal measurements and readout by a FPGA applying a first level trigger algorithm. The Electronics is operated by a digital processing unit comprising a CPU associated to Clocks generators board and a GPS receiver, an event filtering board based on a FPGA and an House-Keeping unit for the instrument monitoring. The CPU controls both acquisition and the data storage. This processing unit is interfaced with the CNES telemetry system to receive commands from ground and to download samples of the event or monitoring data. The whole instrument operates autonomously with a battery package that drives a series of power supply boards that deliver the required voltage to each board.

Keywords: JEM-EUSO, UHECR, space instrument, balloon experiment, instrumentation

1 Introduction

EUSO-Ballon is a telescope aiming at verifying the conceptual design as well as the technologies foreseen to be applied for the construction of the future space telescope JEM-EUSO mission [1]. Even if this instrument is a reduced version of JEM-EUSO, it however includes almost all the required components of the original space mission. The scientific and technical goals on its mission are reviewed in the reference [2]. This instrument will be the payload of a stratospheric balloon operated by CNES, to perform a series of night-flights at altitudes of 40 km, at various earth locations, lasting from a few hours to tens of hours. This programs require payload recovery after landing either in water or hard soil, and repairing after each mission. The special atmospheric environmental conditions and recovery

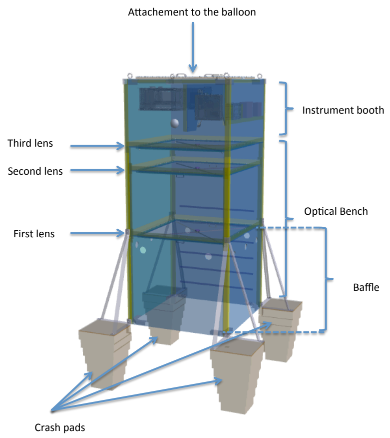

Fig. 1: EUSO-Balloon Instrument Overview.

requirements involved much precautions in the design and implied dedicated tests the realisation of prototypes. First of all, the section 2 gives the overview of the instrument, including its particular mechanical design adapted to the balloon flights. Then the section 3 provides details on the subsystems comprising the instrument highlighting the reasons for the chosen design. Afterward, the section 4 deals with the series of preliminary measurements and tests which are mandatory before the commissioning of the instrument for exploration. And finally, in the section 5, the control and analysis tasks to be performed during the operation are mentioned.

2 The Instrument Overview

The EUSO-balloon instrument structure is shown in the figure 1 and its main characteristics are given in the table 1. This parallelepiped telescope presents a wide field of view of $12^o \times 12^o$ for a collecting surface of 1m$\times$1 m. It points to the nadir direction toward the atmosphere. It basically consists in an optical bench associated to an instrument booth placed at the focal position. The optical bench comprises two lenses. The instrument booth includes the all electronics inside a pressurised watertight box. One side of the instrument booth is provided by the third lens. The instrument includes an external roof-rack permitting the fixation of complementary instrument like an infra-red camera.

2.1 General characteristics and functions

The main characteristics of the instrument are given in the table 1. These parameters will be justified in the section 3 devoted to the subsystems. The optical subsystem includes the optical bench which have the purpose of focusing parallel light rays in a narrow focal point which is pixelized by an array of photodetectors called MAPMTs (Multi-Anode Photomultiplier). The focal surface is instrumented by an electronics which has the properties of a very high sensitivity, in the UV range, fast measurement rate within the microsecond timescale, auto-triggering capability, event filtering and event recording. This electronics is capable to record on disk a burst of 128 consecutive sky pictures separated each-other by a time period of 2.5 μs called the GTU (Gate Time Unit, the basic time unit useful in cosmic rays detection in space).

2.2 Instrument mechanics

The mechanics of the instrument is made of Fibrelam panels, arranged together through Fibreglass sections. The instrument will be coated by an insulating cover to protect the instrument component from fast temperature changes during balloon ascent and descent. Special valves inserted in the optical bench are used to enable pressure equilibrium between indoor and outdoor. Wherever the after-flight fall location occurs, the instrument must be recovered with the smallest induced damages. The bottom part is equipped with crash-pad which absorb brutal acceleration (up to 15G) at landing on ground. A baffle with special holes in the optical bench are used as a piston-effect to damp the shock for a fall over water. The instrument booth which is a totally watertight sealed box, consists of a central aluminium plate on which the various electronic boxes are fixed. One of its side is the third lens. The opposite side is an aluminium radiator used to dissipate the heat generated by electronics equipment by radiation. The instrument is surrounded by buoys to avoid sinking if sea landing and to raise straight up the instrument booth above the water level.

