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Tests of JEM-EUSO First Level Trigger using EUSO-Balloon data

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EUSO-Balloon successfully flew in August, 2014 from Timmins (Ontario, Canada). Its focal surface was an array of 36 Multi Anode Photo-Multiplier Tubes, having 64 pixels each, in total 2304 channels. During its 5 hours flight at floating altitude of 38 km it routinely recorded sequences of 128 consecutive 2.5 μs (Gate Time Unit; GTU) long snapshots of the luminous conditions in its field of view (FoV; 60 km^2) with a spatial resolution of $\sim$ 130 m. In total about $4{\cdot}10^7$ GTU-data were acquired imaging UV background on forests, lakes and clouds, as well as city light conditions and artificial air shower tracks generated by means of a laser installed on a helicopter flying underneath EUSO-Balloon. EUSO-Balloon data were processed a posteriori using the algorithm foreseen for the First Level Trigger of JEM-EUSO. Results show that the algorithm satisfies the requirements on the maximum trigger rate on false positive events. Several helicopter events, mimicking horizontal air showers, were detected.

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1. Introduction

JEM-EUSO is a space mission devoted to the investigation of Extreme Energy Cosmic Rays and neutrinos ($E > 5 \cdot 10^{19}$ eV) from the International Space Station (ISS) using the atmosphere as a giant detector [1]. The telescope is formed by a system of three Fresnel lenses and a focal surface filled with Multi Anode Photo-Multiplier Tubes (MAPMT) read by a front-end electronics based on the single photon counting technique [2]. The trigger system faces different major challenges: a) manage a large number of pixels ($\sim 3 \cdot 10^5$); b) use a very fast, low power consuming and radiation hard electronics; c) achieve a high signal-to-noise performance; d) trigger events on different categories by adjusting the system against variable background level; and e) cope with the limited down-link transmission rate from the ISS to Earth by operating a severe on-board and real-time data reduction. The major sources of background are: a) natural night sky diffuse light, mainly airglow, and slowly varying sources whose light is being reflected from Earth albedo; b) man made sources like city light; c) and transient luminous phenomena in lower and upper atmosphere.

The EUSO-Balloon experiment [3] is a pathfinder mission for JEM-EUSO. The main objectives of the EUSO-Balloon are to perform: a) a full scale end-to-end test of all the key technologies and instrumentation of JEM-EUSO detectors; b) a detailed and precise measurement of the UV background in different atmospheric and ground conditions; and c) a first measurement of air shower tracks from the edge of space. For its first flight, EUSO-Balloon was launched by the French Space Agency CNES from the Timmins base in Ontario (Canada) on the moonless night of 25 August, 2014 UT.

2. Technical requirements

A detailed description of the data acquisition system and electronics of the JEM-EUSO project is reported in [2]. The main points useful for the following discussion on the trigger system and in particular on the First Level Trigger (FLT) are summarised in the following.

The Focal Surface (FS) detector of JEM-EUSO is organised in 137 Photo-Detector Modules (PDM), each composed by 9 Elementary Cells (EC) assembled from 4 MAPMTs having 8×8 pixels each. The readout period, called a Gate Time Unit (GTU), is set at 2.5 μs as a compromise between the available data budget, power consumption and transit time of a signal inside the FoV of a pixel (0.5 – 0.6 km at ground, depending on the FS location). The total amount of data that the electronics has to deal with is of $\sim 3.2 \cdot 10^5$ pixel/FS $\times$ $4 \cdot 10^5$ GTU/s $\times$ 8 bit/pixel $\sim$ 1 Tbps. However, the telemetry budget allocated for JEM-EUSO on the Japanese Experiment Module / Exposed Facility (JEM/EF) is ~300 kbps. This means that a huge data reduction ($\sim 3 \cdot 10^6$) has to be performed on-time by the on-board electronics. Moreover, the limitations imposed by the power budget ~1 kW for the entire telescope and space requirements, such as radiation hard electronics, make the task even more challenging.

