Skobeltsyn Institute of Nuclear Physics

Lomonosov Moscow State University

Recent results from the TUS/LOMONOSOV Space Mission

Klimov P.A.

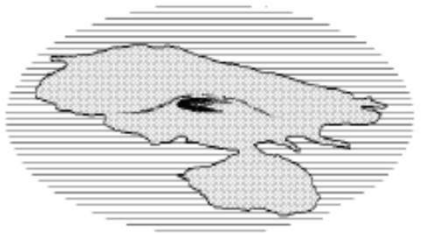
for the Lomonosov-UHECR/TLE collaboration

JEM-EUSO program

VULCANO WORKSHOP 2018

May 20-26, Vulcano, Italy

FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

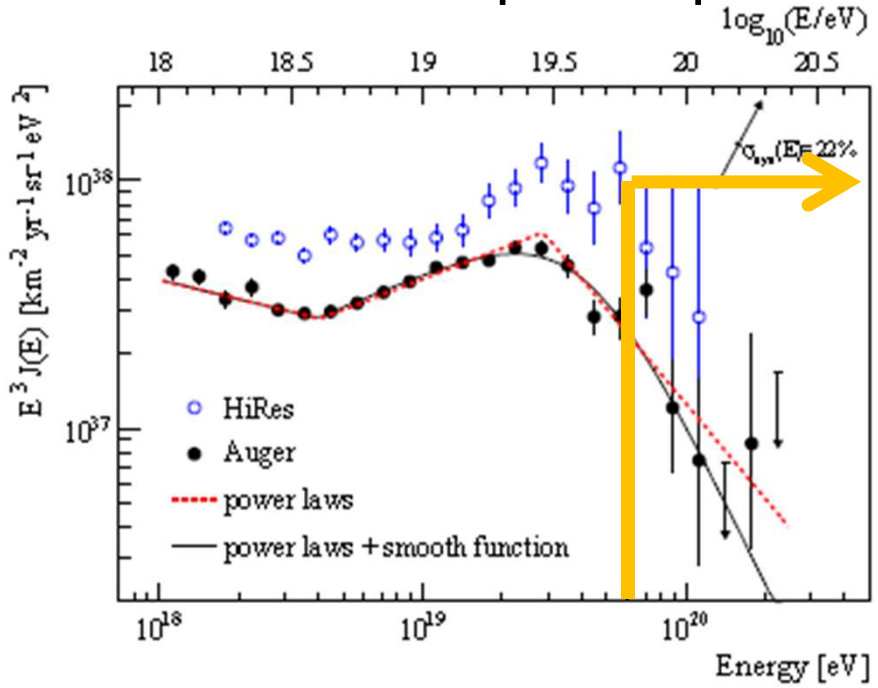


Outline

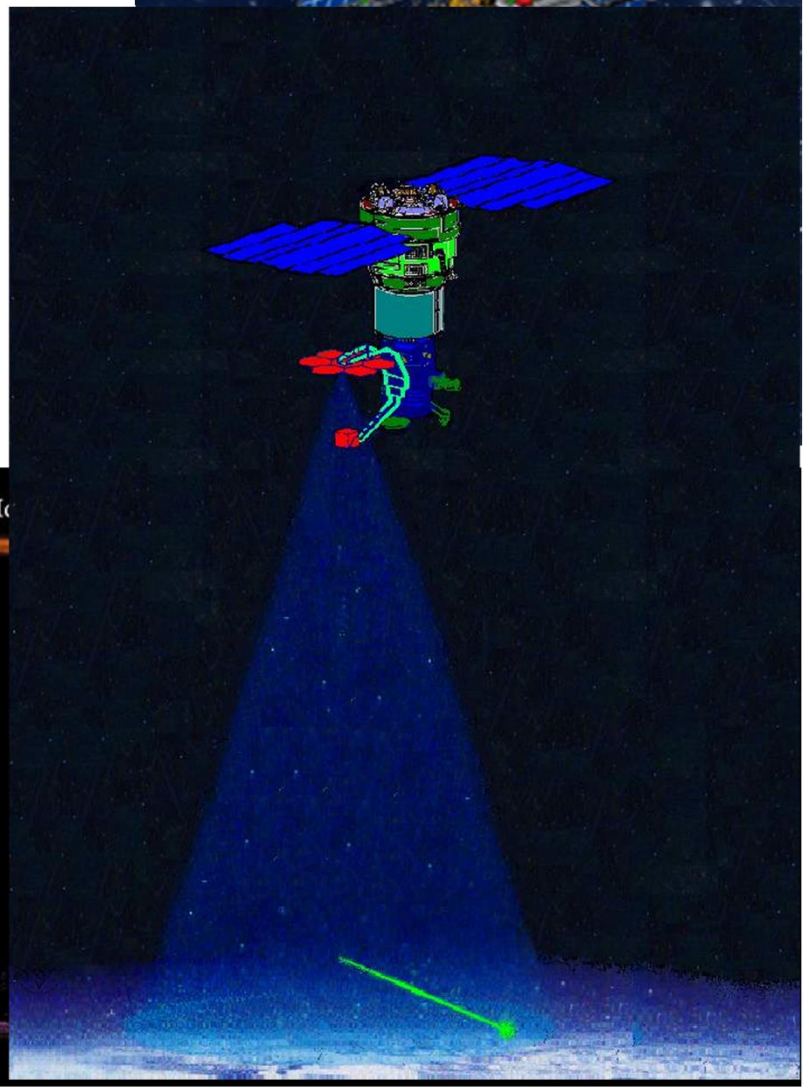
- The TUS detector
- The TUS data and types of events
- Search and analyses of UHECR EAS candidates
- Unusual events
- Conclusions and future plans

Scientific goals of the experiment

Detector TUS is designed as a multifunctional orbital telescope for various luminous atmospheric processes research.

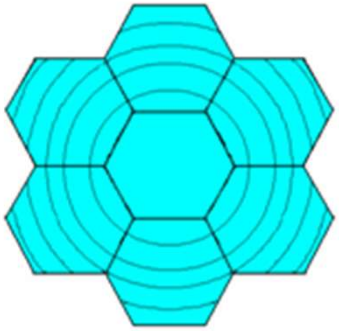


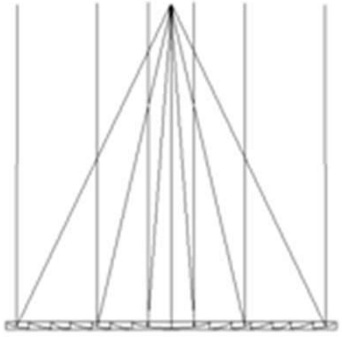
The Pierre Auger Collaboration, Physics Letters B 685, (2010) 239



