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Review

Mini-EUSO on Board the International Space Station: Mission Status and Results

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Abstract: The telescope Mini-EUSO has been observing, since 2019, the Earth in the ultraviolet band (290–430 nm) through a nadir-facing UV-transparent window in the Russian Zvezda module of the International Space Station. The instrument has a square field of view of 44°, a spatial resolution on the Earth surface of 6.3 km and a temporal sampling rate of 2.5 microseconds. The optics is composed of two 25 cm diameter Fresnel lenses and a focal surface consisting of 36 multi-anode photomultiplier tubes, 64 pixels each, for a total of 2304 channels. In addition to the main camera, Mini-EUSO also contains two cameras in the near infrared and visible ranges, a series of silicon photomultiplier sensors and UV sensors to manage night-day transitions. Its triggering and on-board processing allow the telescope to detect UV emissions of cosmic, atmospheric and terrestrial origin on different time scales, from a few microseconds up to tens of milliseconds. This makes it possible to investigate a wide variety of events: the study of atmospheric phenomena (lightning, transient luminous events (TLEs) such as ELVES and sprites), meteors and meteoroids; the search for nuclearites and strange quark matter; and the observation of artificial satellites and space debris. Mini-EUSO is also potentially capable of observing extensive air showers generated by ultra-high-energy cosmic rays with an energy above 10^{21} eV and can detect artificial flashing events and showers generated with lasers from the ground. The instrument was integrated and qualified in 2019 in Rome, with additional tests in Moscow and final, pre-launch tests in Baikonur. Operations involve periodic installation in the Zvezda module of the station with observations during the crew night time, with periodic downlink of data samples, and the full dataset being sent to the ground via pouches containing the data disks. In this work, the mission status and the main scientific results obtained so far are presented, in light of future observations with similar instruments.

Keywords: UV telescope; space telescope; UV emissions; ISS; ultra-high energy cosmic rays (UHECRs); meteors; strange quark matter; transient luminous events

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1. Introduction

The Mini-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory) experiment [1] is part of the program carried out by the JEM-EUSO (Joint Exploratory Missions for an Extreme Universe Space Observatory) collaboration [2]. The goal of the collaboration is to construct a large space telescope to detect ultra-high-energy cosmic rays (UHECRs) from space for the first time.

Sixty years after the first detection of a particle with an energy of 10^{20} eV [3], the origin and nature of UHECRs are still unknown. This is mainly due to the extremely low flux of these particles—about 1 particle/(km^2 × millennium). Currently, two ground-based observatories are observing the sky searching for UHECRs: the Pierre Auger Observatory [4], from the Southern Hemisphere, and Telescope Array [5], from the Northern one. In the future, the observation of UHECRs from space-based experiments will be complementary to that from ground observatories and will offer significant advantages such as an extremely large instantaneous observational area and the capability of observing both Earth's hemispheres with a single instrument, reducing possible systematic uncertainties.

UHECR observation from space is based on the measurement of the fluorescence and Cherenkov light produced in an extensive air shower (EAS). A UHECR that hits the atmosphere produces secondary particles which, on their turn, collide with atoms in the air, producing a shower dominated by electrons and positrons. As they pass through the atmosphere, these particles excite atmospheric molecules, particularly nitrogen, which emit isotropically the characteristic fluorescence light in the ultraviolet (UV) band during de-excitation; the EAS therefore produces a streak of fluorescent light along its path through the atmosphere, depending on the energy and zenith angle of the primary particle. Another detectable component is the Cherenkov light emitted in the direction of travel by the charged, relativistic particles of the EAS and reflected into space from the ground or clouds. Thus, by looking at the Earth's atmosphere from space, a purpose-built telescope can detect these fluorescence and Cherenkov light contributions and study UHECRs.

1.1. The JEM-EUSO Experiments

During the last ten years, the JEM-EUSO collaboration has accomplished many successful missions (see Figure 1) by operating on ground (EUSO-TA [6] (2013–Current)), on stratospheric balloons (EUSO-Balloon [7,8] (2014), EUSO-SPB1 [9] (2017), EUSO-SPB2 [10,11] (2023)) and in space (TUS [12,13] (2016), Mini-EUSO [1] (2019)). Other missions are foreseen for the coming years: K-EUSO [14] and POEMMA [15].

Figure 1. A summary of the projects accomplished by the JEM-EUSO Collaboration: on ground (EUSO-TA), on stratospheric balloons (EUSO-Balloon, EUSO-SPB1, EUSO-SPB2), and in space (TUS, Mini-EUSO).

1.1.1. EUSO-TA (2013–Current)

EUSO-TA [6] is a ground telescope installed at the Telescope Array (TA) site in Utah, USA, in front of the TA fluorescence detector station at Black Rock Mesa. EUSO-TA optical system is composed by two Fresnel lenses and a focal surface with 6 × 6 Multi-Anode PhotoMultiplier Tubes (MAPMTs) with 64 channels each, for a total of 2304 channels. The overall field of view is $\simeq 10.6^\circ \times 10.6^\circ$. The telescope detects cosmic ray events with high spatial resolution of $\simeq 0.2^\circ$ and a temporal resolution of 2.5 μs. About ten UHECR events have been observed to date. In 2022, the detector was upgraded by replacing the focal surface and acquisition system and implementing one similar to that of Mini-EUSO. Moreover, since 2013, the TA site and the EUSO-TA telescope have also been used as an auxiliary experiment for the calibration and testing of the other JEM-EUSO detectors.

