PROCEEDINGS OF SCIENCE

The Mini-EUSO multi-level trigger algorithm and its performance

F. Capel*
KTH Royal Institute of Technology, Stockholm - Sweden
E-mail: capel@kth.se

A. Belov
M.V. Lomonosov Moscow State University, Moscow - Russia

M. Bertaina, F. Fausti, H. Miyamoto
Department of Physics, University of Torino & INFN Torino - Italy

for the JEM-EUSO Collaboration

The Mini-EUSO telescope is designed by the JEM-EUSO Collaboration to observe the UV emission of the Earth from the vantage point of the International Space Station in low Earth orbit. The main goal of the mission is to map the Earth in the UV, thus increasing the technological readiness level of future EUSO experiments and to lay the groundwork for the detection of Extreme Energy Cosmic Rays (EECRs) from space. Due to its high time resolution of 2.5 μs, Mini-EUSO is capable of detecting a wide range of UV phenomena in the Earth's atmosphere. In order to maximise the scientific return of the mission, it is necessary to implement a multi-level trigger logic for data selection on various different timescales. This logic is key to the success of the mission and thus must be thoroughly tested and integrated into the data processing system prior to launch. This article introduces the motivation behind the trigger design and details the testing of the logic through simulations and data taken at the TurLab facility.

35th International Cosmic Ray Conference ICRC 2017-
10-20 July, 2017
Bexco, Busan, Korea

*Speaker.

PoS(ICRC2017)453

1. Introduction

The Mini-EUSO instrument is designed for the measurement and mapping of the UV (300 - 400 nm) night-time emissions from the Earth and is being developed by the JEM-EUSO Collaboration as a pathfinder for the detection of EECRs from space. Future EUSO experiments [1, 2] aim to measure the fluorescence and Cherenkov light produced by EECR induced air showers. Mini-EUSO is currently approved by Roscosmos under the name "UV atmosphere" and al so by the Italian space agency (ASI). It is set to be launched to the Zvezda module on the ISS from where it will look down onto the Earth through a nadir-facing, UV-transparent window. Mini-EUSO is made up of three sub-systems: the Fresnel-based optical system, the Photo Detector Module (PDM) and the readout electronics. There are also two ancillary cameras installed at the level of the front lens that provide complementary information in the visible and near infra-red range. The lenses focus the light onto the focal surface of the PDM, where it is detected by 36 multi-anode photomultiplier tubes (MAPMTs), each with 64 pixels, resulting in a readout of 2304 pixels. Signals are pre-amplified and digitised by the SPACIROC3 ASIC [3] for each time window of 2.5 μs, which is hereafter referred to as one gate time unit (GTU). This data is then passed to the data processing unit for triggering and storage.

With its high temporal and spatial resolution of 2.5 μs and $\sim$ 5 km respectively, Mini-EUSO is capable of mapping the UV emissions of the night side of Earth in unprecedented detail. Such observations are key to the understanding of the detection threshold for EECRs from space, in addition to estimating the duty cycle of future experiments. Furthermore, the instrument is capable of observing a variety of both atmospheric and terrestrial phenomena, such as transient luminous events (TLEs), meteors, space debris, bioluminescence and city lights. The timescale of these events depends on their nature and varies over 6 orders of magnitude, thus a multi-level trigger system is required to maximise the output of the mission. A detailed description of the Mini-EUSO instrument and its scientific goals can be found in [4].

2. The trigger algorithm

The Mini-EUSO trigger logic is implemented in VHDL inside the programmable logic of the Zynq board and has two levels, level 1 (L1) and level 2 (L2), addressing different time scales. As such they are tailored to different atmospheric phenomena and serve complementary scientific objectives. The motivation behind this is to capture events of interest on short timescales, but also to provide continuous mapping over long periods as Mini-EUSO orbits the Earth. In order to achieve this, 3 different types of data are stored, each with different time resolution.

