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Results of the missions within JEM-EUSO program

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Abstract. The JEM-EUSO program includes several missions employing fluorescence detectors to make a proof-of-principle of the UHECR observation from space and to raise the technological level of the instrumentation to be employed in a space mission like K-EUSO and POEMMA. EUSO-TA, installed at the Telescope Array (TA) site in Utah in 2013, has already detected 9 UHECRs in coincidence with TA Fluorescence Detector. EUSO-Balloon flew on board a stratospheric balloon in 2014. It measured the UV intensity on forests, lakes and the city of Timmins as well as proved the observation of UHECR-like events by shooting laser tracks. EUSO-SPB was launched on board a Super Pressure Balloon (SPB) in 2017. It proved the functionality of all the subsystems of the telescope on a long term; observed the UV emission on oceans and had a self-trigger system to detect UHECRs. A more ambitious mission (EUSO-SPB2) is planned. TUS, on board the Lomonosov satellite in orbit since 2016, has detected a few interesting signals in the UHECR trigger-mode. Mini-EUSO is in a final phase of integration and will be installed inside the International Space Station (ISS) in 2019. The main results obtained so far by these experiments are summarized.

1. Introduction

The origin and nature of Ultra-High Energy Cosmic Rays (UHECRs) remain unsolved in contemporary astroparticle physics [1]. To give an answer is rather challenging because of the extremely low flux of a few per km^2 per century at extreme energies such as $E > 5 \times 10^{19}$ eV (EECRs). The objective of the JEM-EUSO program (Joint Experiment Missions for Extreme Universe Space Observatory) is the realization of a space mission devoted to scientific research of EECRs [2]. Its super-wide-field telescope will look down from space onto the night sky to detect UV photons emitted from Extensive Air Showers (EAS) generated by EECRs in the atmosphere.

The JEM-EUSO program includes several missions from ground (EUSO-TA [3]), from stratospheric balloons (EUSO-Balloon [4], EUSO-SPB [5, 6]), and from space (TUS [7], Mini-EUSO [8]) employing fluorescence detectors to make a proof-of-principle of the EECR observation from space and to raise the technological level of the instrumentation to be employed in space missions such as K-EUSO [9] and POEMMA [10] (see Fig. 1). A space project devoted to the study of EECRs such as JEM-EUSO should have enough quality in terms of exposure determination and EAS parameter reconstruction to satisfy the scientific requirements of such an ambitious mission. A review of the key results obtained by each experiment of the JEM-EUSO program in this respect is here described (details can be found in [3] - [17]).

2. EUSO-TA

EUSO-TA is a ground-based telescope, installed at the Telescope Array (TA) site in Black Rock Mesa, Utah, USA. This is the first detector to successfully use a Fresnel lens based optical system

Figure 1. Roadmap and detectors of the JEM-EUSO program. See text for details.

and Multi-Anode Photomultipliers (MAPMT, 64 channels per tube, 2304 channels encompassing a 10.6° × 10.6° field of view - FoV) for detection of UHECRs. The telescope is located in front of one of the fluorescence detectors of the TA experiment (TAFD, see Fig. 1). Since its operation in 2013, the detector has observed several UHECRs and, in addition, meteors. The limiting magnitude of 5.5 on summed frames ($\sim$3 ms) has been established. Measurements of the UV night sky emission in different conditions and moon phases have been performed. These observations serve as a proof of concept for future application of this detector technology for space-based missions.

