

Observation of ELVES with Mini-EUSO telescope on board the International Space Station

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Mini-EUSO is a detector observing the Earth in the ultraviolet band from the International Space Station through a nadir-facing window, transparent to the UV radiation, in the Russian Zvezda module. Mini-EUSO main detector consists in an optical system with two Fresnel lenses and a focal surface composed of an array of 36 Hamamatsu Multi-Anode Photo-Multiplier tubes, for a total of 2304 pixels, with single photon counting sensitivity. The telescope also contains two ancillary cameras, in the near infrared and visible ranges, to complement measurements in these bandwidths. The instrument has a field of view of 44° , a spatial resolution of about 6.3 km on the Earth surface and of about 4.7 km on the ionosphere.

The telescope detects UV emissions of cosmic, atmospheric and terrestrial origin on different time scales, from a few μs upwards. On the fastest timescale of $2.5 \mu\text{s}$, Mini-EUSO is able to observe atmospheric phenomena as Transient Luminous Events and in particular the ELVES, which take place when an electromagnetic wave generated by intra-cloud lightning interacts with the ionosphere, ionizing it and producing apparently superluminal expanding rings of several 100 km and lasting $\approx 100 \mu\text{s}$. These highly energetic fast events have been observed to be produced in conjunction also with Terrestrial Gamma-Ray Flashes and therefore a detailed study of their characteristics (speed, radius, energy ...) is of crucial importance for the understanding of these phenomena.

In this paper we present the observational capabilities of ELVE detection by Mini-EUSO and specifically the reconstruction and study of ELVE characteristics.

1. Introduction

Mini-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory) [1], also known as 'UV atmosphere' in the Russian Space Program, is a 2304 pixel telescope operating in the UV range ($290 \div 430$ nm) and with a field of view of $\approx 44^\circ$. It was installed on the International Space Station (ISS) in 2019, with observations taking place from the Earth (nadir)-facing UV transparent window in the Zvezda module (Figure 1).



Figure 1: Mini-EUSO installed inside the ISS on the UV transparent window of the Zvezda module.

The optical system consists of two Fresnel lenses with a diameter of 25 cm. The focal surface, or Photon Detector Module (PDM), is composed of 36 MultiAnode Photomultipliers (MAPMTs) tubes by Hamamatsu, 64 pixels each, capable of single photon detection. Readout is handled by a SPACIROC-3 ASICs with a sampling speed of $2.5 \mu\text{s}$ (1 Gate Time Unit, GTU). Data are then processed by a Zynq based FPGA board [2] which implements a multi-level triggering [3], allowing the measurement of triggered UV transients for 128 frames at time scales of both $2.5 \mu\text{s}$ and $320 \mu\text{s}$. A continuous acquisition mode with 40.96 ms frames is also performed. In addition to the main detector, Mini-EUSO contains two ancillary cameras in visible ($400 \div 780$ nm) and near infrared ($1500 \div 1600$ nm) ranges to complement the UV measurements and some single pixel UV sensors used to manage the day/night transition [4]. The telescope has a power consumption of 60 W, a weight of 35 kg and its dimensions are $37 \times 37 \times 62 \text{ cm}^3$. The detector was integrated in the uncrewed Soyuz capsule and launched on 2019/08/22, with periodic acquisition sessions taking place since October 2019 [5].

The main scientific objectives of the mission are the search for nuclearites and Strange Quark Matter [6], the study of atmospheric phenomena such as Transient Luminous Events, meteors and meteoroids, the observation of natural (such as clouds or marine bioluminescence) and artificial (such as city lights) nighttime terrestrial UV emissions [7, 8] and of artificial satellites and man-made space debris. It is also capable of observing Extensive Air Showers generated by Ultra-High Energy Cosmic Rays with an energy above 10^{21} eV and detecting artificial showers generated with lasers from the ground [9].

2. Observations of ELVES

For its high sampling speed ($2.5 \mu\text{s}$) and spatial resolution (≈ 4.7 km at the ionosphere altitude (90 km)), Mini-EUSO is well suited to observe Transient Luminous Events (TLEs), upper

atmospheric optical phenomena of electromagnetic nature, connected with thunderstorms. In this work we discuss the observation of ELVEs (Emission of Light and Very low frequency perturbations due to Electromagnetic pulse Sources). ELVES were predicted [10] before observation [11, 12], and last about a few hundred μs .