The L1 trigger receives data with a time resolution of 2.5 μs and looks for signal above background on a timescale of 8 GTU = 20 μs, the timescale of EECR-like events. These events last for several GTU and leave track-like signals which move across several PMTs of the focal surface, depending on the inclination of the shower or laser signal. Each pixel is considered as independent, motivated by the fact that its field of view at ground is 6.11 km, so the time taken for a stationary ground-based light to cross one pixel is at least $\sim$ 20 μs. Each pixel holds 1 byte in a 128-long ring buffer which is overwritten as new data comes in. Pixel signal is integrated over 8 consecutive GTUs in a moving window and compared with the background level, determined over 128 GTU in consecutive blocks, to look for an excess. If the signal is 8σ above background, a trigger is issued, the whole focal surface is read out and a packet of 128 GTU is stored, centred on the trigger. In addition to this, the data integrated over 128 GTU (320 μs) in order to set the background level is then passed to the L2 trigger.

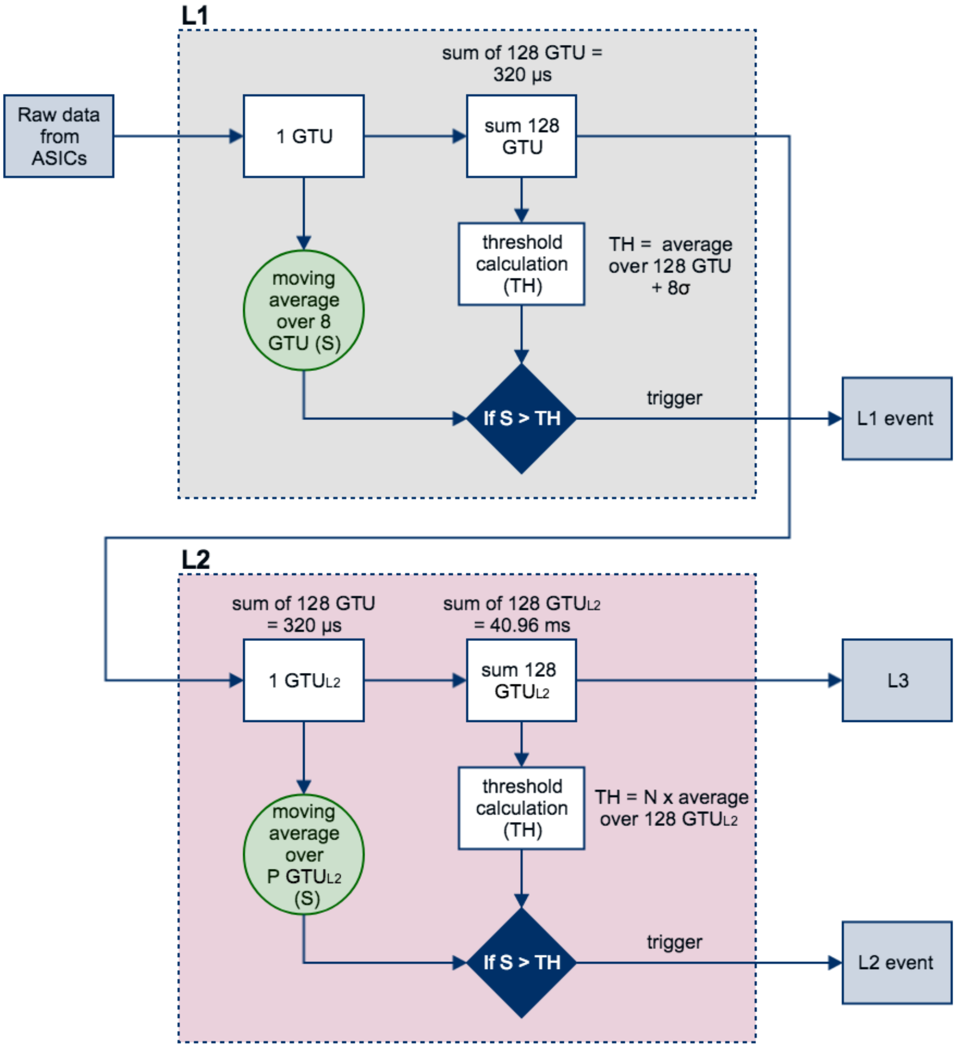

Figure 1: A block diagram summarising the trigger logic. Trigger levels L1 and L2 flag events on timescales of 2.5 μs and 320 μs whilst also preparing 40.96 ms data for the L3. Key parameters such as the threshold (N) and the duration of signal integration (P) can be altered in-flight to optimise the trigger performance. Following software optimisation, N = 4 and P = 8.