1.1.2. EUSO-Balloon (2014)

EUSO-Balloon [7,8], a balloon flight of the CNES (French Space Agency), was a one-night mission with several key innovative features such as Fresnel optics, dedicated ASIC (first-generation SPACIROC, Spatial Photomultiplier Array Counting Integrated Read-OutChip) for the front-end electronics and efficient data processing. It worked nominally and recorded the Earth's night-time UV emissions, showing an anticorrelation of UV-IR brightness. Tracks of laser light from a helicopter that flew below the balloon and Xenon flashers from the ground have also been recorded.

1.1.3. TUS (2016)

The TUS detector [12,13] was the first space-based mission aimed for UHECRs detection. TUS was launched on board the Russian Lomonosov satellite in April 2016 and operated till December 2017. Almost 90,000 events were recorded during the mission, among them lightning discharges, meteors, transient luminous events (TLEs), polar lights and anthropogenic signals. No event has been classified as UHECR candidate.

1.1.4. EUSO-SPB1 (2017)

EUSO-SPB1 (Extreme Universe Space Observatory on a Super Pressure Balloon) [9] was launched on board a NASA long-duration super pressure balloon (SPB) from the NASA balloon facility in Wanaka, New Zealand, in April 2017. Even though the telescope functioned nominally, the flight was shortened to 12 days due to a balloon leak, preventing the detection of a real cosmic ray shower and the detector recovery. Despite this, 25.1 h of data were downloaded allowing the measurement of Earth night-time UV emissions, which represent the background for the detection of EASs, over different kinds of surfaces such as land, ocean and clouds. The EUSO-SPB1 focal surface was improved compared to that of EUSO-Balloon, including SPACIROC-3 ASIC [16], more compact focal surface elements, an enhanced optics performance and an autonomous trigger for events.

1.1.5. EUSO-SPB2 (2023)

On 13 May 2023, EUSO-SPB2 [10,11], a second NASA super pressure balloon, was launched from Wanaka but, again due to a leak in the balloon, the flight lasted only about 32 h, and sank in the Pacific Ocean. It aimed to search for UHECRs ($E > EeV$) and very high-energy neutrinos ($E > PeV$) using ultraviolet fluorescence and Cherenkov radiation, respectively. For these purposes, the mission comprised two independent optical telescopes: a fluorescence telescope (FT) having 108 MAPMTs (three EUSO-SPB1 focal surfaces side by side) at the focal point of a Schmidt telescope with a diameter of one meter and a Cherenkov Telescope (CT) using a Silicon Photomultiplier camera. In addition, an infrared camera (IR) was installed for cloud monitoring. Although the flight was short, all the telescopes performed as planned, confirming their expected functionality through extensive simulations, laboratory and field tests. During the flight period, a large amount of data was downloaded, about 56 GB, consisting of more than 120,000 FT triggers and over 32,000 CT events. The collaboration is currently analyzing this data. No cosmic ray candidates have so far been identified in FT events (in line with the low expected rate of one cosmic ray event every 15 h). The CT data include several triggers from below the limb, providing valuable insights into potential neutrino observations for future missions, and several near-horizontal above-limb Cherenkov signals from EAS caused by cosmic rays: this result not only convalidates the developed triggering procedure, but also proves the feasibility of the technique of detection itself, which was another main goal of the mission.

In what follows in this paper, the in-flight performance of the Mini-EUSO instrument during the first four years of data collection and its first scientific results are described.

2. The Mini-EUSO Instrument

Mini-EUSO [1] is a UV telescope (range 290–430 nm) operating in the International Space Station (ISS) from the UV-transparent window facing the nadir located in the Russian

Zvezda module. Its dimensions ($37 \times 37 \times 62$ cm^3) are therefore determined by the window size and the requirements associated with the Soyuz spacecraft. In addition, its design takes into account safety requirements, such as the absence of sharp edges, a low surface temperature and general robustness to ensure the crew's well-being. Installation on the window is via a mechanical adapter flange and the only connection to the ISS is via a 28 V power supply and grounding cable. The telescope power consumption is $\simeq$60 W, and its weight is $\simeq$35 kg (5 kg flange included). The instrument field of view is squared with a side of 44°, and its spatial resolution on the Earth's surface is 6.3 km^2 (depending on the altitude of the ISS). Mini-EUSO has also single-photon-counting capabilities.