I. First UHECR measurements from space
II. Transient atmospheric phenomena in UV

TUS detector on board the Lomonosov satellite





Fresnel type mirror-concentrator

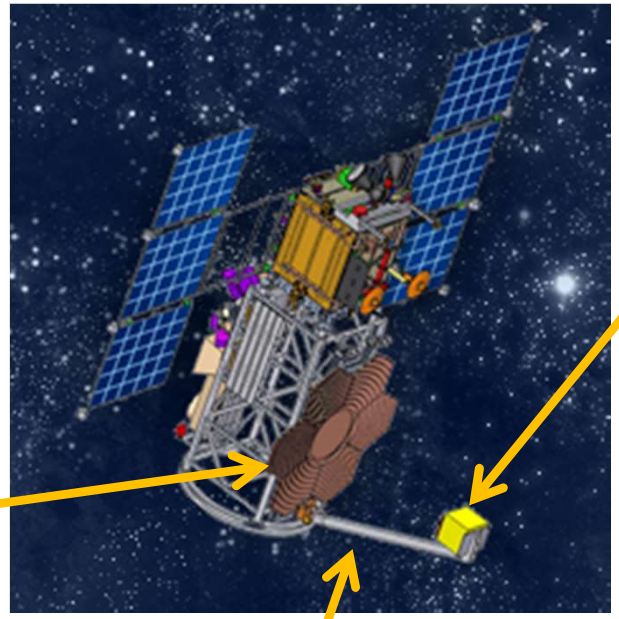
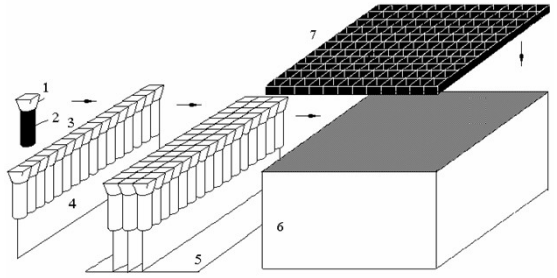


Photo receiver moving system



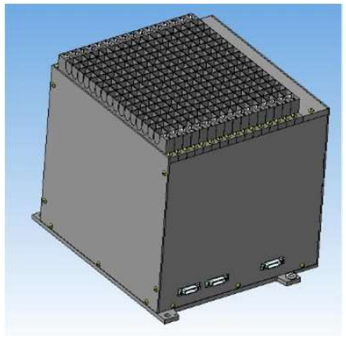


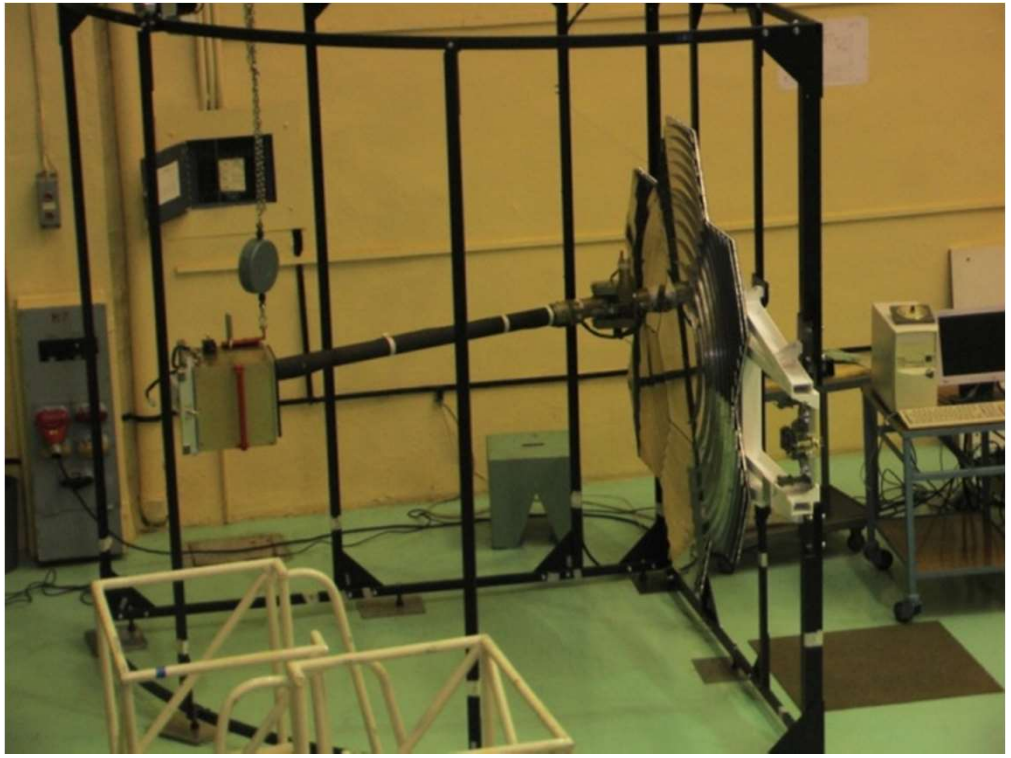
Photo receiver

Mass	60 kg
Power	65 W
FOV	±4,5 degree
Channels	16 modules of 16 PMTs
Pixel size	10 mrad (5×5 km)
Mirror area	~2 m^2
Duty cycle	30%

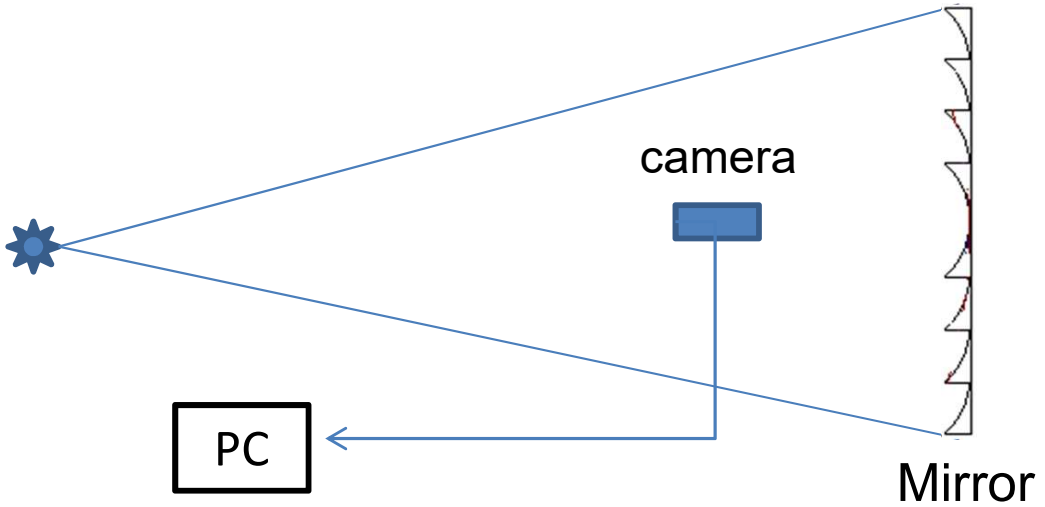
TUS detector trigger and modes of operation

