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Mini-EUSO: a precursor mission to observe Atmosphere and Earth UV emission from the International Space Station

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Mini-EUSO (Extreme Universe Space Observatory) is a space mission developed by the JEM-EUSO International Collaboration, selected and approved by the Italian Space Agency (ASI) and, under the name "UV atmosphere", by the Russian Space Agency Roscosmos, to be carried to the International Space Station (ISS) in one of the next planned launches. The Mini-EUSO instrument is a small, compact telescope to be placed at the UV-transparent, nadir looking window of the Russian module of the ISS. It will perform studies of atmospheric phenomena, observation of meteors, search for strange quark matter and space debris tracking. Key measurements of the UV emissions produced in the Earths atmosphere will be carried out as well. It will also enhance the technological readiness level of the system instrumentation in view of the planned KLYPVE-EUSO mission to ISS (and future missions under study), relying upon the same concept and detection techniques. Scientific, technical and programmatic aspects of this project are discussed.

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[*] Speaker.

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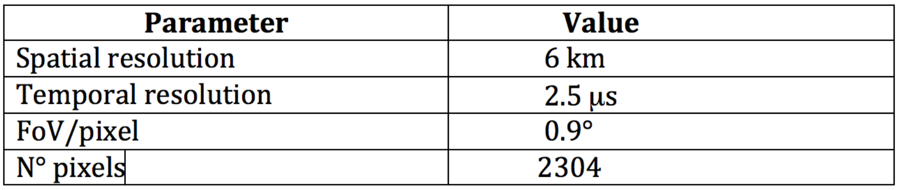
1. Introduction

The measurement and characterization of the UV emissions produced in the atmosphere of the Earth is a key element for any experiment aiming at the observation of Ultra High Energy Cosmic Rays (UHECR) from space. Such measurements, achievable with reasonably small-size, cost-effective devices, besides the intrinsic scientific relevance, can provide useful indications on the design, optimisation and performance of full-scale, long-running instruments to be placed on board orbiting space stations or free-flyer satellites. Mini-EUSO, aiming at the observation and measurement of the UV night emissions from the Earth, is being developed as a pathfinder and a precursor of the planned options for UHECR experiments in space - such as KLYPVE/K-EUSO [1] on the Russian module of the International Space Station (ISS) - and of future missions under study by the JEM-EUSO Collaboration. It comes as a next step in the road-map of JEM-EUSO together with other test experiments developed and carried out by the JEM-EUSO Collaboration, like EUSO-TA [2], EUSO-Balloon [3] and EUSO-SPB [4]. The Mini-EUSO mission, originated as a joint project between Italy and Russia, was selected in Italy by the Italian Space Agency (ASI) and is supported by the National Institute of Nuclear Physics (INFN); then, under the name ”UV atmosphere”, it was approved by the Russian Space Agency Roscosmos and included in the long-term program of space experiments on the ISS. After the signature of a common Scientific Agreement, Mini-EUSO is now an established project between the participating countries of the JEM-EUSO Collaboration.

2. The Instrument

The Mini-EUSO telescope is based on one single element of the basic JEM-EUSO detection unit, the Photo Detector Module (PDM), consisting of 36 Hamamatsu Multi Anode Photo Multiplier Tubes (MAPMT M64), 64 pixels each, for a total of 2304 pixels. The overall instrument is made up of three main sub-systems, the optical system, the PDM and the data acquisition system. Two Fresnel lenses, 25 cm diameter each, form the optical system, which focuses the light onto the PDM Focal Surface reaching a Field of View (FoV) of 44° x 44°. The PDM detects UV photons (300 - 400 nm) and is read out by the data acquisition system with a sampling rate of 2.5 μs and a spatial resolution of $\sim$ 6 km.

The main physical parameters of the instrument are listed in Fig. 1.



Parameter	Value
Spatial resolution	6 km
Temporal resolution	2.5 μs
FoV/pixel	0.9°
N° pixels	2304

Figure 1: Parameters of the Mini-EUSO instrument, including the field of view (FoV)

In addition to the main detector, Mini-EUSO includes two ancillary cameras for complementary measurements in the near infrared (NIR from 1500 to 1600 nm) and visible (VIS from 400 to 780 nm) range with the main task of performing atmospheric monitoring measurements (as the

Lens	Surface	Surface type	Groove pitch (mm)	Number of grooves
	Front	Fresnel	2.29 ∼ 18.85	35
Front lens	Back	Aspherical	N/A	N/A
	Front	Fresnel	4.19 ∼ 23.94	18
Rear lens	Back	Fresnel	1.50 ∼ 17.47	42

Table 1: Characteristics of the Fresnel lens surfaces

thermodynamic phase detection of clouds) [5]. Data from the cameras will help in the measurements of the emissions of the Earth and the study of transient phenomena. Mini-EUSO will be housed in a container, a space qualified mechanical box (Al Ergal), whose CAD design is shown in the left panel of Fig. 2, while the actual Engineering Model - presently in the final integration phase - is shown in the right panel. All the needed interfaces to the transparent, nadir looking, UV-transparent window of the Russian module Zvezda of the ISS will be provided by a special adapter.