The optical system is composed of two 25 cm diameter Poly(Methyl Methacrylate)—PMMA Fresnel lenses, which focus light on a focal surface, or a photon detector module (PDM), consisting of a matrix of 6×6 MAPMTs (Hamamatsu R11265-M64, Hamamatsu Photonics K.K., Shizuoka, Japan), 64 pixels each, for a total of 2304 pixels (see Figure 2, left side). Each MAPMT has a BG3 UV bandpass filter on the input window and is powered by a Cockroft–Walton power supply board, and its front-end electronics consists of a SPACIROC3 board. Data from the entire PDM are then processed by a Xilinx Zynq-based FPGA board that runs a multilevel trigger [17], allowing for the measurement of triggered UV transients for 128 frames on time scales of both 2.5 µs (defined as 1 gate time unit, GTU) and 320 µs. Moreover, a non-triggered acquisition mode with 40.96 ms frames allows for continuous data acquisition. Data collection and storage on 512 GB USB Solid State Disk (SSD) cards, inserted into the telescope side by the cosmonaut before the session, are handled by a PCIe/104 form factor CPU. No direct telecommunication with Earth is present.

Mini-EUSO is also provided with two auxiliary cameras to integrate near-infrared and visible UV measurements [18], three single-pixel UV sensors (a linear photodiode (Analog Devices AD8304ARUZ, Analog Devices, Inc., Norwood, MA, USA) a logarithmic photodiode (Lapis Semiconductor ML8511, LAPIS Semiconductor Co., Yokohama, Japan) and a single-pixel silicon photomultiplier (Hamamatsu C13365, Hamamatsu Photonics K.K., Shizuoka, Japan) used to handle day/night transitions during the data taking, and an 8×8 Silicon PhotoMultiplier (SiPM) imaging array (Hamamatsu C14047-3050EA08, Hamamatsu Photonics K.K., Shizuoka, Japan) [19].

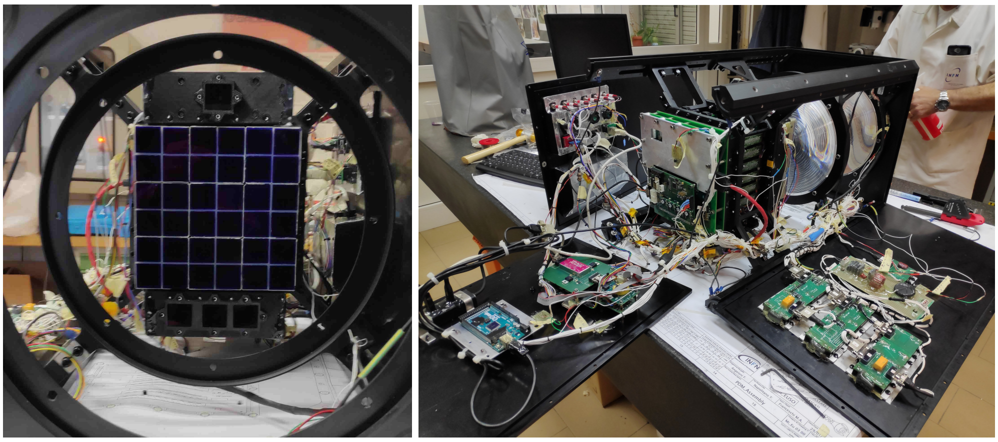

Figure 2. Some photographs shot during the integration. (**Left**): the Mini-EUSO focal surface (FS); UV sensors (below the FS) and the photomultiplier array (above the FS) are visible through the lens frames. Image taken from [1] (© reproduced with permission from AAS). (**Right**): the instrument completely assembled but with the mechanics box opened. Image taken from [20] (© reproduced with permission from SNCSC).

Two models of the detector were produced: the engineering model (EM) and the flight model (FM). The two copies are identical, with the exception that in the PDM of the EM, only the central four MAPMTs are installed, while the remaining components are substituted by inert mass dummies. Additionally, in the EM, the Fresnel lenses have been replaced by flat PMMA elements of equivalent weight.

2.1. Integration and Tests

The instruments were integrated at the INFN Laboratories located in Frascati and Rome Tor Vergata. Figure 2 provides some photographs shot during the integration of the FM. For a more detailed description about the telescope and its first observations, refer to [1].

A series of qualification tests [20] were performed on both the two models. These tests were performed to assure the instruments could safely withstand transport to the launch site, the launch itself, and subsequent operations on-board the ISS. Tests included vibration and shock, electromagnetic interference and compatibility (EMI and EMC, respectively), and thermal-vacuum and environmental tests. Additionally, the Mini-EUSO FM was subjected to field tests in dark sky conditions.

Following qualification and field tests, the FM successfully underwent also several acceptance tests, first in Rome, then in Moscow, and at last at the Baikonur cosmodrome. Acceptance tests consist of a sequence of final checking procedures aimed at certifying that the detector is able to endure the environmental launch conditions and the operations in space, while also assessing conformity with safety requirements.

Currently, the EM is being used as a training model for the various crews responsible for operating Mini-EUSO on the ISS.

2.2. Launch and In-Flight Operations

Mini-EUSO was launched to the International Space Station (ISS) on 22 August 2019, from the Baikonur Cosmodrome in Kazakhstan on board the unmanned Soyuz MS-14 capsule. The instrument was switched on for the very first time on 7 October 2019, after the trained cosmonaut responsible for its operation arrived on the ISS (see Figure 3). Since then, the telescope has been systematically collecting data at regular intervals, with a total of 96 operational sessions operated up to now over four years.

