Sviluppo e test del primo livello di trigger del progetto spaziale JEM-EUSO

Development and testing of the first trigger level of the spatial project JEM-EUSO

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Relatore: **Mario Edoardo Bertaina**

Summary

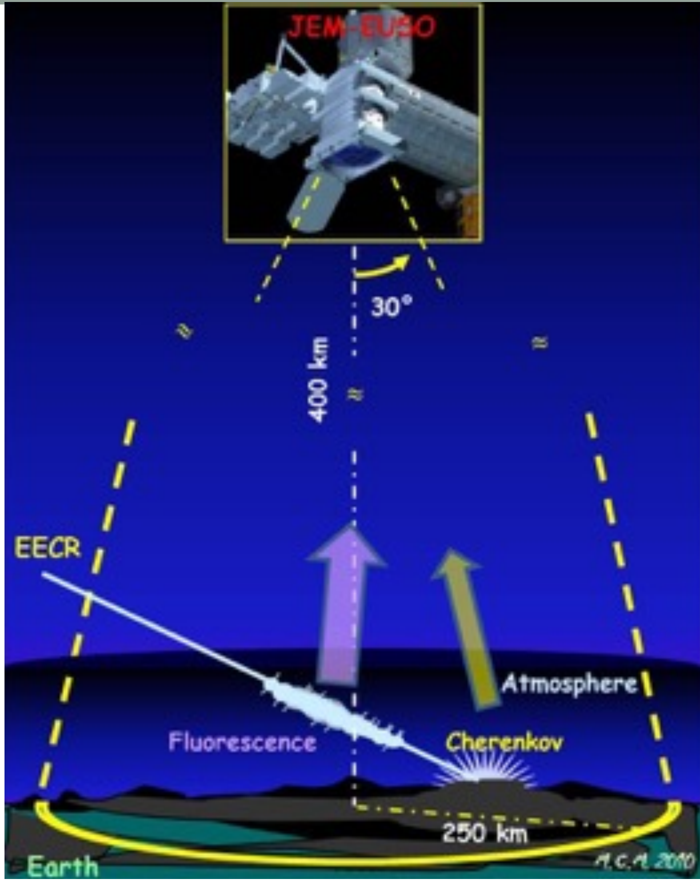
- JEM-EUSO experiment
- JEM-EUSO 1st level trigger logic
- Test of trigger logic at TurLab
- Path finder: EUSO-Balloon
- Offline analysis of trigger logic using EUSO-Balloon data
- Upgrades of trigger logic

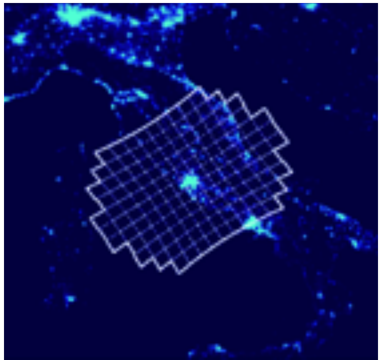
JEM-EUSO

Detection of cosmic ray of E>5×10^{19} eV

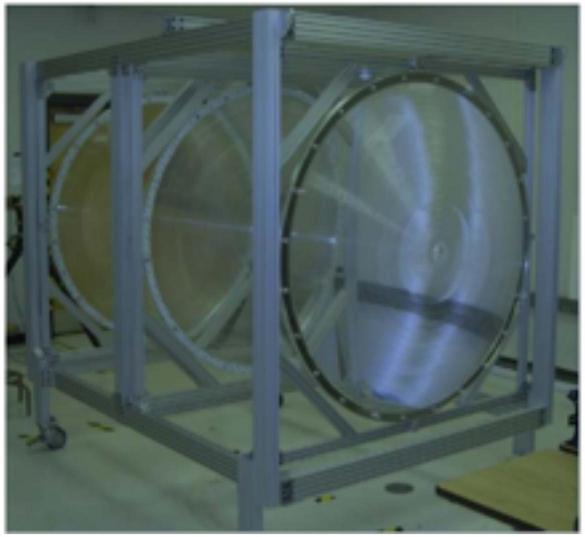
- Orbit height: 400 km
- Orbit period: 90'
- Speed of International Space Station: 7 km/s
- Pixel covered area at the ground: 500×500 m^2
- Single photon counting
- Gate Time Unit (GTU): 2,5 μs
- Standard background (BCKG) on ocean :

  500 phe·m^{-2}·ns^{-1}·sr^{-1} ~ 1 phe·pix^{-1}GTU^{-1}

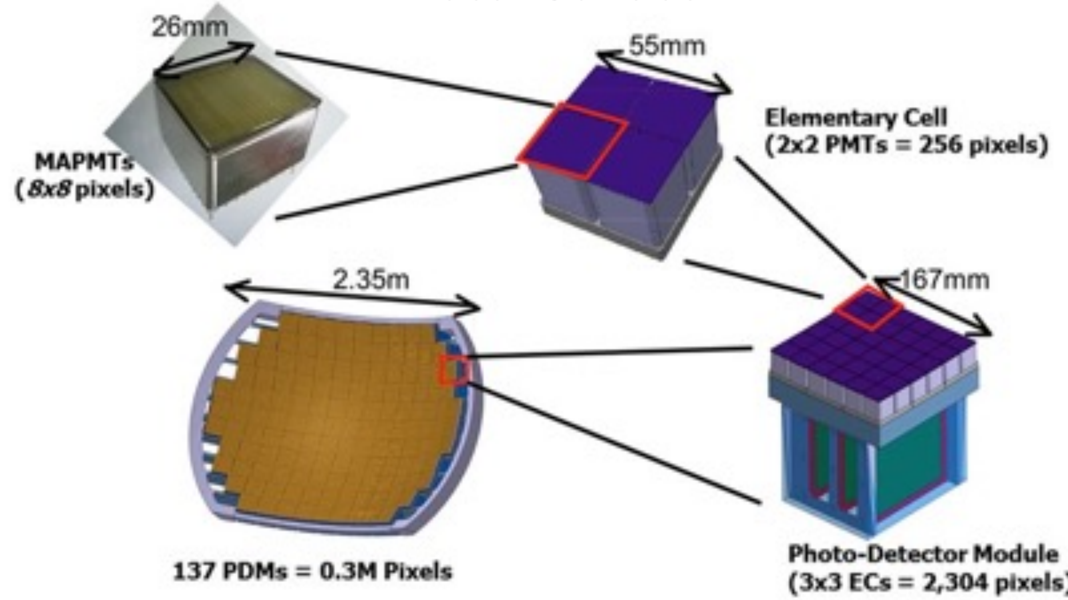


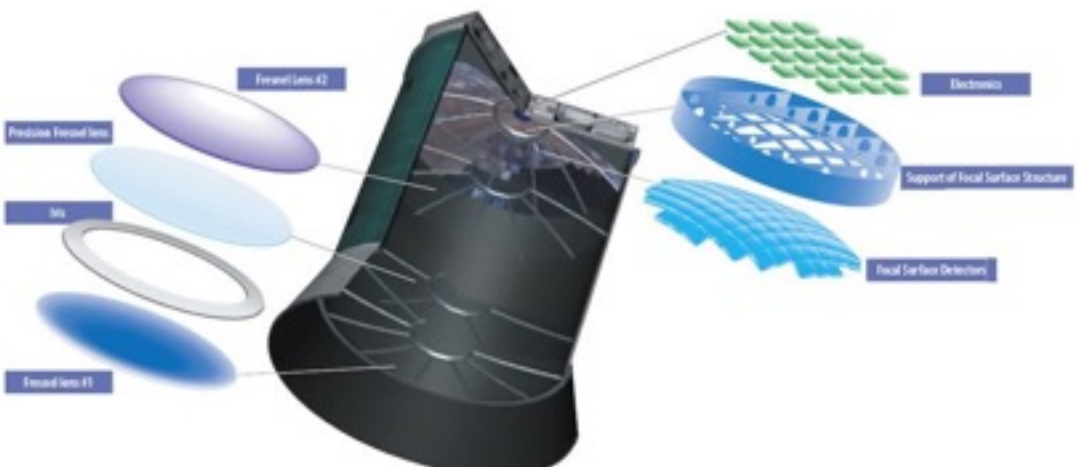


The JEM-EUSO detector



Focal Surface

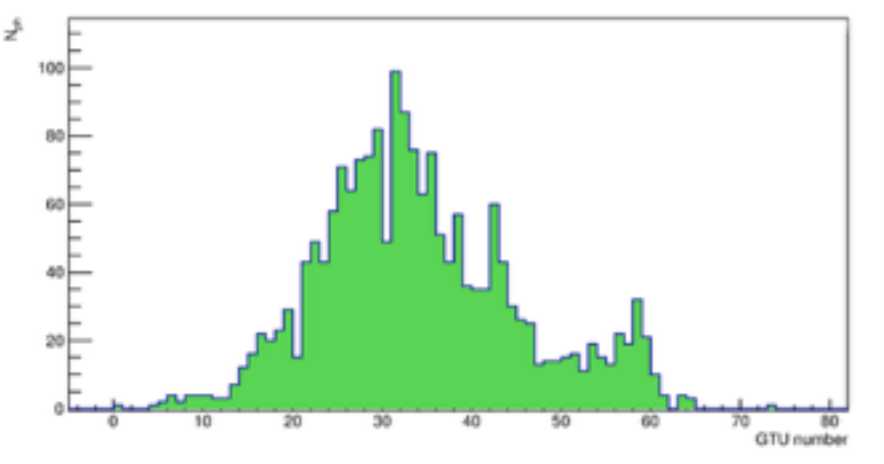




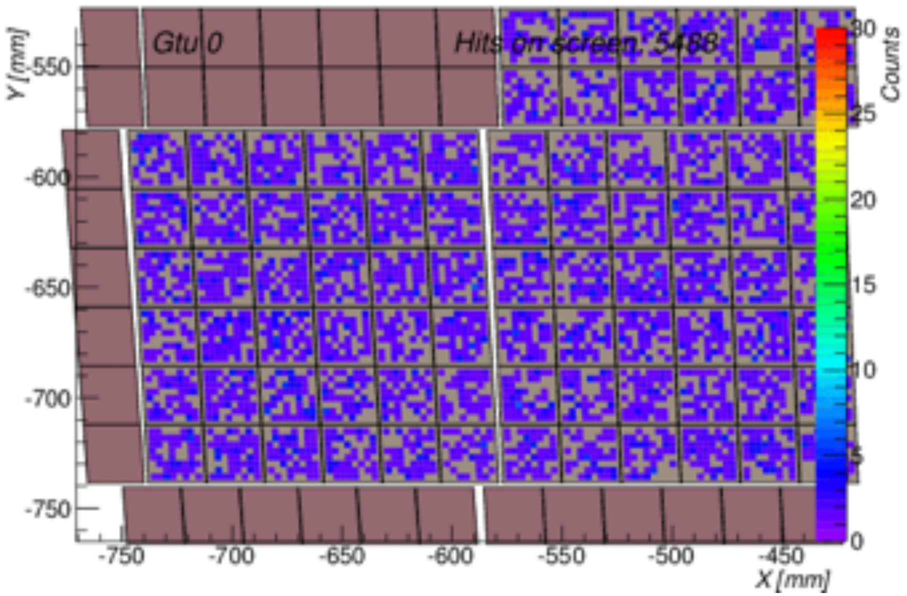
First Target:

Extreme Energy Cosmic Ray (EECR) & Extensive Air Shower (EAS):

- Duration: ~ 200 μs
- Intensity: 5 – 10 counts·pix^{-1}GTU^{-1}



Total number of counts due to a Cosmic Ray



Simulation of a 2×10^{20} eV EECR as detected by JEM-EUSO

Duration and intensity of different light sources

Source	Duration	Intensity [$ph \cdot pix^{-1} \cdot GTU^{-1}$]	Extension on focal surface
Cosmic Ray	~ 200 μs	25 – 60	3×3 pixels box
Lightning	1 – 10 ms	$10^3 – 10^6$	PDM - FS
Meteor	100 ms – 2 s	500 – 2500	MAPMT
City	~ 1 s	50 – 500	Some pixels - FS
BCKG		~1	FS

Trigger

- **Purpose:** on board and real time data reduction
- **GTU:** 2,5 μs (4×10^5 GTU/s) roughly corresponds to the time a light signal takes to cross the pixel's diagonal for an horizontal shower (0.75 km)
- **Amount of data:** 1 Tb/s

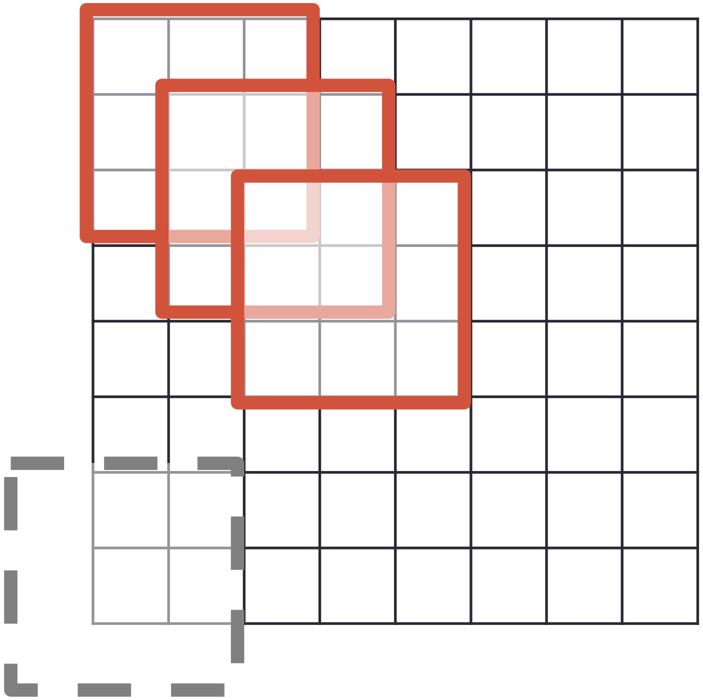
$$3,2\times10^5\, pixel \times 4\times10^5\, GTU/s \times 8bit/pixel \approx 1Tb/s$$

- **Available telemetry resources:** 300 kb/s
- **Needed data reduction:** 3×10^6 (1st + 2nd TL)

1st Level Trigger: persistency tracking trigger (PTT)

- **main objective:** reduce the rate of fake triggers to **1Hz/EC** (9 Hz/PDM)
- **Cosmic ray shower**:
  - generates persistent and spatially confined signal excesses above BCKG
  - the signal excess lasts at most 36 GTUs in the EC FoV
- **1st Level Trigger**:
  - operates at EC level
  - works with 128 GTU blocks
  - searches for signal excesses in 3×3 boxes lasting a few GTUs.

Trigger logic: the 3×3 pixel box



- 3×3 pixel boxes.
- 36 boxes in total in each MAPMT.
- Boxes work independently.
- They partially overlap.
- They cover the entire MAPMT.
- Different MAPMTs do not share any box.

Trigger logic

- N_{C1}: photoelectron counts of each pixel
- N_{C2}: photoelectron counts excess calculated over pixel threshold n^{pix}

$$N_{C2} = N_{C1} - \left(n^{pix} - 1\right)$$

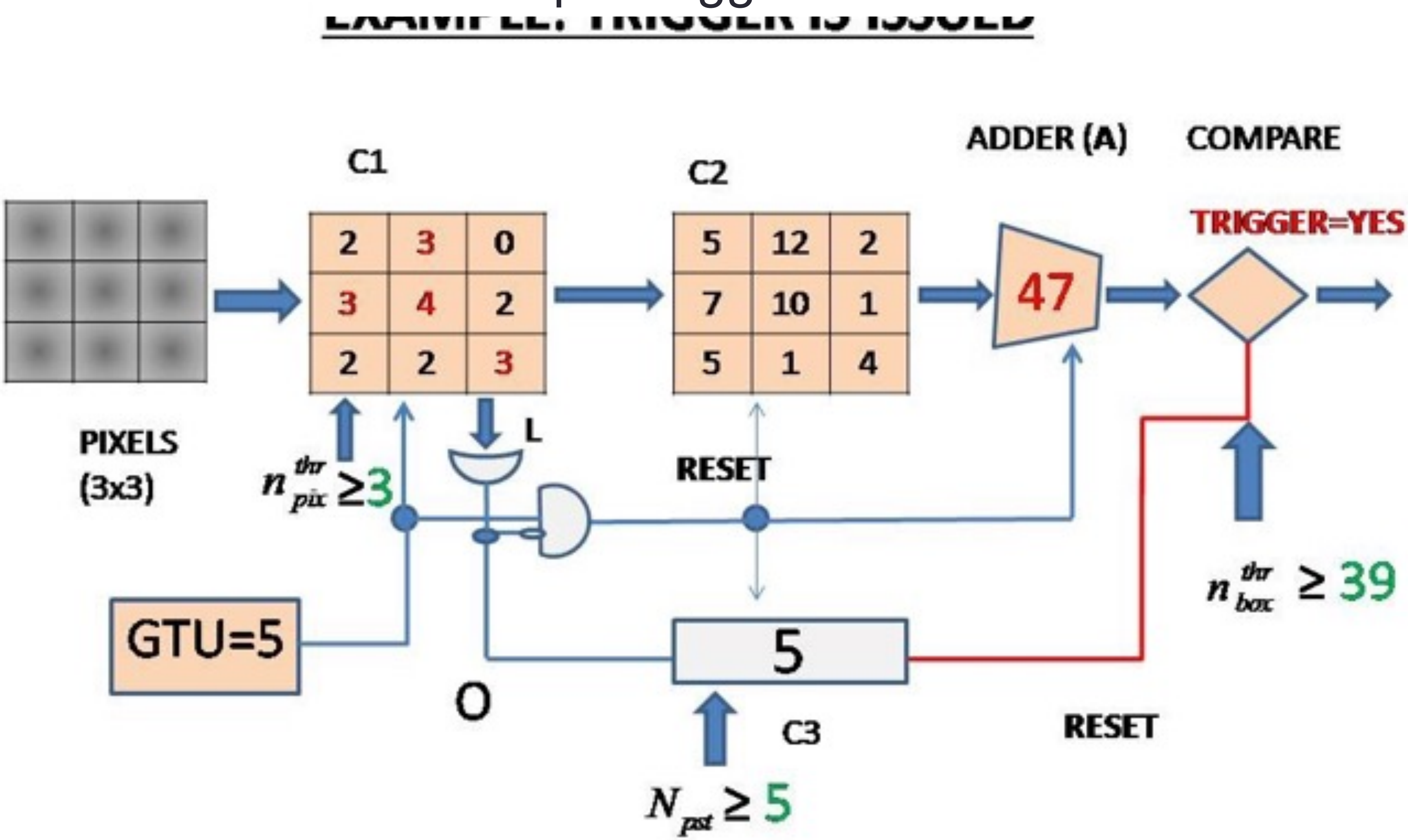
- Excesses on the 3×3 boxes summed up over a number of GTU N_{pst}
- Trigger is issued if the summation is greater or equal than a settled threshold n^{box}

$$\sum_{i=1}^{N_{pst}} \sum_{3\times3} N_{C2} \geq n^{box}$$

Example parameters	
n^{pix}	3
n^{box}	39
N_{pst}	5

Example now!