The L2 trigger receives the integration of 128 GTU (=1 L2 GTU, or GTU_{L2}) as input from the L1. It operates with a similar logic, but with a time resolution of 320 μs, well-suited to capturing fast atmospheric events, such as TLEs and lightning, which have timescales from ~ 10 μs to ~ 1 ms [5]. The term TLE is used to describe many different upper-atmospheric flashes which are generally classified into 3 groups: blue jets, sprites and elves. Blue jets and sprites are localised column-like events which cover only one or a few pixels of the focal surface when viewed from above.

In contrast, elves are large halo-like flashes which can extend over $\sim$ 300 km laterally causing brightening of the whole PDM. Background is set by integrating 128 GTU_{L2}, and this is also stored as the level 3 (L3) data, or 1 GTU_{L3}. An L2 trigger occurs when the signal in 8 GTU_{L2} is N times greater than the background level, and the event is stored. The background is determined as a sum of the pixel counts over 128 GTUs, which is then rescaled on 8 GTUs as shown in Figure 1.

After the accumulation of 128 GTU_{L3}, or every 5.24 s, all stored events from L1, L2 and L3 data are transferred to the CPU for formatting and storage on the disk, with a maximum of 4 events for L1 and L2. If no or less than 4 L1 or L2 triggers are received in this time, instead the last 128 GTU or 128 GTU_{L2} present on the memory are read out. In this way, a continuous and record is kept with an integration time of 40.96 ms whilst also capturing interesting events at faster timescales. This 40.96 ms "movie" will be used to search for meteors, space debris and strange quark matter using offline trigger algorithms, as well as for the mapping of the Earth in UV. The L1 and L2 trigger algorithms are summarised in Figure 1. Assuming that 3 bytes/pixel are recorded and a duty cycle of 25%, the presented trigger algorithm gives a data readout of 2 MB/s. This results in a data storage requirement of 1.3 TB/month, neglecting some ancillary data from the camera and housekeeping systems. In total, it is reasonable to expect the data output to be less than 2 TB/month. This is compatible with the storage capability of the Mini-EUSO solid-state drives which will be returned to ground at regular intervals.

3. Implementation and tests

The trigger algorithm has been implemented on the Zynq board, which forms the core of the readout electronics. This board interfaces with the front-end SPACIROC3 ASICs through a cross board, which provides pixel mapping and data multiplexing. The Zynq board is based on a Zynq XC7Z030 system of programmable logic (Xilinx Kintex7 FPGA), with an embedded dual-core ARM9 CPU processing system. This board does the majority of the data handling including data buffering, ASIC configuration, triggering, synchronisation, and interfacing with a CPU for data storage. Prior to its implementation in hardware, the trigger logic was tested extensively using both simulations and data taken at the TurLab facility.

3.1 L1 trigger tests at Turlab

The EUSO@TurLab project is to mimic atmospheric and luminous phenomena that EUSO style telescopes will observe from Earth orbit [6]. TurLab is a laboratory equipped with a 5 m diameter rotating tank which is 15 m below ground level. Without artificial light, the room is orders of magnitude darker than the night sky. The EUSO@TurLab project makes use of the TurLab rotating tank with a variety of different light sources to mimic relevant UV signatures.

The Mini-EUSO detector is represented by one elementary cell (EC) unit of 4 MAPMTs with a focusing lens (focal length of 50 cm) and the necessary readout electronics. The detector is suspended from the ceiling and looks down on the rotating tank to mimic the observation from orbit. The capability of controlling the tank rotation speed (3 s - 20 min per turn) allows for the reproduction of events of different duration and spatial extent, as seen from ISS, with the same configuration. A variety of different light sources were used in order to recreate relevant events and also reflected ambient light. A more detailed discussion of the setup is reported in [6].