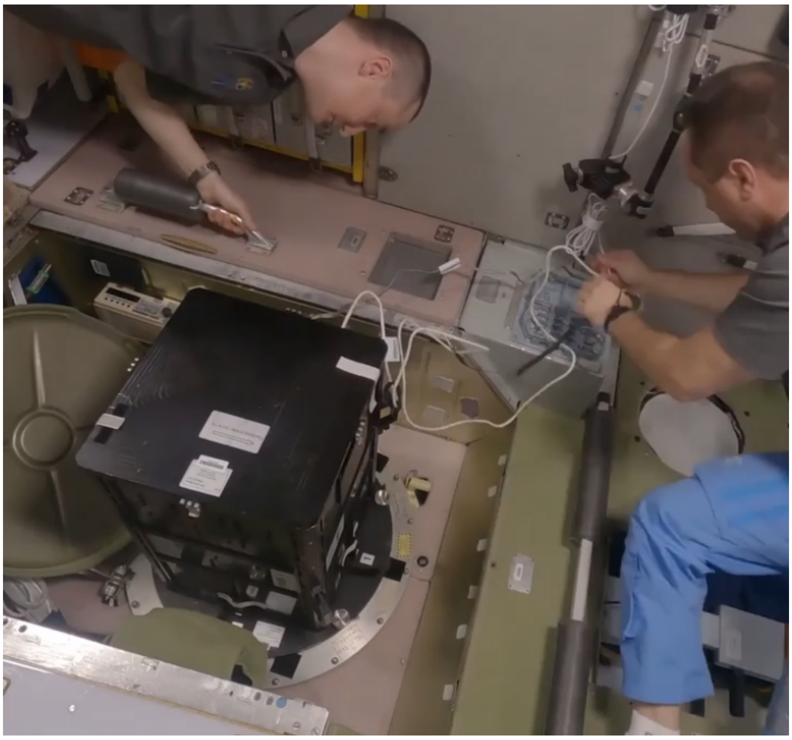

Figure 3. Mini-EUSO installed by two cosmonauts on the UV-transparent window of the Zvezda module.

Mini-EUSO is switched on approximately every two weeks and put in acquisition mode for about 12 h, during the local night of the ISS. At the beginning of each observation session the instrument is recovered from storage, the lens cover removed and the detector mounted on the UV-transparent window of the Zvezda module. The power and ground cables are then connected, a USB SSD card inserted on the side of the instrument and the power switched on. Timing is managed internally with a real-time clock, since no external connections are available to the ISS (the clock's daily drift was measured on the ground and is periodically cross-checked with data collected on board).

At start-up, the initialization program checks whether on the SSD card there are software and/or firmware updates or updated operating parameters intended to override existing ones, and applies them if so. This very flexible approach allows the collaboration to continuously improve operations. At the end of each session, the detector and the SSD card are securely stowed, and the log file and a subset of the acquired data files (typically about 10%, corresponding to the beginning and end of the session) are transmitted to the ground via the ISS telemetry channel to verify the proper functioning of the system.

The pouches containing 25 SSDs are returned to ground every 6–12 months, and at a similar interval, a new pouch containing new SSD cards is dispatched to the ISS.

During these four years of operations, the JEM-EUSO collaboration also performed various in-flight calibration campaigns for studying the instrument's response when exposed to a light source of known intensity. This was carried out by sending pulses of LED light from the ground toward the sky during the ISS passage. Further test campaigns will be conducted in the future.

3. Scientific Objectives and Selected Results

Mini-EUSO was developed, within the JEM-EUSO program, with the main objective of proving the feasibility of studying ultra-high-energy cosmic rays (UHECRs) from space. This primarily consists of demonstrating that a space telescope has a high enough duty cycle, defined as the fraction of time during which atmospheric or man-made light sources do not make it impossible to observe UHECRs from space. The objective is also to establish the potential of detecting short light transients (SLTs) that present similarities in terms of light intensity or pulse duration to what is expected from an extensive air shower (EAS) cascade in the atmosphere. Nonetheless, it is important to note that the lens size of Mini-EUSO (25 cm of diameter) results in a minimum energy threshold for the detection of UHECRs well-above 10^{21} eV, an energy range in which no events have been detected so far. However, the collaboration intends to set an upper limit for the particle flux at these energies, since Mini-EUSO has yet accumulated an exposure comparable to that of ground-based hybrid experiments to date [21,22].

Moreover, through the observation of terrestrial and atmospheric UV emissions from space, Mini-EUSO can achieve many other scientific goals: studying atmospheric processes such as lightning and transient luminous events (TLEs), which include ELVES; observing meteors and meteoroids; searching for interstellar meteors and strange quark matter (SQM); proving the practical feasibility of detecting and tracking space debris from space; and constructing the map of terrestrial night-time UV emissions, both natural and anthropogenic. An overview of Mini-EUSO primary scientific objective is provided in Figure 4 for reference.

In Figure 5, the total signal detected by the focal surface in function of time is shown for signals of different time scales, from the fastest sampling of 2.5 µs (D1 acquisition mode), to the average of 128 D1 frames for D2 mode (320 µs) and to the average of 128 $\times$ 128 2.5 µs frames for D3 acquisitions (40.96 ms). In D3 acquisition mode, the gradual increases are due to passing over regions covered by clouds, while the sharp spikes correspond to lightning.

