Implementation of the First Level Trigger of JEM-EUSO: Results of the First Tests

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for the JEM-EUSO collaboration

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Contents

- The JEM-EUSO program for ultra-high-energy cosmic ray detection from space
- Electronics of the JEM-EUSO pathfinders, definition and implementation of the first level trigger (L1)
- Tests of the L1 Trigger
- Summary
What are cosmic rays?

- High-energy particles in the Galaxy (protons and nuclei)
- Wide energy range, up to macroscopic energies ($10^{20}$ eV $\rightarrow$ several Joules!)
- The flux decreases very rapidly with energy
- Ultra-high-energy cosmic rays (UHECRs) are very interesting
  - Most energetic particles in the universe
  - Challenging for astrophysics
  - Unknown sources
  - Unknown acceleration mechanism
  - Low magnetic rigidity $\rightarrow$ smaller deflections $\rightarrow$ point towards sources?
- But very low flux (1 part/km$^2$/century)
  $\Rightarrow$ **Huge detectors needed!**
  $\Rightarrow$ Go to space $\Rightarrow$ JEM-EUSO collaboration
The detection principle

- High energy cosmic rays produce “atmospheric showers”: cascades of secondary particles
- Up to hundreds of billions of secondary particles!
  - excitation of air molecules
  - de-excitation by fluorescence emission (UV light, isotropic)
  - Cherenkov emission (along shower axis)
- Detection of UV light from the shower, with large field-of-view telescope (2.5 m \( \varnothing \) Fresnel lens optics, \( \pm 30^\circ \) FoV)
  - Reconstruction of the energy and arrival direction of the incoming cosmic ray
The focal surface

Rear lens (focusing)

Front lens (Large field of view)

Diffractive lens (Corrects for chromatic aberration → PSF of ~ 1pixel)

Focal surface

Elementary Cell (EC)

Photo-Detector Module (PDM)

Multi-Anode Photomultiplier Tube (MAPMT)

- High photon detection
- Fast response
JEM-EUSO (Japanese Experiment Module – Extreme Universe Space Observatory)

JEM-EUSO pathfinders

Space

JEM-EUSO (future)
K-EUSO (2019 ~ 2020)
Mini-EUSO (2017)

Balloon

Super Pressure Balloon (2017)
EUSO-Balloon (2014.08)

Ground (looking up)

EUSO-TA (2014 ~ now)
Data encoding

ASIC 1
64 channels

UV filter

ASIC 36

UV filter

MAPMT 1

... ...

MAPMT36

FPGA (Xilinx)
~ 240,000 logic cells
~ 14 Mbits RAM blocks

PMT 6

PMT 1

Data Processor

Photo-Detector Module board
Data structure

Basic information:
Number of photo-electrons recorded in each pixel during a time unit of 2.5 µs

“Gate Time Unit”: 1 GTU = 2.5 µs

Photon count over the entire PDM (2304 pixels) during 1 GTU

- Data organized by “packets” of 128 GTUs

Photon count for 1 pixel as a function of time (discrete values)
## Trigger algorithm

Goal: 1) trigger on cosmic-ray showers, but not on other atmospheric phenomena

→ Discrimination based on the timescale and structure of the signal

2) The L1 trigger parameters will adjust themselves such that the false trigger rate is lower than 1 per second.

<table>
<thead>
<tr>
<th>Event region</th>
<th>Event frequency</th>
<th>Event size</th>
<th>Event duration</th>
<th>Light spectrum</th>
<th>Event energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteors</td>
<td>Atmosphere</td>
<td>5~100 or more /hour</td>
<td>0.5~2 m</td>
<td>0.5 ~ 3 s</td>
<td>Violet to red</td>
</tr>
<tr>
<td>Lightning</td>
<td>Troposphere</td>
<td>3/min</td>
<td>Some km</td>
<td>0.1 s</td>
<td>Violet to red</td>
</tr>
<tr>
<td>Sprites</td>
<td>Mesosphere</td>
<td>unknown</td>
<td>Some km</td>
<td>Some ms</td>
<td>red</td>
</tr>
<tr>
<td>Jets</td>
<td>Stratosphere</td>
<td>unknown</td>
<td>Tens of km</td>
<td>0.4 s</td>
<td>blue</td>
</tr>
<tr>
<td>Elves</td>
<td>Mesosphere</td>
<td>unknown</td>
<td>200 km</td>
<td>&lt; 1ms</td>
<td>red</td>
</tr>
<tr>
<td>Noctilucent clouds</td>
<td>Mesosphere</td>
<td>variable</td>
<td>Some tens of km</td>
<td>hours</td>
<td>solar</td>
</tr>
<tr>
<td>Aurorae</td>
<td>Mesosphere to atmosphere limit</td>
<td>variable</td>
<td>Some hundreds of km</td>
<td>From minutes to hours</td>
<td>Violet to red</td>
</tr>
<tr>
<td>Space debris</td>
<td>Atmosphere</td>
<td>5/day</td>
<td>0.5 ~ 2 m</td>
<td>0.5 ~ 3 s</td>
<td>Violet to red</td>
</tr>
<tr>
<td>Cosmic ray</td>
<td>variable</td>
<td></td>
<td>50 ~ 150 us</td>
<td>UV</td>
<td>variable</td>
</tr>
</tbody>
</table>
**Trigger algorithm**

## L1 Trigger conditions

**CONDITION 1: “Local signal”**

At least 1 pixel in a 3x3 pixels cell with photon count ≥ N (in 1 GTU)

