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The trigger system of the JEM-EUSO Project

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Abstract: JEM-EUSO is a space mission devoted to investigate Extreme Energy Cosmic Rays and Neutrinos (E$>10^{19}$eV) from the International Space Station (ISS) using the atmosphere as a giant detector, which is also the source of the largest fraction of noise (nightglow background). The trigger system should face different major challenging points: a) cope with the limited down-link transmission rate from the ISS to Earth, by operating a severe on-board and on-time data reduction; b) use very fast, low power consuming and radiation hard electronics; c) have a high signal-over-noise performance and flexibility in order to lower as much as possible the energy threshold of the detector, adjust the system to a variable nightglow background, and trigger on different categories of events. A general overview of the architecture of the triggering system of JEM-EUSO is presented.

Introduction

The observational concept of JEM-EUSO [1] is based on the observation of fluorescence and Čerenkov light emitted during the propagation of Extensive Air Showers (EAS), produced by the interaction of an Extreme Energy Cosmic Ray (EECR) or neutrino with the atmosphere. Typically, for a 10^{20}eV EAS, a few thousand photons are expected on the JEM-EUSO detector in few hundred μs with an approximated rate of $\sim$1/day. In general, inclined showers will produce brighter signals as the EAS will develop in the less dense atmospheric layers. The signal will be partly influenced by the presence of cloud layers covering the last stages of the EAS development. Depending on the energy and direction of the primary particle, the expected signal will insist on few pixels for near vertical showers, while it will fire huge portions of the focal surface for near horizontal ones. At the same time, the atmosphere plays a manifold role: it's the medium where the EAS develops, it's the light emission and transmission medium where the light propagates and attenuates from its source location to the telescope site, and it's the source of the largest fraction of noise, the expected UV background. The major sources of background are: a) natural night sky diffuse and slowly varying sources whose light is being reflected through Earth albedo; b) man made sources like city lights; c) transient luminous phenomena in lower and upper atmosphere (below ISS height, $\sim$430km). Concerning a), different contributions have to be considered: Moon phases, diffuse night brigthness (zodiacal light, diffuse star light, planets), airglow. The common effect of diffuse night brightness and airglow is expected to produce an average flux of Φ = 300 - 1000 photons/m^2/ns/sr for clear sky. These values have to be increased by 15% in case of cloudy sky. These estimations are in agreement with recent measurements of the nightglow background [2, 3]. If we accept that the Moon phase will contribute to the average nighglow background by no more than 20% compared to Φ in moonless nights, this means that the observational duty cycle will be $\sim$20%. The effect of man made sources like city lights will, prob-

ably, blind pixels in the Field of View (FoV) for a time corresponding to the persistency of its image within the relevant portion of the FoV. Since the ISS velocity is 7 km/s and the pixel size is $\sim$0.7 km, the expected persistency of a ”steady human source” is on the order of 100 ms. Finally, Transient Luminous Events (TLE) such as Elves, Sprites, Bue Jets and Lightnings will be responsible of the most luminous signals in the night atmosphere with an average occurence of $\sim$700/day. Due to the different time scale and light involved in these phenomena compared to EAS, such events will be very easily recognized. Moreover, the continuous measurement of TLEs is one of the science objectives of the JEM-EUSO mission [4] which will require a special trigger system.
In conclusion, due to the variability of the atmospheric conditions and of the atmospheric phenomena, JEM-EUSO will need a dynamical trigger system capable of continuously adapting the triggering requirements. Moreover, an intelligent trigger system that exploits the peculiarities of the EAS signals on the random nightglow background will be able to operate a massive screening between real and fake events, contributing to lower the energy threshold of the detector.

Technical requirements

In JEM-EUSO baseline, the Focal Surface (FS) of the telescope is conceived as a mosaic of $\sim$6000 multi-anode photomultipliers (MAPMT) with 36 pixels each (R8900-M36), for a total number of $\sim 2 \times 10^5$ channels, arranged in 1500 Elementary Cells (EC) (4 MAPMT/EC). The ECs, which are the basic unit of the front-end electronics are organized in groups of 9 items (3$\times$3) in Photo Detector Modules (PDM), the basic unit of the data acquisition system [5]. The Gate Trigger Unit (GTU) is currently set at 2.5 μs in order to match with the time span required by a light signal to horizontally cross the FoV of a pixel ($\sim$0.7 km). This means that the total amount of data that the electronics has to deal with is on the order of 2×10^5 pixel/FS $\times$ 4×10^5 GTU/s $\times$ 8 bit/pixel $\approx$ 640 Gbps. However, the telemetry budget of the JEM Exposed Facility (JEM/EF) is of $\sim$300 kbps. This means that a huge data reduction (10^6) has to be performed on-time by the on-board electronics. Moreover, the limitations imposed by the power budget ($\sim$1 kW for the entire telescope) and space requirements (radiation hard electronics) contribute to make such task even more challenging.