To satisfy the data-budget requirement, the trigger system to detect Extensive Air Showers (EAS) is organised in two successive levels. The FLT operates at EC level, which is the basic unit of the front-end electronics. Its main aim is to reduce the rate of fake triggers to $\sim$ 1 Hz/EC. The most dominant component of the fake triggers is background fluctuations causing accidental coincidences. Among other causes are: anthropogenic light, lightnings, meteors, and aurorae. The

Second Level Trigger (SLT) is designed to operate at PDM level and it is expected to further reduce the trigger rate to ~ 0.1 Hz/FS [4]. To distinguish an EAS event from any other phenomenon the trigger scheme relies on the basic idea that EASs travel at the speed of light along a line.

3. The First Level Trigger: Persistency Tracking Trigger

The First Level Trigger, named Persistency Tracking Trigger, rejects most of the background fluctuations by requiring a locally persistent signal above the average background lasting a few GTUs. In this trigger level, pixels are grouped in cells of 3×3 pixels. Each inner pixel of an MAPMT belongs to several cells as it can be the center of a cell or it can belong to its edges. Therefore, one MAPMT hosts 36 cells. The cells can not be shared by near-by MAPMTs. A cell issues a trigger if it satisfies the following conditions: a) for a certain number of GTUs (N_{ctd}) in a group of consecutive GTUs (N_{pst}), there is at least one pixel in the cell with a number of counts equal to, or higher than, a preset threshold, $n_{\mathrm{thr}}^{\mathrm{pix}}$; and b) the total number of photo-electrons integrated in the cell is higher than a preset value $n_{\mathrm{thr}}^{\mathrm{cell}}$. N_{ctd} and N_{pst} are set to 3 and 5 GTUs, respectively, while $n_{\mathrm{thr}}^{\mathrm{pix}}$ and $n_{\mathrm{thr}}^{\mathrm{cell}}$ are set as a function of the average background level to keep the rate of triggers on fake events around 1 Hz per EC.

The way to distinguish an EAS from other physical bright phenomena occurring in the atmosphere is its duration. As EASs propagate at the speed of light, the longest duration that they can insist on one single EC is around hundreds of μs. This is much shorter than the minimum duration achievable by lightning (ms), meteors (hundreds of ms) and cities/airplanes (seconds). Starting from the GTU in which the FLT fires, a confirmation counter is activated. For a preset number of consecutive GTUs (N_{GTU}), the confirmation counter is increased by 1 count each GTU in which the FLT is fired. After N_{GTU} GTUs, if the confirmation counter has passed a certain threshold N_{GTU}^{thr}, the trigger is not activated because it indicates that the FLT fired for a fraction of time that exceeded the expected duration of an EAS. Currently, $N_{GTU} = 73$ and $N_{GTU}^{thr} = 72$. However, the two numbers can be adjusted independently. If the value accumulated in the confirmation counter does not reach N_{GTU}^{thr}, the trigger confirmation is issued and the SLT is activated. This mechanism allows reducing significantly the rate of triggers due to uninteresting light sources. The FLT passes to the SLT the information of the time and location of the cells that were fired.

The FLT parameters are set according to the average background level on the MAPMTs. Two methods have been developed. The first one operates at EC level. The 256 pixels in an EC are divided into groups of 8 pixels in 2×4 arrays for a total of 32 such groups.

Every 128 GTUs the average count level in each group of pixels is computed. The highest value is used to assign the FLT thresholds for the next 128 GTUs on the entire EC. This technique allows estimating new thresholds every 320 μs. All the artificial sources like cities, planes, ships, etc. can be considered static at this level. In case of JEM-EUSO the FoV at ground of 8 pixels is between 2 km^2 and 3 km^2 depending on the line of sight of the pixels. Therefore, the computation of the background in groups of the EC has two advantages: a) take into account the non-homogeneous response among pixels in the same MAPMT; and b) reduce the probability that an anthropogenic light source causes triggers. This method was validated with experiments at TurLab [5].

The second method has been developed based on the data taken during the first EUSO-Balloon flight. In this case, thresholds are set at MAPMT level. For each pixel an average background level is calculated every 128 GTUs. The pixel with the highest average count determines the thresholds for the entire MAPMT. This method takes more precisely into account the non-uniformity among pixels, as well as the presence of man-made sources with very limited spatial extension. Section 4 shows a comparison on the performance of the two methods.

The simulation of the trigger logic here described for one EC has been tested on a Xilinx Virtex6 model XC6VLX240T [6] FPGA and it required $\sim 7\%$ of its resources. This implies that in principle such FPGA can host all 9 ECs of a PDM.