Fig. 2 shows an example of a UHECR which has been detected by EUSO-TA, using TA external trigger. It can be seen that re-binning of the images significantly increases the visibility of the tracks making EUSO-TA data more similar to those of ground-based UHECR telescopes, which have much larger pixel sizes. However, such a pixel size is not suited for space-based observations, to which EUSO-TA has been tuned. Simulations of the events made with the OffLine package [11] are also presented in Fig. 2. The shower image can be reproduced to very fine detail, taking into account the uncertainties in EAS reconstruction by TAFD and intrinsic modeling of the detector response. With the implementation of the external trigger, data is collected for each TAFD event. Therefore, an event is considered as detected if a linear trace is found in the EUSO-TA data and a corresponding event in TAFD results. To date, 9 UHECR events (see Fig. 2) have been identified in 130 hours of UHECR-dedicated observations. The distances of these events from the detector vary between approximately 1 and 9 km, while the energy is between $10^{17.7}$ - $10^{18.8}$ eV, according to the TAFD reconstruction. In 2016, simulations were performed, using the updated detector parameters and ESAF (EUSO Simulation and Analysis Framework) simulation code [11], resulting in 8 predicted events, consistent with the 9 UHECR observed to date. This result confirms the general understanding of the detector response through simulations. The proximity of the events and the dead time between frames makes 8 events visible in the detector for a duration of a single frame, and one event for two frames. EUSO-TA does not usually observe the EAS maximum, but a late stage of the shower development, and as such the number of registered photons corresponds to an EAS of lower energy than if the instrument was optimally pointed towards the shower maximum. Therefore, to estimate the instruments capabilities it was necessary to calculate the equivalent energies of the events (E_{eq}), corresponding to the reconstructed energy assuming that EUSO-TA observed the events shower maximum. This calculation is based on the parameters measured by TA for each individual shower. The corresponding points can be used to form a conservative estimate of the detectors energy threshold. In a very simplified approach, one can assume that the minimal number of counts on the focal surface for the UHECR to be detected is constant, proportional

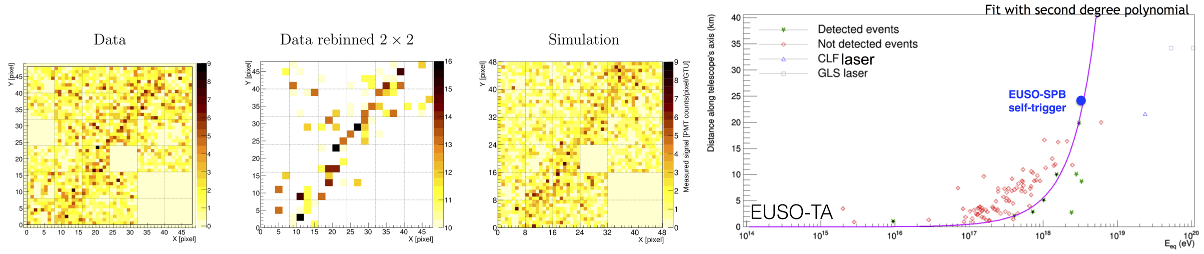

Figure 2. Left: Example of a UHECR observed by EUSO-TA (E ∼10^{18} eV, impact parameter 2.5 km with respect to the telescope, zenith angle of the axis of 35° and azimuth angle of 7°) with different pixel binning and comparison with simulations [11]. Right: All UHECRs detected by TAFD in the EUSO-TA FoV during its operation with non-detected events and laser shots superimposed. The plot shows the equivalent energy of the events as a function of their distance from the detector. The line suggests an estimate of EUSO-TA detection energy threshold while the blue point shows a similar estimate for EUSO-SPB (see text for details).

to its energy and reversely proportional to the square of the distance from the shower axis (R_p). Based on this assumption, $R_p = A \cdot \sqrt(E_{eq})$ is fit to detected events, where A is a free parameter. It can be seen that the strong signals of the TA Central Laser Facility (CLF, EAS equivalent energy of $\sim 10^{19.4}$ eV at a distance of 21 km) and Ground Laser System (GLS, EAS equivalent energy of $\sim 10^{19.7}$ eV and $\sim 10^{20}$ eV at a distance of 33 km) are on the right side of the curve, i.e. in the detectable region, as expected. Moreover, the ground-field tests performed with EUSO-SPB employing an internal trigger logic, indicate that its energy threshold lies on top of the fitting curve supporting the conclusions derived with such method, though EUSO-SPB overall detector efficiency is ∼2 better than EUSO-TA (see details in section 3).

