PROCEEDINGS OF SCIENCE

# The Mini-EUSO telescope on board the International Space Station: first results in view of UHECR measurements from space

**M. Bertaina,[a,b,*] D. Barghini,[a,b,c] M. Battisti,[b] A. Belov,[d,e] M. Bianciotto,[a] F. Bisconti,[f] C. Blaksley,[h] S. Blin,[i] K. Bolmgren,[j] G. Cambiè,[f,g] F. Capel,[k] M. Casolino,[f,g,h] I. Churilo,[l] M. Crisconio,[m] C. De La Taille,[n] T. Ebisuzaki,[h] J. Eser,[o] F. Fenu,[p] G. Filippatos,[q] M.A. Franceschi,[r] C. Fuglesang,[j] A. Golzio,[a,b] P. Gorodetzky,[i] F. Kajino,[s] H. Kasuga,[h] P. Klimov,[e] V. Kungel,[q] V. Kuznetsov,[l] M. Manfrin,[a,b] L. Marcelli,[f] G. Mascetti,[m] W. Marszał,[t] M. Mignone,[b] H. Miyamoto,[b,u] A. Murashov,[e] T. Napolitano,[r] H. Ohmori,[h] A. Olinto,[o] E. Parizot,[i] P. Picozza,[f,g] L.W. Piotrowski,[v] Z. Plebaniak,[a,b,t] G. Prévôt,[i] E. Reali,[f,g] M. Ricci,[r] G. Romoli,[f,g] N. Sakaki,[h] S. Sharakin,[e] K. Shinozaki,[t] J. Szabelski,[t] Y. Takizawa,[h] G. Valentini,[m] M. Vrabel,[t] L. Wiencke,[q] M. Zotov[e] and the JEM-EUSO Collaboration**

[a] *Department of Physics, University of Turin, V. P. Giuria 1, 10125 Turin, Italy*
[b] *INFN Section of Turin, Via P. Giuria 1, 10125 Turin, Italy*
[c] *INAF Astrophysics Observatory of Turin, Via Osservatorio 20, 10025 Pino Torinese, Italy*
[d] *Faculty of Physics, M.V. Lomonosov Moscow State University, ul. Kolmogorova 1(2), 119234 Moscow, Russia*
[e] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State Univ., ul. Kolmogorova 1(2), 119991 Moscow, Russia*
[f] *INFN Section of Rome Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy*
[g] *Department of Physics, University of Rome Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy*
[h] *RIKEN, 2-1 Hirosawa Wako, Saitama 351-0198, Japan*
[i] *APC, Univ Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs de Paris, Sorbonne Paris Cité, 10 Rue Alice Domon et Léonie Duquet, 75013 Paris, France*
[j] *KTH Royal Institute of Technology, Brinellvëgen 8, 114 28 Stockholm, Sweden*
[k] *Technical University of Munich, Arcisstraße 21, 80333 Munich, Germany*
[l] *S.P. Korolev Rocket and Space Corporation Energia, Lenin str., 4a Korolev, 141070 Moscow area, Russia*
[m] *ASI, Italian Space Agency, Via del Politecnico, 00133 Rome, Italy*
[n] *Omega, Ecole Polytechnique, CNRS/IN2P3, Rte de Saclay, 91120 Palaiseau, France*
[o] *Department of Astronomy and Astrophysics, The University of Chicago, 5640 S. Ellis Avenue, Chicago IL 60637, US*
[p] *Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*
[q] *Department of Physics, Colorado School of Mines, 1523 Illinois St., Golden CO 80401, US*

[*] Speaker



https://pos.sissa.it/

PoS(ECRS)082

[r] INFN National Laboratories of Frascati, Via Enrico Fermi 54, 00044 Frascati, Italy
[s] Department of Physics, Konan University, 8 Chome-9-1 Okamoto, Higashinada Ward Kobe, Hyogo 658-8501, Japan
[t] National Centre for Nuclear Research, 28 Pułku Strzelców Kaniowskich 69, 90-558 Łódź, Poland
[u] Gran Sasso Science Institute, Viale Francesco Crispi 7, 67100 L'Aquila, Italy
[v] Faculty of Physics, University of Warsaw, Ludwika Pasteura 5, 02-093 Warsaw, Poland