Example: trigger is issued



$$N_{C2} = N_{C1} - n_{pix}^{thr} + 1$$

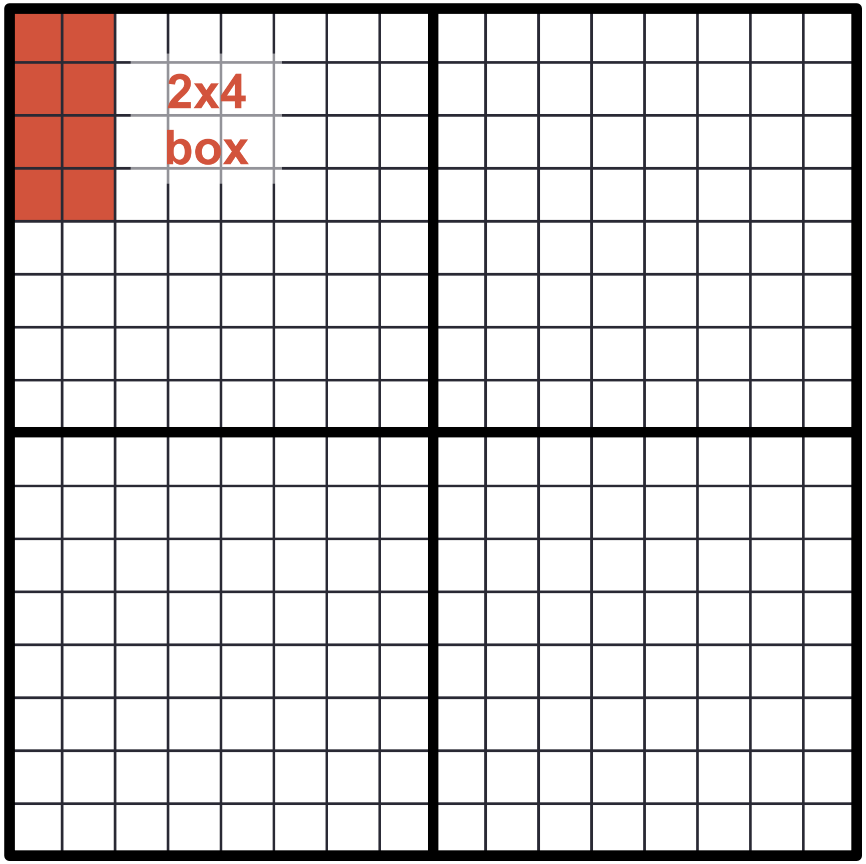
Thresholds

$500 \frac{phe}{m^2 \cdot ns \cdot sr}$ → 1,0

BCKG	n^{pix}	n^{box}	BCKG	n^{pix}	n^{box}
0,5	1	26	3,5	5	68
	...			...	
1,0	2	31	4,0	6	64
	...			...	
1,5	2	53	4,5	7	61
	...			...	
2,0	3	54	5,0	7	78
	...			...	
2,5	4	50	5,5	8	64
	...			...	
3,0	5	46	6,0	8	78

6,0 ← $3000 \frac{phe}{m^2 \cdot ns \cdot sr}$

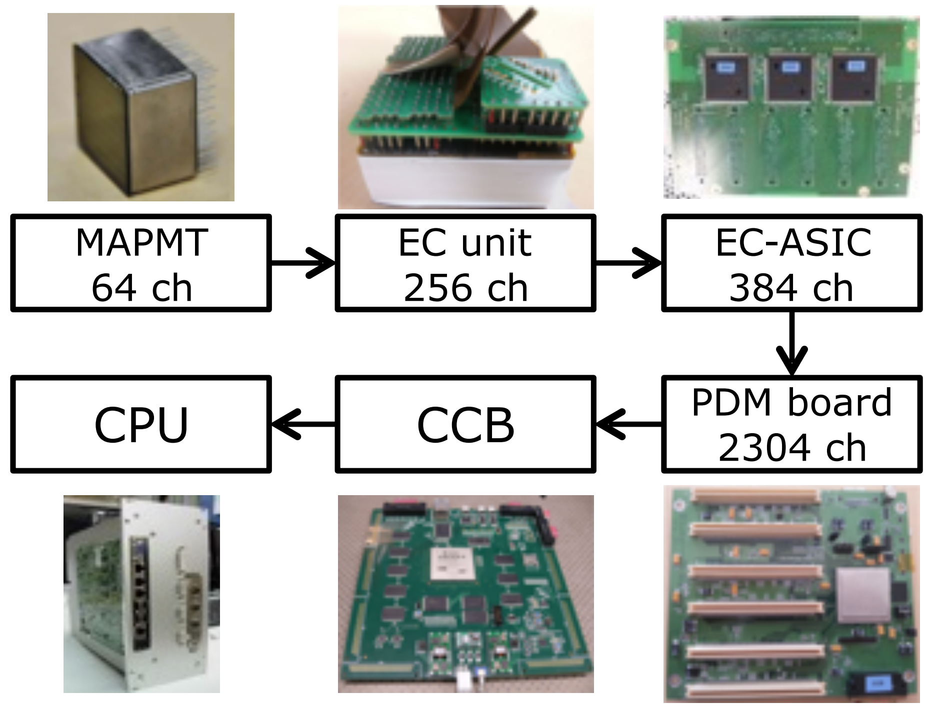
Dynamic threshold setting



- The EC subdivided into 32 2×4 boxes
- 2×4 pixels = 1×2 km^2 area at the ground
- no overlap
- Using a 128 GTU average the relative error is of the order of 3%
- threshold set according to the maximum average background every 128 GTU

Implemented, now testing

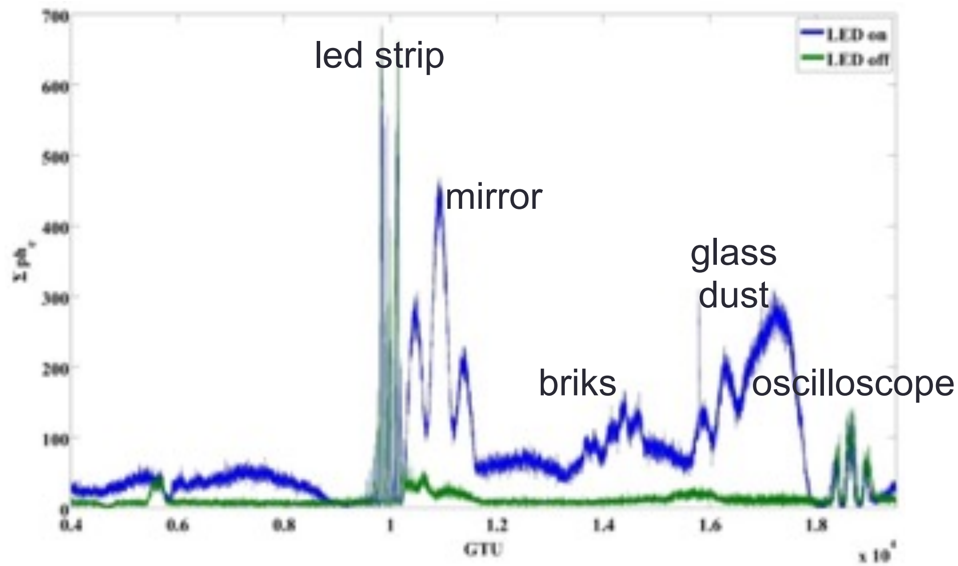
- 1st TL implemented in **FORTRAN**, easy to: **read**, **debug**, **run** and **modify**.

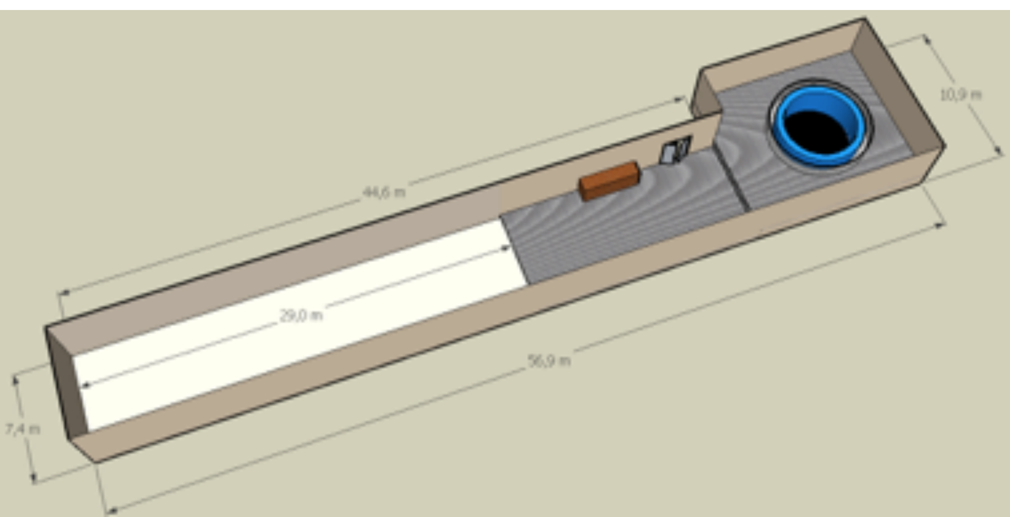


- 1st TL also implemented in **VHDL** code to configure **FPGA**
- FPGA resources employed: 7%
- Cross check between VHDL and FORTRAN: same input → same output.