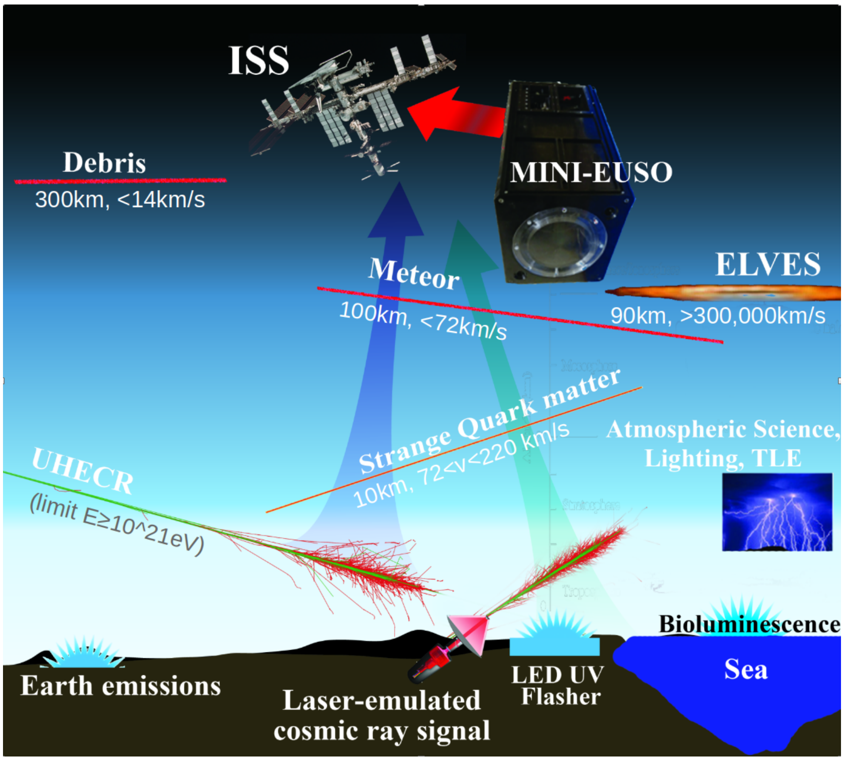

Figure 4. A summary of the Mini-EUSO scientific objectives. The detector is able to observe a large variety of different phenomenon with different intensities and durations, from the very fast atmospheric events, such as TLEs and in particular ELVES, to the slow terrestrial emissions, both natural and anthropogenic. Image adapted from [1] (© reproduced with permission from AAS).

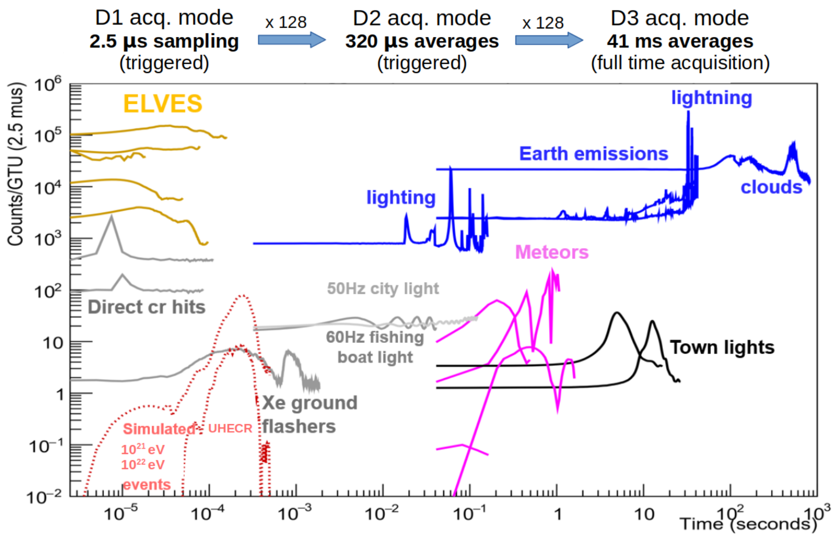

Figure 5. Time profile of different phenomena detected by Mini-EUSO. All the curves are referred to real observed data, except for the simulated UHECR events at 10^{21}–10^{22} eV. Curves are arbitrary scaled along the y axes for illustration purposes. Image adapted from [1] (© reproduced with permission from AAS).

The temporal and spatial profiles of the different signals detected by Mini-EUSO allow us to classify such signals. In the D1 mode, fast events are identified, such as direct cosmic ray hits, ELVES, the flashing of Xenon ground flashers. In the D2 acquisition mode, instead, it is possible to distinguish the modulation of the artificial lights within small town and villages. Lastly, using data acquired in the D3 time scale, meteors can be studied, interstellar meteors can be searched for, and Earth's night-time UV emissions, both natural and anthropogenic, can be mapped.

The main event kinds, ordered from fastest to slowest, are discussed in the following subsections.