*E-mail:* bertaina@to.infn.it

Mini-EUSO is a telescope launched on board the International Space Station in 2019 and currently located in the Russian section of the station and viewing our planet from a nadir-facing UV-transparent window in the Zvezda module. The instrument is based on an optical system employing two Fresnel lenses and a focal surface composed of 36 Multi-Anode Photomultiplier tubes, 64 channels each, with single photon counting sensitivity and an overall field of view of 44°. Main scientific objectives of the mission are the search for nuclearites and Strange Quark Matter, the study of atmospheric phenomena such as Transient Luminous Events, meteors and meteoroids, and the observation of sea bioluminescence. Mini-EUSO can map the night-time Earth in the near UV range (predominantly between 290 – 430 nm), with a spatial resolution of about 6.3 km and different temporal resolutions of 2.5 $\mu$s, 320 $\mu$s and 41 ms. Mini-EUSO observations are extremely important to assess the potential of a space-based detector of Ultra-High Energy Cosmic Rays (UHECRs) such as K-EUSO and POEMMA. In this contribution we describe the detector and show preliminary results in the context of UHECR observations from space. In particular, it is shown that the typical UV nightglow background level is comparable to what was originally estimated for a space-based detector looking down to Earth. The adaptive trigger logic successfully keeps the spurious trigger rate at the designed level of ~1 Hz in nominal conditions and in presence of quasi-static bright sources such as city lights. The logic triggers on UV transients in the $\mu$s time scale due to anthropogenic light sources, such as flashers. These signals can clearly be distinguished from Extensive Air Shower (EAS) events by comparing them with simulated EASs. In addition, they demonstrate the capability of a large space-based detector such as K-EUSO or POEMMA to detect UHECRs above a few times $10^{19}$ eV. The presence of clouds can be clearly recognized by the UV camera in many situations, which is helpful for the calculation of the exposure and for the determination of the atmospheric conditions in case of detection of an EAS.

**** 27th European Cosmic Ray Symposium - ECRS ****
**** 25-29 July 2022 ****
**** Nijmegen, the Netherlands ****

## 1. Introduction

The current main goal in the field of UHECRs (Ultra-High Energy Cosmic Rays) science is to identify their astrophysical sources and composition [1]. For this, increased statistics is one of the essential requirements. A space-based detector for UHECR research has the advantage of a very large exposure and a uniform coverage of the celestial sphere. The aim of the JEM-EUSO program [2] is to bring the study of UHECRs to space. The principle of observation is based on the detection of UV light emitted by isotropic fluorescence of atmospheric nitrogen excited by the Extensive Air Showers (EASs) in the Earth's atmosphere and forward-beamed Cherenkov radiation reflected from the Earth's surface or dense cloud tops. In addition to the prime objective of UHECR studies, a space-based detector will do several secondary studies due to the instrument's unique capacity of detecting very weak UV signals with extreme time-resolution around 1 $\mu$s: meteors, Transient Luminous Events (TLE), bioluminescence, maps of human generated UV light, searches for Strange Quark Matter (SQM) and high-energy neutrinos, and more. The JEM-EUSO program includes several missions from ground (EUSO-TA [3]), from stratospheric balloons (EUSO-Balloon [4], EUSO-SPB1 [5], EUSO-SPB2 [6]), and from space (TUS [7], Mini-EUSO [8]) employing fluorescence detectors to demonstrate the feasibility of the UHECR observation from space and prepare for the large size missions K-EUSO [9] and POEMMA [10].