3 The instrument Subsystems

The instrument is broken down into subsystems defined to be the Optics, the Focal Surface, the Photo-detection with the MAPMT, the Signal measurement with the ASICs, the trigger readout with the PDMB and the CCB, The Data Acquisition System (DAQ) and the utilities like the monitoring also called the House-Keepting and the Power Supplies. Those subsystems are all described succinctly below.

3.1 Optics subsystem

The Optics subsystem involves the three lenses. Its goal is to provide the best focalisation for the smallest focal distance. The focalisation requirement is constrained by the pixel size of the photo detection system. Due to the wide angular field of view, it is necessary to combine 3 flat lenses of which the two external are of focusing Fresnel type for one of their side and the middle lens is purely dispersive to correct for chromatic aberrations. These lenses are manufactured in PMMA material [4]. The ray tracing calculations including the temperature profile expected for flights in cold and warm cases provide a focal length of 1.62 m and a focal point spread width of the order of 2.6 mm, smaller than the pixel size.

3.2 Front-End Electronics

The Focal Surface is constituted by an array of photodetectors called the MAPMTs (Multi-Anode Photomultipliers), which anode signals are measured and digitised by ASICs, themselves are readout by FPGA to run the trigger algorithm. This Focal Surface is arranged into a so-called Photo-Detector module (PDM) which design and effective realisation is described in details in [5]. We review here the main properties of this electronics :

Focal Surface The focal Surface is a slightly curved surface, similarly to that of the JEM-EUSO central PDM, being an array of 48×48 pixels of 2.88mm×2.88mm size exceeding slightly the focal point spread. This granularity fits perfectly the accuracy requirements to make the image the longitudinal profile of Air-shower above 10^{18}eV. Practically, the Focal Surface of the PDM is broken up into 9 sets of identical Elementary cells (EC), which are matrixes of 2×2 MAPMTs. Inside the PDM structure, the 9 EC are disposed and tilted according the appropriate shape required for the Focal Surface.

MAPMTs They are photon detectors consisting of a matrix of 8×8 pixels. Each pixel is associated to an output channel generating a charge or a current called an anode. Their sensitivity is as low as a few tens of photoelectrons and their dynamic range can extend up to few 100 photoelectrons per μs when working at high gain 10^6. This high gain is achieved through 14 dynodes polarised by High Voltage Power Supplies (HVPS) for which the photocathode is set at -900 V. Limited power consumption is obtained with a Crockoft-Walton (CW) high voltages supplier. Dynamic range can be extended up to 10^6 photons if the gain is reduced automatically gradually from 10^6 to 10^4, 10^2 or 30 by fast switches (SW) reacting to the micro-second timescale in case of large current flow is detected in the anodes. In the PDM, there is 9 independent HVPS controlling the 9 ECs. Because a large photon flux generating anode current above 100μA would destroy the tube, an automatic control system reducing the gain or switching off the MAPMT is mandatory to guaranty the tube survival. Practically this switching decision logic is implemented in a FPGA reading out the ASICs.

ASICs 36 ASICs of the type SPACIROC [6] are used to perform the anode signals measurement and digitisation of the 36 MAPMTs. These ASICs have 64 channels. Their analog inputs are DC-coupled to the MAPMT anodes. They process the 64 analog signals in parallel in two modes : 1) in photoelectron counting mode, in a range from 1/3 of photoelectrons up to 100 photoelectrons, by discriminating over a programmed threshold each of the channels, 2) by estimating the charge from 20 pC to 200 pC, by time over threshold determination for exclusive groups of 8 anodes current sums. The 64 analog channels are balanced each-other relatively by gain matching over 8-bits. The discrimination voltage level used in the photo-counting is provided by a 10-bit DAC (Digital to Amplitude converter). In both cases the digitisation is performed by 8-bits counters every GTU. There is no data buffering on the ASIC. The data are transferred to the later stage, a FPGA each GTU under the sequencing of a 40MHz clock.