Figure 2 shows the performance of the trigger logic when tested offline on the acquired data. Despite the presence of several light sources of different intensity, duration and extension, most of the triggers occur in coincidence of TurLab's Arduino EECR-like signal transit in the field of view of the telescope for all four PMTs. When scaled one full PDM, the rate of false triggers is ~ 0.2 Hz which is compatible with the data budget requirements.

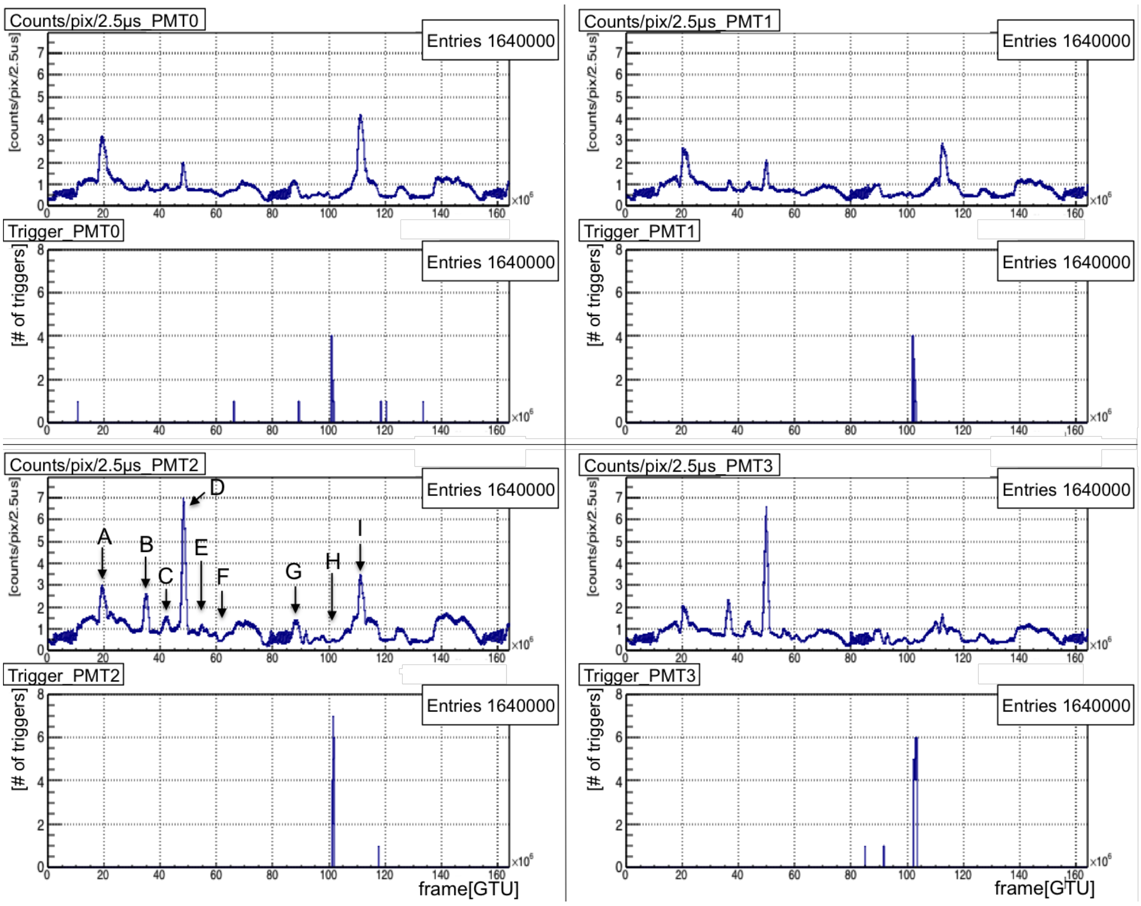

Figure 2: The figure is divided into 4 different blocks. In each block the top plot shows the average number of counts per pixel, normalised to the PMT level and the level in 100 GTU, as a function of time for one PMT. The bottom plot indicates the time of L1 trigger activation, with the y-axis showing the number of triggers. The different letters (from A to I) in the plot of PMT 2 indicate different types of light surface or reflective source present in the tank, which are responsible for a different light intensity seen by the PMTs. In particular, H represents an EECR-like Arduino event which appears small as it covers only a few pixels.