Phenomena	Time sample	Integration time	Oscillogram length
EAS	$\tau = \tau_0 = 0.8$ μs	$t = 2^4\tau = 12.8$ μs	$\Delta T = 256\tau = 205$ μs
Short TLE (elves)	$\tau = 2^5\tau_0 = 25.6$ μs	$t = 2^3\tau = 0.2$ ms	$\Delta T = 256\tau = 6.6$ ms
Long TLE (sprites, jets)	$\tau = 2^9\tau_0 = 0.4$ ms	$t = \tau = 0.4$ ms	$\Delta T = 256\tau = 105$ ms
Micro-meteor	$\tau = 2^{13}\tau_0 = 6.6$ ms	$t = 2^4\tau = 105$ ms	$\Delta T = 256\tau = 1.7$ s

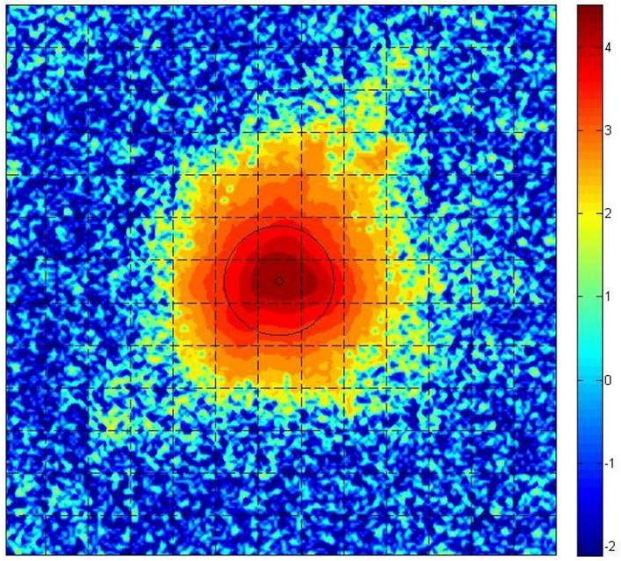
Tests in MSU and NIIEM



PSF measurements in NIIEM, Istra

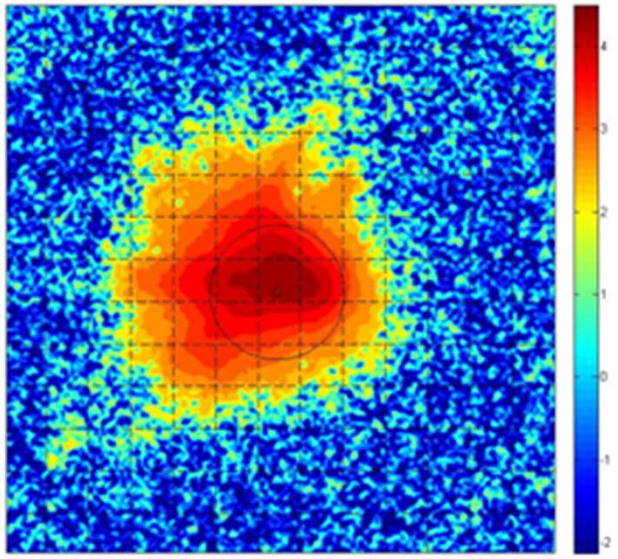


θ = 0°



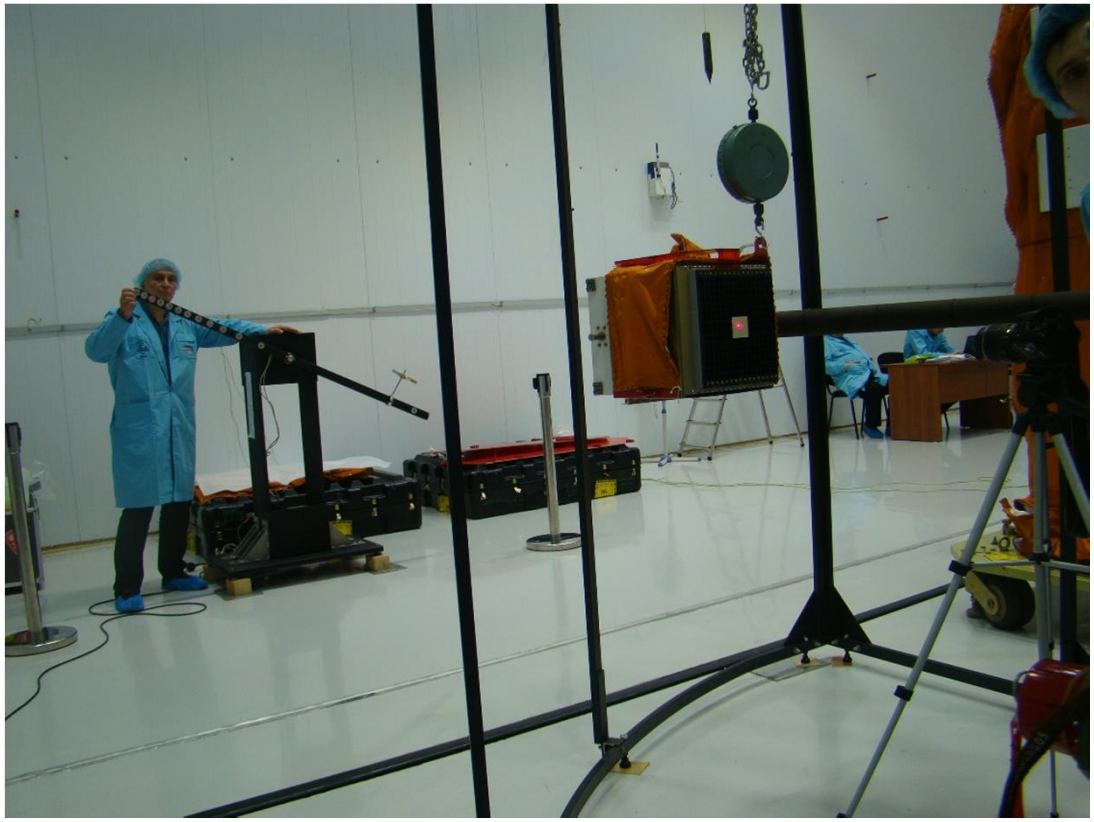
$D_{1/2}$ = 11 mm, D_{70} = 20 mm

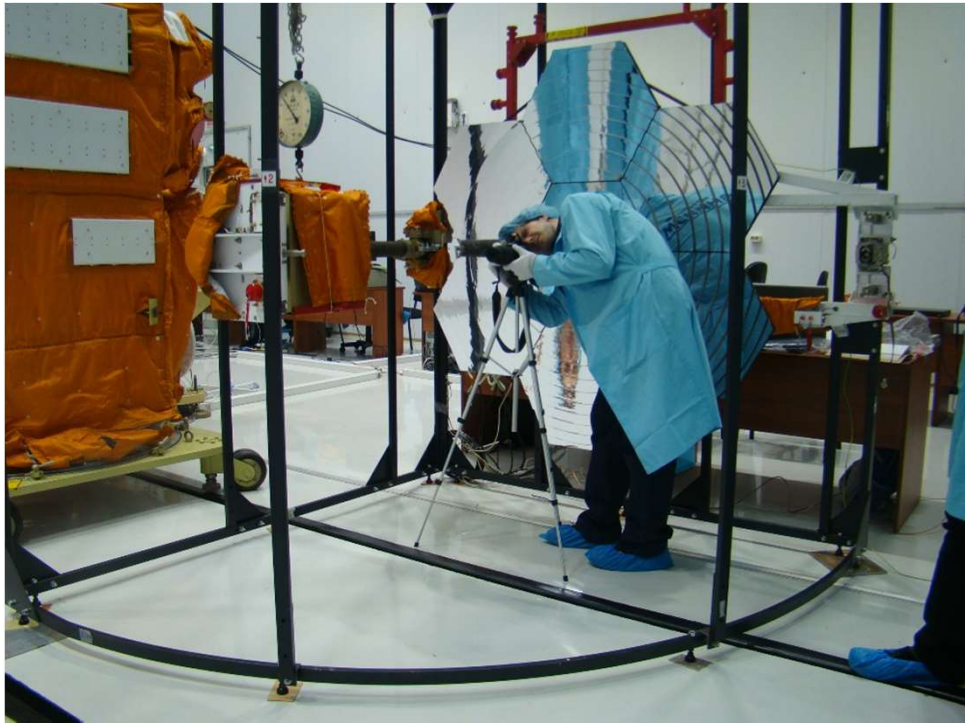
