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Abstract The EUSO@TurLab project aims at performing experiments to reproduce Earth UV emissions as seen from a low Earth orbit by the planned missions of the JEM-EUSO program. It makes use of the TurLab facility, which is a laboratory, equipped with a 5 m diameter and 1 m depth rotating tank, located at the Physics Department of the University of Torino. All the experiments are designed and performed based on simulation of the expected response of the detectors to be flown in space. In April 2016 the TUS detector and more recently in October 2019 the Mini-EUSO experiment, both part of the JEM-EUSO program, have been placed in orbit to map the UV Earth emissions. It is, therefore, now possible to compare the replicas performed at TurLab with the actual images detected in space to understand the level of fidelity in terms of reproduction of the expected signals. We show that the laboratory tests reproduce at the order of magnitude level the measurements from space in terms of spatial extension and time duration of the emitted UV light, as well as the intensity in terms of expected counts per pixel per unit time when atmospheric transient events, diffuse nightlow background light, and artificial light sources are considered. Therefore, TurLab is found to be a very useful facility for testing the acquisition logic of the detectors of the present and future missions of the JEM-EUSO program and beyond in order to reproduce atmospheric signals in the laboratory.

Keywords Ultra-High Energy Cosmic Rays · JEM-EUSO · TurLab

1 Introduction

The main objective of the Joint Experiment Missions for Extreme Universe Space Observatory (JEM-EUSO) program [1], is the realization of ambitious

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space-based missions devoted to scientific research of Ultra-High Energy Cosmic Rays (UHECRs, E $>$ 10^{18} eV), as well as Extreme Energy neutrinos (EHEν, E $> 5 \times 10^{19}$ eV) and ν_τ. Looking downward from a Low Earth Orbit (LEO), a JEM-EUSO-like detector [2] will identify UHECRs and EHEν by observing the fluorescence emission from the generated Extensive Air Showers (EAS) during their passage through the atmosphere. This paper focuses only on UHECRs even though very similar signals would be expected from EHEν. The Earth's atmosphere works as detector medium for UHECRs but, at the same time, it is the main source of many other transient signals whose origin is natural, such as Transient Luminous Events (TLEs) [3], meteors, nightglow variations, and bio-luminescence, or anthropogenic, such as ground flashers and space debris, and whose duration and extension is quite variable in space (from less than 1 m to more than 100 km) and time (from μs to seconds scale). It could even be the place to search for unknown phenomena and only hypothesized forms of matter (e.g. nuclearites [4]). All these phenomena could be considered as a source of background and disturbance for the observation of UHECRs, but on the other hand they represent by themselves scientific targets. It would be, therefore, valuable to build a sufficiently flexible instrument with the main goal being the UHECR and neutrino science, but at the same time, capable of contributing to the exploration and understanding of other scientific targets. The experiments of the JEM-EUSO program launched so far have already provided first results in this respect [5, 6].

The JEM-EUSO program includes several missions from ground (EUSO-TA [7]), from stratospheric balloons (EUSO-Balloon [8], EUSO-SPB1 [9], EUSO-SPB2 [10]), and from space (TUS [11], Mini-EUSO [12]) employing fluorescence detectors to demonstrate the UHECR observation principle from space in view of the future large size missions K-EUSO [13] and POEMMA [14]. They all share the same concept of an optical system varying between order of 10^{-1} and 10 m^2 size with an angular resolution in the range 0.05 - 1 degree, and a focal surface of the order of 10^2 - 10^5 pixels, either with Multi-Anode Photo-Multiplier Tubes (MAPMTs) or/and Silicon Photo-Multipliers (SiPMs).

The main task of the Data Acquisition (DAQ) chain and in particular for the trigger system is to deal with the highly variable conditions of the atmosphere which might induce an excessive spurious trigger rate, well above the sustainable one. The possibility to reproduce at some extent in laboratory the various atmospheric conditions that the detector would observe from space is very much beneficial as it would allow to cross-check and refine the acquisition logic, avoiding to discover possible inefficiencies or malfunctionings while in space.

The core objective of the EUSO@TurLab project [16] is to test the electronics and trigger system of the different detectors of the JEM-EUSO program in quasi-real conditions in terms of light intensity, as well as spatial and temporal light variations. The use of the TurLab tank allows reproducing experimentally variable light conditions, recreating orbit sights and events as expected to be seen by JEM-EUSO. The experiments performed at TurLab were designed based on simulation results of the expected light signals seen from space. Thanks to the experimental data retrieved by TUS and more recently by Mini-EUSO, it is now possible to compare them with those collected at TurLab to understand at which level of fidelity they reproduce the actual observations from space. It is important to emphasize that it is out of the scope to reproduce exactly the natural and artificial phenomena as seen from space as it would require an infinite set of experiments to reproduce the Earth's atmophere with all its phenomena. What primarily matters is the capability of reproducing them at least at the order of magnitude level in terms of temporal duration, spatial extension and luminous intensity. This is important because it validates the concept of the EUSO@TurLab project and, if needed, refine the future tests in order to emulate even more precisely the specific signals expected in space. Moreover, the TurLab facility can be used to test on ground upgraded acquisition firmware with high reliability prior to implement them on-board satellites or balloons with a significant resource saving.

The paper is organized as follows. Section 2 summarizes the main characteristics of the space-based missions of the JEM-EUSO program. Section 3 describes the TurLab facility and the phases of the EUSO@TurLab project with the different setups used to emulate UV transients. Section 4 compares in details the signals reproduced at TurLab with those in space focusing on: a) light intensity and variation from diffuse sources; b) spatial and temporal evolution of the signals from urbanized areas, meteors, lightning, flashers and EAS. Section 5 describes experiments conducted at TurLab regarding other applications such as remediation of space debris and ocean studies, and reports on campaigns performed with instrumentation of the JEM-EUSO program. Perspectives and conclusions are subject of Section 6.

2 Synthetic description of the JEM-EUSO detectors

One of the observational principles of a space-based instrument aiming to investigate UHECRs science is based on the detection of the UV (300 - 430 nm) fluorescence photons produced along the track of EASs in the atmosphere. These signals last typically 50 - 150 μs and extend on tens of kilometers in size depending on the zenith angle of the EAS. Due to the fact that UHECRs above 5×10^{19} eV have a flux lower than 1 event per century per square kilometer [17], huge exposures are necessary to collect sufficient statistics. Moreover, the detector should have good enough temporal and spatial resolutions to properly image the event and reconstruct the track. In the following, the most relevant parameters of the original JEM-EUSO telescope are briefly mentioned to provide some references. A more detailed description of the mission, its aims, detection strategy and expected performance is reported in [2].

The JEM-EUSO telescope is conceived with a Field-of-View (FoV) of $\sim$0.85 sr orbiting on-board the International Space Station (ISS). The optics is composed of three Fresnel lenses with a 4.5 m^2 optical aperture. The telescope records the EAS-induced tracks with a time resolution of 2.5 μs (Gate Time

Table 1 Approximated values for the typical parameters of the different space missions of the JEM-EUSO program.

Parameter	JEM-EUSO	TUS	Mini-EUSO	K-EUSO	POEMMA
Orbital height (km)	400	480	420	400	525
Orbital speed (km/s)	7.7	7.6	7.7	7.7	7.6
Pixel FoV (deg)	0.075	0.6	0.9	0.11	0.084
Pixel FoV at ground (km)	0.55	5	6.5	0.8	0.76
Full FoV (km)	460	80	340	290	435
Pixel FoV duration (ms)	72	660	860	130	100
Optics size (m^2)	4.5	2	0.05	5	6
Time resolution (μs)	2.5	0.8	2.5	1	1

Unit; GTU). The Focal Surface (FS) detector is formed by 137 Photo Detector Modules (PDMs) composed of $\sim$5000 MAPMTs in total (36 MAPMTs per PDM, 64 pixels each). The FS detector is highly pixelated in $\sim 3\times10^5$ channels providing a spatial resolution of $\sim 0.074°$, equivalent to $\sim$0.55 km at ground seen from an altitude of $\sim$400 km. An optical filter is placed in front of each MAPMT to select photons in the fluorescence bandwidth. Since the ISS orbits the Earth in the latitude range of $\pm 51.6°$, moving at a speed of $\sim$7.7 km s^{-1}, the variability of the FoV observed by JEM-EUSO is much higher than that observed by ground-based experiments. Indeed, the pixel-FoV changes completely every $\sim$70 ms. Moreover, making $\sim$15.5 orbits per day, every 45 minutes on average the ISS has a transition between day and night regions. In reality, the illumination period depends on the β angle of the ISS, which is the angle between the orbital plane of the station and the Sun-Earth vector. Therefore, the night and day portions of the orbit significantly differ depending on the period of the year.