3. EUSO-Balloon & EUSO-SPB

EUSO-Balloon [4] was launched by CNES from the Timmins base in Ontario (Canada) on the moonless night of August 25, 2014. After reaching the floating altitude of ∼38 km, EUSO-Balloon imaged the UV intensity in the wavelength range 290 - 430 nm for more than 5 hours before descending to ground. The refractor telescope consisted of a similar apparatus as EUSO-TA (two Fresnel lenses of ∼1 m^2 size and a Focal Surface -FS- filled with MAPMTs). The spatial and temporal (Gate Time Unit - GTU) resolutions of the detector were 130 m and 2.5 μs, respectively. The full FoV in nadir mode was $\sim 11°$. During 2.5 hours of EUSO-Balloon flight, a helicopter circled under the balloon operating UV flashers and a UV laser to simulate the optical signals from UHECRs, to calibrate the apparatus and to characterise the optical atmospheric conditions. During flight EUSO-Balloon took more than 2.5 million images that have been analysed to infer different information: study of the performance of the detector; response of the detector to the UV flasher and laser events; UV radiance from the Earth atmosphere and ground in different conditions: clear and cloudy atmosphere, forests, lakes, as well as city lights.

The measurement of UV light intensity is relevant for a JEM-EUSO-like mission as it is one of the key parameters to estimate the exposure curve as a function of energy [12]. However, EUSO-Balloon uses a very different approach compared to previous measurements as it is based on an wide-FoV and wide-bandwidth optical refractive system with very fine spatial and temporal resolutions, which requires a careful computation of the optics and detector response to translate the detected counts into an absolute measurement. From the point of view of the capability of a space-based observatory for EECRs, the essential point is the number of counts per GTU at pixel level. Such pedestal should be dark enough to detect a EECR track on top. Fig. 3

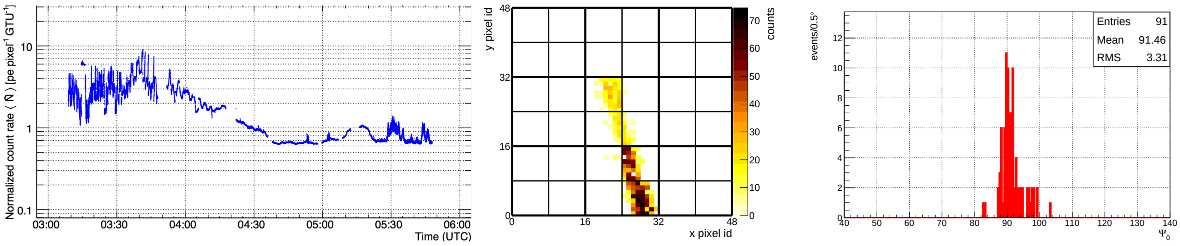

Figure 3. Left: Average normalized count rates $\langle\hat{N}\rangle$ as a function of the packet time [13]. Center: Example of a laser track detected by EUSO-Balloon. Right: Zenith angle reconstruction of the helicopter laser shots of energy 15 mJ with a 2-parameter fit method [14].

shows the average normalized count rates $\langle\hat{N}\rangle$ as a function of the packet time (breaks are due to technological tests foreseen for the flight). The count rate, $\hat{N}_0$, for clear atmosphere conditions is an input parameter to the EAS simulations used to estimate the reference aperture for EECR observations. The corresponding absolute intensity (I_0) is useful for the design of any space-based EECR observatory, independent of the configuration of the instrument. In EUSO-Balloon, only the back-scattered light from the airglow and extraterrestrial light contributes to the measured diffuse light. The reflectivity of the clouds is expected to be higher than clear atmospheric conditions. According to the pilot of the helicopter clear conditions were present between 04:38 and 04:52. Based on the average of the distribution in that time window, the reference $\hat{N}_0$ value is $\sim$0.65, the FWHM of the pixel distribution being $\sim$0.03. Between 04:20 and the end of measurement, when the artificial lights of Timmins and surroundings were out of the FoV, the count rate varies within a factor of $\sim$2. This gives the maximal difference of UV intensity between clear and cloudy sky conditions during flight. Ray trace simulations were then performed using the OffLine code to translate $\hat{N}_0$ in I_0 values. In the area with no artificial light sources, based on the airglow and starlight models, the measured count rate from the diffuse light under clear atmosphere conditions corrsponds to I_0 = 300 - 320 photons m^{-2} sr^{-1} ns^{-1} in the 300 − 500 nm band. This value is consistent with previous measurements and confirms a good understanding of the detector performance also in this respect, which is very important in view of JEM-EUSO.