3.1. Direct Hits

Direct cosmic ray hits occur when cosmic rays interact with the photocathode or the BG3 filter of the focal surface directly, through either direct ionisation or emission of Cherenkov light. Typically, these kinds of event last a few GTUs and release a high signal in one or a few pixels. These signals display a distinctive pattern characterized by a rapid rise followed by an exponential decrease resulting from the de-excitation of the physically hit components. Figure 6, left panel, shows a direct cosmic ray hit with its typical exponential decrease.

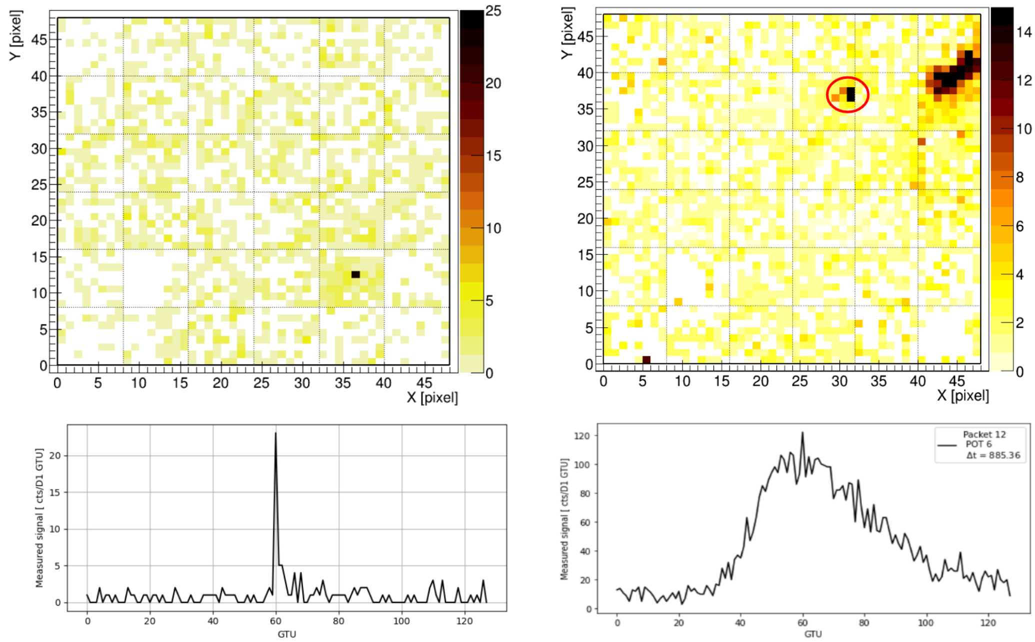

Figure 6. (**Left**): A direct cosmic ray detected by Mini-EUSO: A low-energy (≃GeV) cosmic ray hits the detector's focal surface perpendicularly, causing a bright signal in a single pixel (the number of photoelectron counts/GTU is indicated on the Z-axis). The corresponding plot at the bottom shows the light-curve of the hit pixel. (**Right**): An EAS-like event (or, more properly, a short light transient, SLT) detected by Mini-EUSO. This particular event was detected just off the coast of Sri Lanka that appears as a luminous area in the upper right corner of the focal surface. The SLT shows up as a small group of pixels (in the red circle) and presents a bi-Gaussian light curve characterised by a faster rise and slower decay. The shown light curve is the sum of all 6 pixels above the threshold (POT in the legend) in the packet.

3.2. UHECRs

The high threshold energy and the short exposure of Mini-EUSO resulted in no detection of UHECRs so far. However, the detection of SLTs indirectly confirms the capability of the JEM-EUSO technology to potentially identify UHECRs from space, since they exhibit similarities from the point of view of light profile, intensity, duration and pixel pattern on the focal plane, although all of these features do not coincide simultaneously in a single event. Of more importance is the fact that Mini-EUSO has proved that these events cannot be misinterpreted as true EAS-induced signals, eliminating concerns for future observations. For further details refer to [23].

A SLT event is any flashing signal lasting more than 200 μs not originated by a ground flasher (see Section 3.3). In Figure 6, right panel, an example of the signal generated on the focal plane by a SLT together with its light curve is shown. The light-curve present a bi-Gaussian shape, with a faster rise and a slower decay, with a relatively long signal. It appears reasonable to assume, although no study has yet confirmed it, that the origin of these fast flashing lights is related to thunderstorm activity in the atmosphere. This event was compared to several simulated EAS events with different energy and zenith angle, some of which are presented in Figure 7. Of the simulated EAS events, none of them match either the image topology or the duration of the SLT light profile (Figure 6, right panel). Specifically, the light footprint on the focal surface from the SLT event (Figure 6, top-right panel) is consistent with a nearly vertical event (Figure 7, top-middle panel, in the red circle), but the SLT time duration (∼80 GTUs) (Figure 6, bottom-right panel) far exceeds the time required by a vertical EAS for developing in the atmosphere and reaching the Earth's surface (∼30 GTUs) (Figure 7, bottom-middle panel), while it is more similar to the time required by an inclined EAS (Figure 7, bottom-right panel).