Along the years, the JEM-EUSO concept has evolved in a short- and long-term development program with different missions from ground, balloon and space-platforms with different complexity and objectives. Namely, the JEM-EUSO mission itself could not be realized. The EUSO-TA on ground and the missions on balloons aim to develop and test the key elements of the JEM-EUSO concept, in order to raise their technological readiness level and demonstrate the fluorescence technique from suborbital altitudes. The TUS and Mini-EUSO telescopes are designed to serve as path-finder and/or small scale missions for the K-EUSO and POEMMA middle and large class missions. Table 1 provides a summary of the main parameters of the different space telescopes within the JEM-EUSO program, which are of relevance for the EUSO@TurLab measurements. Due to the totally different flight speed of stratospheric balloons, typically 2 - 3 orders of magnitude slower than space missions in Low Earth Orbits, replicas of flight paths of EUSO-SPB can not be reproduced with the same fidelity as for the space projects. However, in some cases this is not an issue. As an example, if the main purpose of the tests is to verify that the trigger thresholds are adjusted fast enough in time to follow the variations of the light intensities, then a positive result on a test

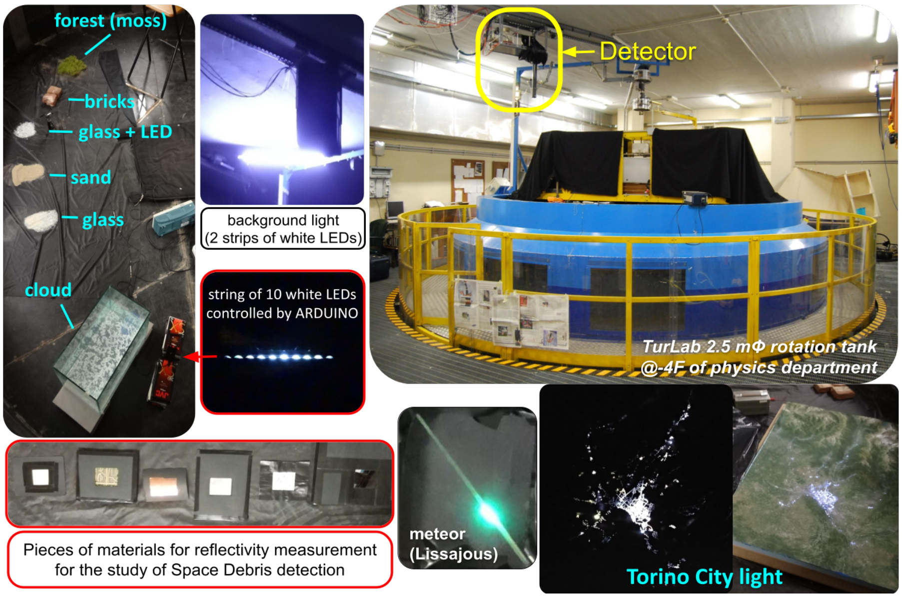

Fig. 1 TurLab tank (right-top) setup with the EUSO@TurLab detector hung on the ceiling, light sources and materials to reproduce atmospheric phenomena that a detector in space can observe. Bottom left side shows examples of materials which might become space debris (see Section 5 for details). Right bottom part of the figure shows a reproduction of the city of Turin which is used in the experiments at TurLab to mimic city lights (see text for further details).

performed by simulating space orbits is a guarantee that the trigger logic will satisfy the requirements also for balloon speeds.

3 The EUSO@TurLab project and relative development phases

TurLab is a laboratory, equipped with a 5 m diameter rotating tank, located at the Physics Department of the University of Torino (see Fig. 1) [15]. The system has been conceived mainly for studying fluid-dynamics problems where system rotation plays a key role in the fluid behavior, as it happens in atmospheric and oceanic flows at different scales.

The tank can be filled up to 70 cm with water (both fresh or salty) and can rotate with periods that span from about few seconds to several minutes. For fluid-dynamics experiments the facility is equipped with cameras and an advanced system for digital recording and data processing. The TurLab facility is located 15 m underground. Therefore, it is possible to work in extremely dark conditions and hence the light intensity in the room can be varied by researchers.

The tank can be used in various settings, which allow the study of different atmospheric phenomena. A few examples are: a) it can be filled with fluids of different density to study fluid behaviour in stratified conditions both with or without rotation; b) convection can be generated and studied with different approaches; c) two fans can create an air flow, between about 1 and 7 m/s, that induce waves on the fluid surface, which allow the study of the air-water interaction or/and create conditions of infinite fetch that can be deeply analyzed with fluid-dynamics techniques or with two waves probes; d) the possibility of different surface roughness allows studies of fluid turbulent properties in the boundary layer; e) the facility can be used as a model of the rotating Earth system to simulate parts of terrestrial surface by reproducing different environments using water (ocean, fog and clouds) and withour water (snow, grass, land) and their albedo.

The leading idea of the EUSO@TurLab project is reproducing the variations of luminosity and possible luminous events that a telescope of the JEM-EUSO program will encounter during its mission. To realize an emulation of observations from the ISS, the TurLab rotating tank is used with a series of different configurations to recreate the Earth views, and the EUSO@TurLab apparatus is hung on the ceiling above the tank pointing towards the nadir to emulate a JEM-EUSO telescope [18].

Most relevant feature at TurLab is changing the light conditions and light sources. Diffuse light in the tank is obtained by the reflection of the light emitted by a LED suspended on the tank structure and pointing towards the ceiling. Light sources are essentially of two kinds: a) direct light emitting sources; b) materials reflecting room light as can be seen in Fig. 1. As light emitting sources a variety of things are used, with the intent of reproducing different kinds of observations from space: a) a replica of the Torino region to emulate artificial lights from cities, villages and roads; b) LEDs driven by a pulse generator, and/or smashed glass illuminated by LEDs for fast luminous events such as lightnings; c) an oscilloscope producing Lissajous curves, for events such as meteors; d) LEDs and optical fibers driven by Arduino [19] (Fig. 2 (a)). Arduino is an electronics platform and we use it to control light sources with very short timing (minimum 1 μs) or to recreate complicated luminous phenomena, such as elves. Till now UHECRs are recreated with a strip of 10 LEDs while elves are reproduced with optical fibers arranged in a quarter circle and illuminated by LEDs (Fig. 2 (b)). For the UHECRs, we regulate the variation of light intensity during the EAS development by varying the intensity of each LED using variable impedances (Fig. 2 (c)).

Regarding the EUSO@TurLab apparatus itself, different detectors and readout-electronics setups have been adopted along the years, all using a 1-inch lens as optical system. The typical focal lengths used in our system vary between 30 and 50 cm. Taking into account that the pixel pitch is $\sim$3 mm, the angular resolution is of the order of 0.3° - 0.6°. A constant diffused background light is produced by a high power LED lamp illuminating the ceiling. Different materials are used to obtain variations in the intensity of the reflected light inside the tank. A cloud-like scenario is created using a small container placed inside the tank filled with 2-3 layers of water with different salt concentrations and layers of suspended particles to reproduce cloud albedo. High Voltages (HV), DC power supplies, function generators and monitoring oscilloscopes

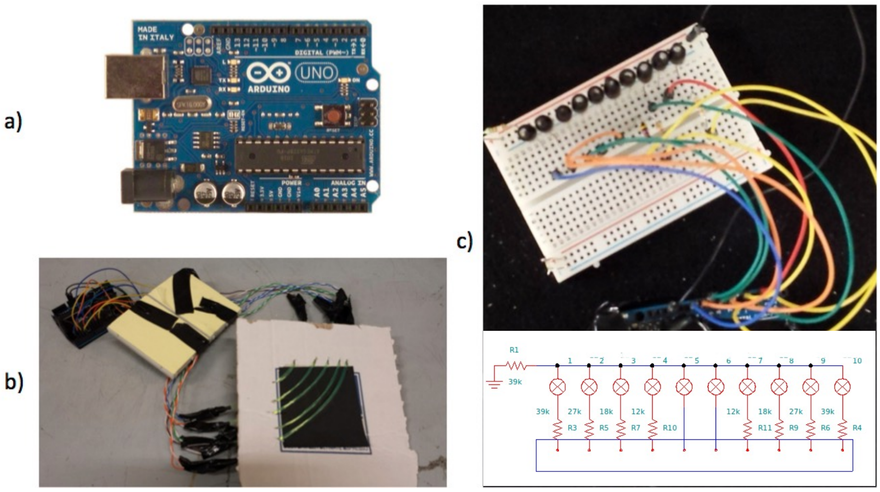

Fig. 2 The Arduino UNO board is shown in a). Pictures of the electronic circuits employed so far to mimic elves (b) and EASs (c) are displayed as well. The expanding arcs of an elve are reproduced by illuminating sequentially the various fibers. EAS are obtained by sequentially switching on the various LEDs. By means of different impedences the intensity of the emitted lights follows the typical raising and decreasing shape of an EAS signal.

are on the desk by the side of the tank with a PC with LabView [20] interface. They are used to power the EUSO@TurLab apparatus, pilot the different light sources and monitor the apparatus response and data acquisition. ROOT [21] and ETOS [22] software are used for monitoring and analysis.

The capability of changing the rotation speed of the tank gives the opportunity of producing slower and faster light transitions (within a factor of ∼20) adapting the experiment to the intended situation. In general, the fact that the tank can be rotated with periods reaching 20 minutes allows reproducing entire night orbits or significant portions of them. The possibility of controlling light illumination allows recreating moonrise and moonset, or day and night transitions. On the other hand, to simulate the residence time of point-like sources in the FoV of a pixel, it is important to reproduce similar angular speed as seen from orbit. Table 2 shows a few examples in order to obtain two extreme cases: JEM-EUSO and Mini-EUSO configurations (see Table 1).

Along the years, different types of electronics read-out were used, improving step by step the capability to replicate the on-board measurements and the EUSO@TurLab apparatus has gone through three different phases.

The EUSO@TurLab apparatus used in the first phase (2010 - 2014) [23] consists of a 5×5 pixels MAPMT: Hamamatsu R8900-M25 [24], hung from the ceiling and pointing towards nadir; 25 cables, 25 m long, connecting each pixel of the MAPMT with the electronics; standard NIM and CAMAC electronics and a PC for acquiring measurements with LabView. The electronic system is very different from the JEM-EUSO one, although it is based on the same detection principle of the single photon-counting. With this setup it is not

Table 2 Rotation speed of the tank to reproduce the equivalent transition time of a point-like source in the FoV of one pixel for the JEM-EUSO and Mini-EUSO cases taken as the two extreme conditions of table 1. In the following it has been assumed that the light source is located at 2 m distance from the lens of the EUSO@TurLab apparatus and that it is positioned close to the edge of the tank where the circumference is ∼15 m. The two cases of 30 cm and 50 Focal Length (FL) are considered.

Instrument	Time to change pixel FoV (ms)	Rotation period of TurLab (s)	
		30 cm FL	50 cm FL
JEM-EUSO	72	54	90
Mini-EUSO	860	640	1060

possible to reproduce the JEM-EUSO time scale, with a GTU of 2.5 μs and a 25 ns double-pulse resolution (which is the one expected for JEM-EUSO). Therefore, 400 ns double-pulse resolution and 40 μs GTU are adopted to keep the same saturation characteristics in photon-counting as in JEM-EUSO. A very unwanted feature of such an electronics configuration, which is resolved in the latest phases is the delay in the PC acquisition: 30 ms dead time for each measurement. Hence, for EUSO@TurLab, 1 GTU consists of 40 μs sampled every 30 ms.