**CONDITION 2: “Persistency”**

CONDITION 1 must be met by the same cell during P consecutive GTUs

**CONDITION 3: “Global signal”**

The total number of p.e. in the cell during P consecutive GTUs must be ≥ S

Essentially the signal has to be stronger than N for longer than P GTUs and sum to more than S.
Example of a trigger sequence

Local threshold: $N = 3$ photoelectrons (in 1 pixel)
Minimum persistency: $P = 5$ GTUs
Total global signal threshold: $S = 39$
Example of a trigger sequence

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Tests of the trigger algorithm

Series of tests of the internal Level1 trigger at the level of 1 elementary cell (EC)

1\textsuperscript{st} test: at Laboratoire Astroparticule \& Cosmologie (APC) in Paris, France
   • Internal Level 1 (L1) trigger functionality using dark box, with LED light

2\textsuperscript{nd} test: at TurLab in Torino, Italy
   • July 19\textsuperscript{th}~28\textsuperscript{th}, 2015 and August 23\textsuperscript{rd}~29\textsuperscript{th}, 2015
   • Internal Level 1 (L1) trigger with different kinds of emulated light sources

3\textsuperscript{rd} test: EUSO-TA site in Delta, Utah, USA
   • October 6\textsuperscript{th}~19\textsuperscript{th}, 2015
   • First field test for internal Level 1 (L1) trigger

The L1 tests were successful

=> The L1 trigger is now implemented in the EUSO-SPB instrument
   (Long-duration flight operated by NASA, scheduled on April 2017)
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Results of L1 trigger test | At APC (Paris, France)

- Test Internal L1 trigger functionality using a dark box and a pulse signal using LED

![Diagram of experimental setup with labeled parts: Dark box, Triggered Elementary Cell (EC), Photo-Detector Module (PDM), LED (378nm), Triggered time, ~30cm between dark box and LED.]

Graphs showing data from the test.
Tests of the trigger algorithm

Series of tests of the internal Level1 trigger at the level of 1 elementary cell (EC)

1\textsuperscript{st} test: at Laboratoire Astroparticule & Cosmologie (APC) in Paris, France
\begin{itemize}
  \item Internal Level 1 (L1) trigger functionality using dark box, with LED light
\end{itemize}

2\textsuperscript{nd} test: at TurLab in Torino, Italy
\begin{itemize}
  \item July 19\textsuperscript{th}~28\textsuperscript{th}, 2015 and August 23\textsuperscript{rd}~29\textsuperscript{th}, 2015
  \item Internal Level 1 (L1) trigger with different kinds of emulated light sources
\end{itemize}

3\textsuperscript{rd} test: EUSO-TA site in Delta, Utah, USA
\begin{itemize}
  \item October 6\textsuperscript{th}~19\textsuperscript{th}, 2015
  \item First field test for internal Level 1 (L1) trigger
\end{itemize}

The L1 tests were successful

=> The L1 trigger is now implemented in the EUSO-SPB instrument
(Long-duration flight operated by NASA, scheduled on April 2017)
• The TurLab facility is used for oceanic and atmospheric physics experiments (in the Physics department of the University of Torino). It is equipped with a 5 m diameter rotating tank.
• Tank rotation $\rightarrow$ light sources pass in the field of view of the detector (1 EC + lens)
Results of L1 trigger test | At the Turlab facility (Torino, Italy)

- Light sources inside the tank, to mimic various physical phenomena

**Horizontal**
- "cosmic-ray-like event"
  - trigger OK

**Vertical**
- "cosmic-ray-like event" (permanent emission)
- "city light" + ambient "background light"
  - NO trigger

**"meteor-like event"** (longer timescale)
Results of L1 trigger test | At the Turlab facility (Torino, Italy)

- Successful test: trigger on the cosmic-ray like events only
- Additional test: trigger on cosmic-ray-like event near to a city-like background

- Level 1 trigger on the cosmic ray track, even though the MAPMT next to it is contaminated by intense city-lights

⇒ PMTs can work independently, even within the same elementary cell (EC)

NB: This is crucial to maximize the duty cycle and acceptance of the instrument: in the presence of a city, the rest of the field of view can still be used to detect cosmic rays!
Tests of the trigger algorithm

Series of tests of the internal Level1 trigger at the level of 1 elementary cell (EC)

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The L1 tests were successful

\textbf{=>} The L1 trigger is now implemented in the EUSO-SPB instrument
  (Long-duration flight operated by NASA, scheduled on April 2017)
Results of L1 trigger test | At TA-EUSO site (Utah, USA)

- Laser
- 10°
- ~34 km
- EUSO laser site
- EUSO-TA site

Trigger EC

GTU 50, GTU 51, GTU 52, GTU 53, GTU 54, GTU 55, GTU 56, GTU 57
Trigger efficiency as a function of laser intensity (mimicking a cosmic-ray shower)

The trigger efficiency decreases as the laser energy is lowered.

Should allow EUSO-SPB to detect O(10) cosmic-ray showers
Summary

→ I was in charge of L1 level trigger and PDM board.

→ We have implemented the L1 trigger algorithm in the PDM board of the JEM-EUSO pathfinders for cosmic ray detection from space.

→ We successfully tested the L1 trigger functionality in Turlab Torino (triggering on air showers and not on other lights)

→ We are studying the behavior as a function of light intensity on EUSO-TA (in Utah, USA)

→ We have implemented the L1 trigger in the EUSO-SPB balloon instrument to be flown on an ultra long duration balloon flight in 2017 (NASA)

→ The SPB balloon should be able to detect, for the 1st time, a cosmic ray shower from above by UV light

→ Longer term: full JEM-EUSO mission for UHECR study from space, with an unprecedented effective acceptance (much larger than on the ground)