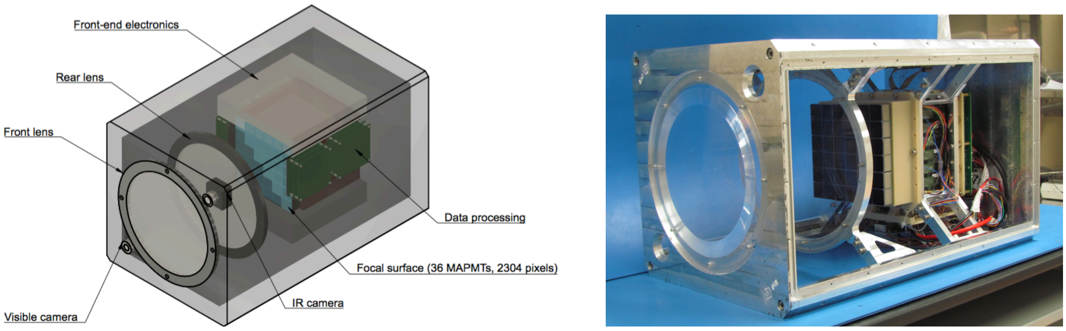


Figure 2: Left: Mechanical box CAD design. The instrument dimensions are $(37\times37\times62)\ cm^3$, the weight is $\sim$ 30 kg and the power $\sim$ 50 W; Right: Mini-EUSO Engineering Model.

The optical system designed for Mini-EUSO consists of two double sided flat Fresnel lenses and the focal surface, as shown in Fig. 3. The diameter of both Fresnel lenses is 250 mm. The Mini-EUSO optics has a low focal number F# 0.6, and the effective focal length is 150 mm. Its Field of View (FoV), as already mentioned above, is 44° x 44° at r = 85 mm on the focal surface. The material of the Fresnel lenses is made of UV transparent PMMA (polymethyl methacrylate). The thickness of the lenses, 11 mm, reduces the mass of the optics resulting in a light system (∼0.3 kg/lens). The main characteristics of the Fresnel lenses are shown in Table 1, and the point spread function of the optical system is shown in Fig. 4. The photon collection efficiency (PCE), calculated from a raytrace simulation of the active optical system by a code specifically developed, is ∼45% which takes into account several loss factors as surface reflection, material absorption, surface roughness, Fresnel facet back cut and support structure obscuration.

The data acquisition system is an evolution of the system used in the previous EUSO pathfinders, such as EUSO-TA, EUSO-Balloon and EUSO-SPB, incorporating the functionality of several subsystems into one single board. Each PMT is read out by a 64 channel SPACIROC3 ASIC [6] operating in single photon counting mode. This data is digitized for each acquisition window of

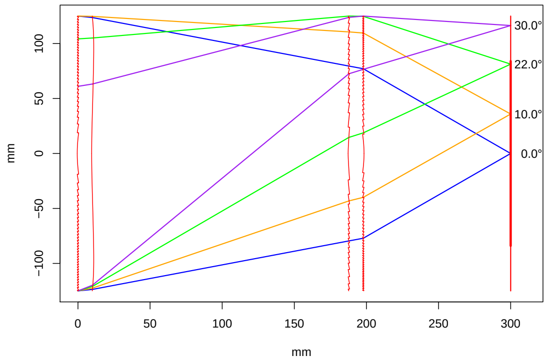


Figure 3: Mini-EUSO optical system design.

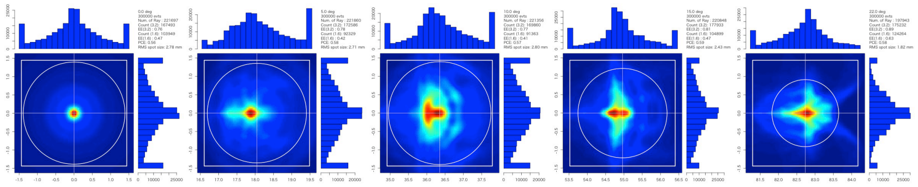


Figure 4: Point spread function of the optical system for light coming parallel with different inclinations (from left to right, 0°, 5°, 10°, 15° and 22°). The white square is a size of pixel of MAPMT and the white circle is RMS spot size.