The instrumentation used in the second phase (2015 - 2017) [25] is upgraded compared to the first phase by using an Elementary Cell (EC) unit (4 MAPMTs, 64 channels each) and the readout by the JEM-EUSO front-end electronics with an ASIC evaluation board. The main improvement of this configuration consists in collecting data with 2.5 μs resolution by means of the JEM-EUSO instrumentation. However, the data readout introduces a 50 ms dead time between packets of 128 GTUs. The trigger configuration is not implemented either. This is the electronics used at the time of the EUSO-Balloon flight and of the installation and first campaigns of the EUSO-TA telescope. During the second phase TurLab hosted campaigns to test the trigger performance in view of the EUSO-SPB1 mission. For these campaigns the PDM that flew on EUSO-Balloon was employed as a detector. At the time of these campaigns the trigger configuration was implemented in FPGA.

In the third phase (since 2018) [26, 27] a significant change in the read-out electronics is applied, which is the one employed in the Mini-EUSO configuration that records data with different time resolutions (2.5 μs, 320 μs, and 41 ms). With this configuration, no dead time exists between acquired data at 41 ms time resolution (D3 data). In parallel, it is possible to acquire up to 4 packets of data with 2.5 μs (D1 data) and 320 μs (D2 data) time resolutions, every 5.24 s. This configuration is shown in Fig. 3. During this phase, the Mini-EUSO Engineering Model (Mini-EUSO EM) was tested as well (2018) to check the DAQ and trigger performance [28] (Fig. 21).

All along the different studies described in this paper, unless differently mentioned, the conventional time unit (GTU) used in the plots is the shortest time unit adopted in the acquisitions which is 2.5 μs for second and third phases, and 40 μs for the first phase.

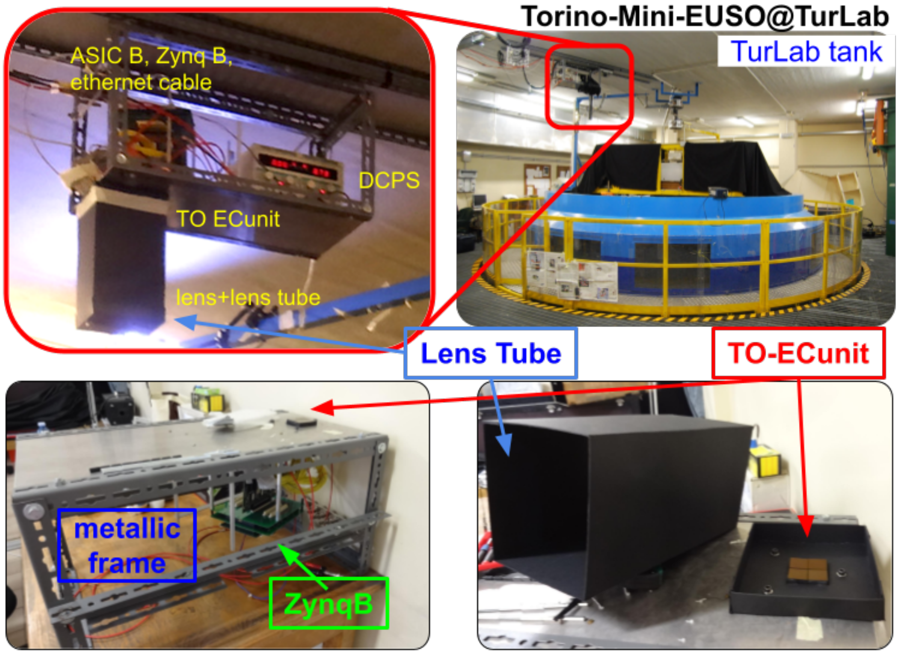

Fig. 3 The EUSO@TurLab configuration in the third phase consists of a lens tube with a 1-inch plano-convex lens, an EC unit, front-end electronics based on SPACIROC3 ASICs, the Zinq board connected to a PC via ethernet cable, where the CPU software, a dedicated software for Mini-EUSO data processing system, is installed. Electronics boards and MAPMTs are powered by external low and high voltage power supplies (DCPS), respectively. A metallic frame is used to hold the experimental setup and to fix it on the ceiling.

4 Comparison between TurLab measurements and space observations

Thanks to the data collected by Mini-EUSO and TUS it is possible to compare the measurements obtained with the replica at TurLab to the data acquired by the experiments, in order to understand at which level of accuracy the light intensity and light profiles are reproduced with EUSO@TurLab. A first overall comparison can be done by looking at the data collected in typical orbits at TurLab using the electronics setups employed in the three different phases as summarized in Section 3 (see Figs. 4, 5, 6, and 7) with those published by Mini-EUSO [6] (see Fig. 8).

Figs. 4 and 5 show measurements taken during the first phase. The MAPMT photo-electron counts (sum of counts from 25 pixels) during a complete 10 minute long rotation of the tank are shown. Different configurations are reproduced as explained in the following. In Fig. 4, the room light is the same for the two curves, with the LED over the tank switched ON. The green curve refers to the tank without any source on it, while the blue one represents the tank covered with a collection of different materials and direct light sources.

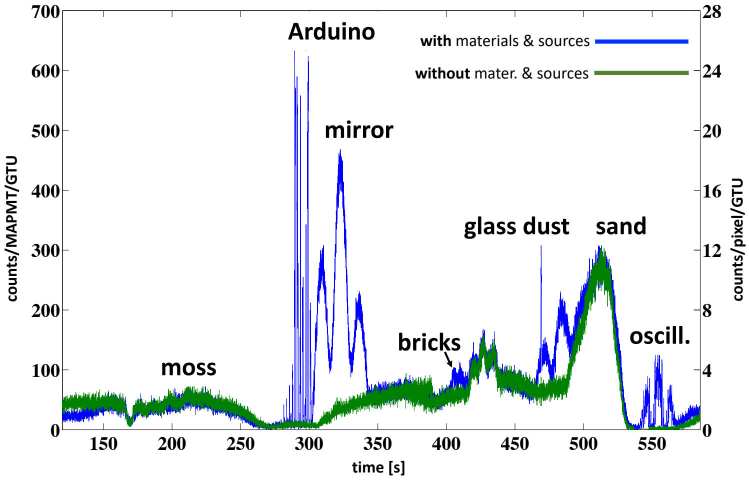

Fig. 4 A 10 minutes long rotation of the tank equipped with different sources: moss, Arduino 10 LED strip, mirror, bricks, glass dust, sand, and oscilloscope. The sum of the 25 pixels (Phase 1) is indicated on the left side of the vertical axis, while the right side shows the average count rate per pixel. The green curve refers to the tank without any source in it, while the blue one represents the tank covered with a collection of different materials and direct light sources. The unexpected response of the sand is due to the fact that it was placed in a region of the tank which is particularly bright when the LED on the tank is ON as it can be seen from Fig. 5.

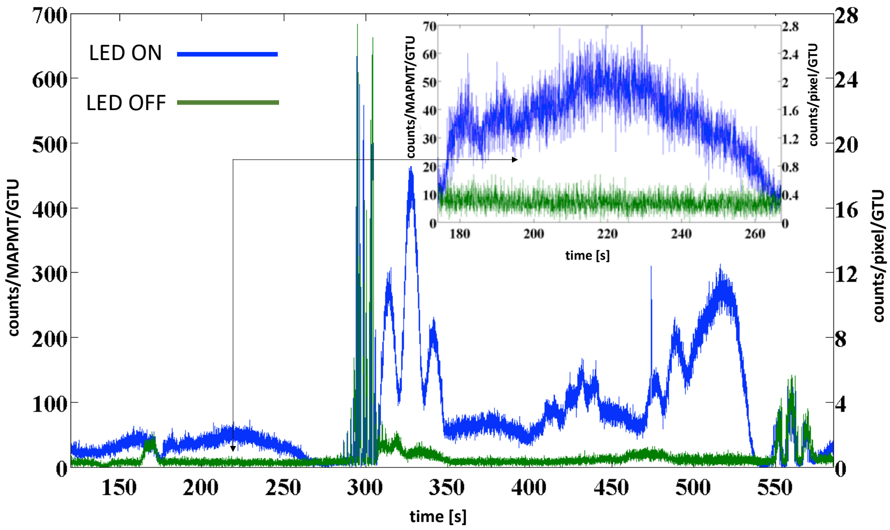

Fig. 5 Response to different light room conditions with materials inserted as in Fig. 4 (Phase 1). The LED over the tank is ON or OFF in blue or green curve, respectively. A portion of the plot is zoomed in the inset to better appreciate the count level with LED OFF. See text for details.