Up to now 17 ELVES have been observed with Mini-EUSO in the first year of data, mostly in the low latitude regions (Figure 2), including three double-ringed ELVEs and one three-ringed ELVE.

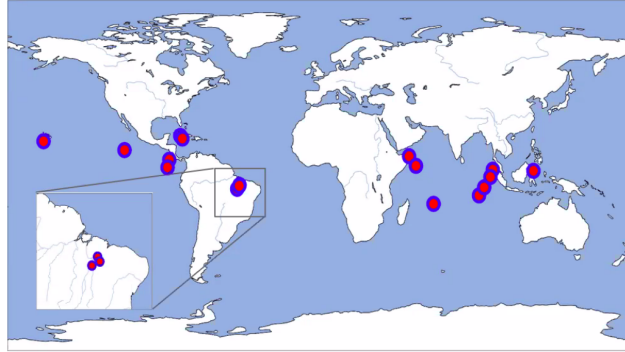


Figure 2: Map of the 17 ELVES detected with Mini-EUSO. ELVES are distributed mainly along the equatorial region.

Mini-EUSO observes ELVES in the 2.5 μs time scale as large ring-like upper atmospheric emissions that appear to be expanding at superluminal speed and last $\approx 100 \mu s$.

In Figure 3 are shown the pictures of a typical ELVE entering the field of view of Mini-EUSO as observed (on 2020/05/26) by the Focal Surface (FS). The ELVE is observed for ≈ 140 GTUs, corresponding to $\approx 320 \mu s$. This event is peculiar because the lightning causing it (and thus the ELVE centre) is in the field of view (f.o.v) of the instrument (for all other events observed the centre of the event is outside the f.o.v.) In this image sequence, the left column of three EC units (12 PMTs) is temporarily working at a reduced voltage (about 1/1000 sensitivity) due to a previous bright lightning activity that triggered the safety mechanism and caused the gain of these photomultipliers to be reduced. This allows to see the lightning in the centre left of the focal surface, which generates the ELVE ring expanding toward the centre and the right part of the FS.

Determination of ELVE centre. To determine the coordinates of the centre of the ELVES, an iterative algorithm has been developed to fit ELVES' rings with circles. Given a single time frame, the algorithm stores the positions of the detector's pixels where an above-threshold signal was detected, recognizes if there is a circle arc to fit and gets the best fit parameters. The circle fitting problem is about detecting circles in images and computing their mathematical representation. As known, a circle of radius R and centre coordinates (a, b) is described by the equation $(x - a)^2 + (y - b)^2 = R^2$. The goal of circle fitting algorithms is to calculate the parameters (a, b, R) of the circle that best fits the image's data points (x_i, y_i) , supposed to lie on a circle arc. Fitting curves is a notoriously difficult problem, and many efforts have been spent to develop a robust algorithm, which tolerates noisy images and gets the best fit parameters even for smaller (incomplete) arc data. Many algorithms have been developed for the fitting circle problem in the past. An algorithm, which is not sensitive to outliers and to data noise, and that allows to identify outliers and remove them,