The helicopter events revealed to be extremely useful to understand the system's performance and to test the capability of EUSO-Balloon to detect and reconstruct EAS-like events. Laser tracks are used to test the reconstruction algorithms [14]. The analysis is based on the geometry of the triggered pixels. The typical time fit of a laser event and the direction reconstruction are shown in Fig. 3 after requiring basic quality cuts: a) a set of events of same energy (15 mJ, equivalent to $\sim 10^{20}$ eV EAS); b) a track lasting at least 4 GTUs. It is important to remember that the read-out period of 2.5 μ is optimised for JEM-EUSO, which is expected to detect EAS at $\sim$400 km distance, instead of $\sim$35 km as in case of EUSO-Balloon. The fact that EAS-like tracks can be reconstructed in EUSO-Balloon is quite promising in view of JEM-EUSO.

EUSO-SPB was launched on April 25th, 2017, from Wanaka New Zealand as a mission of opportunity on a NASA Super Pressure Balloon (SPB) test flight planned to circle the southern hemisphere [5]. The primary scientific goal was to make the first observation of UHECR-EASs by looking down on the atmosphere with an optical fluorescence detector from the near-space altitude of 33 km. After 12 days 4 hours aloft, the flight was terminated prematurely in the Pacific Ocean about 300 km SE of Easter Island due to a leak in the balloon. The telescope was similar to EUSO-Balloon. An autonomous internal trigger was implemented according to [15] to detect UHECRs. About 30 hours of useful data were collected during night time.

In October 2016, the fully assembled EUSO-SPB detector was tested for a week at the EUSO-

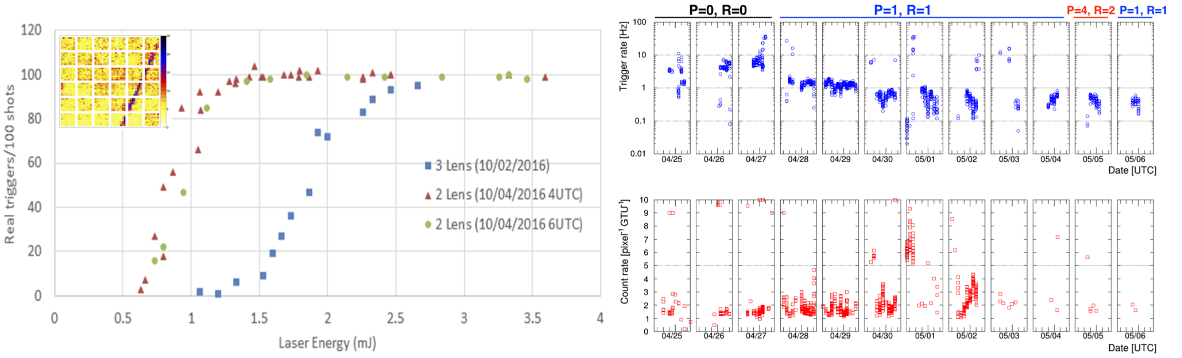

Figure 4. Left: trigger efficiency as a function of GLS energy with 2 and 3 lens systems for vertical shots. An example of GLS track (2 mJ energy) is displayed on the top-left corner. Right: Trigger rate (top) and average count rate measured at pixel level (bottom) in flight. P and R define variations of the trigger logic that were tested on flight.

TA site to measure its response and to calibrate it by means of a portable Ground Laser System (GLS). Observations of CLF, stars, meteors were performed. The left side of Fig. 4 shows an example of a GLS track detected by EUSO-SPB as well as the trigger efficiency curve of the 2 and 3 lens system as a function of GLS energy. With the 2 lens system, which is the one that flew from Wanaka, the $\sim$50% trigger efficiency is reached at laser energies whose luminosity is equivalent to $\sim$45° inclined EAS of E $\sim 3 \times 10^{18}$ eV seen from above by a balloon flying at 33 km altitude. This condition is represented by the blue point displayed in Fig. 2.

Right side of Fig. 4 shows the average pixel count and trigger rates during flight. The pixel count rate will be used to determine the exposure. The different intensity levels are due to changing conditions, such as clear atmosphere, clouds and presence of moon light. The trigger rate was on average compliant with JEM-EUSO requirements. The analysis of the collected data is ongoing. Tracks of cosmic rays directly crossing the detector have been recognized. However, no EAS track has been clearly identified yet. Simulations post-flight indicate that the number of expected events is $\sim$1 in the available data sample, confirming pre-flight assumptions for such a flight duration. Analyses are on still on going.