## 2. The Mini-EUSO space telescope

Mini–EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory, known as *UV atmosphere* in the Russian Space Program) [8] is the first detector of the JEM-EUSO program to observe the Earth from the International Space Station (ISS) and to validate from there the observational principle of a space-based detector for UHECR measurements. Mini-EUSO is a telescope operating in the near UV range, predominantly between 290 – 430 nm, with a square focal surface corresponding to a field of view (FoV) of $\sim 44°$. Its spatial resolution at ground level is approximately $6.3 \times 6.3$ km$^2$. Mini-EUSO was launched with the uncrewed Soyuz MS-14, on 22 August 2019. The first observations, from the nadir-facing UV transparent window in the Russian Zvezda module, took place on October 7, 2019. The detector size ($37 \times 37 \times 62$ cm$^3$) was thus constrained by the dimension of the window and the Soyuz spacecraft. Installation to the window is done via a mechanical adapter flange, and the only connection to the ISS is via a 28 V power supply and a grounding cable. The detector is usually installed during onboard night-time a couple of times per month, approximately at 18:30 UTC with operations lasting about 12 hours until the following local morning (Fig. 1). So far, more than 70 sessions of data acquisition have been performed. Data are stored locally on 512 GB USB solid state disks. After each data-taking session samples of data (about 10% of stored data, usually corresponding to the beginning and the end of each session) are copied and transmitted to ground to verify the correct functioning of the instrument and subsequently optimize its working parameters. The pouches containing all stored data are then returned to Earth every ~12 months by the Soyuz spacecraft.

The optics are based on two 25 cm diameter Fresnel lenses in Polymethyl methacrylate (PMMA). This material allows for a light (11 mm thickness, 0.87 kg/lens), robust, and compact design well suited for space applications. The Mini–EUSO focal surface, or Photon Detector

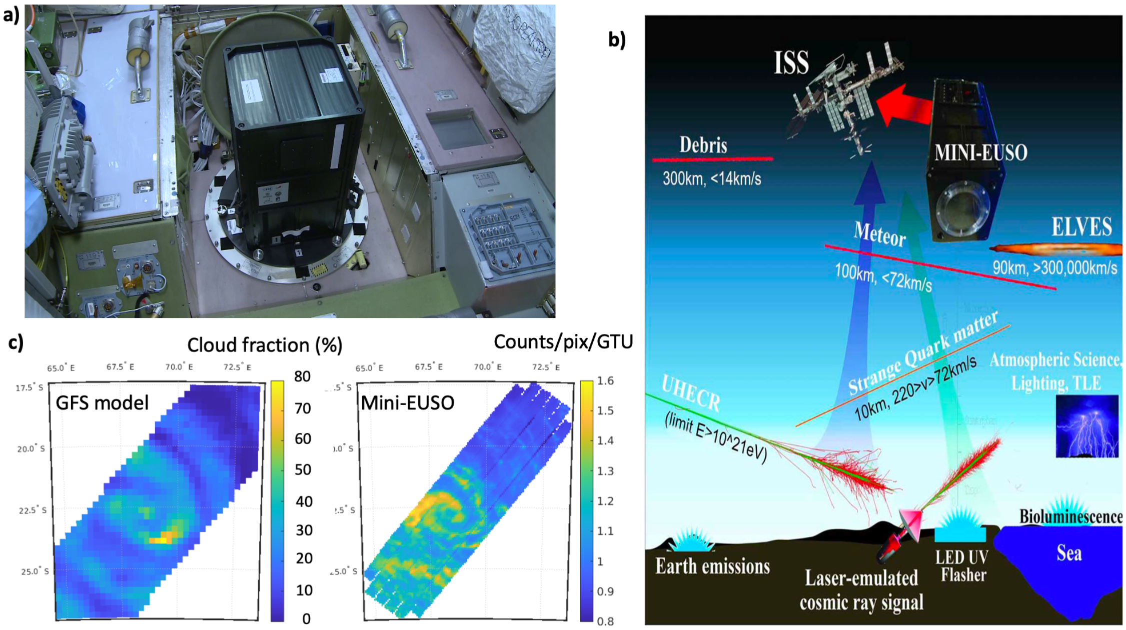


**Figure 1:** a) Mini-EUSO attached to the Zvezda module on the ISS; b) from space, Mini–EUSO can observe a variety of phenomena in the UV range; c) on the left cloud fraction (%) due to a cyclon in the Indian ocean as foreseen by the GFS atmospheric model and on the right the Mini-EUSO counts (per pixel and GTU). Where the cloud fraction is expected to be higher, Mini-EUSO registers higher counts level.