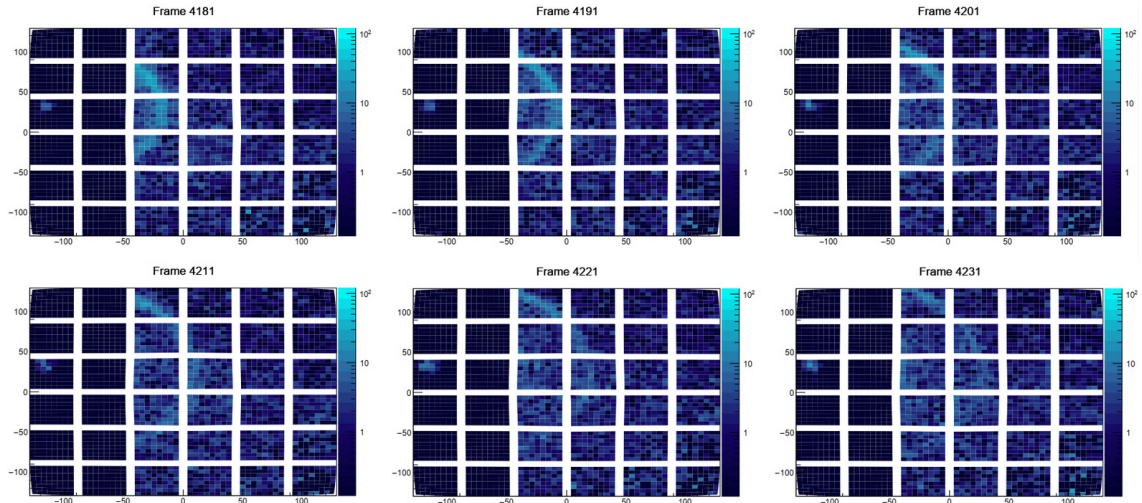


Figure 3: A sample of frames of an ELVE being observed in the focal surface of Mini-EUSO. Pictures are 10 frames apart, corresponding to $5 \mu\text{s}$ ($2.5 \mu\text{s} \times 10$). Note the dead area between different PMTs; some of the light between pixels is captured by the Winston cone (inverted pyramid) at the border of PMTs.

is the one proposed by Ladrón de Guevara [13]. The developed algorithm exploits the advantages of the circle fitting method proposed in [13], and fits the data points by minimizing the sum of the geometric distances to the data points:

$$F(a, b, R) = \sum_i \left[\sqrt{((x_i - a)^2 + (y_i - b)^2) - R^2} \right] \quad (1)$$

The minimization of such function is performed by applying a steepest descent algorithm, which tries step by step to correct the prediction for the circle that best fits the starting data points, by moving the circle centre of an amount that depends on the position of the data points with respect to the predicted circle. The algorithm has been improved by introducing weight factors, so that each data point contributes to the displacement of the circle centre by an amount that depends not only on its position with respect to the circle, but also on the number of photo-electrons detected by that pixel. The optimal circle computed by the algorithm on one of the time frames of the ELVE event proposed above is depicted in Figure 4. The Mini-EUSO pixels whose coordinates were used to fit the circle are marked with black dots. The circle has its centre in $(-88, 27)$ km and radius equal to 71 km. Notice how the algorithm is able to find the circle that best fits the points even if there are some outliers in the bottom right corner of the image. Moreover, the circle passes through the pixels where a greater amount of photo-electrons was detected, as those pixels contribute most to the iterative computation of the best fit parameters.

Determination of arc parameters, radius and energy. In Figure 5 is shown the plot of the number of counts detected as a function of the radial distance R (on the Y axis) at time t (the X axis). The ELVE can be seen as the high-count line, growing as function of time (the horizontal band with $R < 80$ km has fewer counts due to the aforementioned lower gain). Fitting the count profile at each frame time with a Gaussian function we can determine the position of the radius of the ring and its thickness. As an example, we show in Figure 6 the projection on Y axis for the frame 4236 and the

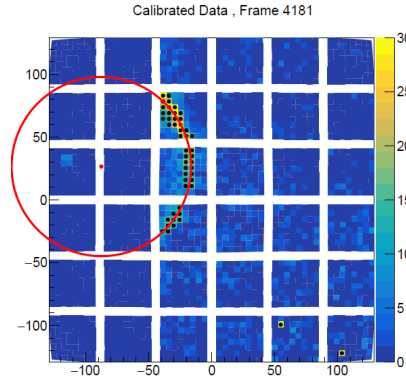


Figure 4: Circle that best fits the data of one frame of an ELVE being observed by the focal surface of Mini-EUSO. The circle has its centre in $(-88, 27)$ km and radius equal to 71 km.