The Focal-Surface electronics and the Trigger System

The trigger system has to be selective in order to tag the EAS-produced signal while rejecting the background in an efficient way. The trigger system consists of trigger modules that are independently operated for each PDM. The trigger system is operated in the following 3 modes: a) normal mode with 2.5 μs GTU for routine data taking of EAS; b) slow mode with a programmable GTU up to a few ms, for the studies of TLEs and meteorites; c) detector calibration mode with a GTU value suitable for calibration runs. To reject the background, JEM-EUSO electronics operates with several trigger levels. As the trigger system is intimately connected with the Focal-Surface electronics, a brief description of the electronics will follow.
The Focal-Surface electronics of JEM-EUSO, extensively employing ASICs, is composed of 4 hierarchies: EC electronics, PDM control electronics, PDM cluster (which consists of $\sim$20 PDMs) control electronics and FS control electronics.JEM-EUSO employs FPGA also for the read-out and control boards to make use of a more sophisticate trigger algorithm (Track Trigger Algorithm - TTA) without loosing flexibility as well as to reduce the required power consumption. In order to increase the trigger efficiency of lower energetic EAS, the TTA searches for signals moving on the FS at the speed of light along straight lines. Such analysis is performed at on-time speed by FPGA and DSP.
Concerning the EC electronics, JEM-EUSO collaboration has initiated to design an original front-end ASIC with a radiation-tolerant deep-sub micron CMOS process. The front-end ASIC includes an impedance mathcing circuit, an integrator, a comparator as well as current-source and current-sink circuits which feed currents at the input node of the integrator. A fast pulse from a MAPMT goes through the impedance matching circuit and is converted to a voltage signal by the integrator circuit before being fed into the comparator circuit, that delivers a high logic signal when the integrator's

output exceed a pre-determined level. Once the comparator circuit delivers high logic, the current-source circuit is activated to linearly damp the integrator output until the integrator output goes below the threshold comparator. The width of the high logic signal is proportional to the input charge. The back-end FPGA counts clock during the interval of the high logic delivered by the comparator circuit, and then, the amount of input charge is converted into a binary value. This scheme can keep linearity in energy measurement over a wide dynamic range. Concerning the trigger scheme, since signals necessary for a trigger decision are concentrated virtually on a single FPGA, we can implement and advanced trigger scheme without requiring additional power.
The numbers of photoelectrons counted by the Front End Electronics (FEE) on EC are collected by every PDM where the TTA generates the 1^{st} trigger at PDM level. The rate at 1^{st} level is controlled not to exceed 7 Hz/PDM. This process needs at least 2.3 Gips, and is done by 2 FPGA chips, Xilinx "Qpro Virtex2 Rad-Tolerant 105 MHz". In parallel to the above described method, that will be used for routine data taking of EAS, a slow mode is also implemented for studies of meteorites and TLEs. In such case, the PDMs release the photoelectron numbers integrated for 50 μs every 3.5 s. The 1^{st} trigger events selected at PDM level, are sent to the cluster control electronics which manages 8 PDMs. A second refined trigger method is used in order to reduce the event rate at 0.1 Hz on the entire FS, in order to match the 300 kbps imposed by the telemetry budget. This process is done by DSP with high reliability (TI "SMJ320C6701"). As for the control of the operating state and data flow, decentralized processing is done with the MPU on the FS control electronics. The FS control electronics communicates with the Mission Data Processor.

The Track Trigger Algorithm

The core of the trigger logic is the Track Trigger Algorithm that has been specifically developed for this purpose. Every GTU the pixel data are divided into 3 categories: Red (R), Yellow (Y) and White (W) pixels. R pixels are defined as those with 'high' number of photoelectrons (N_{phe}: $N_{phe} \geq N_{thr,r}$) and will be used as a seed for the TTA. Y pixels have a moderate photoelectron content ($N_{thr,y} \leq N_{phe} < N_{thr,r}$). W pixels have a low N_{phe} ($N_{phe} < N_{thr,y}$) and they will be discarded for the rest of the analysis. The thresholds $N_{thr,y}$ and $N_{thr,r}$ depend on the average background level and need to be continuously adjusted to the atmospheric conditions in order to satisfy the requirement $N_{red} < 10$ and $N_{yellow} < 400$ to limit the computational power. The algorithm has a predefined set of implemented directions (16) covering the whole phase space, and EAS are searched as bright spots moving on the FS along such directions at the speed of light for $\Delta t = N_{GTU}$ (N_{GTU} = 9 GTU in the current version). This is the most peculiar characteristics that distinguishes an EAS from excesses of the random background. In the following we define θ and ϕ respectively as the zenith (θ = 0° means the nadir direction of EUSO) and azimuth angles of EAS. Such angles are related to ΔX and ΔY distances imaged by the track on the X-t and Y-t projections and to the on-ground pixel size (ΔL) by the following relationships: $\phi = arctg(\Delta X/\Delta Y)$ and $\theta = 2 \cdot arctg(C \cdot \sqrt{(\Delta X^2 + \Delta Y^2)})$ with the constant $C = \Delta L/(c \cdot \tau_{GTU})$, where c is the light speed and τ_{GTU} indicates the GTU time span. Upon receiving the alert by a Red pixel at time t_0, the algorithm defines a box of $m \times m$ pixels (currently m = 2), that at $t = t_0$ includes the R pixel, and the contents of Y and R pixels inside such box are integrated for the time span $\Delta t/2 - t_0 \leq t \leq \Delta t/2 + t_0$. The location of the box in consecutives GTUs depends on the specific directions implemented on the algorithm, according to the relationships just above introduced. In particular, for an almost vertical shower, the box will insist almost on the same pixels for the entire Δt, while for almost horizontal showers, the box will continously shift and the photoelectron content of other pixels will be acquired. The dimension of the box is strictly related to the EAS spot size on the optics and to the pixel size, while Δt and the total number of preset directions of TTA depend on the computational speed. The total number of photoelectrons ($N_{tot}(\theta, \phi)$) integrated inside the box for Δt on a specific direction (θ, ϕ) is sent to a comparator. If $N_{tot}(\theta, \phi)$ exceeds a preset threshold $N_{thr,tot}$ ($N_{tot} \geq N_{tot,thr}$), a 1^{st} level trigger is issued by