Module (PDM), consists of a matrix of 36 Multi-Anode Photomultiplier Tubes (MAPMTs, Hamamatsu Photonics R11265-M64), arranged in an array of $6 \times 6$ elements. Each MAPMT consists of $8 \times 8$ pixels, resulting in a total of 2304 channels. The MAPMTs are grouped in Elementary Cells (ECs) of $2 \times 2$ MAPMTs. Each EC has an independent high voltage power supply (HVPS) and board connecting the dynodes and anodes of the four photomultipliers. The HVPS system is based on a Cockroft-Walton circuit. The system has an internal safety mechanism which operates either reducing the collection efficiency of the four MAPMTs or reducing the MAPMT gain when particularly bright signals occurr [8]. These statuses of reduced efficiency are called *cathode-2* mode. The nominal working condition is instead called *cathode-3* mode (which is the one assumed in the rest of the paper unless stated otherwise). The switching from *cathode-3* to *cathode-2* mode are usually due to lightning strikes or due to very bright light sources like large cities. The recovery to the *cathode-3* mode takes place only few ms after the light level has decreased to a sufficiently low value, to avoid continuous oscillation between *cathode-2* and *cathode-3* modes when the light level is close to the switching value.

The effective focal length of the system is 300 mm, with a Point Spread Function (PSF) of 1.2 MAPMT pixels. UV bandpass filters (2 mm of BG3 material) with anti-reflective coating are glued in front of the MAPMTs to predominantly select wavelengths between 290 nm and 430 nm.

The system has a single photon-counting capability with a double pulse resolution of $\sim 6$ ns. Photon counts are summed in Gate Time Units (GTUs) of 2.5 $\mu$s. The PDM Data Processor (PDM-DP) stores the 2.5 $\mu$s GTU data stream (D1) in a running buffer on which runs the trigger code. The algorithm searches for a signal above 16 standard deviations from the average in any pixel of the focal surface. Both the average and root mean square (rms) are calculated in real time to take into account varying illumination conditions. In case of a trigger, the 128 frame buffer (64 frames before the trigger and 64 after it) is stored in memory. Independently from the trigger, sums of 128 frames (320 μs, D2) are continuously calculated and stored in another buffer where a similar trigger algorithm, at this time scale, is running. Similarly, sums on 128 D2 frames (40.96 ms, D3) are calculated in real time and continuously stored. Every 5.24 s, 128 packets of D3 data, up to 4 D2 packets and up to 4 D1 packets (if triggers were present) are sent to the CPU for storage. A more detailed description of the trigger algorithm is reported in [12], which represents an adaptation of the trigger logic conceived for JEM-EUSO [13], while the on-board performance of the trigger system is summarized in [14].

Mini-EUSO has been designed to detect a photon rate per pixel from diffuse sources (nightglow, clouds, cities, etc.) in the range of values expected from a large mission in space such as the original JEM-EUSO mission [11] or the future detectors K-EUSO or POEMMA. The pixel FoV is, therefore, ~100 times larger in area with respect to the FoV of a JEM-EUSO pixel (0.5 km × 0.5 km), to compensate for the optical system ~100 times smaller, constrained by the dimension of the UV transparent window where Mini-EUSO is installed during the data taking sessions. As a consequence, the energy threshold of Mini-EUSO for UHECRs is well above $10^{21}$ eV, roughly 2 orders of magnitude higher than the original JEM-EUSO one. Mini-EUSO monitors the atmosphere and studies the nature, extension and duration of the transient lights, to investigate the capability of detecting light signals from EASs and minimize the rate of spurious events. Thanks to its large FoV, Mini-EUSO also acts as an atmospheric monitor detector, observing different natural or anthropogenic phenomena (see Fig. 1) ranging from the UV emission of clouds (D3 data), lightning and thunderstorm activity and study of TLEs (D1 and D2 data), in particular elves, up to much slower events (D3 data) like meteors or nuclearites [15], with a sensitivity to fainter events beyond the usual capabilities of atmospheric monitor detectors, thanks to the dimension of its optical system.