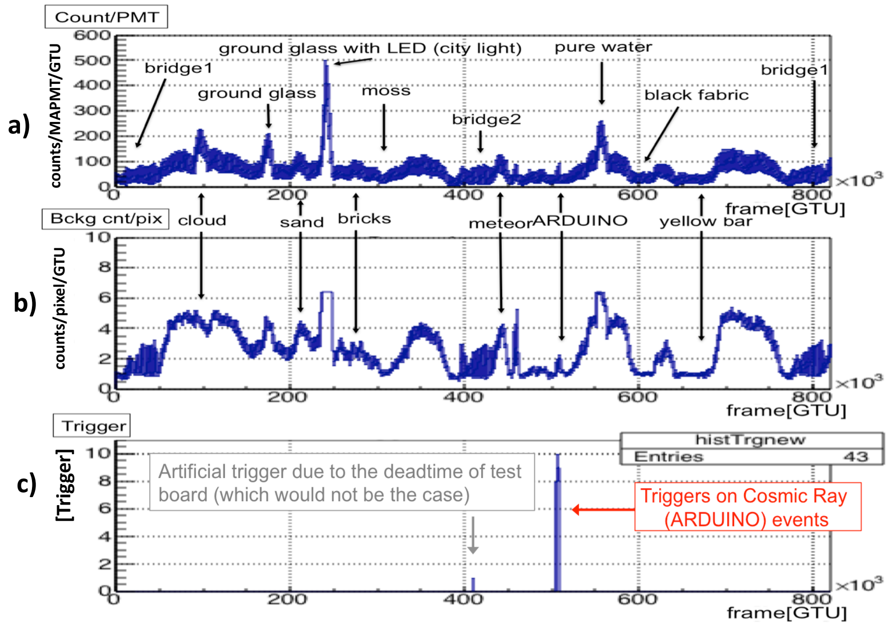

Fig. 6 The panel a) shows the raw data (counts/PMT, 64 pixels, Phase 2), while panel b) shows the corresponding background level which is used to set the threshold for the FLT and panel c) shows the result of the FLT, as a function of frame number (GTU = 2.5 μs), respectively. We obtained 100% trigger efficiency for EAS-like events. A few triggers at around frame 410,000 are due to the 50 ms of dead time among packets, which would not be the case of actual JEM-EUSO observation operated with the PDM board with no dead time. The re-adjustement of the trigger thresholds, which is obtained by re-calculating the average measured background level per each pixel every 320 μs, would have prevented the trigger to occur.

In Fig. 5, the two curves refer to different room light conditions with the tank covered with all the sources shown in Fig. 4. The LED over the tank is ON or OFF in blue or green curve, respectively. As predictable, when light emitting sources are in the FoV of the EUSO@TurLab apparatus, there is no difference between the detected light when the LED over the tank is ON or OFF. On the other hand, there is a fundamental change in the response of different reflecting materials. The inset in Fig. 5 is a zoom showing the minimum level of luminosity obtainable at TurLab which is present in different positions inside the tank, with different materials on it. An average value of 0.3 counts/pixel/GTU is obtained with LED OFF. With LED ON the typical value is around 2 counts/pixel/GTU. These are all different levels of 'background' light that can be used to check the sensitivity to the detection of EAS-like events by the trigger system.

The top panel of Fig. 6 shows the result of UV intensities in a full rotation of the tank with various materials during the second phase campaign when a JEM-EUSO EC unit is employed. The plot shows the summed counts of a PMT (=64 pixels) as a function of time in GTUs. An average value of 0.5 -

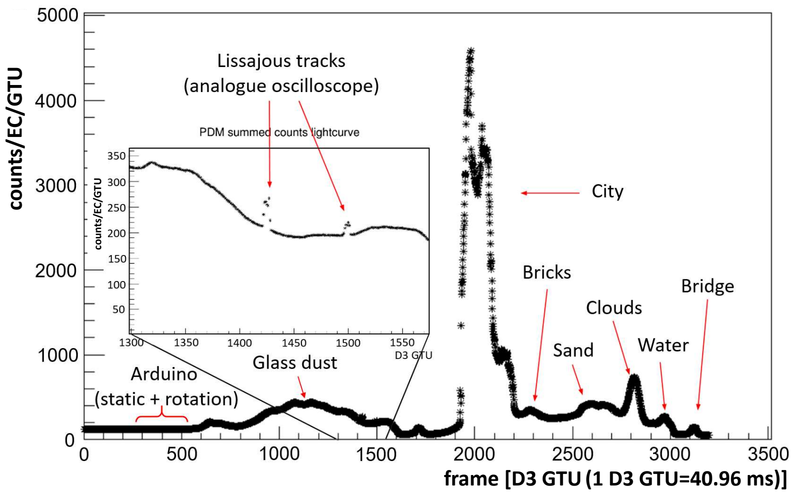

Fig. 7 Light curve of D3 data for a whole tank rotation with a speed of 2 min/rot (Phase 3). All the reflections from materials in the FoV are recorded as a continuous "movie" in D3 data while D1 and D2 stores only the events that they are targeting to trigger in their own time resolution (up to 4 events per D3 packet). Counts are renormalized to D1 GTUs. Figure adapted from [28]. See text for details.

2 counts/pixel/GTU is obtained depending on the portion of the tank in the FoV without emitting lights.

The middle and bottom plots concern one of the typical analyses performed on the data, which is the evaluation of the First Level Trigger (FLT) performance, the JEM-EUSO one in this specific case. The middle panel shows the averaged counts per pixel which is used to set the FLT threshold, while the bottom shows when FLTs are issued based on signals in that PMT, as a function of GTU. Almost all triggers coincide with passing over the Arduino driven LED chain, which emulates EAS-like events, as expected. Only one trigger is not associated to an EAS-like event. Instead, it is due to a specific location near one of the two bridges crossing the tank. In this location the variations of light reflection are too fast for the 50 ms of dead time among packets and the trigger logic is not able to properly re-adjust the threhsolds in due time. This is one of the essential tests that validated the trigger logic prior to the EUSO-SPB1 flight.

Fig. 7 shows the emulation of one orbit taken during the third phase with the latest electronics configuration. The sum of 256 pixels is shown (one EC unit). In this case it is possible to collect data at three different sampling times. There is no dead time for D3 data. This is the closest configuration to the data taking in orbit with Mini-EUSO. The typical counts are between 0.3 and 1.5 counts/pixel/GTU.

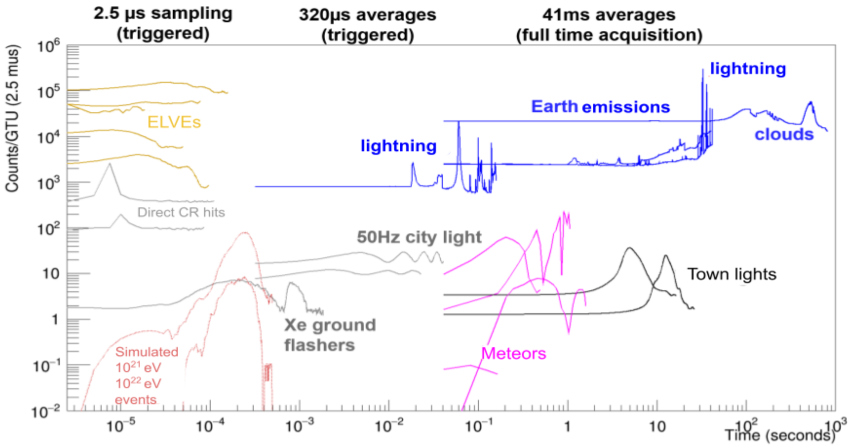

Fig. 8 Temporal profile of various signals observed by Mini-EUSO. The fastest sampling rate (2.5 μs) allows detecting EAS-like events, elves and other fast phenomena. The averaged sampling can be used to characterize slower events such as lightning, meteors, UV emissions of artificial and natural origin. All curves refer to experimental data from ISS altitude except the light curves of UHECRs which come from MonteCarlo simulations. The temporal profiles are relative to the number of pixels involved in the phenomena. As an example, clouds and Earth emissions express the counts integrated on the full PDM. Image adapted from [6].

4.1 First general comparisons with Mini-EUSO observations

A few general considerations on the comparison of the light intensities recorded at TurLab in the different phases and by Mini-EUSO as shown in Fig. 8 are reported in the following. They can be easily done due to the relatively large surface area of the emitting sources. For more circumscribed areas a more refined comparison is needed.

1 The typical background level in Mini-EUSO is of the order of 1 count/pixel/GTU (see Mini-EUSO count rate in the first part of the 'Town lights' temporal profile in Fig. 8). It can vary by a factor of two or more depending on the viewed surface (ground, sea, grass, etc.) and on the pixel response. The values reproduced at TurLab, where different materials are used to change the albedo, are in agreeement with these intensities as they vary typically between 100 - 500 counts/EC/GTU which correspond to 0.4 - 2 counts/pixel/GTU.
2 In presence of clouds the light intensity in Mini-EUSO increases by a factor of $\sim$ 2 - 3 and this is well reproduced at TurLab where clouds increase the light signal by a similar amount.
3 By switching the lights OFF the background level is reduced to similar conditions recorded by Mini-EUSO when the HV protection system is activated and the MAPMT efficiency is reduced by 1 - 2 orders of magnitude (see Fig. 17 for a more detailed comparison). In fact, Mini-EUSO is equipped with a HV protection system that reduces by orders of magnitude the collection efficiency of the MAPMTs when the light intensity

exceeds ∼100 counts/pixel/GTU. This is done by changing the voltage set at photo-cathode level. The setup at TurLab is not provided with such a safety mechanism.

4 Light intensities of cities in the Mini-EUSO data are typically 10 − 100 times brighter than the pedestal level. Similar results are obtained at TurLab, where ‘city’ light is 5 - 30 times brighter than the typical room light reflection by the bottom of the tank.

5 LED pulses and glass dust can reproduce intense spikes with short duration (see Fig. 4) that can mimic lightnings as detected by Mini-EUSO.

These comparisons indicate that strong light intensities and the overall standard brightness levels are replicated in all three phases of the project typically within a factor of ∼2-3. Along the years, the major improvement is related to the acquisition system which became more and more representative of the electronics system in flight. Nevertheless, since its setting up EUSO@TurLab has been conceived at a reasonable level of fidelity with typical observations from space.

Moreover, it is important to remind here that Mini-EUSO has been designed in such a way to detect similar photo-electron counts per pixel as in JEM-EUSO in case of diffuse light sources to test the electronics response in conditions which are as similar as possible to what was expected for JEM-EUSO. This is done by compensating the $\sim 10^{-2}$ times optics aperture with $\sim 10^{2}$ times wider pixel FoV. Therefore, these results on diffuse light sources are representative also in view of the future large missions K-EUSO and POEMMA which have similar apertures and instantaneous FoV.