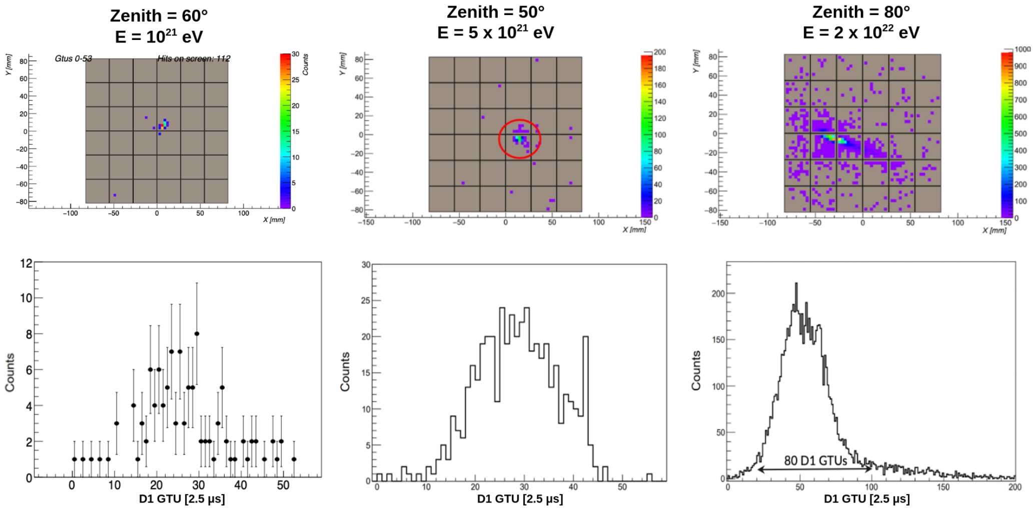

Figure 7. ESAF (EUSO Simulation and Analysis Framework) [24] simulation of proton-generated EASs of different energies and zenithal angles. (**Left**): Due to the high energy threshold, an EAS event of 10^{21} eV is at the limit of Mini-EUSO's triggering capability. (**Middle**): At about 5×10^{21} eV, the signal of shower with a zenith angle of a 50° is distinctly visible and has a duration of ∼30 GTUs (∼75 µs). The signal stops when the EAS reaches the ground. (**Right**): With a zenith angle of 80° and energy of 2×10^{22} eV, the light curve is not truncated and the signal lasts for ∼80 GTUs (∼200 µs).

3.3. Ground Flashers

Ground flashers, typically equipped with Xenon lights, are used as warning signals to aircraft, alerting them to the presence of structures like buildings or towers. These flashers vary in terms of their brightness and duration of blinking, typically lasting for a few hundred µs (see Figure 5). Mini-EUSO often detects these flashers multiple times as they traverse its field of view [25]; this characteristic makes them easily distinguishable even if they have similar signals to SLTs.

3.4. ELVES

ELVES (emission of light and very low-frequency perturbations due to electromagnetic pulse sources), which are part of the transient luminous events (TLEs) family, are observed as rapidly expanding luminous rings in the ionosphere. The typical ELVES lifetime is about 0.5 ms; this means that several 2.5 µs frames (on average 200) are associated with each event. In addition, the high spatial resolution (5 km at the ionosphere altitude) of the instrument and the fact that the telescope observes the ring expansion from above allow for a detailed analysis of the ELVES morphology (e.g., position, maximum radius, expansion velocity). In the available dataset, 37 ELVES have been identified, including single-ringed ELVES and multiple ELVES [26].

3.5. Artificial Light Modulation

A modulation of the artificial lights can be identified in Mini-EUSO data in the D2 time scale with a frequency of 50 or 60 Hz. This kind of modulation is more evident in smaller towns and villages where all the lights are linked to a single transformer. In contrast, larger cities, with different sections connected to various transformers and different phase arrangements, exhibit less pronounced modulation. Figure 5 shows the light modulation patterns observed in India, Canada, and from some fishing boats in the Indian Ocean.

3.6. Lightning

Lightning are transient atmospheric events lasting $\simeq$1 s which can partially or completely illuminate the focal surface, sometimes leading to the activation of the high voltage safety system [27]. When the satellite passes over regions characterized by high lightning activity, these events can extend over several hundred seconds. The time profiles of various lightning strikes observed in both D2 and D3 mode are shown in Figure 5.

3.7. Meteors

Meteors are observed by Mini-EUSO by looking for linear tracks moving in the field of view in the D3 time scale. The signals produced by meteors vary in intensity and duration according to their mass, speed and incidence angle. While looking for meteors, we also search for interstellar meteors and nuclearites.

To the best of our knowledge, Mini-EUSO is the first space-based mission to allow for a systematic study of meteors, mainly including the measurement of meteor light-curves and the determination of the meteor flux over a wide range of magnitudes. Furthermore, in some cases at least, it allows for the calculation of the original heliocentric orbits of meteoroids.

Mini-EUSO is capable of measuring meteor events with magnitude up to +5, with a significant statistic ($\simeq$2.4 meteors/min). In the present dataset, Mini-EUSO has successfully classified approximately 24,000 events as meteor events. More details about the analysis and complete results can be found in [28], together with the results from interstellar meteor search.