Prior to the launch, the instrument underwent a series of integration and acceptance tests in Rome, Moscow, and Baikonur cosmodrome, where it was integrated in the uncrewed Soyuz capsule. A systematic test of the acquisition logic was performed at the TurLab facility [16] of the University of Turin and at the Astrophysical Observatory of Turin (INAF-OATo) [17].

## 3. First results in view of UHECR measurements from space

Between October 2019 and October 2022, 70 sessions were performed. Each session lasts on average 8 orbits, each of which contains ~30 minutes of nighttime data. For the first 44 sessions the complete set of data is available on ground. The most interesting collected data for UHECR measurements are those taken by the first level trigger (D1 data) and by the continous data taking in D3. The D1 data allow testing the trigger logic for UHECRs and to understand the different sources of UV light signals in this time domain. The D3 data allow to create UV maps in different moon conditions on the ocean and on the land.

A detailed analysis of the events collected by the level 1 trigger logic has been performed on a dataset of 34.7 h containing more than $4.7\times10^4$ triggered events. The expected functioning of the logic has been confirmed. The trigger rate on spurious events remains within the requirements in nominal background conditions (~1 Hz), while it saturates in the presence of thunderstorm activity. The dead time related to thunderstorm areas corresponds to locations where the UHECR can not be observed due to the presence of high clouds. In that context such dead time issue does not significantly reduce the observation capabilities of a space-based mission. The trigger logic proves effective in avoiding excessive trigger rates in the presence of static anthropogenic lights such as cities confirming the effectiveness of solutions such as the adaptive thresholds, necessary to prevent static light sources from triggering. Different kinds of events are detected such as elves and anthropogenic flashers, among others. All classes of events have characteristics that make them different from an EAS track. However, this trigger capability demonstrates the possibility of a space-based mission to trigger on events with a time duration and light shape similar to, although still different from, what is expected from a UHECRs. An example is shown in Fig. 2. Left panel shows a simulated proton EAS of $5\times10^{19}$ eV with a 60° zenith angle as expected to be seen by JEM-EUSO, while the right panel displays a repetitive flasher signal detected by Mini-EUSO near the Missoula city in Michigan, US. The signal intensity at peak level and the integrated number of counts in a limited portion of the events is comparable. Aside from the different shape of the light

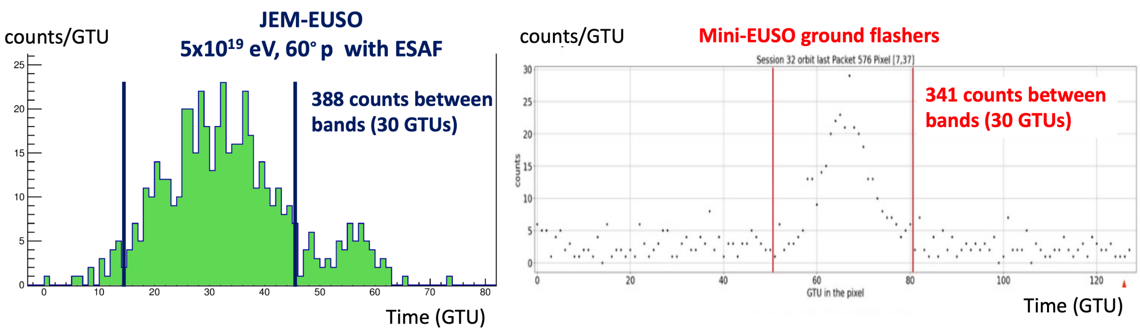


**Figure 2:** Left side: simulated proton EAS of $5\times10^{19}$ eV with a 60° zenith angle as expected to be seen by JEM-EUSO. Right side: repetitive flasher signal detected by Mini-EUSO near the Missoula city in Michigan, US.

curve, the anthropogenic signal can be recorgnized in Mini-EUSO data also due to the fact that it is repeating several times with a constant time delay (~10 ms for this specific event).