Another important comparison is on the spatial extension and temporal durations of localized light emissions, either emitted or diffused lights, performed at TurLab to check for similarities with Mini-EUSO observations. The temporal duration of light sources is flexible by rotating the tank at different speed. Figs. 9, 10 and 11, show some examples of localized light sources generated at TurLab with different solutions (i.e. city lights, sand, cloud or meteor). Mini-EUSO equivalent observations are shown in Figs. 12 and 13. A specific and more quantitative comparison for some typology of signals is provided in the following.

4.2 City lights

A first comparison is done with city lights. Fig. 9 shows the representation of Torino city and surroundings at TurLab. Two images show that villages and cities brigthen few pixels or entire MAPMTs, depending on their spatial extension. This example is compared with images taken by Mini-EUSO (see Fig. 12) on West Bengal in India. This is a densely inhabitated region with the metropolis of Kolkata and other towns and villages in the area. In the Mini-EUSO FoV, the largest urban areas extend on an EC or a MAPMT scale, while smaller villages appear in groups of 2-4 pixels. This is similar to the

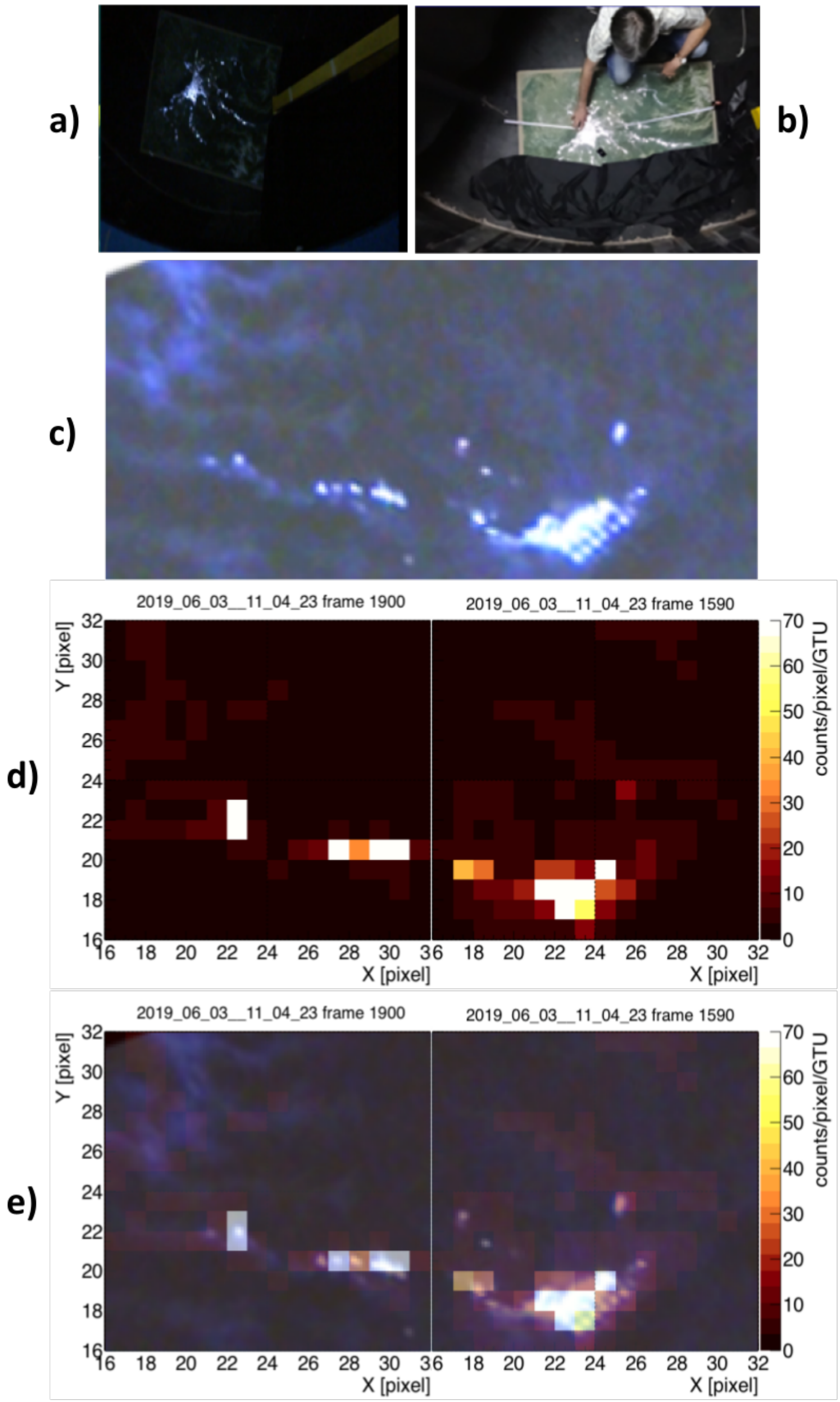

Fig. 9 The a) panel shows the reproduced region of Torino viewed 'by night', when the tank is illuminated for the JEM-EUSO conditions. Panel b) shows the same image without 'by night' conditions. The c) panel shows a zoomed picture of a specific area taken with a camera, while d) panel shows the same area as detected by the JEM-EUSO setup. The superposition of c) and d) is displayed in e).

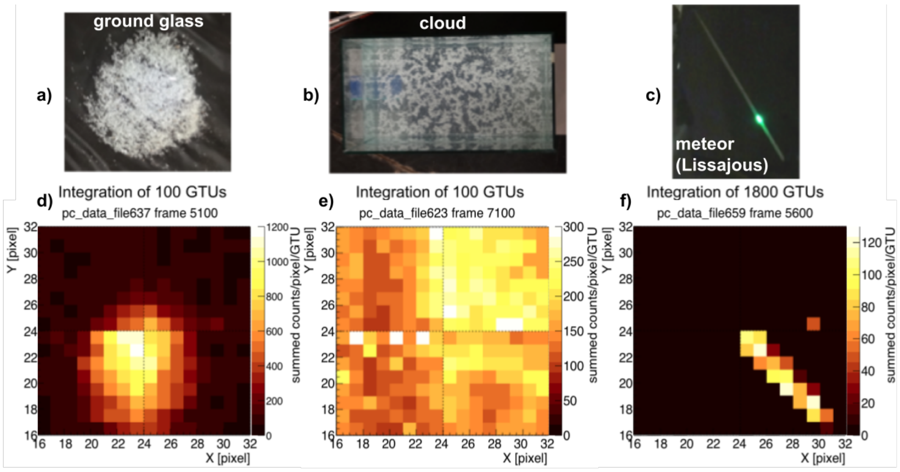

Fig. 10 Top: Examples of UV images obtained by the EC unit (2×2 MAPMTs, phase 2) passing by the various materials during the full tank rotation (∼9 min to be in the range of suitable speeds for Mini-EUSO comparisons, see Tab. 2): a) city light is emulated by a ground glass illuminated by an LED; b) cloud is emulated using particles suspended in water; c) meteor track is reproduced using an analog oscilloscope. Bottom: the three plots in d) - f) show the corresponding images of a) - c) obtained during each event and integrated during the indicated number of D1 GTUs.

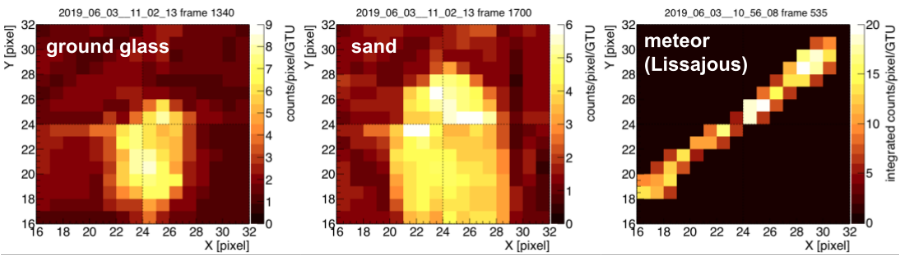

Fig. 11 Similar plots as in Fig. 10 but integrated over 1 D3 GTU which have been acquired during the third phase with the 41 ms time resolution available.

transit of Torino map at TurLab. When Torino city is in the FoV, half EC is illuminated while small villages illuminate only few pixels.

The comparison with Mini-EUSO is, therefore, validated. In case of a much finer pixel FoV, like in JEM-EUSO, the spatial distribution would scale by a factor of 100 in area. Therefore, the EC-scale bright areas would correspond to 100 km^2 areas (like the city light reproduced using glass dust in Fig. 10) and localized bright spots to 1 km^2 areas.

From the point of view of the light intensity, both plots in Fig. 10 and in Fig. 11 show that city lights are order of at least 10 times brighter compared to surroundings. This confirms the good representation of urbanized areas at TurLab. Regarding the the speed at which images flow through the pixel's FoV, by adapting the rotation speed of the tank, it is possible to properly