4. Application to EUSO-Balloon flight-data

The logic of the FLT has been applied offline to the measurements performed at TurLab (see [7] for a detailed description of tests and results) and to the data acquired by EUSO-Balloon flight of Timmins in August, 2014. A detail description of the EUSO-Balloon instrument and of the preliminary results of the first flight are reported in [3, 8]. The focal surface consisted of 1 PDM (an array of 36 MAPMTs having 64 pixels each, for a total of 2304 channels). During its 5 hours flight at floating altitude of 38 km it routinely recorded packets of 128 consecutive GTUs of the luminous conditions in its FoV ($\sim$ 60 km^2) with a spatial resolution of $\sim$ 130 m. The trigger was provided by the internal CPU clock with a 18 Hz rate. Therefore, data packets consisted of 320 μs of data recorded every $\sim$55 ms. Runs of different packet lengths, 2000 and 200 packets respectively, were acquired. In total about $4{\cdot}10^7$ GTUs were recorded with imaging UV background on forests, lakes and clouds, as well as city light conditions and artificial EAS tracks generated by means of a laser installed on a helicopter flying underneath EUSO-Balloon [9]. The time variation of the average counts recorded by a typical pixel during the entire flight is shown in Fig. 1. Urban areas are responsible for the high counts recorded in some portions during the flight (i.e. Timmins between 03:00 – 04:00 UTC). The central region with low counts is due to the passage of EUSO-Balloon on forests, lakes, and clouds.

Before running the code a mask was applied to remove from the analysis all the pixels not properly working ($\sim$15%).

The analysis focused on the periods in which an helicopter flew underneath EUSO-Balloon, shooting different types of light sources ($\sim 6{\cdot}10^6$ GTUs in total). Runs were separated in two blocks, the nominal ones in which the average background level was $\sim$0.6 counts / pixel GTU, and the others in which a mine was in the FoV of the detector, causing much brighter light conditions (5 – 10 counts / pixel GTU).

The sequence provided by the light system was as in the following (see [9] for details). First, a UV LED signal was shot for 12 GTUs with increasing luminosity to achieve a projected number of photoelectrons at PDM level raising from $\sim$1 to $\sim$50 counts. The sequence of LED intensities was kept constant during the entire flight. This light-signal appears on the FS as a static source and can be used to determine the effective threshold to issue the trigger. About 25 GTUs after the end of the LED signal, an $\sim$5 mJ laser shot lasting 7.5 ns was fired. The laser event took at maximum 10 GTUs to cross the entire FoV of the telescope. This signal reproduces artificially the expected track from an $\sim 10^{20}$ eV EAS crossing the FoV horizontally. From the FLT point of view, this is in principle the least optimised signal to be used for triggering. In fact, due to the projected FoV of one 3×3 pixel-cell of $\sim$400 m ×400 m, the signal would insist in the cell for only $\sim$1 GTU, not

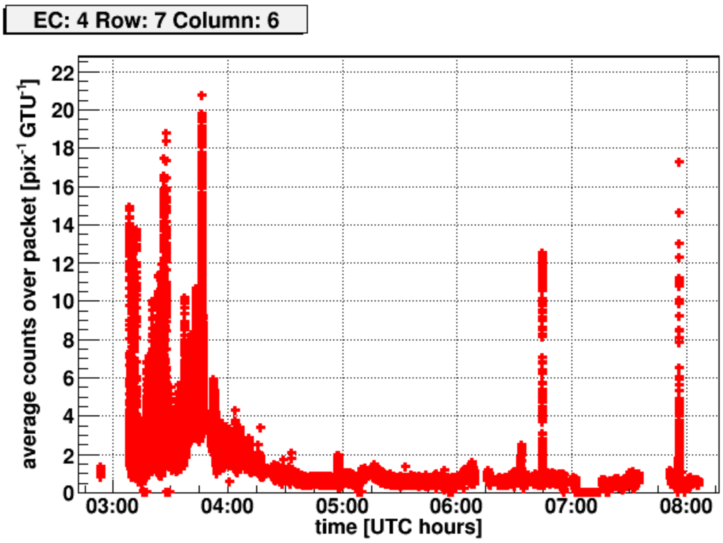

Figure 1: Time variation of the counts recorded by one typical pixel every GTU along the entire flight. Data are averaged per packet (blocks of 128 GTUs). See text for details.

matching the 5 GTUs integration of the signal excess in the cell. For this reason, to increase the chance probability of triggering, a Xenon (Xe) flasher lamp was fired ∼5 μs after the laser shot for a 8 GTU duration. The variable light intensity of the Xe-flashers was reaching the maximum after the first 3 GTUs and then decreasing for the remaining time. Four different absolute intensities were used to mimic different EAS energies.