The D3 data taken by Mini-EUSO allow a first comparison with the assumed background levels in JEM–EUSO, K–EUSO and POEMMA to verify that the estimated performance is based on justified assumptions. Table 1 shows Mini-EUSO results on the average UV emissions in different conditions: clear and cloudy conditions, sea and land, various lunar phases as reported in [18]. Assuming no-moon conditions and typical land/ocean and clear/cloudy atmosphere ratios equal to 30/70, the average background level is ~1.3 counts/pixel/GTU.

A plausible way to re-scale this value to expectations for JEM-EUSO is obtained by taking into account the ratio of the FoVs of a pixel ($L$), optics apertures ($A$) and telescope efficiencies ($\epsilon$) between Mini-EUSO and JEM–EUSO telescopes (the average background levels for K-EUSO and POEMMA have been obtained similarly to the JEM-EUSO one). The expected background ratio ($R(ME/JE)$) between Mini-EUSO and JEM-EUSO is then:

$$R(ME/JE) = \left(\frac{L_{ME}}{L_{JE}}\right)^2 \times \frac{A_{ME}}{A_{JE}} \times \frac{\epsilon_{ME}}{\epsilon_{JE}} = 1.4 \pm 0.3, \quad (1)$$

where $L_{ME} = 6.3$ km, $L_{JE} = 0.55$ km, $A_{ME} = 0.05$ m$^2$, $A_{JE} = 4.5$ m$^2$, $\epsilon_{ME} = 0.080 \pm 0.015$ (according to the preliminary results discussed in [18]) and $\epsilon_{JE} = 0.085$. This implies that the expected average background value for JEM–EUSO is (0.9 ± 0.2) counts/pixel/GTU, indicating that the average value of ~1.1 counts/pixel/GTU assumed for JEM–EUSO [11] is well within the current estimation and confirms the robustness of the assumptions employed in those estimates.

| counts/pixel/GTU | clear sea | clear land | cloudy sea | cloudy land | cloudy all |
|---|---|---|---|---|---|
| No-moon | 0.9 | 1.4 | 1.3 | 1.7 | 1.4 |
| Half-moon | 1.8 | 2.8 | 13.0 | 8.1 | 9.7 |
| Full-moon | 37.6 | 35.1 | 50.7 | 51.1 | 51.0 |

**Table 1:** Average emission values (counts/pixel/GTU) for sea and ground for various lunar phases and cloudiness. Half-moon includes Moon fractions between 0.4 and 0.5, and full-moon includes fractions between 0.9 and 1. The brightest pixels (above the 99th percentile) were excluded when calculating the mean and standard deviation to mitigate the effects from bright anthropogenic sources. For conditions with multi-modal distributions, the mode closest to the average is displayed. Table adapted from [18].

Finally, Fig. 1 shows in panel c) a comparison between the cloud fraction (%) due to a cyclone in the Indian ocean as foreseen by the Global Forecast System of NASA and on the right the Mini-EUSO counts per pixel taken in D3 mode but normalized to the D1 GTU. Where the cloud fraction is expected to be higher, Mini-EUSO registers higher counts level. This is obtained in no moon condition and shows the capability of the UV camera of Mini-EUSO to detect the presence of clouds. This is very helpful for the calculation of the exposure and for the determination of the atmospheric conditions in case of the detection of an EAS candidate. These results have to be considered preliminary as a more detailed study on the comparison between atmospheric conditions and Mini-EUSO measurements is currently on going.

## 4. Acknowledgements

This work was supported by the Italian Space Agency through the agreement n. 2020-26-Hh.0, by the French space agency CNES, and by the National Science Centre in Poland grants 2017/27/B/ST9/02162 and 2020/37/B/ST9/01821. This research has been supported by the Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Applied Space Research" and by Russian State Space Corporation Roscosmos. The article has been prepared based on research materials collected in the space experiment "UV atmosphere". We thank the Altea-Lidal collaboration for providing the orbital data of the ISS.