2.5 μs. The output of the SPACIROC3 ASIC is then passed to the photodetector module data processing system (PDM-DP) that was specially developed for the experiment. The PDM-DP consists of three boards, the cross board, the Zynq board and the power board as shown in Fig.5. The cross board contains three synchronized Xilinx Artix7 FPGAs to perform data gathering from the ASICs, pixel mapping and data multiplexing. The Zynq board contains a Zynq XC7Z030 system of programmable logic Xilinx Kintex7 FPGA [7], [8] and performs all data handling operations including data buffering, configuration of the SPACIROC3 ASICs, triggering, synchronization, and interfacing with the separate CPU system for data storage. A multi-level trigger [9] is implemented in the Zynq board for the mini-EUSO instrument to perform measurements in various time scales (temporal resolutions 2.5 μs, 320 μs, 40 ms) in order to maximise the scientific output of the instrument . This trigger was successfully implemented and tested during the laboratory tests of the equipment. The CPU, a PCIe/104 form factor, performs the control of the instrument sub-systems as well as the data management and storage, housekeeping, switching between operational modes and collecting data from the NIR and VIS cameras.

3. Mini-EUSO mission objectives

3.1 Science objectives

Mini-EUSO will be able to provide information of the UV background photon radiance in the wavelength range 300 - 400 nm. The collected data so far (see Tatiana experiments [10]) give as a

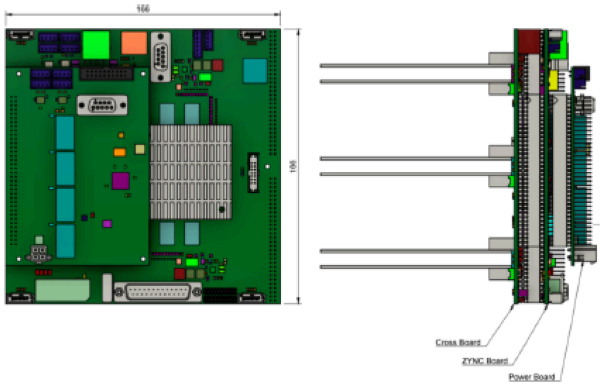


Figure 5: PDM-DP is shown with dimensions in mm. The 3 separate boards are shown with the mechanical support for the SPACIROC3 ASICs on their left.

reference number B $\approx$ (3 - 9)$\cdot 10^{11}$ photons $\cdot$ m^{-2} $\cdot$ s^{-1} $\cdot$ sr^{-1}. This value is estimated on the darkest Earth surfaces such as oceans and forests or deserts. However, the value can increase by a factor of $\approx$ 2 in presence of clouds, and even by an order of magnitude or more in presence of the moon or for urbanized areas. Balloon experiments, such as NIGHTGLOW [11], BABY [12] and EUSO-Balloon [3] provide relevant information on the UV background reflected from ground, but not a direct detection of the airglow emission which is located around 100 km altitude. Mini-EUSO, with its spatial resolution of $\sim$ 6 km and a temporal one of 2.5 μs, will be able to characterize in a much detailed way the intensity and variation of the UV radiance, airglow included, as a function of time and position of the ISS. These data will be of very much relevance in the proper estimation of the exposure curve of space-based experiments such as JEM-EUSO [13]. Despite its very high energy threshold for cosmic ray detection ($E_{thr} \sim 5 \times 10^{20}$ eV, with its annual exposure of $\sim$ 15,000 km^2 year sr), Mini-EUSO will provide a significant contribution in estimating an absolute limit on the cosmic ray flux above those energies for a null detection. Fig. 6 shows the expected light curve and track on the PDM of an Extreme Energy Cosmic Ray with energy $E = 10^{21}$ eV.

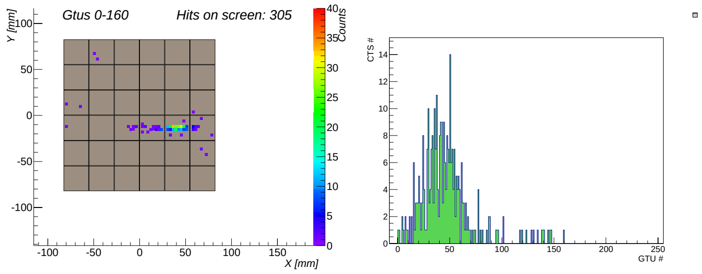


Figure 6: Left: Number of counts recorded in Mini-EUSO by simulating a 10^{21} eV cosmic ray event with 80 degrees inclination from nadir axis. Right: Light curve produced by such a shower. In both plots the UV background light is not added.