The integrated number of counts in a typical packet (RUN=043202, packet=1960) in which all the light sequence was imaged, is shown in Fig. 2. The LED and Xe-flasher signals are located around pixel with coordinates of X=5 and Y=25.

The time variation of the signal in the 3×3 pixel-cell centred around (X=5,Y=25) during the entire packet is displayed in the left panel of Fig. 3. The LED light appears between 19 and 31 GTUs, followed by the laser shot at 55 and 56 GTUs and by the Xe-flasher between 58 and 65 GTUs. An after pulse from the Xe-flasher occurs between 70 and 73 GTUs.

The number of trigger alerts occurred in all the ECs during the packet is displayed in the right panel of Fig. 3. The image refers to the version of the trigger where the thresholds are defined calculating the background at pixel level ('Pixel-bckg' in the following). A quite similar result is obtained also for the version in which thresholds are defined by calculating the background in groups of 2×4 pixels ('Group-bckg' in the following). The EC=4 successfully detects the whole sequence of UV-LED, laser and Xe-flasher light at the correct timing. A slight time delay in the alerts is a consequence of the 5 GTU-integration condition. EC=5 and EC=6 trigger as well on the laser event slightly shifted in time as expected. The FLT does not trigger on background.

Similarly to this event, all the runs in which the helicopter was flying underneath EUSO-Balloon were processed with the FLT. A synchronisation between the light emission and the acquisition of EUSO-Balloon was not possible. Taking into account that the acquisition time of the PDM data was only 320 μs every ∼55 ms (∼0.6%), the vast majority of the events could not be detected. Moreover, some events could only be partly detected. Nevertheless, the FLT found more

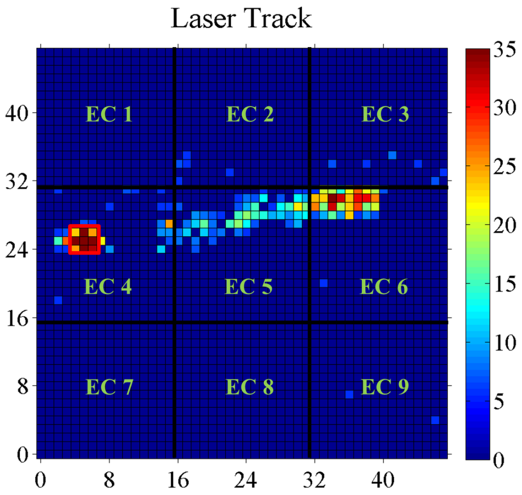

Figure 2: Image of a helicopter event obtained by integrating the counts in each pixel for the whole packet=1960 of RUN=043202 (128 GTUs). A threshold is applied to the minimum signal level to emphasise the location of the track. The UV-LED and Xe-flasher signals are centred around pixel at axis of abscissae X=5 and axis of ordinates Y=25.

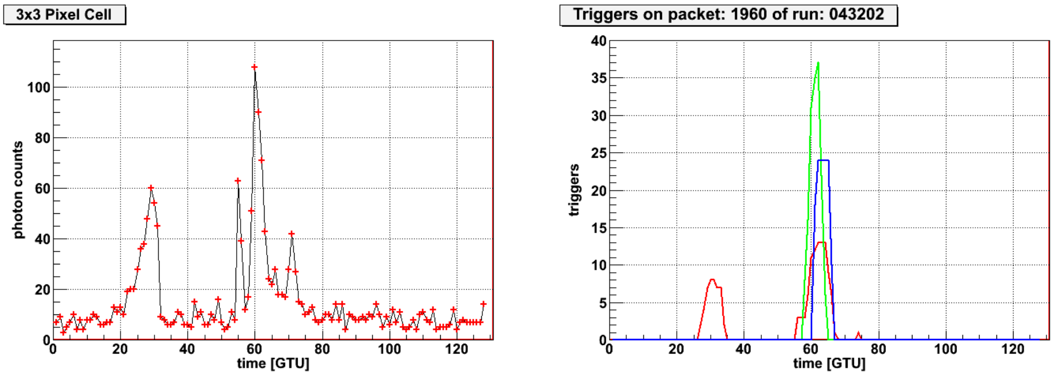

Figure 3: Left: Number of counts recorded in the 3×3 pixel-cell centred around (X=5,Y=25) during the entire packet. See text for details. Right: Sequence of trigger alerts in the EC where the pixel (X=5,Y=25) is located during the entire packet. See text for details.