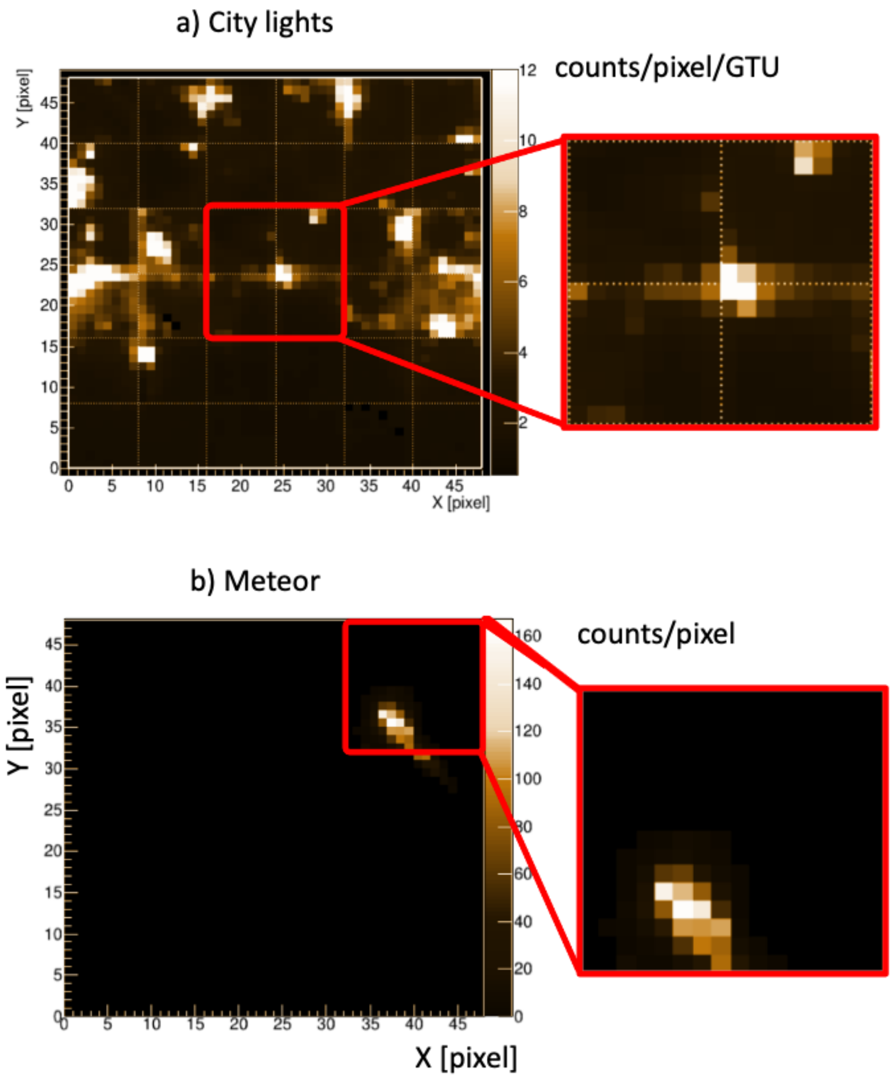

Fig. 12 Images taken by Mini-EUSO (figure adapted from [6]): a) one frame of 320 μs of an urban area on the East coast of India (West Bengal); b) a meteor track integrating over 41 ms time frames; For both plots, a zoom on a single EC scale of 16×16 pixels has been made for a better comparison with EUSO@TurLab images.

reproduce it for different space experiments. In these comparisons the tank was rotated with a ∼9 min period to be in the expected range of speeds which are comparable for Mini-EUSO (see Tab. 2).

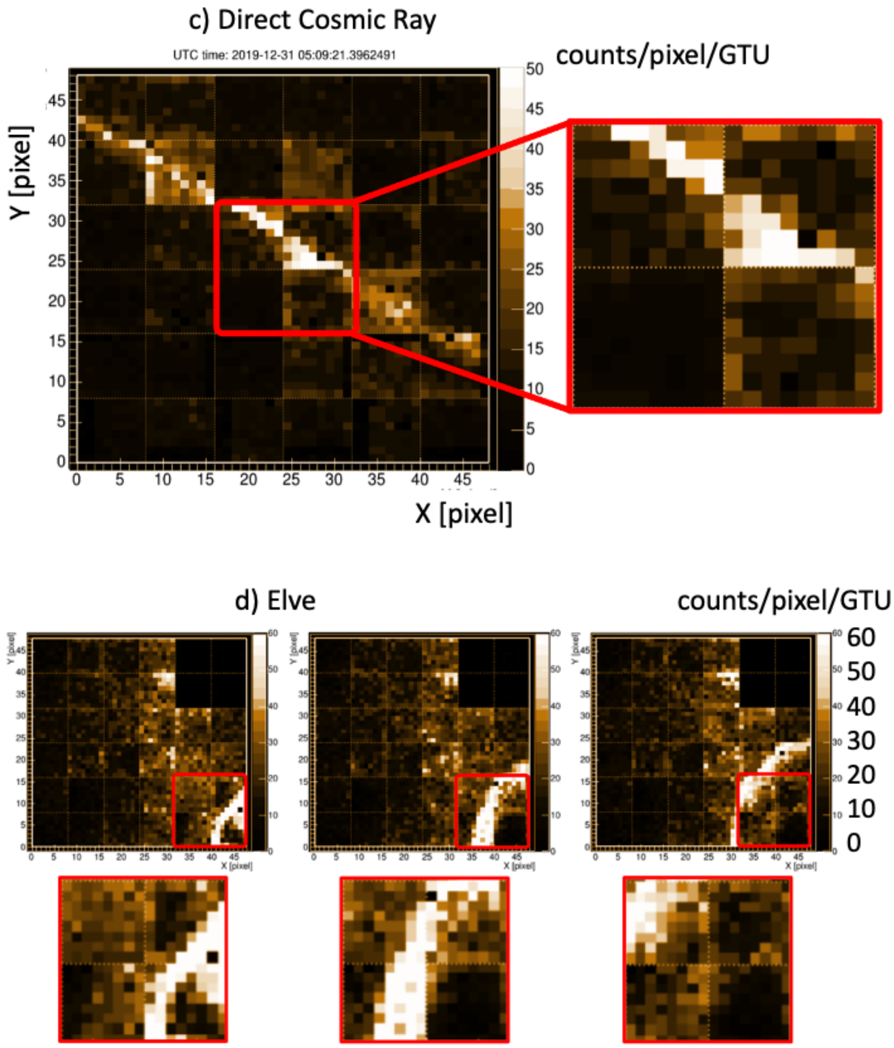

Fig. 13 Images taken by Mini-EUSO (figure adapted from [6]): c) a direct cosmic ray which hit the focal surface of Mini-EUSO almost parallel to it (the cosmic ray crosses the entire FS in one single frame of 2.5 μs); d) time evolution of an elve where the three frames shown here have a duration of 2.5 μs each and are separated by 7.5 μs. For both plots, a zoom on a single EC scale has been made for a better comparison with EUSO@TurLab images.

4.3 Meteors

The first example of track events is shown in Fig. 10 (f) and it is represented by meteors. They last typically hundreds of ms up to a few seconds in case of very bright events. Fig. 12 (b) shows a very bright meteor seen by Mini-EUSO. The signal is ~100 times the nominal background level and it lasts for more than 1 sec (see Ref. [6] for details) and extends on 1 MAPMT. This is similar to what is shown in Fig. 10 in terms of spatial extension and contrast of luminosity but this depends on the magnitude of the meteor. By controlling the light intensity of the analog oscilloscope it is possible to change extension and duration of the signal. As a different example, the meteor shown in Fig. 11 has a much longer spatial extension.

4.4 Flashers and cosmic rays

Another example of track-like events are EAS-like events. At TurLab an Arduino board controlling a line of 10 white LEDs is used to emulate a single EAS propagating through the atmosphere at the speed of light, resulting in a total duration of about 40 GTUs. As can be seen in Fig. 14, this signal no longer stays within one pixel during 10 GTUs, with the center of light moving clearly between subsequent GTUs.

Since Mini-EUSO has an energy threshold above 10^{21} eV, it is very unlikely to detect UHECRs. However, direct cosmic rays can interact in the detector and generate EAS-like events but with a much shorter duration (1 GTU). An example of such a direct cosmic ray is shown in Fig. 13. Similar events could be reproduced at TurLab by extending the LED strip and switch on at the same time all the LEDs. The light intensity of 50 counts/pixel/GTU matches the experimental measurements as shown in the right-bottom plot of Fig. 14, even though here the LEDs are switched on at subsequent times. This is an unexpected class of events that was not foreseen during the setting up of the EUSO@TurLab project but that could be easily reproduced in future tests.

Another example of localized and fast flash comes from the TUS mission and it is shown in Fig. 15. According to [30] the event is measured in perfect observation conditions, with clear atmospheric conditions and no extended anthropogenic light sources in the vicinity, as an ultraviolet track in the nocturnal atmosphere of the Earth. The most plausible interpretation of the event implies its anthropogenic nature, namely a flasher source on ground. However, it is not possible to rule out other origin of the event [30]. As no clear EAS track has been seen from space by the experiments of the JEM-EUSO program, we use this event for comparisons with TurLab measurements of EAS tracks, as this specific event shows some similarities in terms of kinematics and light curve with those expected from an EAS. The energy of the event is reconstructed to be well above 10^{21} eV if EAS simulations are used to assign an equivalent energy. In this case the event appears to have a duration comparable to the TurLab event displayed in the bottom part of Fig. 14 having both a $\sim$100 μs duration. However, the reconstructed energy of the TUS event is extremely high and the LED intensities of the Arduino circuit at TurLab do not match it. The Arduino circuit is currently tuned to emit comparable light intensities with expectations from UHECRs simulations in the 10^{20} eV region for the JEM-EUSO detector. They are also comparable with expectations for Mini-EUSO in case of 10^{22} eV UHECRs (see Fig. 8). Anyway, the