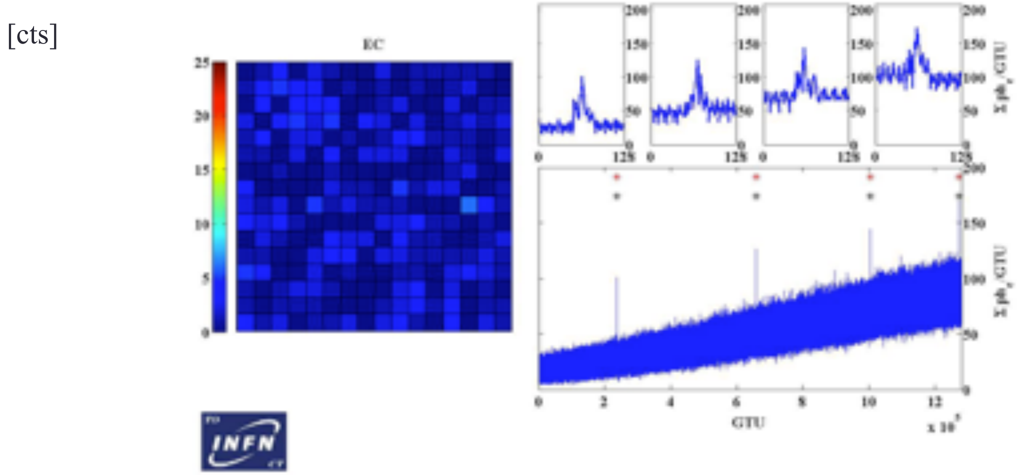
TurLab current setup

- Rotating tank replicates movement of FoV
- 5×5 pixels MAPMT
- One lens
- Light sources
- Different albedo materials
- electronics