3.2 Trigger tests with simulations

The EUSO Simulation and Analysis Framework (ESAF) [7] is currently used as the simulation and analysis software for the JEM-EUSO and its pathfinder missions. ESAF performs the simulation of the shower development, photon production and transport in the atmosphere, and detector simulations for optics and electronics. In addition to EECR simulation, ESAF also allows the simulation of longer duration phenomena such as TLEs, meteors, space debris and cities, allowing to test the different levels of the trigger logic.

Figure 3 shows the resulting trigger efficiency and corresponding geometrical aperture for the detection of EECRs simulated with a background level of 1 count/pixel/GTU, corresponding to ideal night-time conditions [8]. This shows that the threshold energy of this trigger on Mini-EUSO is $E_{th} \sim 1 \times 10^{21}$ eV. Despite this value being too high for EECR detection, Mini-EUSO will make use of ground-based laser systems to demonstrate the in-flight functionality of the trigger logic and will provide an absolute limit on the EECR flux above such energies for a null detection.

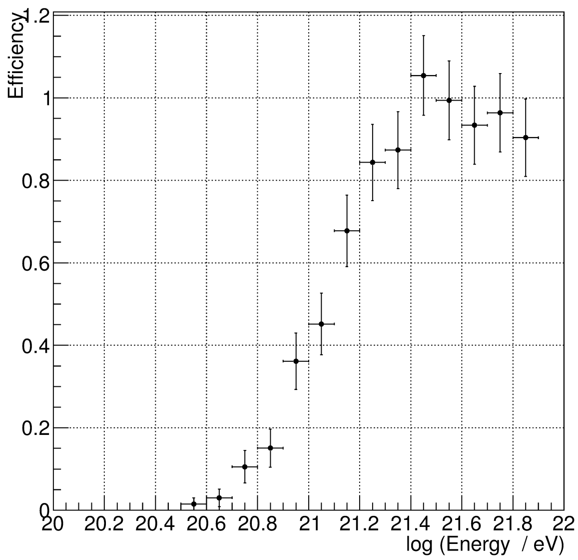

Figure 3: The detection efficiency is shown as a function of the air shower energy, E, in eV. A UV background level of 1 count/pixel/GTU was assumed for this figure.

The L2 trigger algorithm was verified and optimised using simulated TLE events (namely blue jets, elves and sprites), again assuming a background level of 1 count/pixel/GTU. Two key parameters, the threshold level (N) and the integration window of the trigger for signal comparison (P) were varied to investigate their effect on the trigger efficiency. The trigger performs well for N = 4 and P = 8× 320 μs frames. Figure 4 shows the trigger response to 5 different simulated TLEs. It should be noted that a longer signal integration window increases the sensitivity of the algorithm to the more diffuse elves, but at the expense of the detection of the more localised blue jets and sprites. The final implementation of the L2 trigger will allow for these parameters to be adjustable in-flight. The testing of the trigger algorithm confirmed its ability to distinguish events of interest from background and also allowed approximate lower limits to be set on the absolute magnitude M, of the TLEs that Mini-EUSO will be able to detect: Typical sprites and blue jets with M $\sim$ 3, and elves with M $\sim$ 1.

3.3 Trigger tests in hardware

Following the implementation of the trigger algorithm in the hardware of the Zynq board, it was then tested using a pulse generator to induce L1 trigger events. This allowed to test the data acquisition chain from the SPACIROC ASIC board to the L1 trigger in the Zynq board of the data acquisition system. In order to do this, a pulse generator was connected via a kapton cable