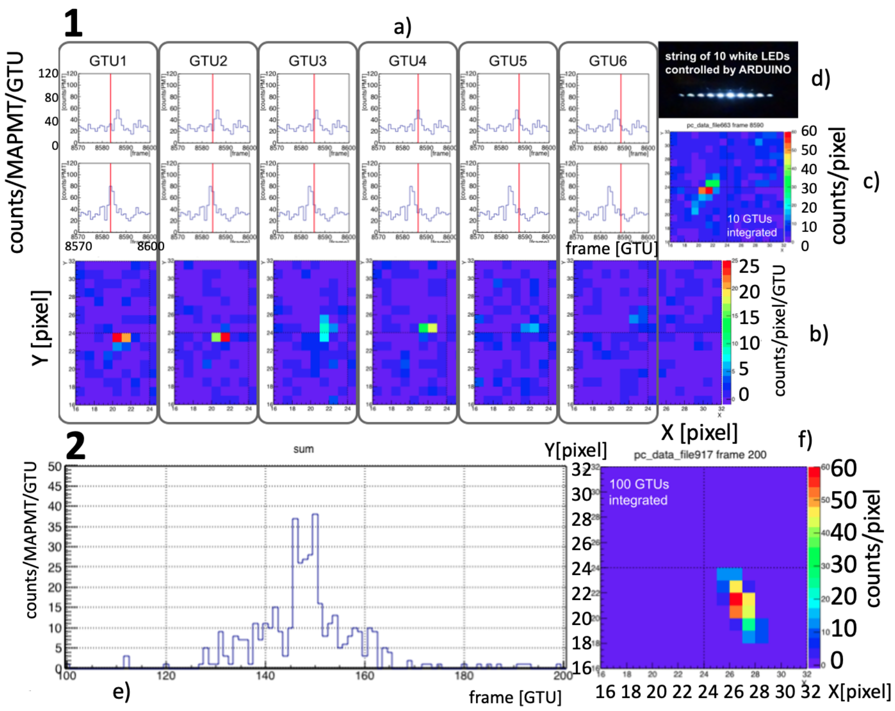

Fig. 14 Reproduction of EAS-like tracks at TurLab in the second phase. Part 1 of the figure shows in 1-a) for 6 GTUs the same light sequence (total counts on 1 MAPMT as a function of 2.5 μs GTUs) obtained by illuminating the FoV of the MAPMT with the Arduino-driven LED sequence shown in 1-d). In these 6 panels the total number of counts on one MAPMT is displayed with a red line indicating the specified GTU. The bottom 6 plots (1-b) show the corresponding images at MAPMT level. The 10 GTU integrated image is displayed in 1-c). The average background level is set at $\sim$0.5 counts/pixel/GTU. Part 2 of the figure shows for another Arduino-driven event the integrated counts during the event in 2-e) and the full light track in 2-f). In this case no background light is present. Figure adapted from [29].

light intensity is a parameter that can be adjusted to suitably reproduce the correct light intensity as expected from space-based observations.

4.5 Lightning and TLEs

Another dominant category of events seen from space is lightnings and TLEs. They represent a wide class of different phenomena on variable time scale and spatial extension ranging from a few kilometers to hundreds of kilometers like in the case of elves. Fig. 16 shows three frames of an elve viewed by TUS. The event is generated outside the FoV and the ring develops within it. The event is short in time and fast in speed (order of the light-speed).

Fig. 17 shows $\sim$240 seconds of the Mini-EUSO data. Examples of lightnings are detected together with city lights and counts from uninhabitated areas. In

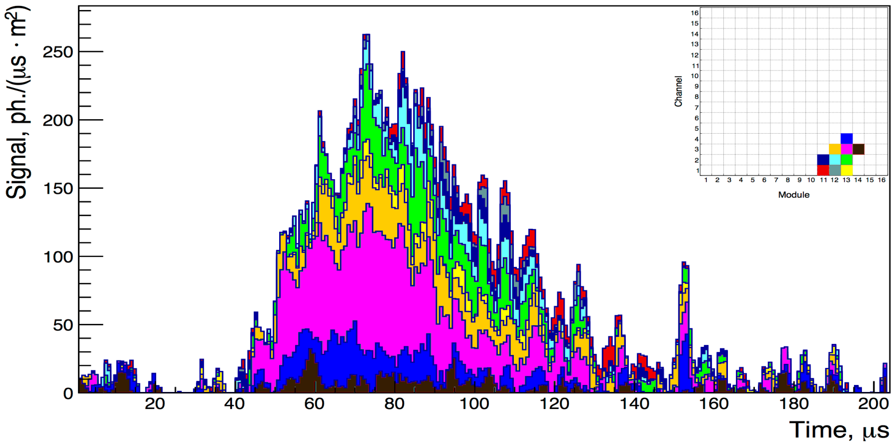

Fig. 15 The light curve of the TUS161003 event as the signal of the ten hit channels stacked together. The insert shows the positions of the hit pixels in the focal surface. Figure adapted from [30].

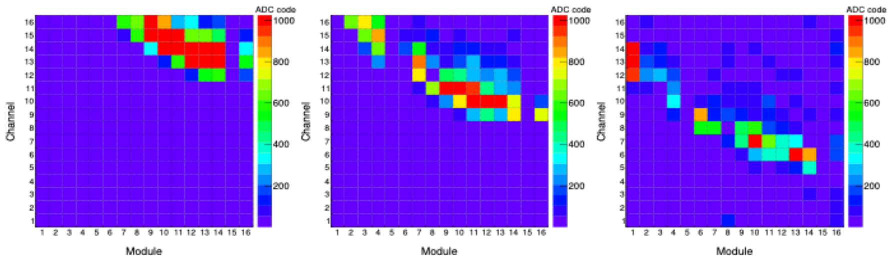

Fig. 16 Snapshots of the focal plane show the arc-like shape and movement of an image of the elve registered on 23 August 2017, through TUS detector's field of view. The snapshots were taken at 136 μs, 168 μs and 200 μs from the beginning of the record. Colors denote the signal amplitude in ADC codes. Figure taken from [5].

general, lightnings appear as spikes lasting tens or hundreds of milliseconds depending on the location of the event and the signal increases by 1 - 2 orders of magnitude. They are seen only in portion of the FoV if happening outside it, or they can affect the entire FoV with different intensities if occurring within the viewing area, partly due to the scattering of the light by the optical system on the entire FS. If the lightnings are too intense the internal protection system is activated (Cathode 2 mode) and MAPMTs work at a reduced efficiency to avoid too large currents that could damage the MAPMTs. In this condition the count rate becomes almost negligible on uninhabitated areas.

At TurLab lightnings are created by pulsing an LED on glass dust which generates an uneven reflection of light (see Fig. 18). A variety of signals is generated by changing the intensity and repetition time of the pulsed LED. The intensity shown here is an order of 100 times the background light level. The duration of the pulses is ∼1 s but it can be controlled. The spatial extension

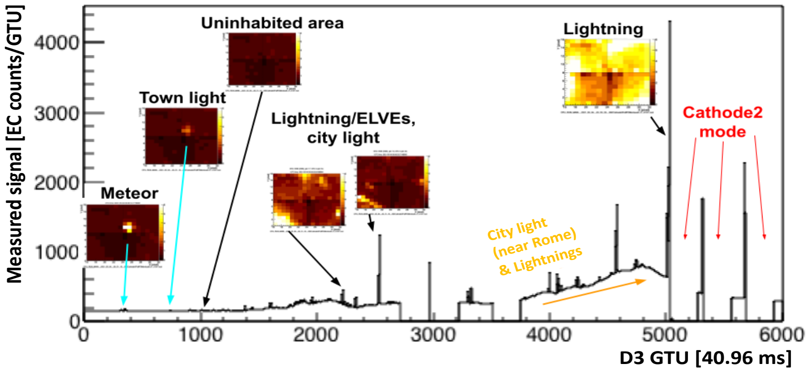

Fig. 17 An example of ∼240 seconds of Mini-EUSO data with signals due to different sources: meteor, town and city lights, uninhabitated areas, lightnings and elves. At the end of the sequence the internal protection system is activated (Cathode 2 mode) and MAPMTs work at a reduced efficiency to avoid too large currents that could damage the MAPMTs. Each inset corresponds to a matrix of one EC (16×16 pixels). Figure adapted from [27].

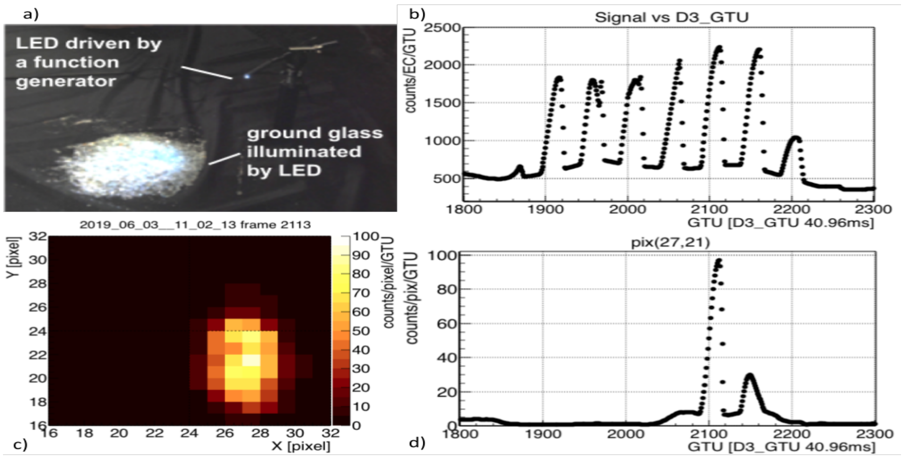

Fig. 18 At TurLab ligthning are generated by illuminating glass dust with a white pulsed LED (a). The panel b) shows a train of the generated pulses during the motion of the tank, while c) displays the size of the event and d) a detail of one light pulse as seen by the pixel with the highest counts.

of the signal seen by the camera is comparable to those of the experimental measurements. It can be noticed that depending on the position of the light source in the FoV, the entire MAPMT, or only a portion is illuminated, like in the Mini-EUSO detections.