## References

[1] A. Coleman et al., *Ultra-High-Energy Cosmic Rays: The Intersection of the Cosmic and Energy Frontiers*, *accepted for publication at Astrop. Phys.* [astro-ph/2205.05845]

[2] M. Ricci (JEM-EUSO Coll.), *The JEM-EUSO Program*, *J.Phys.Conf.Ser.* **718 n.5** (2016) 052034.

[3] G. Abdellaoui *et al* (JEM-EUSO Coll.), *EUSO-TA – First results from a ground-based EUSO telescope*, *Astrop. Phys.* **102** (2018) 98-111.

[4] J.H. Adams Jr. *et al* (JEM-EUSO Coll.), *A Review of the EUSO-Balloon Pathfinder for the JEM-EUSO Program*, *Space Sci. Rev.* **218** (2022) 3.

[5] L. Wiencke and A. Olinto for the JEM-EUSO Coll., *EUSO-SPB1 Mission and Science*, *PoS(ICRC2017)* **301** (2017) 1097.

[6] J. Eser, A.V. Olinto, L. Wiencke for the JEM-EUSO Coll., *Science and mission status of EUSO-SPB2*, *PoS(ICRC2021)* **395** (2021) 404 [astro-ph/2112.08509].

[7] P. Klimov *et al* (TUS Coll.), *The TUS Detector of Extreme Energy Cosmic Rays on Board the Lomonosov Satellite*, *Space Sci. Rev.* **212** (2017) 1687-1703 [astro-ph/1706.04976].

[8] S. Bacholle *et al*, *Mini-EUSO Mission to Study Earth UV Emissions on board the ISS*, *ApJS* **253** (2021) 36 [astro-ph/2010.01937].

[9] P. Klimov *et al* (JEM-EUSO Coll.), *Status of the K-EUSO Orbital Detector of Ultra-High Energy Cosmic Rays*, *Universe* **8** (2022) 88 [astro-ph/2201.12766].

[10] A. Olinto *et al* (POEMMA Coll.), *The POEMMA (Probe of Extreme Multi-Messenger Astrophysics) observatory*, *JCAP* **06** (2021) 007 [astro-ph/2012.07945].

[11] J.H. Adams Jr. *et al.* (JEM-EUSO Coll.), *An evaluation of the exposure in nadir observation of the JEM-EUSO mission*, *Astrop. Phys.* **44** (2013) 76-90 [astro-ph/1305.2478].

[12] A. Belov *et al.* (JEM-EUSO Coll.), *The integration and testing of the Mini-EUSO multi-level trigger system*, *ASR* **62/10** (2018) 2966-2976 [astro-ph/1711.02376].

[13] G. Abdellauoi *et al.* (JEM-EUSO Coll.), *Cosmic ray oriented performance studies for the JEM-EUSO first level trigger*, *NIMA* **866** (2017) 150-163.

[14] M. Battisti *al.* (JEM-EUSO Coll.) *Onboard performance of the level 1 trigger of the mini-EUSO telescope*, *ASR* **70/9** (2022) 2750-2766.

[15] J.H. Adams *et al.* (JEM-EUSO Coll.) *JEM-EUSO: Meteor and nuclearite observations*, *Exp. Astr.* **40** (2015) 253-279.

[16] P. Barrillon *et al.* (JEM-EUSO Coll.) *The EUSO@TurLab project in the framework of the JEM-EUSO program*, *Exp. Astr.* (2022).

[17] F. Bisconti *et al.* (JEM-EUSO Coll.) *Preflight qualification tests of the Mini-EUSO telescope engineering model*, *Exp. Astr.* **53/1** (2021) 133-158.

[18] D. Barghini *et al.* (JEM-EUSO Coll.), *Observation of night-time emissions of the Earth in the near UV range from the International Space Station with the Mini-EUSO detector*, *Remote Sens. Environ.* **284** (2023) 113336.