Trigger The Instrument includes two trigger stages. The level 1 trigger (L1) implemented in the FPGA of a PDM-Board (PDMB), belonging to the Front-End Electronics. The PDMB readouts the data from the 36 ASICs from a PDM each GTU to compute the trigger L1. It principle consists in searching an excess of signals over background in groups of 3×3 pixels, with enough time-persistence, which signal sum over time exceed a preset value. The background

Parameter name	values
1:General parameters	
Field of View	$12^o \times 12^o$
Aperture	1 $m^2 \times$ 1 m^2
Height	2.66 m
Width	1.21 m
Weight	300 kg
2:Optics	
Focal Length	1.62 m
Focal Point Spread (RMS)	2.6 mm
3:Focal Surface	
Curvature Radius	2.5 m
Number of Pixels	2304
Pixel FOV	$0.25^o \times 0.25^o$
Pixel size	2.88 mm×2.88 mm
BG3 UV Filter transmittance	98 %
Wavelength range	290 nm - 430 nm
Number of MAPMTs	6× 6
4:PhotonDetection (MAPMTs)	
Number of channels	64
Photon detection efficiency	35 %
Gain	10^6
Pulse duration	2 ns
Two pulses separation	5 ns
Dynamic Range	1 - 100 photons
Maximum tube current	100 μA
4:Signal Measurement (ASIC)	
Sampling period (GTU)	2.5 μs
Photon Counting (64 ch), photoelectrons	0.3 pe (50 fC) - 30 pe (5 pC)
Charge to Time Conv (8 ch)	2 pC (10 pe) - 200 pC (100 pe)
Readout Clock	40 MHz
6:Triggers (FPGA, Virtex 6(L1) and Virtex 4(L2))	
L1 rate	7 Hz (1-100 Hz)
L2 rate	Max 50 Hz
7:Event readout and DAQ (CPU, Clocks, GPS)	
Event size	330 kB
Data flow	3.24 Mb/s
Readout Clock	40 MHz
Event dating	at μs level
8:Instrument Monitoring (microcontroler)	
9:On/Off capability, alarms, temperature and voltage control	
10:Power supply	
60 batteries cells	225 W during 24 hours, V: 28 V

Table 1: Typical parameters of the instrument

rate seen by pixel is monitored continuously to adjust in real-time the trigger threshold which are adjusted such the L1 rate is kept a a fixed level of a few Hz compatible with the DAQ readout rate. The trigger is evaluated each GTU. Because Air-Shower may extend over 100 GTU, this trigger has the buffering capability of 128 consecutive GTU. To reduced the dead-time induced by event readout, the event buffer is doubled.

3.3 Data acquisition

The data acquisition system is part of the computing system DP (Data Processing). It comprises the CCB designed to produce the second level trigger L2, which is described in [7]. For each generated L1 trigger, the CCB read the data corresponding to the 128 consecutive GTU from the PDMB buffer. In JEM-EUSO, the CCB is devoted to the combination of 9-PDMB triggers and to reduce the resulting combined trigger rate to about a few Hz or less compatible with the data storage capabilities of the DAQ. The triggering role of the CCB in EUSO-Balloon is marginal as there is only one PDM. However it has the task to read the whole event from the Front-End and to pass it to the CPU. The L2 decision is propagated to the Clock-Board (CLK-B, based on a Xilinks Virtex5 FPGA) generating all the clocks used by the electronics, itself associated with a GPS-Board (GPSB) to provide the event time tagging data with an accuracy of a few microseconds. The CPU (Motherboard iTX-i2705 model, processor Atom N270 1.6 GHz) merges the event data with the time tagging data to build an event of a size of 330 kB, leading to a data flow of 3MB/s for a 10 Hz L1-L2 trigger. The CPU write all the data on disks (1 TB CZ Octane SATA II 2.5 SSD) and may also send to telemetry a subset of flagged events by CCB for event monitoring.

3.4 Monitoring

The instrument behaviour is controlled at low frequency by the House-Keeping system (HK) which is a part of DP. It is based on a commercial micro controller board (Arduino Mega 2560) designed to control temperatures, voltages, and alarms raised by several boards. The CPU poll from time to time the alarms and initiate corresponding foreseen actions. HK is connected to the telemetry system to receive basic commands namely those that allow to turn on-off most of the boards power supplies through relay control.

3.5 Power supply and electrical architecture

The instrument runs autonomously thanks to a set of 60 batteries providing 28 V (225 W during 24 H) to a set of Low-Voltage boards generating isolated-decoupled lower voltages to the PDM (HVPS and PDM-B), DP (CPU, CCB and HK). The electrical architecture follows the EMC rules to prevent floating reference voltage induced by bad grounding (ground current loop effect).

4 Assembly and Tests

After fabrication, the subsystems directly related to the physics measurements need to be calibrated in an absolute way. The goal of the absolute calibration is to relate a measured digitised signal into the true number of photons impinging on the Focal Surface or on the first lens. Thus the Optics and the photo-detection done by the MAPMTs are will be calibrated. Other subsystems like the trigger has to be tested once the instrument is close to final assembly. Each of the subsystems of the instrument are calibrated if necessary and tested before the full integration. Then the assembled instrument is then tested entirely.