Meteor and fireball observations are key to the derivation of both the inventory and physical characterization of small solar system bodies orbiting in the vicinity of the Earth. For several decades, observation of these phenomena has only been possible via ground-based instruments. Mini-EUSO has the potential to become one of the first operational space-based platforms to share this capability. In comparison to the observation of extremely energetic cosmic ray events, meteor phenomena are very slow, since their typical speeds are of the order of a few tens of km/sec. By scaling the JEM-EUSO performance in meteor detection [14], Mini-EUSO will be sensitive to meteors with magnitudes $M < +5$.

The observing strategy developed to detect meteors may also be applied to the detection of Strange Quark Matter (SQM) and nuclearites [15], which have higher velocities, a wider range of possible trajectories, but move well below the speed of light and can therefore be considered as slow events as well. The possible detection of nuclearites and SQM greatly enhances the scientific rationale behind the Mini-EUSO mission. Preliminary estimations of the sensitivity of Mini-EUSO detection of nuclearites are under study.

Discovered in the late eighties, Transient Luminous Events (TLE), such as red sprites, elves and blue jets are still poorly known. These phenomena, occurring in the upper atmosphere, have been widely studied in recent years. Previous satellite missions (Tatiana-1, Tatiana-2 [10], RELEC [16]) indicate a high luminosity in UV wavelengths and high frequency of TLEs (especially weak ones).This may affect UHECR measurements and must be carefully studied before the main mission. Additionally, UV night airglow measurements are currently being conducted by the TUS experiment on board the Lomonosov satellite [17], [18]. TUS has a spatial resolution of 5 km, similar to that of Mini-EUSO.

Another relevant issue would be the observation of space debris. In more than 50 years of space flight, over 30,000 t of satellites and rockets have been sent to space. It is estimated that almost 3000 t [19] of non-functioning space debris remain in Low Earth Orbit (LEO) in varied forms ranging from fragments to switched off rocket bodies and fully intact multi-ton satellites. Since their orbital velocities are very high, collisions can involve relative impact velocities of the order of 10 km/s, even the fragments with greater than MJ kinetic energies may cause a severe or catastrophic damage on functioning satellites such as the ISS. As described in [20] Mini-EUSO could be used as a prototype system for tracking such space debris. A super-wide field-of-view telescope (such as JEM-EUSO) and a novel high efficiency fibre-based laser system (CAN) could constitute a very useful orbiting debris remediation system.

Other scientific objectives of Mini-EUSO include the bio-luminescence observation above the sea from space and atmospheric science by coupling UV measurement together with simultaneously taken IR and VIS images. The science objectives of Mini-EUSO are discussed in more detail in [21]

3.2 Technological objectives

Besides the previously described scientific objectives, Mini-EUSO addresses some important issues by the technological point of view that are summarized as follows:

- First use of Fresnel lenses in Space (meant at an altitude higher than the top of atmosphere $\sim$40 km).
- Optimization and validation of JEM-EUSO observational scheme.

- Increase of the Technological Readiness Level (TRL) of JEM-EUSO instrumentation, a typical parameter in the development of devices to be qualified and certified for space.
- Test and R&D of advanced solutions for future space missions, such as studies on development of SiPM (Silicon Photomultiplier) based photosensors for space applications [22].

4. Programmatic aspects - Towards the launch

Thanks to a common effort put in place by the JEM-EUSO Collaboration, Mini-EUSO has passed crucial tests on each subsystem in different locations (Japan for the lenses, France for the front-end electronics, Russia for the Data Acquisition system and the mechanical interfaces to ISS, Italy for the CPU, the mechanics, the trigger and the LVPS, the ancillary cameras and the SiPM, Poland for the HV system, Sweden for the software, Mexico for the housekeeping, and several other countries for the procurement of the MAPMTs). The integration and calibration of the Engineering Model (EM) is undergoing its final tests in the laboratories and clean rooms of the Physics Department at the University of Rome Tor Vergata. They will be successively followed by specific qualification tests (thermo-vacuum, vibration, e.m. compatibility, outgassing etc.) at the Kayser Aerospace Company in Italy. Finally, the EM will undergo the acceptance tests in Russia. Immediately after passing this milestone, the integration of the Flight Model completed with all the flight subsystems - prepared in the meanwhile - will take place in the same laboratories in Rome, followed by the delivery to Russian Space Agencies Roscosmos and Energia for the final phases preceding the launch.
ASI and Roscosmos are setting up the final agreements to choose one of the next launch increment mission to ISS with the Progress carrier and select and train the astronauts who will operate Mini-EUSO on board.

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