θ = 3,5°

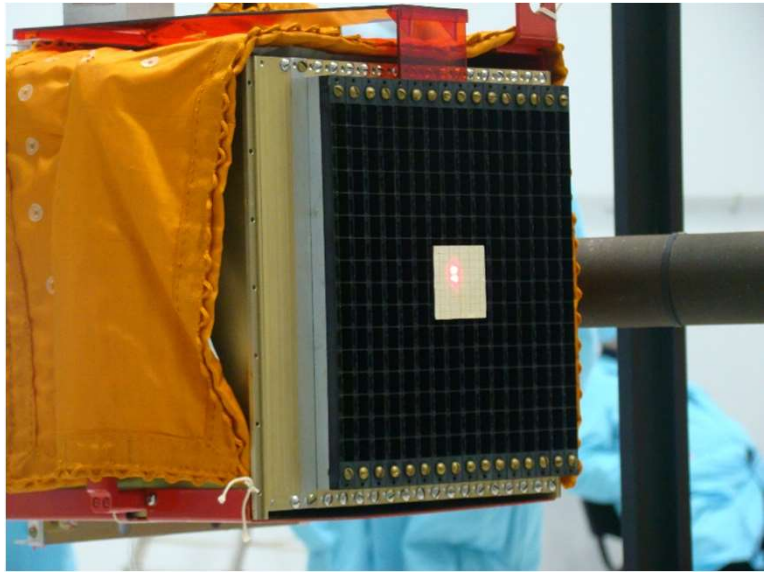


$D_{1/2}$ = 15 mm, D_{70} = 27 mm

Preflight tests on the cosmodrome Vostochny







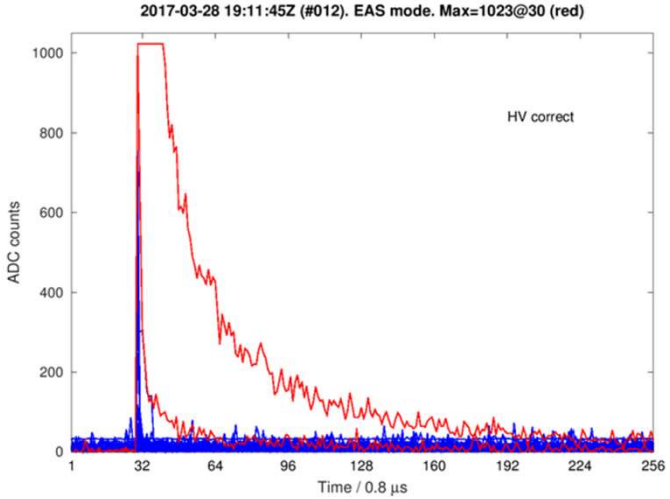

ПОЛЕТНЫЙ
ГОЛОВНОЙ!!

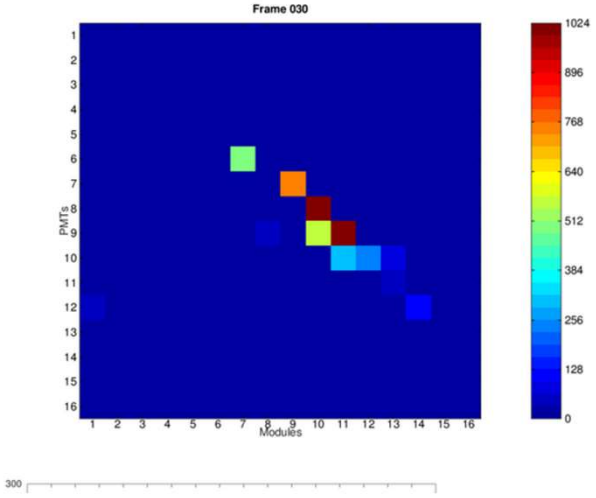

April, 28 2016

TUS began measurements on May 19, 2016

- EAS mode (0.8 μs) – 1.5 year
  - UV background and fake trigger sources study
  - EAS search, ELVES, cities, lightning, unusual UV flashes
- TLE-1 mode (25.6 μs)– few days of operation
  - couple of hundreds us duration events
- TLE-2 mode (0.4 ms)– few weeks
  - many lightning, anthropogenic sources
- METEOR mode (6.6 μs) – 1.5 months
  - thunderstorm data and dozen of meteors

