Mini-EUSO onboard of the ISS for UV terrestrial and cosmic emission detection: space qualification and calibration

G Cambiè, on behalf of the JEM-EUSO collaboration
Istituto Nazionale di Fisica Nucleare, Sezione di Roma2 Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
E-mail: giorgio.cambi@roma2.infn.it

Abstract. The Mini-EUSO (Multi-wavelength Imaging New Instrument - Extreme Universe Space Observatory) telescope is designed to observe the UV emission of the Earth from the vantage point of the International Space Station (ISS) in low Earth orbit. Mini-EUSO will map the Earth in the UV range (300 - 400 nm) offering the opportunity to study a variety of atmospheric events such as Transient Luminous Events (TLEs) and meteors, as well as searching for Strange Quark Matter (SQM) and bioluminescence. The instrument comprises a compact telescope with a large field of view (44°), based on an optical system employing two Fresnel lenses for light collection, focused onto an array of 36 multi-anode photomultiplier tubes. The resulting signal is converted into digital, processed and stored via the electronics subsystems onboard. In addition to the main UV detector, Mini-EUSO contains two ancillary cameras for complementary measurements in the near infrared (1500 - 1600 nm) and visible (400 - 780 nm) range and also a SiPM (Silicon PhotoMultiplier) array which will increase the Technology Readiness Level (TRL) of this ultrafast imaging sensor.

1. Introduction
Mini-EUSO [1] is a mission supported by ASI (Italian Space Agency) and ROSCOSMOS (Russian Space Agency) belonging to the JEM-EUSO (Joint Experiment Missions) collaboration, which aim is to study Ultra High Energy Cosmic Rays (UHECRs) interacting with the Earth atmosphere. The JEM-EUSO collaboration has developed succesfully three different mission in the past years: EUSO-TA [2] (Telescope Array), a detector sharing the same Mini-EUSO optics and electronics hosted to the Millard County (Utah) site since 2015 currently running; EUSO-Balloon [3] (2014) and EUSO-SPB (Super Pressure Balloon) (2017) which were two experiment onboard a super pressure balloon for a long duration flight. TUS/ [4] (Tracking Ultraviolet Setup), a Russian mission onboard the Lomonosov satellite launched on April 28th 2016 included in the program. Mini-EUSO is a telescope which will be hosted onboard the ISS (∼ 400 km altitude), on a nadir-facing UV transparent window, inside the russian Zvezda module. It has been launched with the Soyuz MS-14 spacecraft (an unmanned only cargo expedition) from the Bajkonur Cosmodrome (Kazakhstan) on August the 22nd 2019. Mini-EUSO will represents a test bench for the future, larger and much performing satellite K-EUSO [5] (KLYPVE) and POEMMA [6] (Probe Of Extreme Multi-Messenger Astrophysics). In the following will be presented the mission overview, the characterization and tests made...
2. Mission Objectives

Even though recent results from on ground experiments showed that no Cosmic Ray (CR) should exceed the energy threshold of $10^{20}$ eV due to the GZK (Greisen-Zatsepin-Kuzmin) suppression, Mini-EUSO main objective is to observe UHECR (which energies are above $10^{21}$ eV) signature or, at least, it plan to put an upper limit for a null detection. Regarding the CR flux, at these energy scale it is crucial to observe the largest area possible. For the first time, Mini-EUSO will perform this measurement from space and this new challenging approach, will provide great improvements to the study of UHECR. Referring to the Heitler shower production model [7], the depth of shower maximum (which represent a measure of the depth of material penetrated by the shower particles before being almost completely absorbed) as a function of the starting depth $X_0$, the interaction length $\lambda$, the total number of particles produced $N_{\text{max}}$, the primary particle energy $E_0$ and the critical energy $E_c$, which correspond to the energy at which no more interaction could occurs, is estimated to be

$$X_{\max} = X_0 + \lambda \ln \left( \frac{E_0}{3N_{\max}E_c} \right) g \cdot cm^{-2}.$$ 