3.8. Night-Time UV Earth Emissions

Seen from space, the Earth's night-time UV emissions move through the field of view, and thus on the focal plane, with an apparent velocity equal to the ISS orbital speed (approximately 7.7 km/s). Consequently, a specific point on the Earth's surface remains visible from Mini-EUSO for about 50 s (equivalent to 1000 frames in D3 mode) making it possible to create ground maps with excellent spatial resolution and low statistical fluctuations. The temporal profile of a single pixel shows a gradual increase in luminosity when a village or town enters in its field of view (see Figure 5), the duration of this increase depends on the size of the source. Figure 8 shows the map of UV emissions over Italy and part of Europe reconstructed by Mini-EUSO.

For a comprehensive review of Mini-EUSO's capabilities in the reconstruction of UV maps refer to [27], while the complete dataset (.png, .dat and .kmz files) of the UV maps published in the previous article is available for downloading in [29].

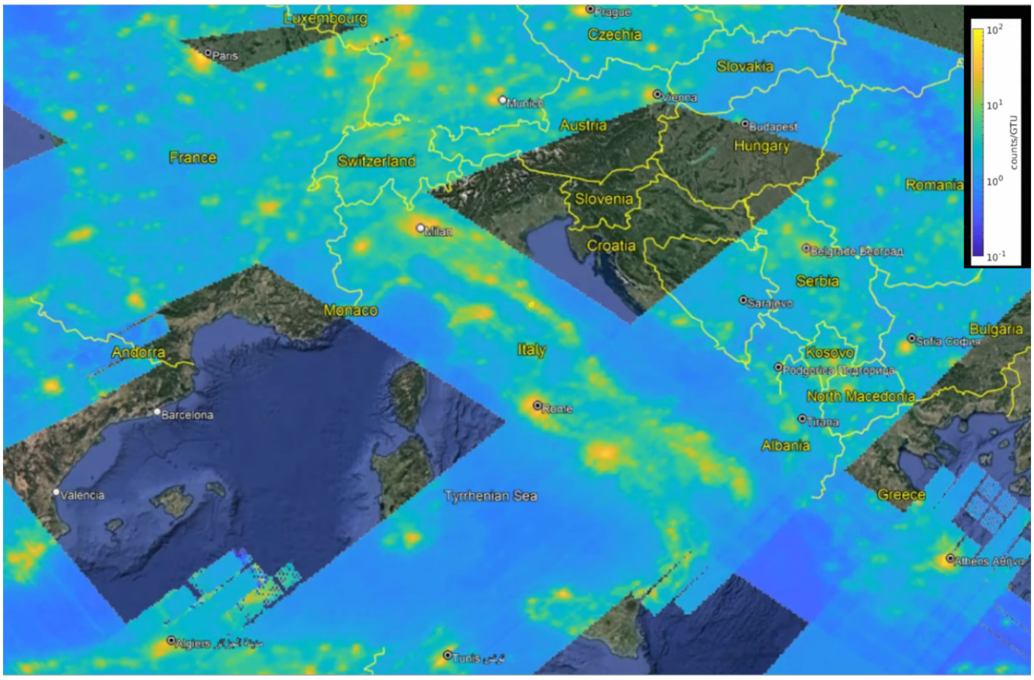

Figure 8. The map of night−time UV emission over Italy and part of Europe. Coastlines are well reconstructed and the main cities are easily identifiable. UV intensity is usually ≃1 count/pixel/GTU on oceans and lands without urbanisation.

4. Conclusions

In this work, the pre-flight activities and the in-flight operations of the Mini-EUSO instrument are described. The telescope has been actively collecting data on board the ISS for a duration of four years so far, and it continues to behave nominally. Its performance during this time has proven to be immensely valuable in assessing the detection capabilities of future and larger space detectors, such as K-EUSO or POEMMA. Mini-EUSO measured the Earth's UV background with unprecedented accuracy, contributing significantly to estimating the real duty cycle of a future mission. Some preliminary results were also reported about the observation of ELVES, and meteors. These results prove the multidisciplinary nature of a UHECR space-based observatory.

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Data Availability Statement: The data about Earth night-time UV emissions, related to the article [29], are openly available in the Mendeley repository at http://doi.org/10.17632/57fmn7rh4n.4 (accessed on 20 March 2023).

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EAS	Extensive Air Shower
ELVES	Emission of Light and Very Low-Frequency perturbations due to Electromagnetic Pulse Sources
EM	Engineering Model
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ESAF	EUSO Simulation and Analysis Framework
FM	Flight Model
GTU	Gate Time Unit
ISS	International Space Station
JEM-EUSO	Joint Exploratory Missions for an Extreme Universe Space Observatory
MAPMT	Multi-Anode PhotoMultiplier Tube
Mini-EUSO	Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory
PDM	Photon Detector Module
PMMA	Poly(Methyl Methacrylate)
SiPM	Silicon PhotomMultiplier
SLT	Short Light Transient
SSD	Solid State Disk
TLE	Transient Luminous Events
UHECR	Ultra-High-Energy Cosmic Ray
UV	Ultraviolet

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