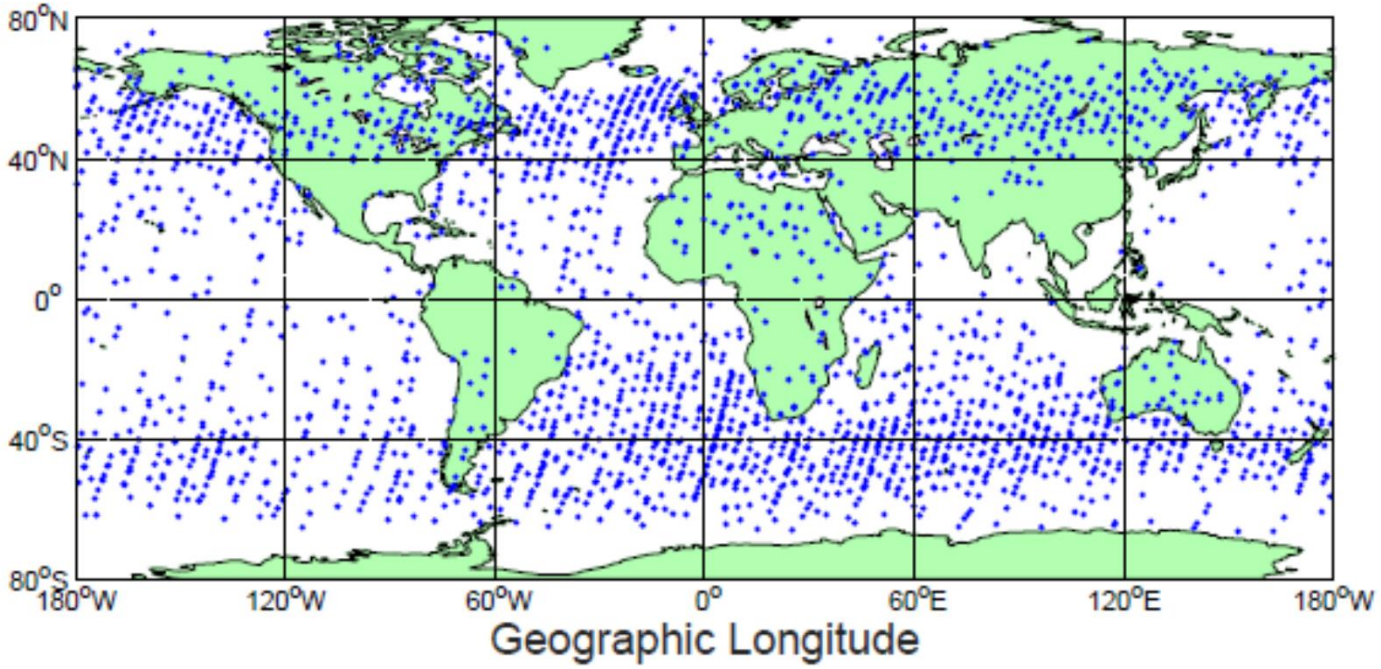
Short pulses, less than 1 µs (Charge particles tracks)