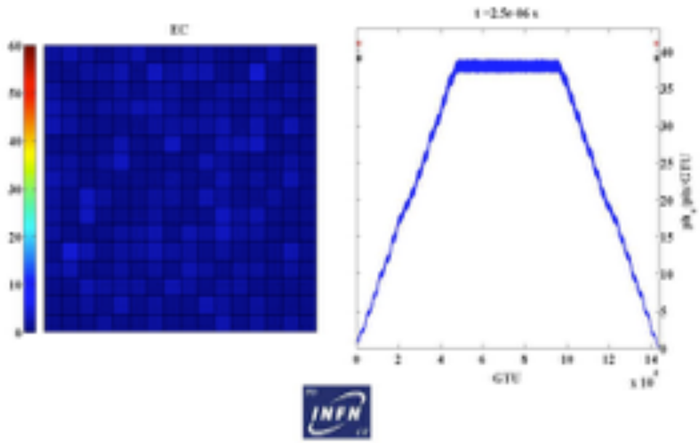


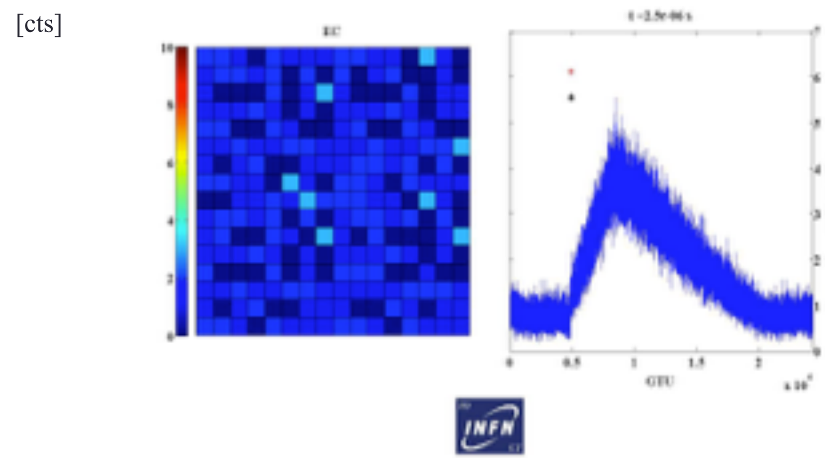


TurLab replicas



Cosmic Ray

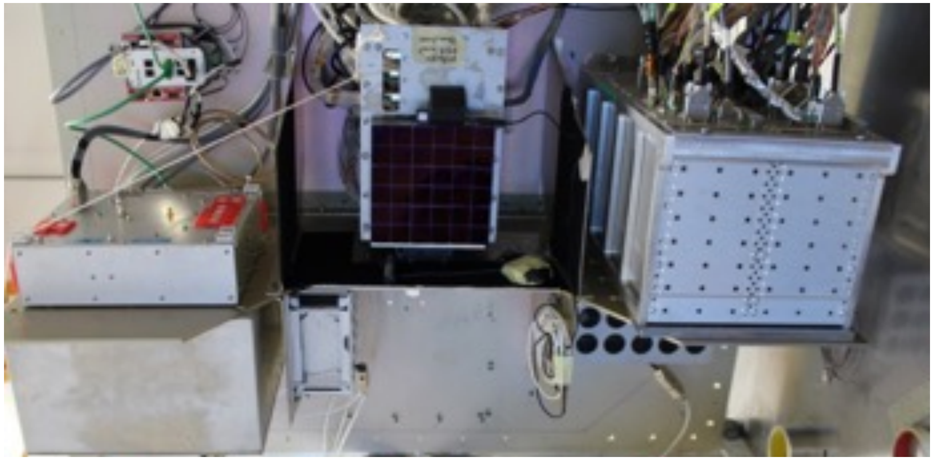


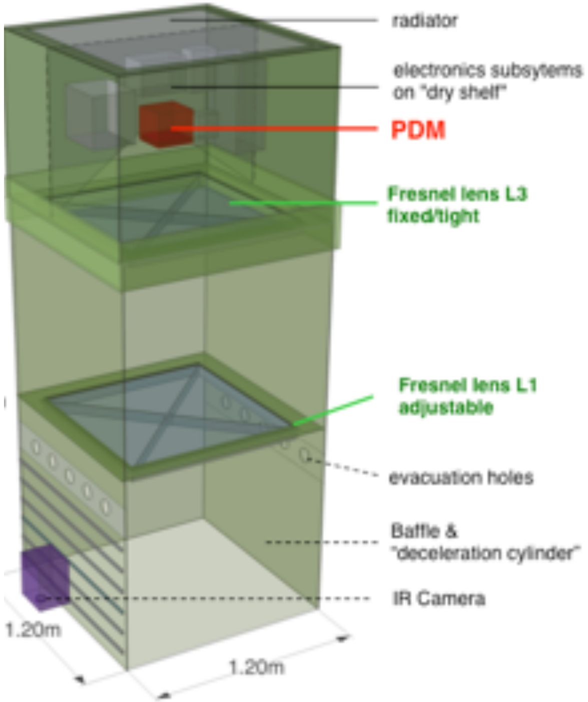


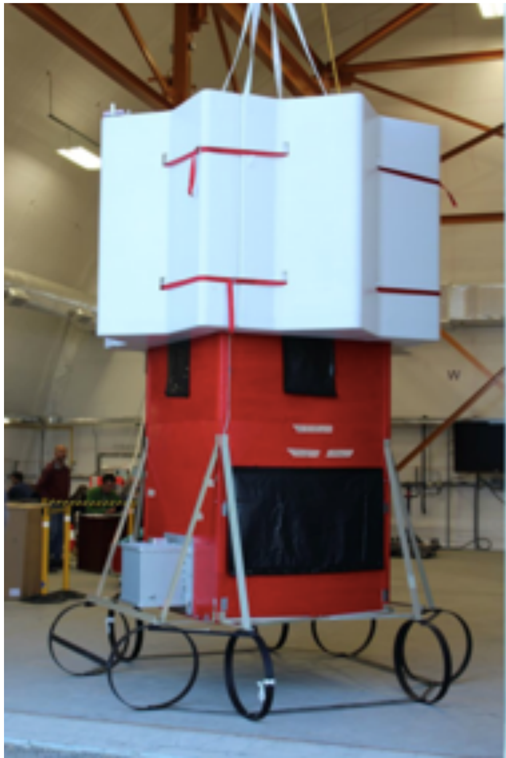
Transition over a city

Lightning

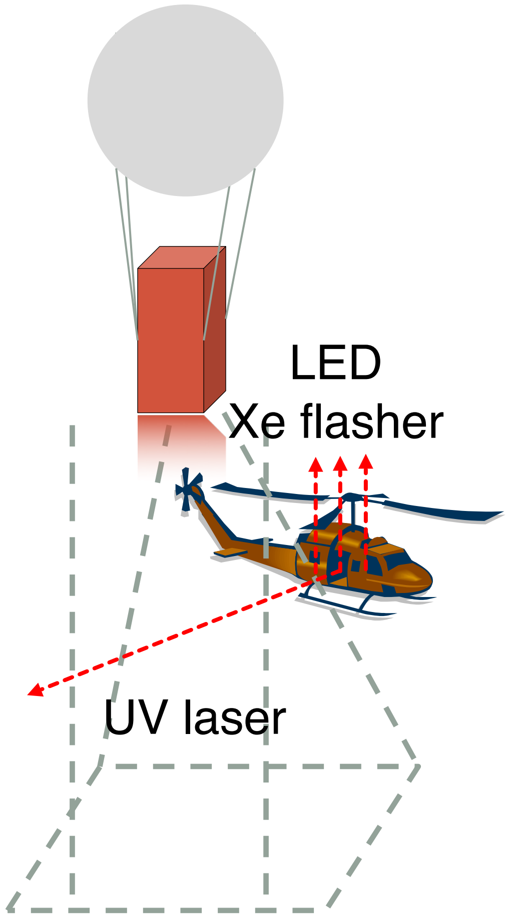
EUSO-Balloon

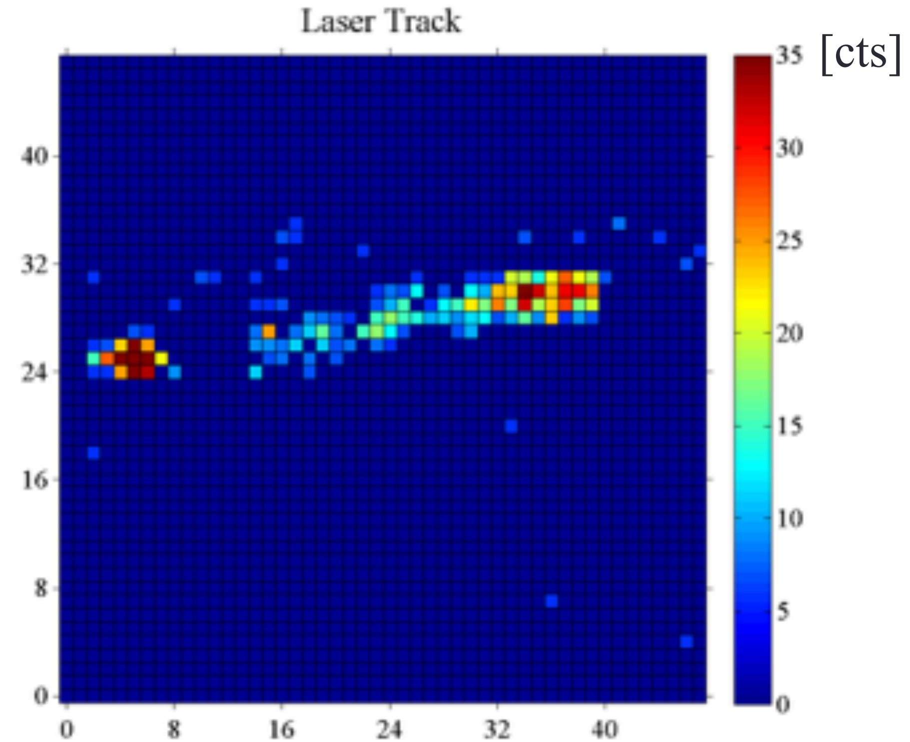






EUSO-Balloon



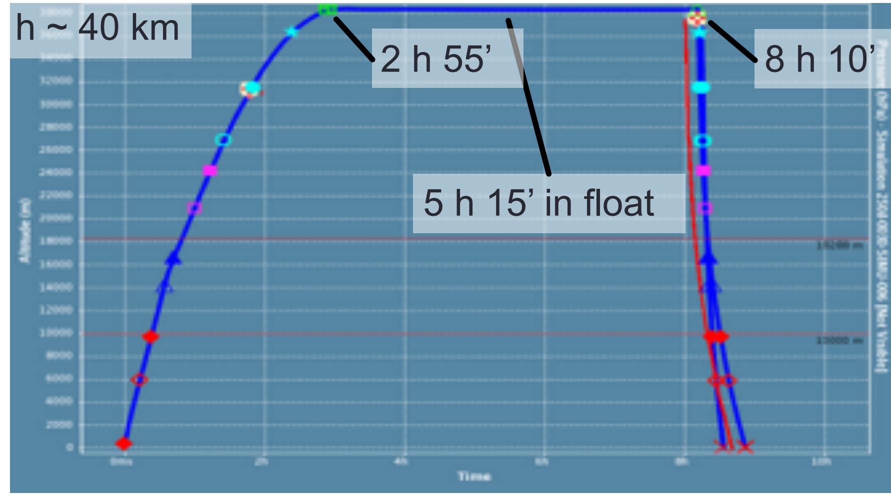


UV light sources:

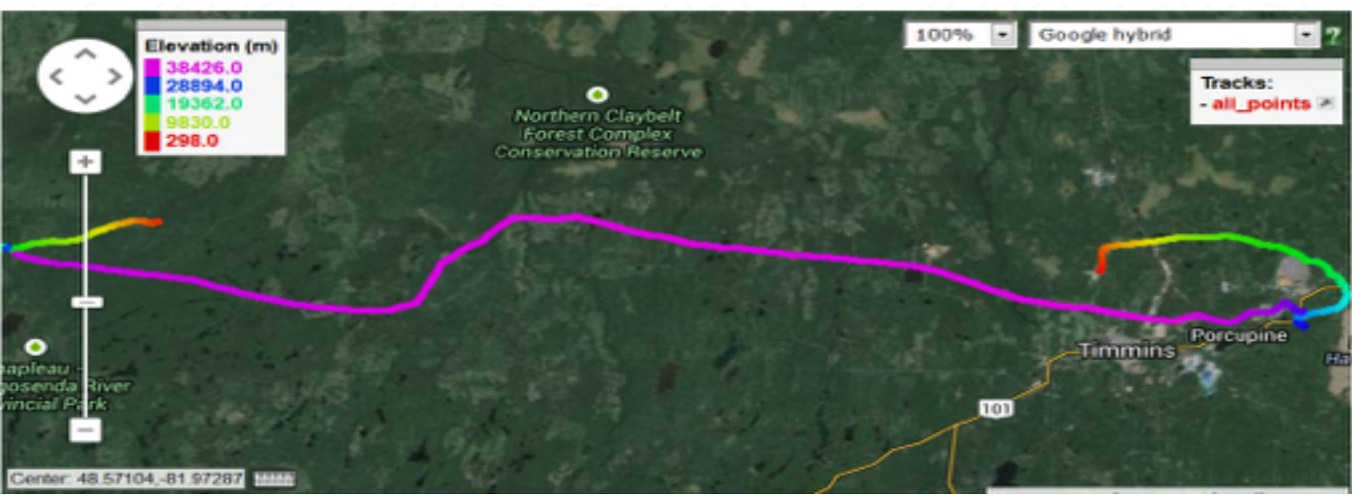
- **LED:** pointed directly to detector
- **Flash:** pointed directly to detector
- **UV Laser**: laser pulsed across FoV
- 5 mJ Laser ~ 10^{20} eV CR

EUSO-Balloon flight

Date of flight: 08/25/2015

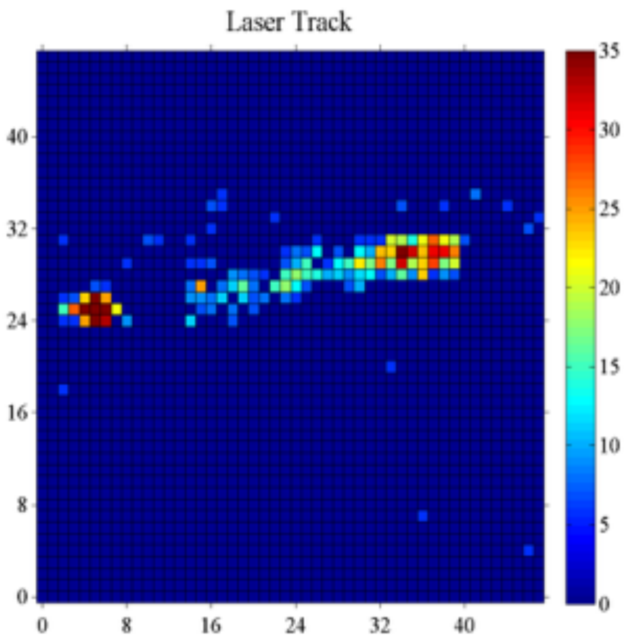


Vertical profile of the 9 hours flight of EUSO-Balloon

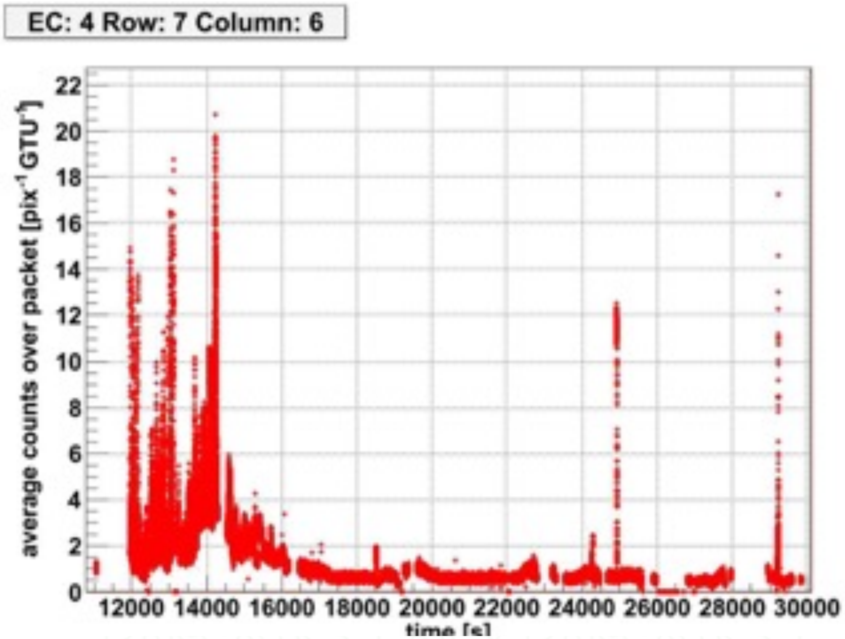


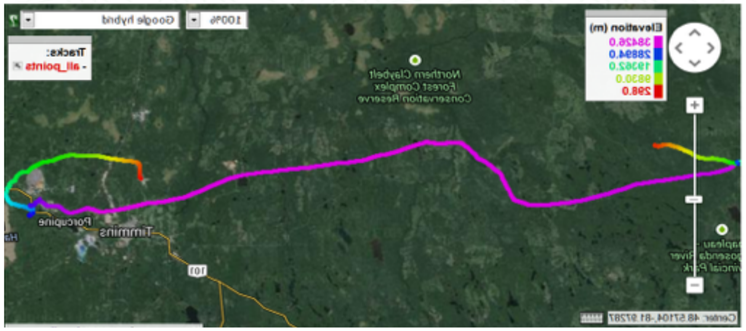
Horizontal profile of the 9 hours flight of EUSO-Balloon

Data from PDM and IR camera



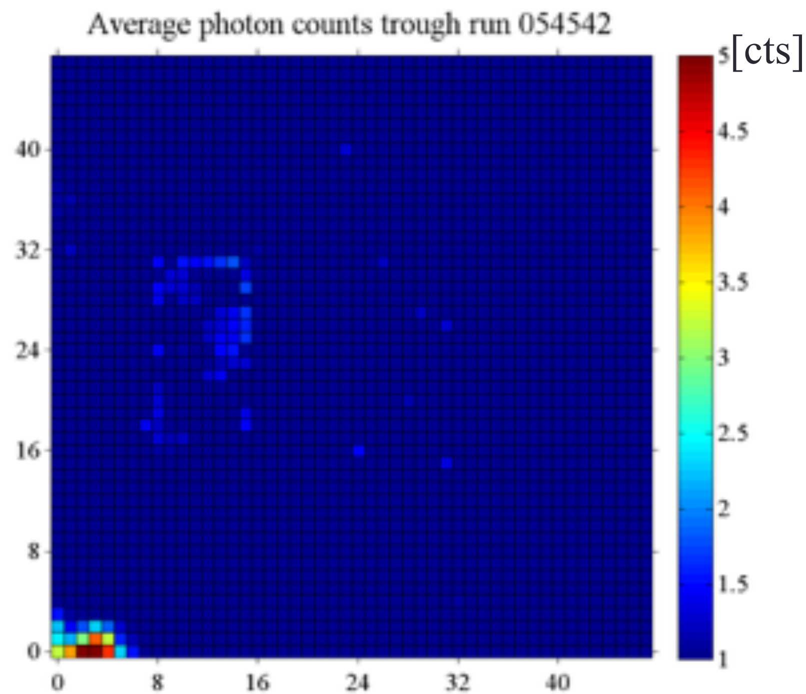
Laser track as detected by the PDM





Evolution of one pixel during the entire flight

Trigger conditions



BCKG conditions:

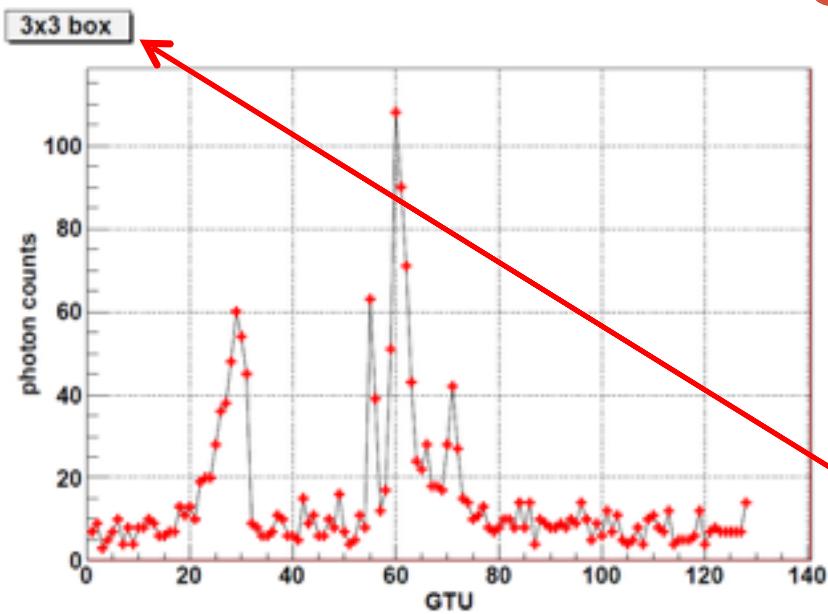
- Ground light sources
- Background fluctuation
- Balloon rotation movement

Data taking conditions:

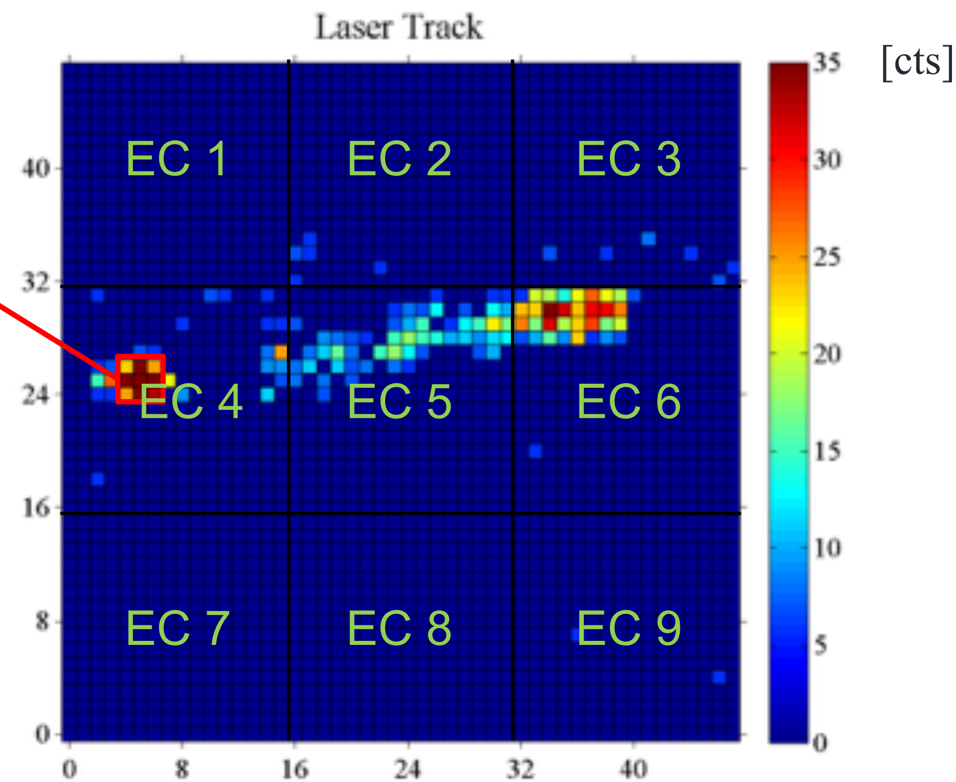
- GPS synchronization between helicopter and balloon clock (lost during the flight)
- Taking 128 GTU packets with 20 Hz rate, a problem for our thresholds algorithm

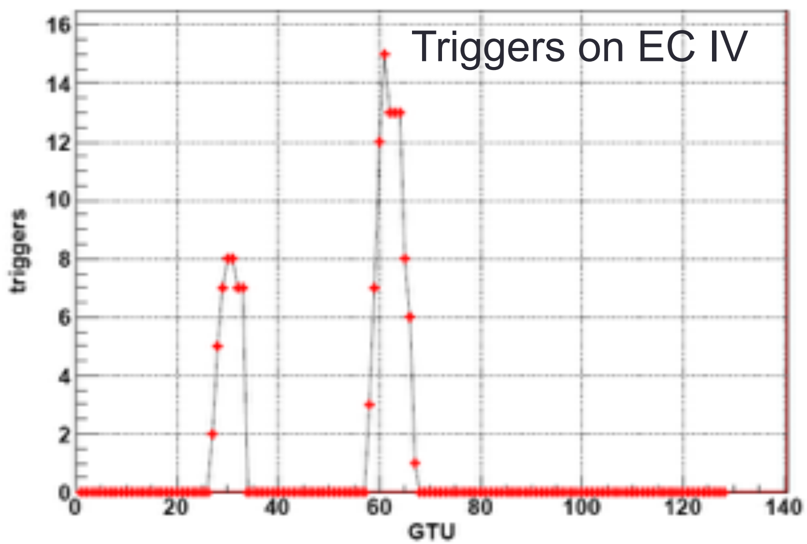
Most serious problems: balloon rotation and delay from packet to packet

First check of trigger response



Evolution through the entire run of counts on the 3×3 box centered on the most counting pixel.

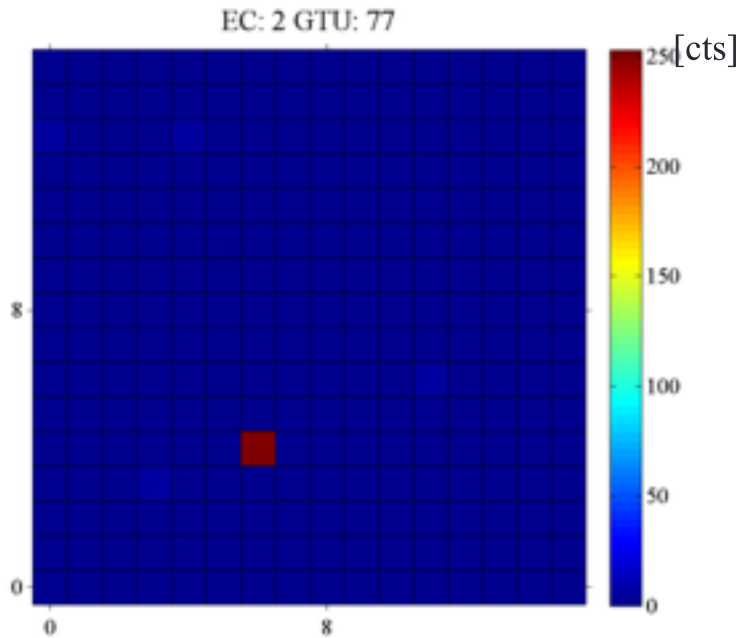




Triggers on EC 4 as a function of time.

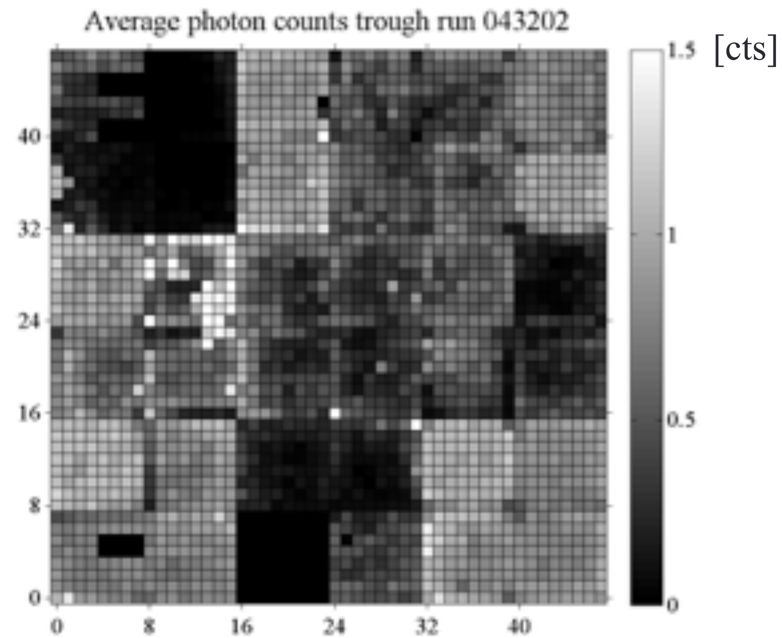
Problems with raw data

Out of control pixels



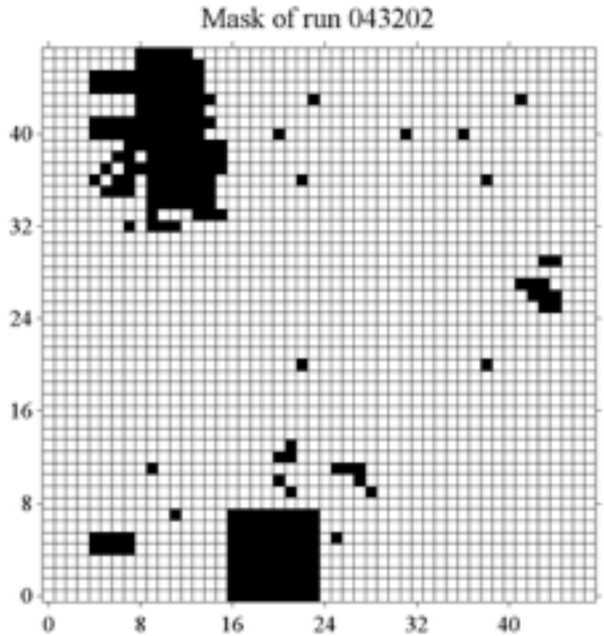
- Isolated pixels, in some GTUs, give us a lot of photon counts.
- This number is not due to light source
- It is a problem for the trigger logic