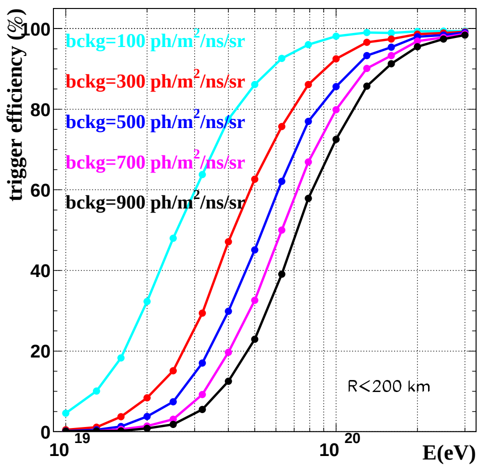

Figure 1: Trigger efficiency curves of JEM-EUSO for different nightglow background levels on the entire FoV.

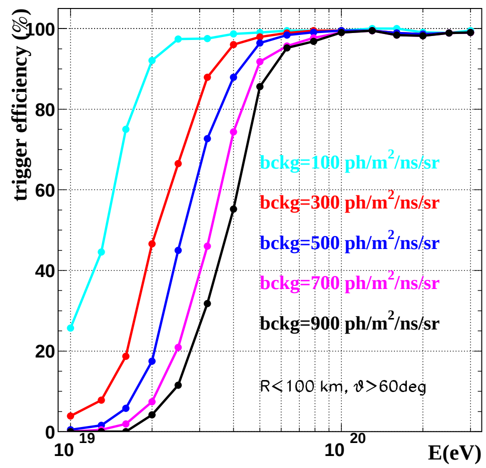

Figure 2: Same as Fig. 2 for selected conditions (R $<$ 100 km and $\theta > 60°$).

the PDM. $N_{tot,thr}$ depends on the average atmospheric background and it is set in order to limit the 1^{st} level trigger rate to 7 Hz/PDM.
A more refined trigger system at 2^{nd} level will further operate a selection to reduce the event rate at 0.1 Hz/FS (10^3 reduction) by using different techniques: repeating the TTA algorithm on a more refined set of directions around the direction triggered by the 1^{st} trigger level, and by taking into account the shower profile and the possible presence of the Čerenokov mark, further parameters that distinguish a real EAS from a fake event.

Performance and conclusions

Fig. 1 and 2 show preliminary results on the trigger efficiency curve as a function of the shower energy for JEM-EUSO's 1^{st} trigger level in clear sky condition and nadir mode. Fig. 1 shows the case of events detected on the entire FoV, while Fig. 2 restricts the selection on the center of the FoV (R $<$ 100 km from the nadir) and for inclined showers ($\theta > 60°$). These figures show very interesting points: a) the importance of a dynamic trigger system capable to continuously adjust its parameters in order to keep an almost constant trigger rate for varying background conditions; b) a sufficiently high trigger efficiency even in case of high background level for energies E $> 10^{20}$ eV; c) selective criteria based on the EAS location inside the FoV and on the shower direction in order to cover the region E $> 4{\cdot}10^{19}$ even in case of high background levels; d) the possibility to explore the entire region of energies E $> 2 \cdot 10^{19}$ during low nightglow background conditions. The tuning of the TTA parameters is still on going to further improve the trigger performance. Finally, it has to be noted that the improvement of the trigger system should proceed in parallel with the refinement of the shower reconstruction algorithms as the ultimate threshold of the detector is set by the accuracy in the estimation of the most important EECR parameters (energy, direction, composition).

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