than 270 events in which at least 2 ECs were triggered almost in coincidence, as a consequence of the laser track. It might be possible that other events triggered, but were not recognised by this simple approach. Other algorithms are being developed by the collaboration to search for helicopter events. However, they require much more computational resources, therefore, can not be implemented on-board JEM-EUSO for a real-time acquisition.

Another complication, compared to JEM-EUSO, is represented by the fact that EUSO-Balloon was spinning with variable angular velocity during the flight. Therefore, the images of urban areas at the edges of the FoV were entering and exiting many times from the line of sight of the border pixels, creating discontinuities in the luminosity. This situation becomes more relevant when the data are not provided continuously but at bunches of 128 GTUs with ∼55 ms dead time in between. In fact the background is calculated every time based on the previous 128 GTUs of acquired data that in this case occurred 55 ms before in time. As summarised in the following, however, the FLT successfully overcame these complication.

As mentioned before data were divided in two intervals, namely when the balloon was flying on forests and lakes, and when an urban light source was appearing in the FoV. The former lasted ∼8.5 s of data while the latter ∼6.5 s. The count-rate on the pixels illuminated by the urban light was one order of magnitude higher than in nominal conditions.

Table 4 summarises the number of triggers on laser events and on any other type of events in the two intervals with nominal and urban-like background. The table compares the results using the two methods for threshold setting. Both methods detect very similar number of events, 277 and 274, respectively, and satisfy the requirement of ∼1 Hz/EC in ‘Nominal’ background conditions. However, the ‘Pixel-bckg’ is compliant with the requirements also in case of ‘Urban-like’ conditions, while the ‘Group-bckg’ method does not. In general, the ‘Pixel-bckg’ method seems to be more selective, as the rate of other triggers is lower also in ‘Nominal’ background conditions. A more detailed analysis performed on the total number of trigger alerts on laser events during ‘Nominal’ background conditions shows that it decreases by ∼13% (24902 alerts out of 28660) compared to the ‘Group-bckg’ method.

NOMINAL BCKG.			
Method	Laser	Others	rate Others
‘Group-bckg’	128	56	6.6 Hz
‘Pixel-bckg’	126	17	2.0 Hz
URBAN-LIKE BCKG.			
Method	Laser	Others	rate Others
‘Group-bckg’	149	1941	299 Hz
‘Pixel-bckg’	148	59	9.1 Hz

Table 1: Number of triggers on laser events and on any other type of events in the two periods with ‘Nominal’ and ‘Urban-like’ background. The table compares the results using the two methods for threshold setting: ‘Pixel-bckg’ and ‘Group-bckg’.

The cells which triggered with the lowest signal on the UV-LED light in event RUN=043202, packet=1960 can be used to provide some insights on the minimum amount of light excess needed to trigger. By using the 7 lowest count values in EC=4 which gave a trigger alert, the average signal excess was 81 ± 13 counts on top of an average background level of 39 ± 1 counts. This means that the minimum signal required to trigger in the 3×3-pixel cell is 2.1 ± 0.3 times of the background level. ESAF [10] simulations of EUSO-Balloon performance indicate that this value is obtained by vertical EAS of energy $\sim 5 \times 10^{18}$ eV. This value can be considered as an upper limit to the energy threshold of EUSO-Balloon as simulations indicate that high zenith-angle EAS would provide higher signal.

5. Conclusions

The first level trigger of JEM-EUSO has been summarised. It has been applied to the data recorded by the first EUSO-Balloon flight and it shows to satisfy the requirements on the maximum trigger rate on false positive events. Several laser induced events, emulating horizontal EAS, were detected. Currently, the trigger logic is being implemented on the PDM board of EUSO-Balloon for an on-board and real-time detection of EAS in future flights.

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