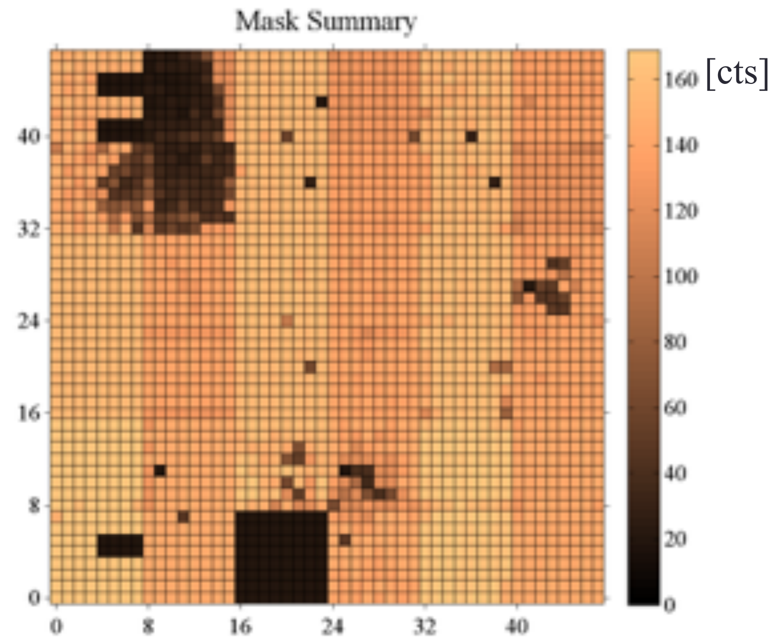
Low efficiency areas



- Some pixels of the EC have very low gain
- BCKG on 2×4 boxes is underestimated

Our solution: the **mask**





We generate a mask to:

- Remove all the pixels that give too many counts
- Do not count turned off pixels in the 2×4 average threshold algorithm to calculate a more reasonable BCKG

1st TL performance

041731 – 052559 (dark BCKG)

Run	Trigger	Laser	Other sources
041731	16	14	2
042351	1	1	0
042407	15	14	1
042614	3	3	0
042806	9	0	9
042957	9	7	2
043147	0	0	0
043202	20	18	2
043401	5	2	3
051610	25	24	1
051805	7	5	2
051959	6	5	1
052152	15	10	5
052344	1	1	0
052358	38	19	19
052559	14	5	9
	184	**128**	**56**

$$\nu = \frac{56}{8{,}5s} \approx 6{,}6 \frac{Hz}{PDM}$$

052753 – 254542 (very noisy BCKG)

Run	Trigger	Laser	Other sources
052753	199	29	170
052945	272	14	258
053139	29	0	29
053154	141	15	126
053352	283	6	277
053550	101	23	78
053743	167	5	162
053936	43	2	41
053951	221	14	207
054152	93	9	84
054348	272	21	251
054542	269	11	258
	2090	**149**	**1941**

$$\nu = \frac{1941}{6{,}5s} \approx 300 \frac{Hz}{PDM}$$

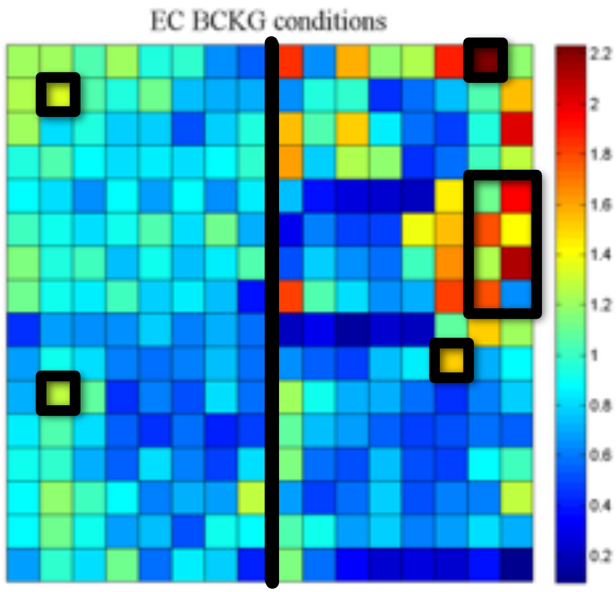
BCKG calculation using single pixel

Thresholds:

- Calculated using single pixel average over 128 GTU
- Settled at MAPMT level

Using "2×4" Algorithm:

- BCKG: 1,5
- n^{pix}: 2
- n^{box}: 53



Using "Single pixel" Algorithm:

MAPMT	BCKG [phe·pix⁻¹GTU⁻¹]	n^{pix}	n^{box}
Top left	1,3	2	45
Top right	2,2	3	62
Bottom left	1,3	2	45
Bottom right	1,5	2	53

“Single pixel” algorithm performances

041731 – 052559 (dark BCKG)

Run	Trigger	Laser	Other sources
041731	12	11	1
042351	1	1	0
042407	15	15	0
042614	3	3	0
042806	0	0	0
042957	9	7	2
043147	0	0	0
043202	20	19	1
043401	3	3	0
051610	24	23	1
051805	4	4	0
051959	6	5	1
052152	13	10	3
052344	1	1	0
052358	23	19	4
052559	9	5	4
	143	126	17

$$\nu = \frac{17}{8{,}5s} \approx 2{,}0 \frac{Hz}{PDM}$$

052753 – 254542 (very noisy BCKG)

Run	Trigger	Laser	Other sources
052753	32	29	3
052945	20	14	6
053139	1	0	1
053154	36	14	22
053352	8	6	2
053550	27	23	4
053743	10	5	5
053936	3	1	2
053951	15	14	1
054152	12	9	3
054348	29	21	8
054542	14	12	2
	207	148	59

$$\nu = \frac{59}{6{,}5s} \approx 9{,}1 \frac{Hz}{PDM}$$

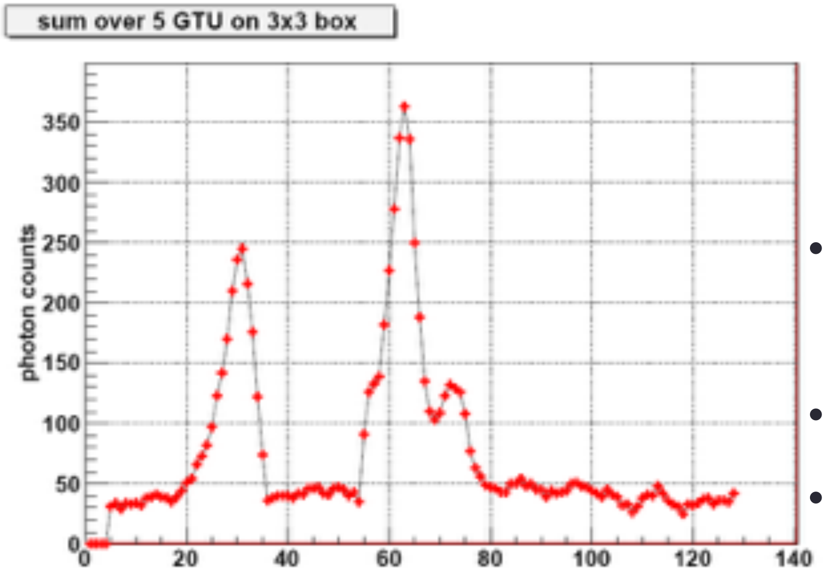
“2×4” vs “Single Pixel”

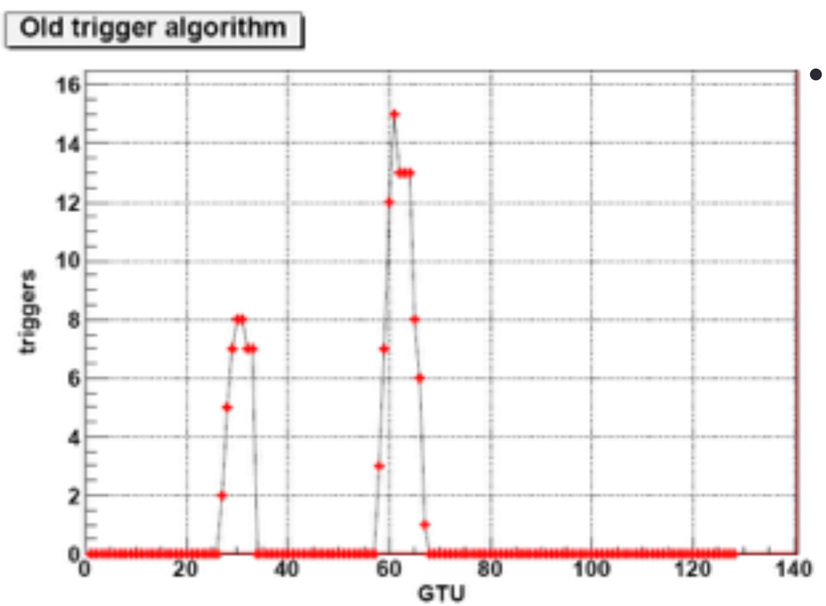
Version	Dark BCKG	Ground light source	Total
2×4	128	149	277
Single pixel	126	148	274

sample	$N_{2\times4}$	N_S	$N_{2\times4}-N_S$	$(N_{2\times4}-N_S)/N_{2\times4}$
All	105129	82314	22815	0,22
STD BCKG	**28660**	**24902**	**3758**	**0,13**
VN BCKG	76469	57412	19057	0,25

There is a 13% loss of triggering boxes as a result of setting thresholds at MAPMT level according to the highest BCKG value on the MAPMT.