Hence, the greater the energy, the greater the depth ($> 850 g \cdot cm^{-2}$ for an UHECR). This means that, for Extensive Air Shower (EAS) developing horizontally in high atmosphere, which are not detectable on the ground, the detector field of view should be as large as possible. Moreover, Mini-EUSO will produce a high-resolution map of night-Earth UV emission, focusing on terrestrial background sources, thus providing an invaluable starting point for future missions. Beyond UHECR, Mini-EUSO will observe many other phenomena as meteoroids, bioluminescence, Transient Luminous Events (TLEs) such as blue jets, sprites and elves that occur in the upper atmosphere as well as space debris track detection to investigate the possibility of using laser ablation for their removal. Mini-EUSO will also focus its eye on the study of SQM. According to the strange matter hypothesis, these particles can have cosmological origin, being produced during the QCD (Quantum ChromoDynamics) confinement phase transition or can be generated inside the neutron stars and even after UHECR interaction in Earth’s atmosphere [8].

![Figure 1. JEM-EUSO road map.](image-url)
3. The Telescope

Mini-EUSO is a compact telescope with dimension $37 \times 37 \times 62 \, \text{cm}^3$. It consists of two main subsystem: Optics and Photo Detector Module (PDM). Mini-EUSO optics consists of two double sided, 25 cm diameter, PMMA (Polymethyl methacrylate) Fresnel lenses which will focus light onto the Focal Surface (FS) with a large field of view ($\alpha = 44^\circ$). Neglecting the Earth curvature, from the ISS point of view, the estimated observable area as a function of telescope orbit $H$ is:

$$A = \pi (H \tan(\alpha))^2$$

which correspond to $6.76 \times 10^4 \, \text{km}^2$ for the total FS which consists of an array of 36 Hamamatsu 64 channels Multi Anode PhotoMultiplier Tubes (MAPMTs) divided into 9 Elementary Cells (ECs), for a total of 2304 pixels. The spatial resolution per pixel is $0.8^\circ$ in a timescales up to $2.5 \, \mu\text{s}$ called GTU (Gate Time Unit), covering Earth surface in the latitude range covered by the ISS ($\pm 51.6^\circ$). This approach is unique, not only for the huge area covered respect to the onground experiments, but also because both Earth’s hemispheres can be observed with one instrument, thus applying the same systematic error. Each MAPMT is powered by a Cockroft-Walton power supply board and present a BG3 UV filter on the entry window. The PDM comprises both the optics and the read out electronics: 6 SPACIROC3 [9] (Spatial Photomultiplier Array Counting Integrated ReadOutChip) Asic boards built on purpose, a Xilinx Zynq XC7Z030 system on chip and a PCIe/104 form factor CPU. In addition to the main detector, Mini-EUSO contains: two cameras for complementary measurements in the near infrared and visible range, three single pixel UV sensors used as switches for day/night recognition and a 64 channels Multi-Pixel Photon Counter (MPPC) imaging SiPM C13365 module provided by Hamamatsu Photonics read by a multiplexing board made on purpose. For the first time in space, thus increasing its TRL, a SiPM matrix will perform UV frame as the MAPMT FS with higher spatial resolution although a smaller field of view.

![Figure 2. Telescope mechanical body with subsystems.](image1)

![Figure 3. Mini-EUSO flight model fully integrated.](image2)

![Figure 4. Mini-EUSO focal surface.](image3)