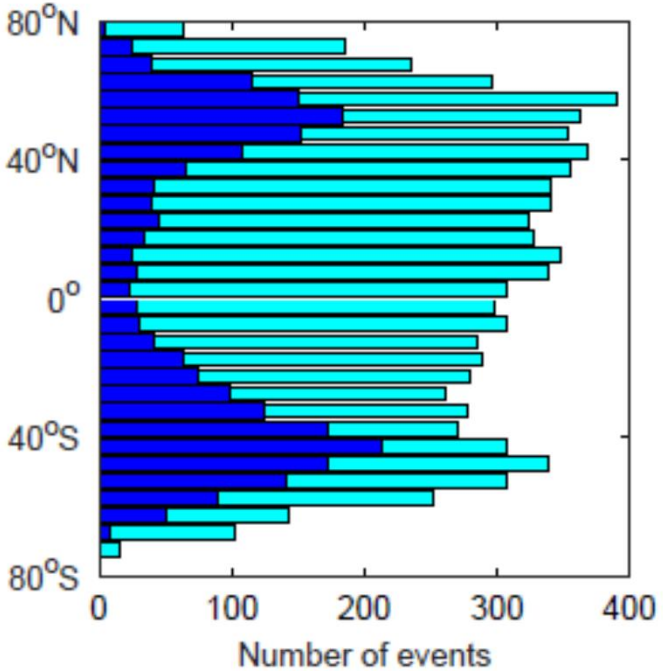




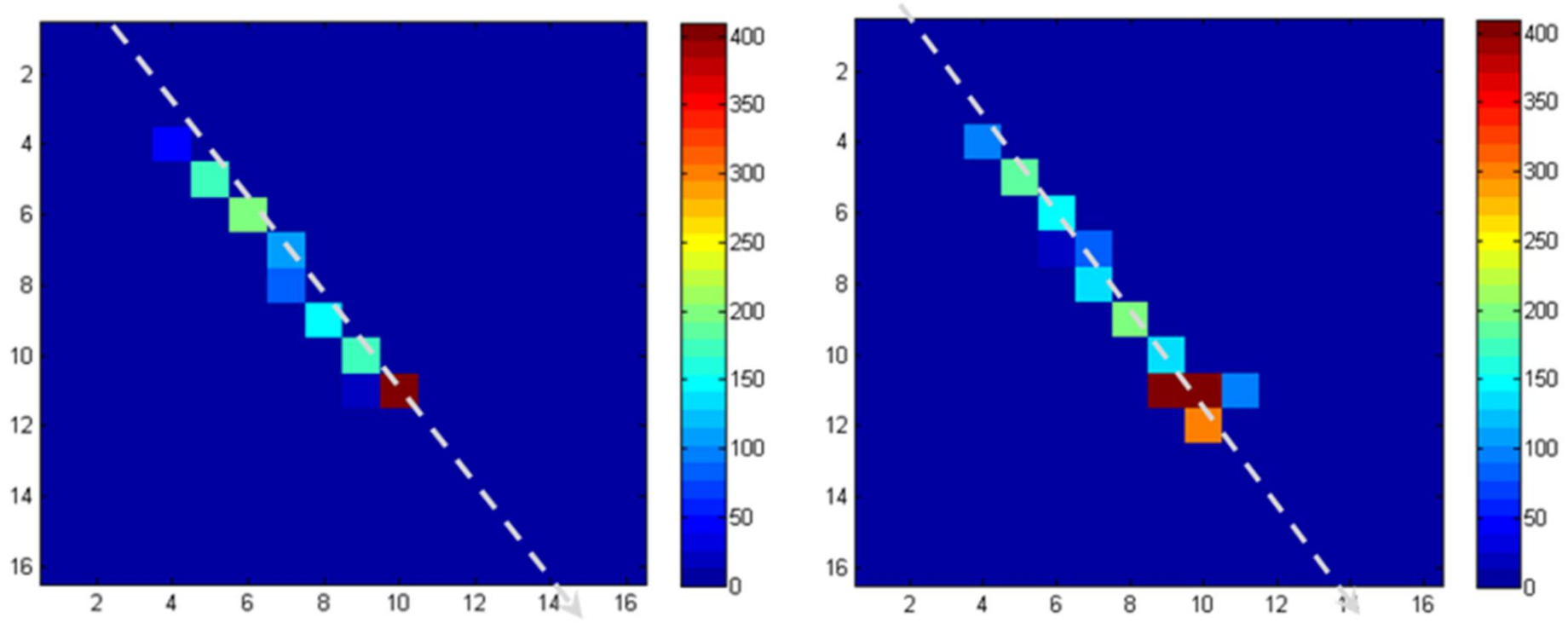
Typical event

Geographical distribution





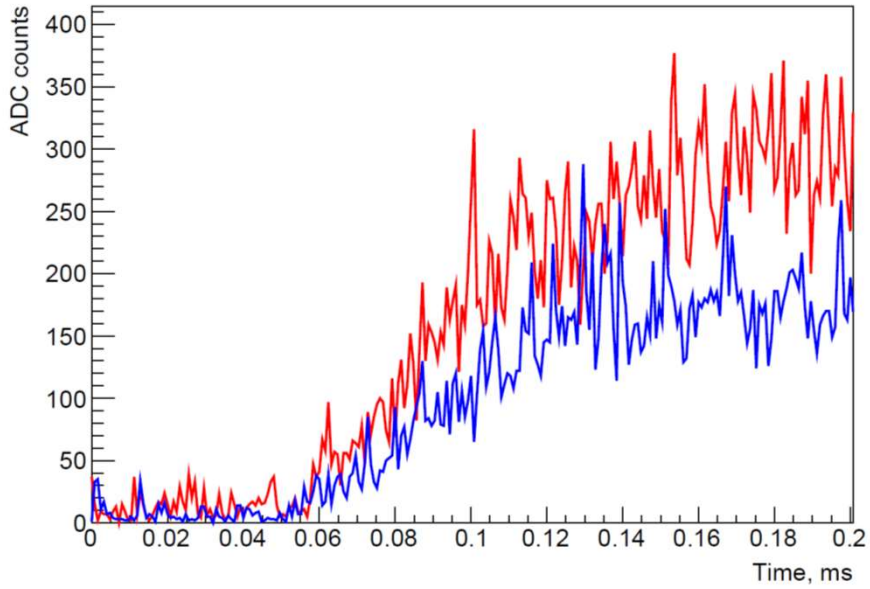
Geant4 simulation of signal from protons passing UV filter in front of PMTs

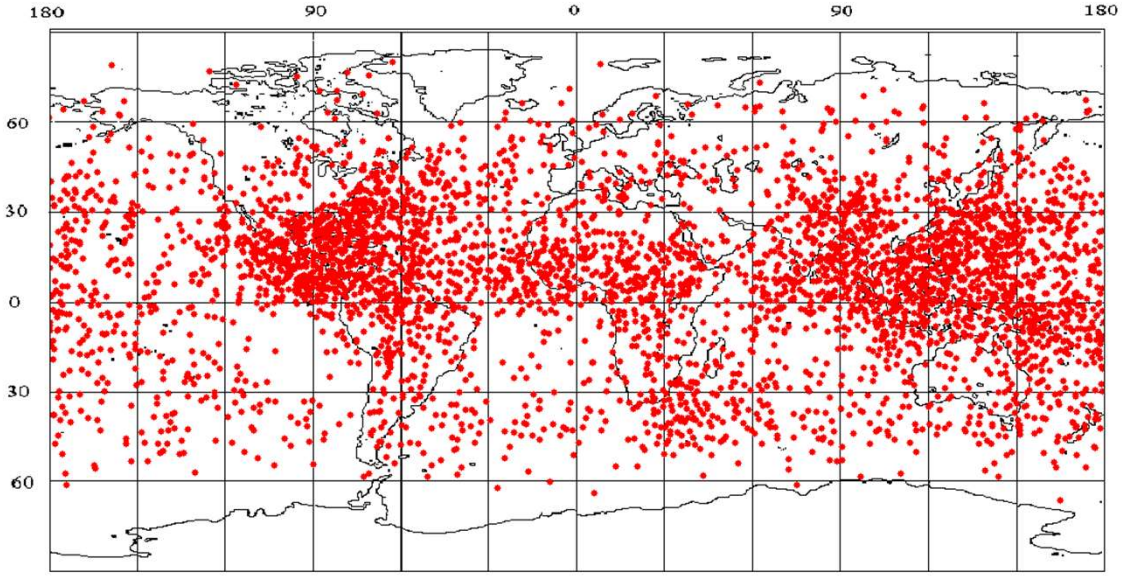


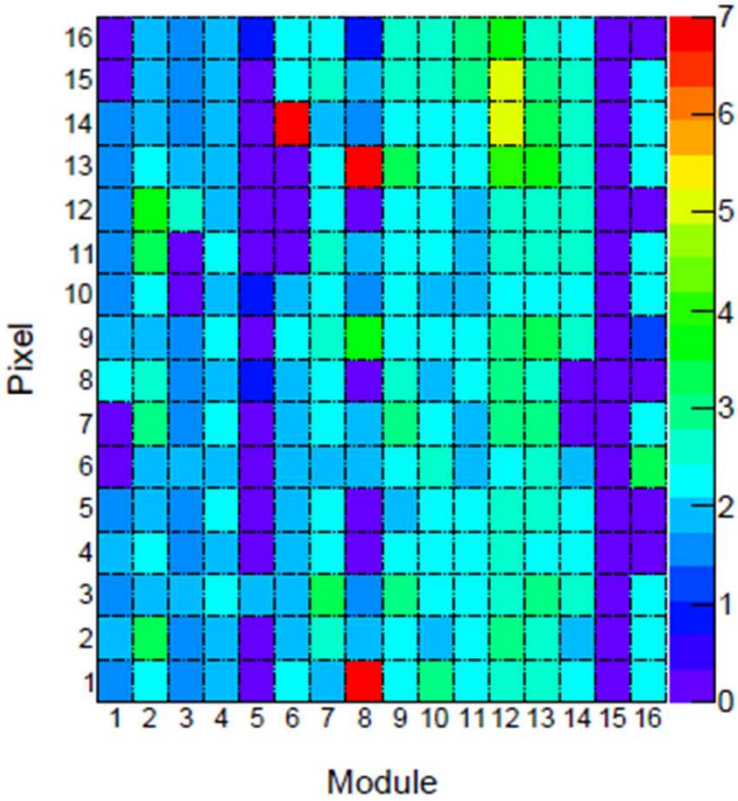
15 % of trigger were caused by this type of events

The anti-trigger was developed (search for instant change of ADC code and trigger blocking for 100 μs) to eliminate them and increase the exposure time.