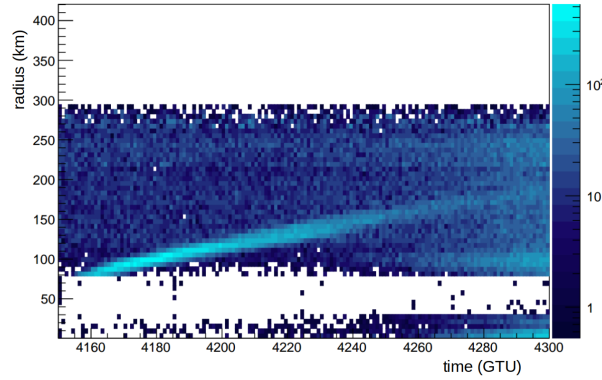


Figure 5: Counts (Z-axis) as a function of radial distance R from the ELVE centre (Y-axis) and time (GTU, X-axis) for the ELVE measured with Mini-EUSO.

corresponding Gaussian fit. Note the very high signal/noise ratio for this event that allows to clearly identify the peak of the circle. The Radius-time expansion profile of the event, $R(t)$, is shown in Figure 7. The simple geometry of a spherical expanding electromagnetic wave interacting with the plane geometry of the ionosphere result in the following equation:

$$R(t) = \sqrt{c^2 t^2 - (h - h_0)^2} \quad (2)$$

where $R(t)$ is the radius of the ELVE as function of time; c is the speed of light; h is the altitude of the ionosphere, h_0 is the altitude of the lightning /intra-cloud discharge that causes the event.

The velocity of apparent propagation of the ELVE is consequently given by:

$$V(t) = \frac{dR}{dt} = \frac{c^2 t}{\sqrt{c^2 t^2 - (h - h_0)^2}} = \frac{c^2 t}{R(t)} \quad (3)$$

tending asymptotically to c when $ct \gg (h - h_0)$.

In Figure 7 is also shown the linear fit of the asymptotic velocity of propagation; for the ELVE considered case we get: $v = 301,000 \pm 2,000$ km/s, consistent with c .

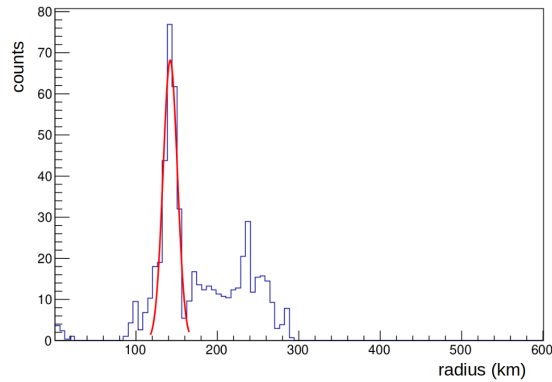


Figure 6: Fitting of the total energy detected in the PDM in a single GTU (frame 4263) as function of the distance from the centre. X-axis: radial distance from the ELVE centre in km; Y-axis: number of counts at a given distance. The Gaussian fit is used to determine the radius-time relationship for subsequent analysis.

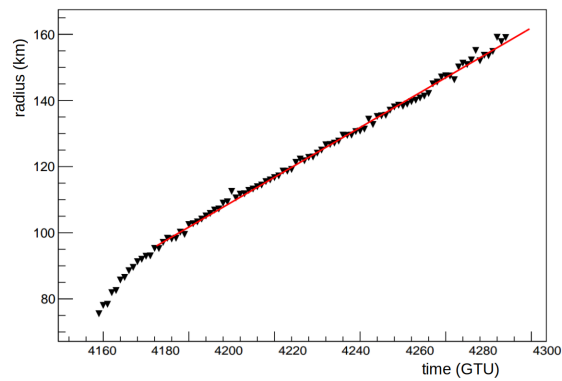


Figure 7: Radius of the ELVE as a function of time. The linear fit gives the asymptotic speed of light; for the ELVE considered case we get: $v = 301,000 \pm 2,000$ km/s, consistent with c

3. Conclusions

In this work we have presented the observation capabilities of ELVES by Mini-EUSO detector. Initial analysis of the data received in the first year of operations confirms the correct functioning of the instrument and the high precision measurements of this class of TLEs can contribute to shed light on the various phenomena involved. Furthermore, in the near future it will be possible to make joint observations with other detectors on board the ISS such as Altea-Lidal [14] and ASIM [15].

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