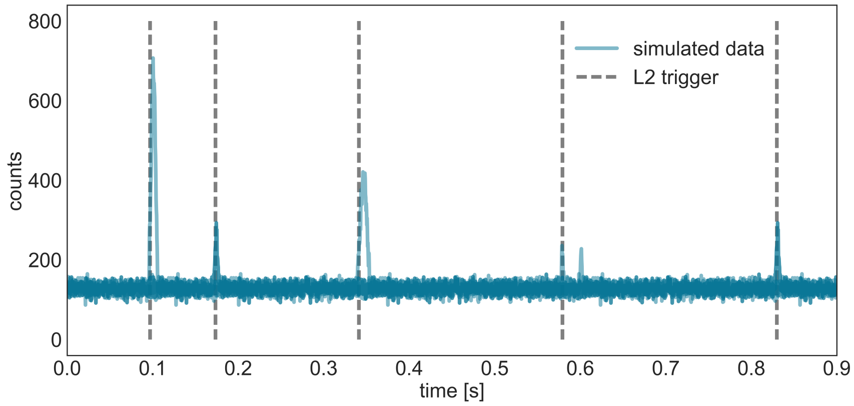

Figure 4: The result of running the L2 trigger algorithm on simulated TLE events. The events simulated here (from left to right) are a blue jet, a sprite, another blue jet, an elf and a final sprite. The light curve is plotted for the triggered pixels and the events were spread over different areas of the focal surface. Grey dashed lines mark an L2 trigger.

to the MAPMT interface on the EC ASIC board, set to generate an input pulse of 100 mV (≈ 2 photo-electron charge equivalent for a 5×10^6 PMT gain) with a duration of 8 ns. This was then connected directly to the Zynq board. The trigger algorithm was programmed to give a L1 event signal to an output pin of the Zynq board upon triggering. This L1 event signal was measured using an oscilloscope. The input pulse amplitude and shape were chosen to simply verify the correct operation of the trigger algorithm in terms of signal over threshold, and not to correspond to a typical signal expected to be detected during the Mini-EUSO mission. As shown in Table 1, the time between pulses was fixed at 100 ns.

The number of pulses was varied for a burst rate of 1 Hz where a burst is a sequence of pulses separated by 100 ns. A constant threshold value on the first version of the EC ASIC board (SPACIROC 1), prior to the upgrade to the SPACIROC 3 ASICs. The main improvements present in the SPACIROC3 are reduced power consumption, improved double pulse separation and a larger charge dynamic range [3]. For the simulated noise level of ~ 1 count/pixel/GTU, the L1 logic is expected to start triggering with high effective trigger ratio above ~ 30 pulses. This is indeed confirmed by the results shown in Table 1.

4. Conclusion

The Mini-EUSO trigger algorithm has been implemented in the Zynq Board FPGA. Before this implementation, the trigger algorithm was tested successfully using simulations and data generated as part of the EUSO@TurLab project. Once implemented in the FPGA, the trigger was then tested using a pulse generator and the complete data acquisition chain. Following this, the data acquisition system will now be integrated with the Mini-EUSO instrument for end-to-end testing of the whole instrument. Following these initial verifications, more sophisticated tests of the trigger performance in hardware are currently under way making use of simulated and in-flight data from the recent flight of EUSO-SPB passed directly into the front-end electronics.

Table 1: Table showing the results of the pulse generator tests of the L1 trigger. Measurements were taken with fixed intervals of 100 ns between pulses and a burst rate of 1 Hz. The effective trigger ratio is the number of triggers divided by the number of expected triggers. An effective trigger ratio of 102% is due to statistical fluctuations in the background for which the average value was 1 count/pixel/GTU.

No. of pulses	**No. of trigger/min**	**Effective trigger ratio [%]**	**Burst** [μs]
40	61	102	4
38	60	100	3.8
36	60	100	3.6
34	42	70	3.4
32	37	62	3.2
30	37	62	3
20	10.3	17	2

Acknowledgments

This work was partially supported by the Italian Ministry of Foreign Affairs and International Cooperation, Italian Space Agency (ASI) contract 2016-1-U.0, State Space Corporation ROSCOSMOS, the Russian Foundation for Basic Research, grant #16-29-13065, and the Olle Engkvist Byggmästare Foundation. The technical support of G. Cotto, R. Forza, and M. Manfrin during validation tests at TurLab is deeply acknowledged. We dedicate this proceeding to Yoshiya Kawasaki and Jacek Karczmarczyk, who passed away in 2016.

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