An additional Atmel 2560 10-bit microcontroller board is used for ancillary sensor read-out. The LVPS (Low Voltage Power Supply) boards, consisting of three PCB modules mounting different Vicor DC-DC converter which stabilize the 28 V input voltage coming from ISS and provides power for all subsystems, preserving the entire instrumentation from spike and polarization inversion. Primary and secondary grounds are isolated each other. The Mini-EUSO power consumption is around 55 W.
4. Space Qualification Test
The General Technical Requirements for Experiment, Equipment and Technical Documents on board ISS required several test to be performed on the instrument as: Electro-Magnetic Interference and Conductive (EMC/EMI); vibration and shock; high/low pressure, thermal and humidity functional tests. Only the two major tests will be discussed on this work: the EMC/EMI and the vibration/shock. The aim of EMC/EMI tests is to verify that Mini-EUSO Instrument does not produce any undesired electromagnetic radiated emissions and that is capable to withstand different irradiations from external sources. Low and High Frequency (LF/HF) Conductive Interference, Electrical Field Intensity Produced by HF Emissions and Inrush current are intended to ensure the ISS safe. The setup and a test result for conductive interference are shown in Fig. 5 and Fig. 6.

![Figure 5. Mini-EUSO EMC/EMI qualification tests inside the anechoic chamber.](image)

![Figure 6. Mini-EUSO Conductive Interference spectrum response in range (30 ÷ 200 MHz). The continuous line is the threshold for successfully passed test.](image)

The vibration and shock qualification procedure required to demonstrate that Mini-EUSO payloads is able to sustain the random vibration launch loads. All procedures were performed with a former resonance survey. Random vibrations concern all the three spatial axis X, Y and Z with different timing and overall strenght starting from a maximum of 7.42 g to a minimum of 3.58 g. Also seven shock with 3 ms duration ±40 g strenght were required. The hardware under test is fixed to a shaker and on a slip table surface shown in Fig. 7 and Fig. 8.

![Figure 7. Mini-EUSO Vibration set-up scheme for Z axis.](image)

![Figure 8. Mini-EUSO accommodation on the shaker - X direction.](image)

5. Calibration and Field Test
Mini-EUSO is intended to work in a single photoelectron (PE) counting mode which has advantages over analog measurement in terms of signal-to-noise ratio. The 64 signals from
MAPMT anodes are digitalized and discriminated to count photon triggered pulses and to measure the photon intensity, thus, allowing to set a threshold for the MAPMT single PE detection. This analysis is made through the S-curve plot which shows the number of triggered pulses as a function of the ADC pulse height threshold. Each channel is an 8 bit threshold step, so that we can distinguish the typical noise pedestal (low charge accumulation on the anode) from the lower rising slope representing photon reaching the FS (see Fig. 9). It is possible also to adjust the gain noting that the pedestals, occurring around 150 ADC counts (see Fig. 10), are shifted along different channels so the PE production is not uniform over all PDM. Note that the ADC bins are different in the two plot.

![Figure 9](image1.png)

**Figure 9.** Top: Single pixel S-curve. Bottom: S-curve derivative. In order to figure out the threshold for the single PE production the derivative must be analyzed. In this case it is visible that our working point falls around 540 ADC value. (On x-axis ADC threshold, on y-axis measured counts).

Data analysis is made through ETOS (EUSO TO Tree) a scientific software which was expressly generated for all experiments belonging to the JEM-EUSO program. In Fig. 11 we are showing a field test, which represent a night sky frame taken in zenith position at latitude N 42°05'55" and longitude E 13°05'18".

![Figure 11](image2.png)

**Figure 11.** Mini-EUSO night acquisition frame on August 2019 analysed with ETOS.

The same night we had also the possibility to detect a meteor burning in the sky as showed below. The event lasts 360 ms as one can see in time reported on the top of each frames.
6. Conclusions

Mini-EUSO is actually onboard the ISS and it is in the commissioning phase. First data transmitted showed that the detector is working properly. It was able to detect meteors from space, UV emissions from earth (cities light), TLEs and other phenomena under investigation right now. In conclusion, we have proved that the telescope is able to reveal physical phenomena of scientific interest, moreover, we expect shortly, through the analysis of the first data, to confirm the reliability of its functionality in space for the study of CR, as well as of the SQM.

Figure 12. Meteor burning in atmosphere (hot spot in frames) detected by Mini-EUSO telescope during ground test. Each frame represent the FS mean counts over 40 ms exposure time, for a total duration of 360 ms.

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