Energy Threshold





- Average **signal** on which the trigger shoot: 81±13 counts
- Average **noise** on relative 33 box: 39 ±1 counts
- Average **ratio** between the signal and the noise: 2.1±0.3
- This kind of signal excess in expected in a CR event with E ~ 5×10^{18} eV

Conclusions

- The 1st TL of JEM-EUSO was tested at TurLab and using EUSO-Balloon data.
- The original version of the 1st TL was successful triggering on:
  - Replicas of cosmic ray events at TurLab (performed using Arduino platform)
  - Laser events of EUSO-Balloon
- Data from EUSO-Balloon shows too high rate of triggers due to:
  - strong non-uniformity of pixel response,
  - Electronic noise,
  - Not suitable definition of BCKG level.
- “Single Pixel” version of 1st TL implemented:
  - It allows the correct BCKG calculation algorithm,
  - Rate of triggers on laser events decrease of 13%.

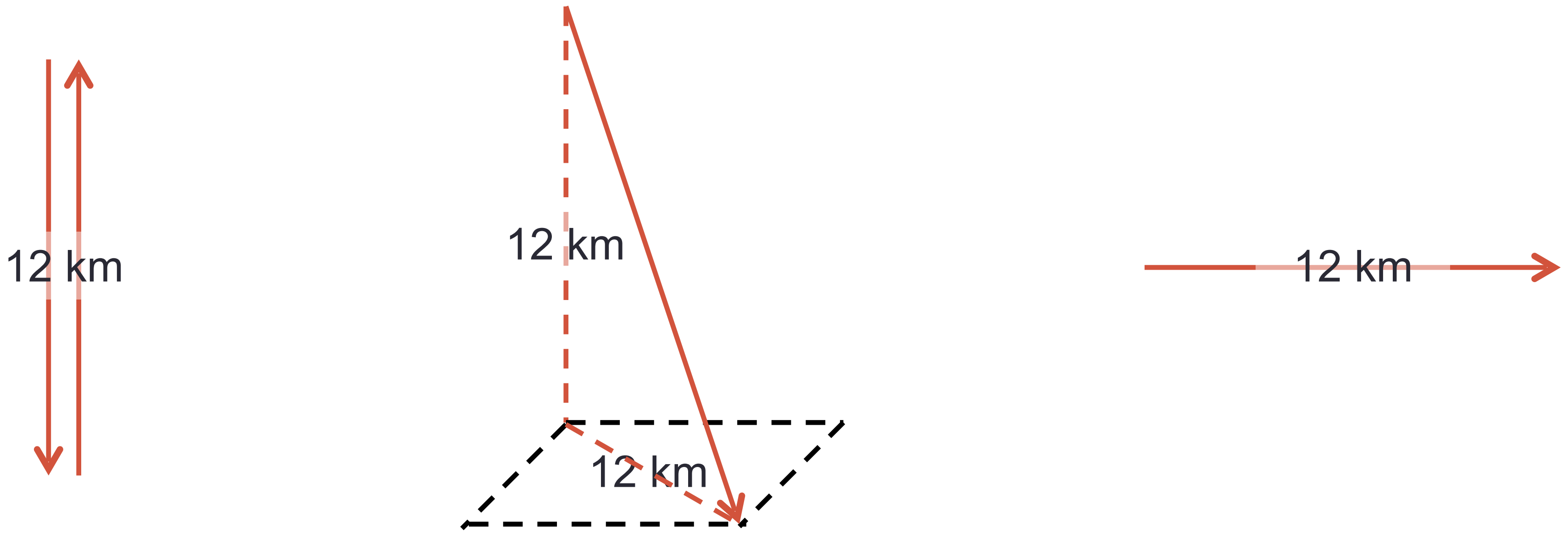
Next steps

- Current version of VHDL code employs the 11% of FPGA resources, modifications will be implemented to decrease this use and to better fit with specific FPGA
- Going to test at TurLab an EC similar to balloon one as a part of Eu-HIT project:
  - “Detection and Imaging of turbulent states of ocean and atmosphere by means of a JEM-EUSO-like detector at the TurLab facility (EUSO@TurLab)”.
  - Responsible: Dr. Sylvie Dagoret-Campagne Laboratoire de l'Accelerateur Lineaire, Universite Paris Sud-XI
- In next months I will continue those activities with EUSO-Balloon data during an Erasmus Traineeship in Laboratoire de l'Accelerateur Lineaire, Universite Paris Sud-XI.

Thank You!!!

- Pubblications related to my work:
  - M. Bertaina,..., G.Suino,..., for the JEM-EUSO Coll..: "EUSO@TurLab: An experimental replica of ISS orbits" EPJ Web of Conferences, Vol. 89, pag. 03003 (2015)
  - G. Suino et al. for the JEM-EUSO Coll.: "Test of JEM-EUSO 1st level trigger using EUSO-Balloon data", Proc. 34th International Cosmic Ray Conference, Den Haag, 29 Jul - 6 Aug 2015.
  - G. Contino, ... G. Suino, et al. for the JEM-EUSO Coll.: "The EUSO@TurLab project", Proc. 34th International Cosmic Ray Conference, Den Haag, 29 Jul - 6 Aug 2015.

Lifespan of a CR signal in an EC



$$\Delta t = 2\frac{12km}{0{,}75\frac{km}{GTU}} = 32GTU$$

$$\Delta t = \frac{12km}{0{,}75\frac{km}{GTU}\tan\left(\frac{\pi/4}{2}\right)} = 39GTU$$

$$\Delta t = \frac{12km}{0{,}75\frac{km}{GTU}\tan\left(\frac{\pi/2}{2}\right)} = 16GTU$$

$$\Delta t = \frac{\Delta s[km]}{0{,}75\left[\frac{km}{GTU}\right]\tan\left(\frac{\vartheta}{2}\right)} = [GTU]$$

Preliminary helicopter triggers

Run				EC-II				EC-V			EC-VI				EC-VIII			EC-IX			Helicopter
Type	number	**packet**	…	**gtu**	**x**	**y**	…	**gtu**	**x**	**y**	**gtu**	**x**	**y**	…	**gtu**	**x**	**y**	**gtu**	**x**	**y**	
CPU	052344	**84**		**24**	**17**	**43**		**20**	**25**	**25**	**19**	**35**	**22**		**24**	**30**	**13**	**21**	**33**	**14**	Y

A laser event is typically characterized by few ECs triggering almost in time.

In the table we reported:

For each **packet** and **EC** where a trigger occurs, the **position of the 3×3 cell** which gave the maximum signal excess and the relative **GTU.**

Founded around 240 laser events

Still remaining some false trigger!

"Single pixel 2 GTU" algorithm features

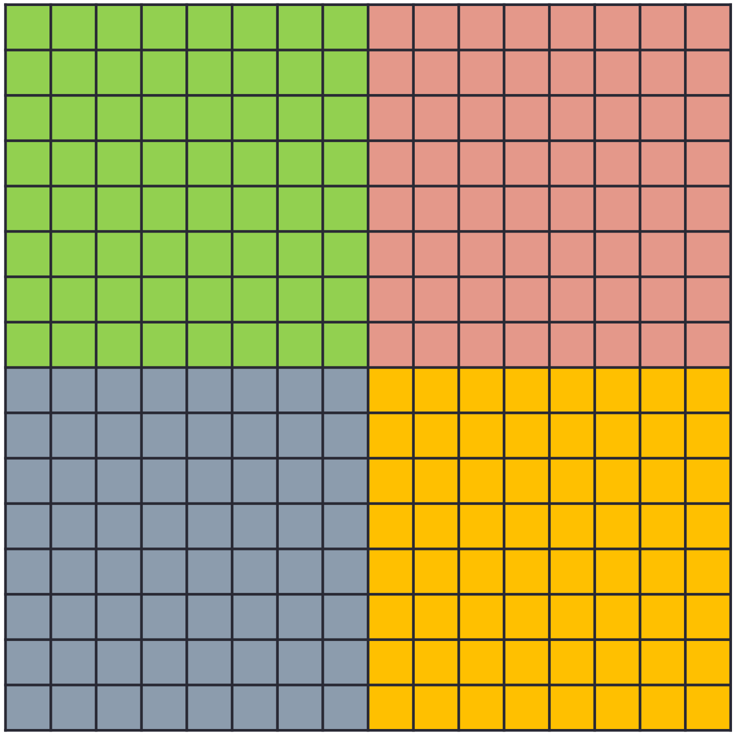
Check:

- done on the summation of counts of 3×3 boxes **over 2 consecutive GTU**

$$\sum_{i=1}^{2} \sum_{3\times3} N \geq n^{box}$$

Thresholds:

- Calculated using single pixel average over 128 GTU
- Settled at MAPMT level



"Single pixel 2 GTU" algorithm performance

041731 – 052559 (dark BCKG)

RUN	trigger	true	?
041731	13	11	2
042351	2	1	1
042407	14	14	0
042614	3	3	0
042806	0	6	0
042957	8	5	3
043147	0	0	0
043202	18	18	0
043401	2	2	0
051610	26	25	1
051805	5	5	0
051959	6	5	1
052152	13	10	3
052344	1	1	0
052358	22	18	4
052559	10	5	5
	143	**129**	**20**

$$\nu = \frac{20}{8{,}5s} \approx 2{,}4Hz$$

052753 – 254542 (very noisy BCKG)

RUN	trigger	true	?
052753	33	27	6
052945	27	15	12
053139	1	0	1
053154	21	13	8
053352	9	6	3
053550	30	24	6
053743	8	5	3
053936	2	2	0
053951	16	14	2
054152	13	9	4
054348	27	21	6
054542	16	12	4
	203	**148**	**55**

$$\nu = \frac{55}{6{,}5s} \approx 8{,}5Hz$$