Thunderstorm signal in EAS mode

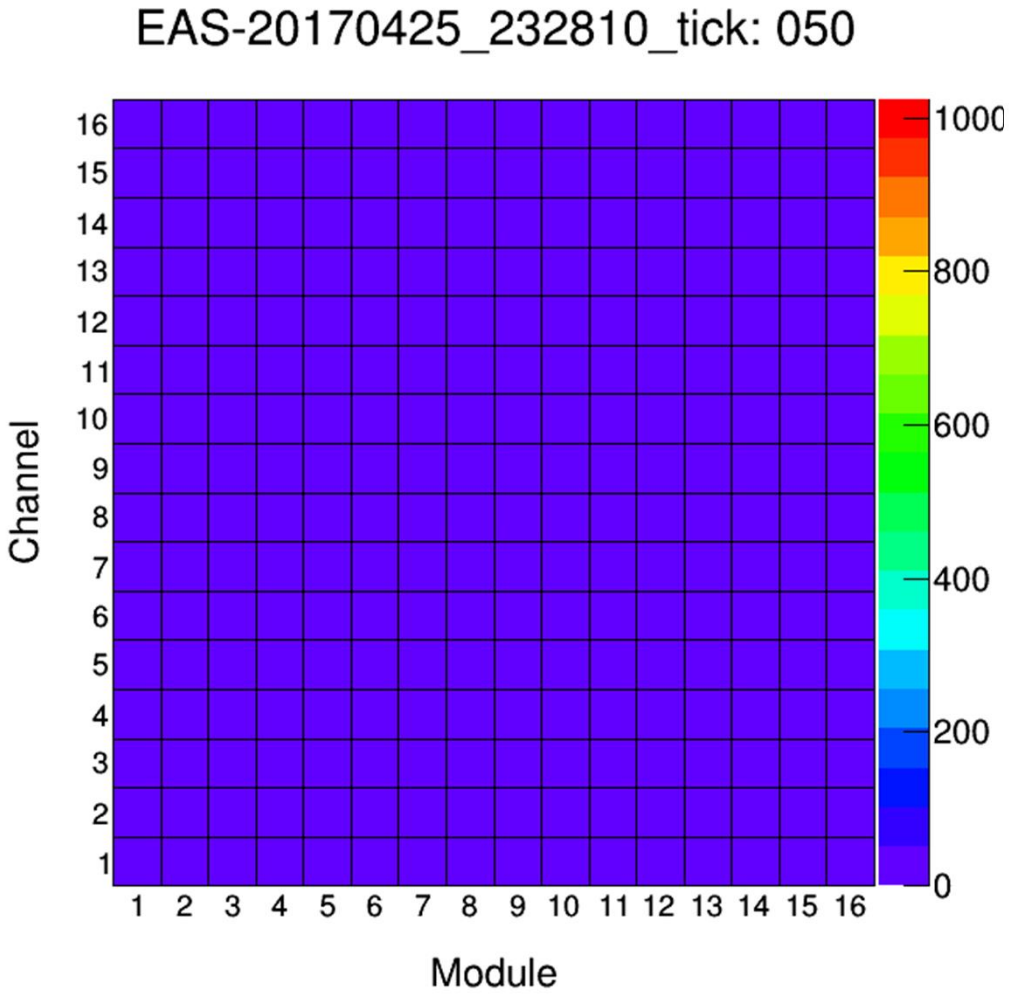


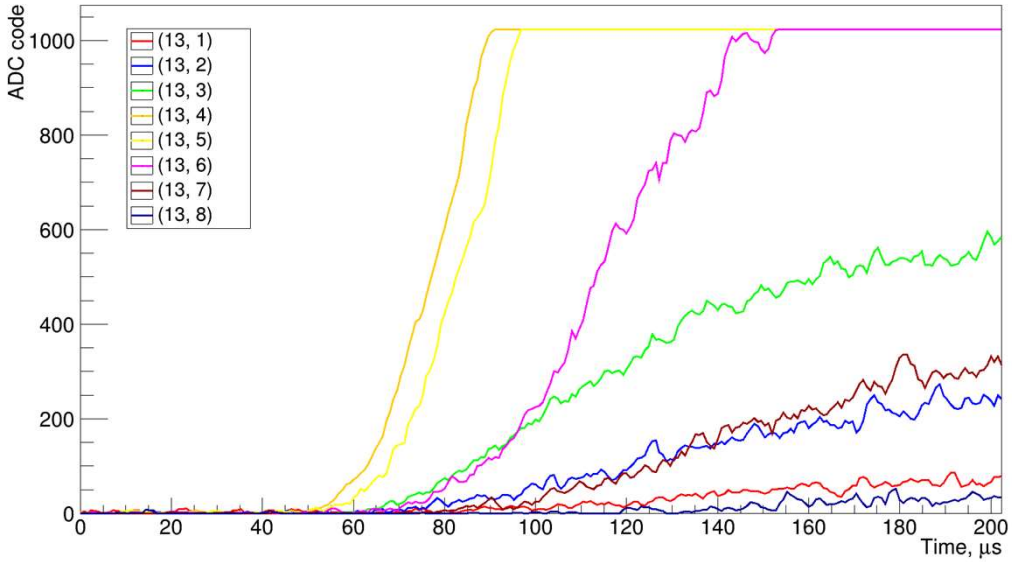


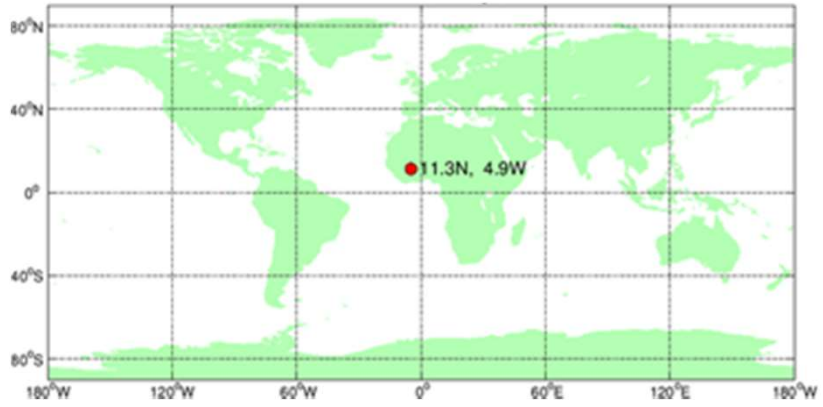


- ✓ “Slow” rising of signal
- ✓ Correlation with thunderstorm regions
- ✓ Large are of luminosity, stray light outside FOV.