A more ambitious mission is currently under development, EUSO-SPB2 [6]. It will be equipped with 3 telescopes to observe UHECRs and try to catch ν_τ induced EAS, employing a Schmidt camera optics in view of POEMMA. The flight is expected by 2022.

4. TUS & Mini-EUSO

The Track Ultraviolet Setup (TUS) detector was launched on April 28th, 2016 as a part of the scientific payload of the Lomonosov satellite. TUS [7] is the world's first orbital detector aiming at detecting EECRs. The satellite has a sun-synchronous orbit with an inclination of 97.3°, a period of $\sim$94 min, and at altitude of 470 - 500 km. The telescope consists of two main parts: a modular Fresnel mirror-concentrator with an area of $\sim 2\times2$ m^2 and 256 PMTs arranged in a 16×16 photo-receiver matrix located in the focal plane of the mirror. The pixel's FoV is 10 mrad, which corresponds to a spatial spot of $\sim$5 km × 5 km at sea level from a 500 km orbit altitude. Thus, the full area observed by TUS at any moment is $\sim$80 km × 80 km. TUS is sensitive to the near UV band with a time resolution of 0.8 μs in a full temporal interval of 256 time steps. During its operation TUS has detected about 8×10^4 events that have been subject to an offline analysis to select among them those satisfying basic temporal and spatial criteria of EECRs. A few events passed this first screening. In order to perform a deeper analysis of such candidates, a dedicated version of ESAF as well as a detailed modeling of TUS optics and detector are being

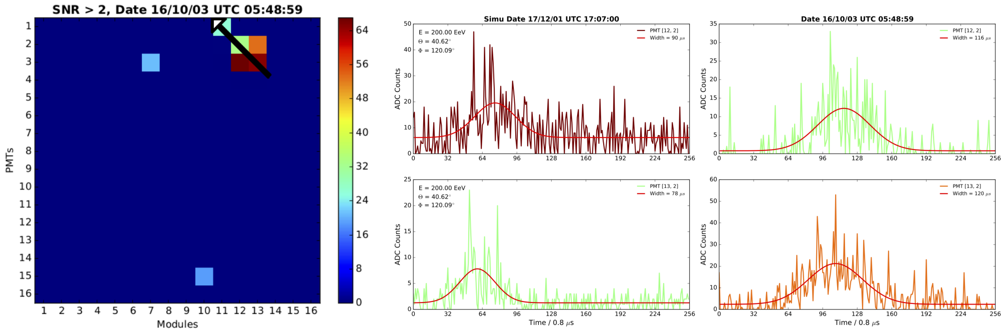

Figure 5. Left: Event 161003 occurring over Minnesota on October 3rd 2016. Right: Comparison between signals from ESAF simulation and those from the 161003 event for corresponding PMTs. Left panels: Signals in PMTs from ESAF simulation (EAS angle from the zenith $\theta = 41°$). Arbitrary units are used as the calibration of the detector response in simulation is still in progress. Right panels: Signals in the same PMTs taken from the candidate event.

developed. Fig. 5 shows an example of event which has passed first EECR selection criteria. A deeper analysis and comparison with simulations is still on going. A detailed study of this event is presented elsewhere [16] which includes also the study of weather conditions and presence of artificial lights. This example shows the importance of TUS measurements to determine analysis strategies in view of K-EUSO.

Mini-EUSO [8] is a UV telescope to be placed in 2019 inside the ISS, looking down on the Earth from a nadir-facing window in the Russian Zvezda module. Mini-EUSO will map the earth in the UV range (290 - 430 nm) with a spatial and temporal resolutions of ~5 km (like TUS) and 2.5 μs, respectively. Mini-EUSO has a FS similar to EUSO-TA. The optical system consists of 2 Fresnel lenses of 25 cm diameter with a large FoV of ~19°. A multi-level trigger [17] will allow the measurement of UV transients at different time scales, complementing TUS observations. Laboratory experiments with Mini-EUSO engineering model and simulations confirm the sensitivity of Mini-EUSO to EECR-like transients around 10^{21} eV.

4.1. Acknowledgments

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