At TurLab elves are generated by means of an Arduino circuit that drives LED signals going through wavelength shifter fibers (see Fig. 19). By changing

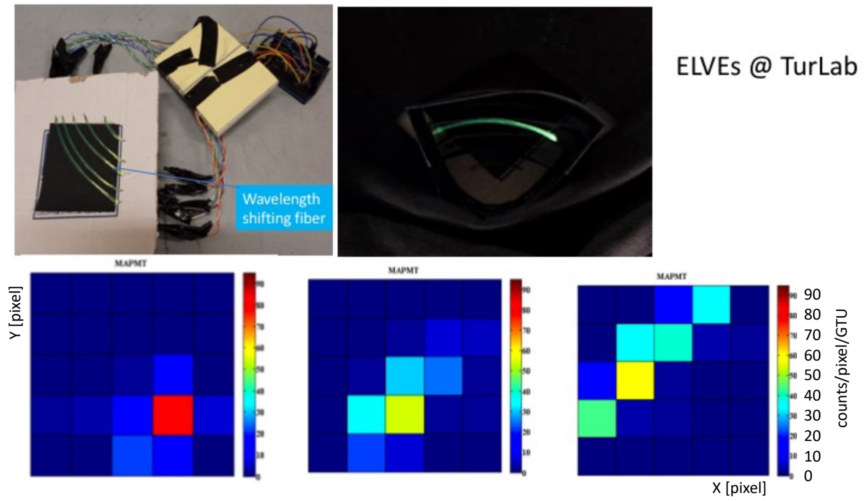

Fig. 19 At TurLab elves are generated by means of an Arduino circuit that drives LED signals going through wavelength shifter fibers. By changing the temporal sequence of the switches, faster or slower events are created. Three frames of a sequence are plotted in the bottom part of the picture.

the temporal sequence of the switches, faster or slower events, the shortest ones being at μs scale, as in case of cosmic ray-like events, are created. The anular shape of the signal is comparable with the TUS and Mini-EUSO detected events. A direct comparison of the detected light intensity with TUS can not be done as the signal is not converted in photon intensity, however, it is in line to what is observed with Mini-EUSO (see Fig. 13). In Fig. 19 the images are taken in the first phase of the project, using a MAPMT with 25 pixels. With finer pixeling the image will look more spread out on the MAPMT.

5 Other applications

TurLab is a laboratory for geo-fluid-dynamics studies. Therefore, experiments related to this field are being conducted at TurLab within the EUSO@TurLab project. The response of the EUSO@TurLab apparatus is studied in presence of waves and/or foam inside the tank. A change in the UV reflection is observed if water contains patches of foam.

As a different branch of tests, a study of the effect of the reflection of light from waves is performed. The tank is filled with 1 m of water and industrial fans are used to generate sea waves. A lamp illuminates the water and the reflected light is retrieved by the MAPMTs above the tank and stored on disk. Inside the tank, water dedicated probes measure the amplitude of waves. A Fourier analysis of the wave amplitude and of the light intensities show that peaks occur at the same frequencies (see Fig. 20). This indicates that the intensity of the light is correlated with the wave amplitude.

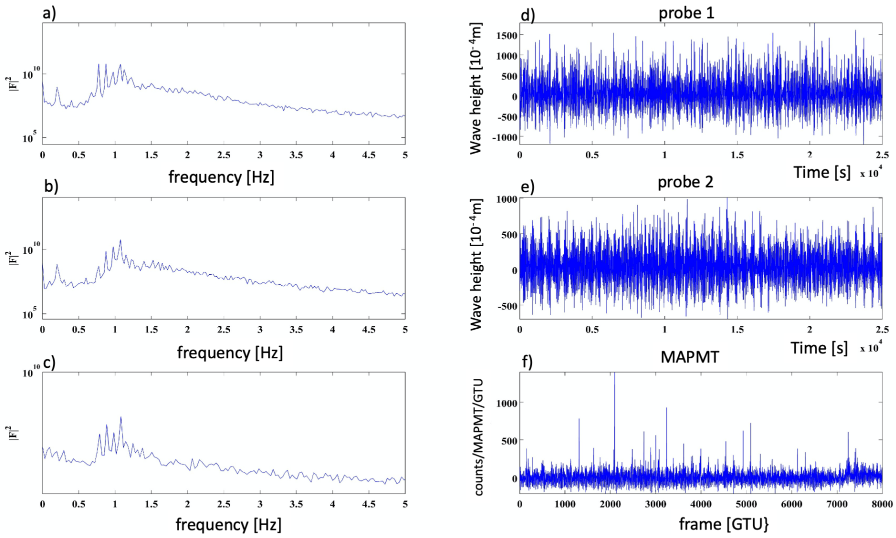

Fig. 20 Right side: the panels d) and e) show the wave heights measured with dedicated probes as a function of time. The panel f) show the MAPMT counts recorded at similar times due to the reflected light of a lamp illuminating the water. Left side: Fourier analysis of the plots on the right side. Both probes (a and b) and MAPMT intensities (c) show peaks at similar frequencies.

The results of the two types of experiments here described might indicate that imaging experiments of the JEM-EUSO program could be sensitive to ocean phenomena. This can be tested by analizing the data collected by Mini-EUSO in space. An example of the importance of such monitoring is related to whitecaps. They are a major source for wave energy dissipation and represent an important mechanism for air-sea exchange of gasses. Bubble bursting produces marine aerosols that contribute to climate regulation and whitecaps are reflector of light radiation responsible for increase of the albedo [31].

As the third miscellaneous application, at TurLab we tested the detection principle of space debris using the concept developed in [32]. It is based on an orbiting debris remediation system comprised of a super-wide field-of-view telescope (like JEM-EUSO) and a novel high-efficiency fiber-based laser system (CAN). The JEM-EUSO telescope detects the reflected light from a centimeter-sized space debris illuminated by moon or sun. The light comes from the back of the telescope, which is viewing the dark sky. After tracking the debris thanks to its albedo for a while, a very powerful laser system would de-orbit it with laser pulses.

To verify this idea, we performed dedicated experiments at TurLab. Fig. 21 shows the setup for reproducing Space Debris (SD) detection principle. The apparatus of Mini-EUSO EM is hung on the ceiling above the TurLab tank, with a “Sun visor” to avoid the direct light from the high power LED which is emulating the Sun light. The aluminum ball under the apparatus of Mini-EUSO EM is attached to the edge of a stand which is fixed to the bottom

Fig. 21 TurLab setup for SD detection by the Mini-EUSO EM. The FS of Mini-EUSO EM apparatus is protected by a "Sun visor" to avoid the direct light from the white LED which is fixed outside of the tank, mimicking the Sun light. An aluminum ball under the apparatus of Mini-EUSO EM is attached to a solid stand which is fixed to the bottom of the tank. As the tank rotates, the aluminum ball moves within the EUSO@TurLab apparatus FoV being illuminated by the LED. Image adapted from [33].

of the tank. As the tank rotates, the ball moves within the FoV of the Mini-EUSO apparatus being illuminated by the LED, while the apparatus remains in the shade of the Sun visor. The results of this test confirmed the observation concept. Moreover, different materials such as polished aluminum foil, canned aluminum, unpolished aluminum foil, mirror, copper foil, white paper, balled aluminum foil, a sample of Kevlar, electronics board (see bottom left Fig. 1), which often compose SD, are placed on the bottom of the tank, within the FoV of the EUSO@TurLab apparatus, in order to measure the relative reflectances of these materials. These results are used to estimate the sensitivity of Mini-EUSO and the other detectors of the JEM-EUSO program in recognizing SD. More details about these experiments and relative results about material reflectances and Mini-EUSO sensitivity to SD are reported in [33].

Finally, dedicated campaigns are performed using the EUSO-Balloon PDM recovered after flight to test the response of the trigger logic to be implemented in EUSO-SPB1 campaign, and using the Mini-EUSO EM as shown in Fig. 21. In case of EUSO-Balloon, the FLT logic is validated. The system that automatically adjusts the thresholds to keep the rate of triggers on background fluctuations below 1 Hz/EC even in case of slow background variations, is effective. The FLT detects EAS-like events with light intensities of $\sim$20 counts/MAPMT/GTU, which are comparable to those JEM-EUSO would observe in the expected energy range ($E > 5\times10^{19}$ eV) and in presence of low nightsky background intensities $\sim$0.2 counts/pixel/GTU. The FLT shows to be quite effective in rejecting city-like and lightning type of events. Only few spurious triggers occur [25].

Regarding the Mini-EUSO EM, aside from the SD test already mentioned, the data acquisition and control software are validated [34]. Tests performed on the FLT logic indicate that the trigger thresholds has to be increased compared to the originally planned ones to satisfy the required trigger rate on non standard background conditions such as in very low background environment or in presence of city lights. Such stricter thresholds are currently employed in Mini-EUSO on the ISS, confirming the importance of the TurLab tests prior to instrument flight [28].

6 Conclusions and perspectives

The EUSO@TurLab project is an ongoing activity with the aim at reproducing in a laboratory environment the luminous conditions that a project of the JEM-EUSO program sees while flying in space. Along the years, the instrumentation at TurLab has evolved to re-create more and more settings. In parallel the electronics setup has improved by acquiring the same front-end electronics employed in the missions of the JEM-EUSO program to emulate as close as possible the real conditions. At the beginning the setup was fine tuned based on simulation results of how different phenomena, such as nightglow background, clouds, EAS-like events, meteor tracks, cities, lightings among others, were expected to be seen from space. Thanks to the Mini-EUSO and TUS missions it is now possible to compare past results with those obtained by real measurements. It is proven that the experiments at TurLab reproduce with a good reliability the phenomena seen from space in terms of spatial extension, duration and light intensities. This is important because it allows in future to test the electronics of the new missions of the JEM-EUSO program prior to flight and to use the TurLab as a facility to emulate flight observations. Moreover, it will be possible to test upgrades of the mission firmware prior to implement them on-board, saving resources and time for tests in space. The trigger logic of the EUSO-SPB1 and Mini-EUSO missions was deeply tested at TurLab. The good performance of the firmware of both instruments in flight is also merit of the variety of conditions that were tested with success at TurLab to emulate several environmental or/and luminous conditions that the telescopes would encounter. Finally, we tested the response of this kind of detectors for space debris observation and for marine and atmospheric science, that will be verified in space. They show the potential of JEM-EUSO sensors in these fields, and at the same time demostrate the versatility of the tests that can be conducted at TurLab.

At present, the EUSO@TurLab apparatus is being upgraded. It will be employed in the tests of the trigger logic under definition for the EUSO-SPB2 mission, and in the tests of a new front-end electronics for SiPM detectors, which is currently under development for the measurement of both fluorescence and Cherenkov light emissions from EAS by space-based detectors (FluChe project [35]).

7 Conflict of Interest

The authors declare that there is no conflict of interest.

8 Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding authors on reasonable request.

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