4.1 The optical tests

Even if the focal length of each lens and the combined focal length can be predicted by calculation, the real values resulting from the machining are poorly known at several centimetres accuracy. This is not enough to achieve a resolution smaller than the pixel size. The relative distance between the three lenses and the Focal Surface has to be measured experimentally by using a large parallel UV beam along optical axis, sent over the first lens and measuring the Focal Length by adjusting the position of a CCD camera to get a narrow point-like focused spot.

4.2 Measuring the MAPMT performances

Each channel of the MAPMT is characterised by its photodetection efficiency (product of the photocathode quantum efficiency and the collection efficiency) and by the gain of the phototubes. This measurement is firstly done before their mounting inside EC-Units (see [9]) and also after the EC-Units assembly. This measurement is done by illuminating by a LED (controlled by a NIST) the photocathode in single photoelectron mode [8] to measure the single photoelectron spectrum for each of the 2304 pixels of the instrument camera. This procedure allows to determine the exact high voltage to apply to each of the MAPMT photocathodes for each EC-Units.

4.3 The ASIC settings

The ASICs measure the single photoelectron spectrums at nominal high voltage for each of the channels by performing S-curve (by performing series of runs by ramping the discriminator voltage). Because the relative gain of the channels inside an EC-Unit differs slightly from one-another, the ASICs allow balancing the discrepancies between the channels. This done once the PDM is mounted and each MAPMT is associated to an ASIC. Then the nominal discriminator threshold at 1/3 of a photoelectron to apply to each ASIC is established.

4.4 The Trigger tests

Once the PDM is mounted, the L1 trigger algorithm performance is checked by illuminating the Focal Surface by the light spot moving closely to speed-of-light, generated by an ”old” persistent-screen scope.

4.5 The Instrument tests

The final tests will be performed after the integration of all subsystems inside the instrument. A check of the correct final position of the lenses as well as that of the Focal Surface will be done by lighting up the first lens by a parallel UV beam along the optical axis. The size of the focused point on the Focal surface will be minimised by finely adjusting the position of the PDM at the sub-millimetre scale. At the end of the integration and at launch site, basic health tests on the electronics will be performed by illuminating in single photon mode uniformly the Focal Surface or the first lens by a LED-controlled as described in [8].

5 Operation and Analysis

During the balloon flight operation, the instrument will be controlled from ground by an operator using a control program [10] interfaced to the TC/TM system (Telecomand and Telemetry) NOSYCA of CNES. At a given altitude reached by the ballon, a command will be issued to turn on the instrument. The HK system will turn on one by one each of the subsystems while the monitoring parameter will be downloaded at ground. When every parameters looks perfect, the Balloon operator can launch the DAQ program running on the CPU. He will control basic run parameters, namely the background rate calculated by the PDMB. Conventionally the thresholds auto-adapt to the required L1-L2 rates unless the operator forces another mode of trigger settings. At any moment, the operator can shut down the instrument. This will be done when the balloon descent will be activated.

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References

[1] J.H. Adams Jr. et al. - JEM-EUSO Collaboration, Astroparticle Physics 44 (2013) 76-90 http://dx.doi.org/10.1016/j.astropartphys.2013.01.008
[2] P. von Ballmoos et al. - EUSO-BALLOON: a pathfinder for observing UHECR's from space, this proceedings, paper 1171,
[3] T. Mernik et al. ESAF-Simulation of the EUSO-Balloon, this proceedings, paper 875,
[4] Manufacturing of the TA-EUSO and EUSO-Balloon lenses, this proceedings, paper 1040,
[5] P. Barrillon et al., The Front-End Electronics of the EUSO-Balloon UV camera,this proceedings, paper 765,
[6] H. Miyamoto et al., Performance of the SPACIROC front-end ASIC for JEM-EUSO, this proceedings, paper 1089,
[7] J. Bayer et al., Second level trigger and Cluster Control Board for the JEM-EUSO mission,this proceedings, paper 432,
[8] P. Gorodetzky et al., Absolute calibrations of JEM-EUSO,this proceedings, paper 858,
[9] C. Blaksley, Photomultiplier Tube Sorting for JEM-EUSO and EUSO-Balloon, this proceedings, paper 628,
[10] L.W. Piotrowski et al. On-line and off-line data analysis for the TA-EUSO and BALLOON-EUSO experiments, this proceedings, paper 713,