Powerful lightning UV flash in the FOV of the detector

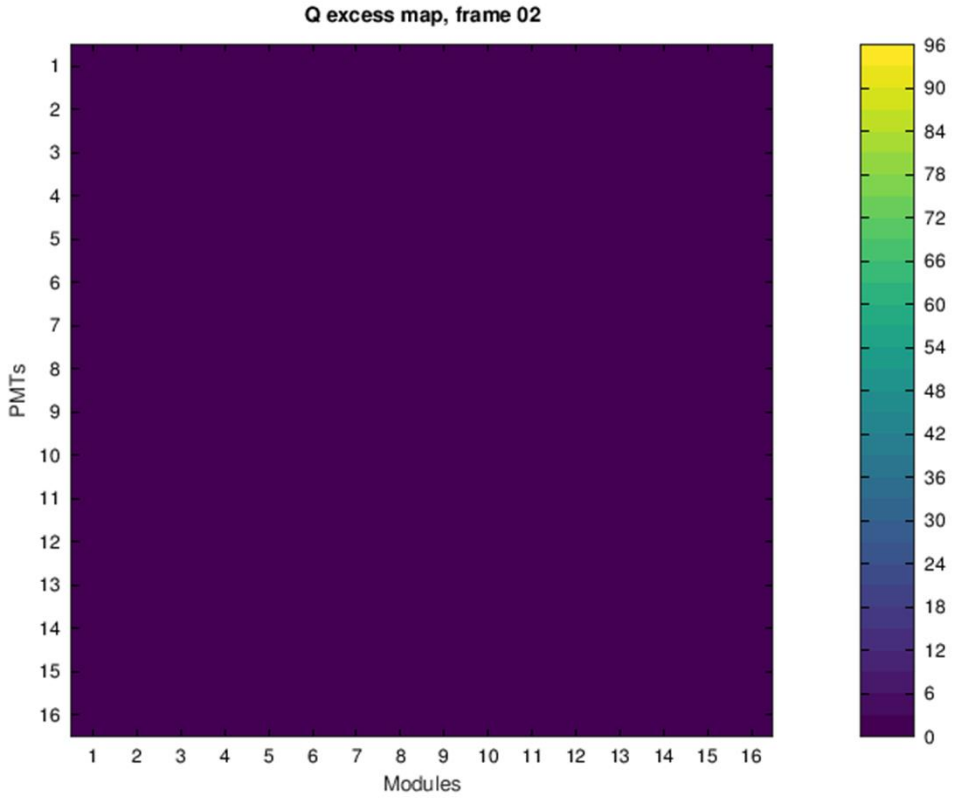


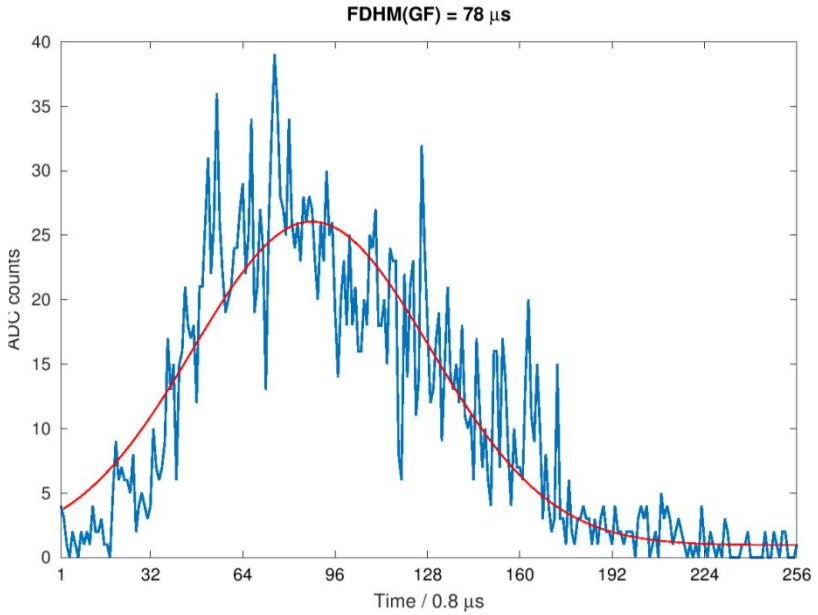


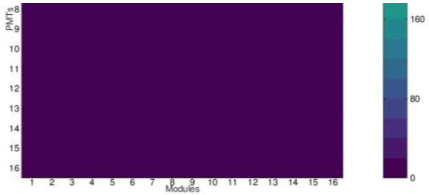


From database of lightning detection network **Vaisala GLD360**:
2017-04-25 23:28:09.417 **11.2112** **-4.6118** +16.9

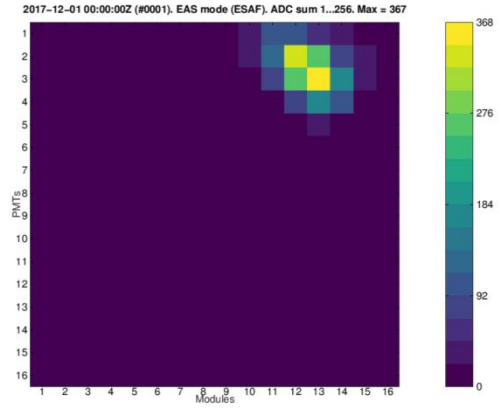
EAS search. Simulations.







E=200 EeV



θ = 60°

For the TUS detector simulation we use the ESAF – JEM-EUSO simulation code with recently implemented TUS design.

C. Berat, S. Bottai, D. De Marco et al., *Full simulation of space-based extensive air showers detectors with ESAF*, *Astroparticle Physics* **33** (May, 2010) 221–247

Search for extreme energy cosmic ray candidates in the TUS orbital experiment data

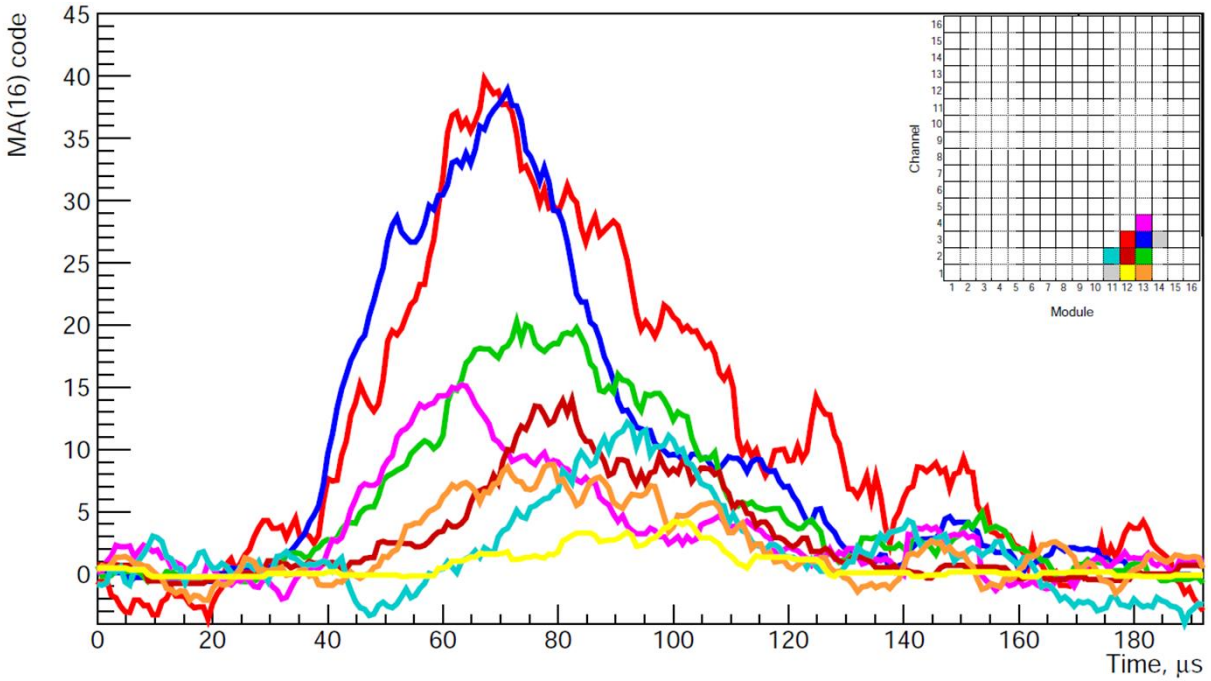
The total exposure of TUS in EAS mode is ~10^3 km^2 yr sr. (~4% of night side operation time during moonless period taking into account dead time).

It gives expected number of events:
~0,5 ev/year (PAO spectrum) or ~2 ev/year (TA spectrum)

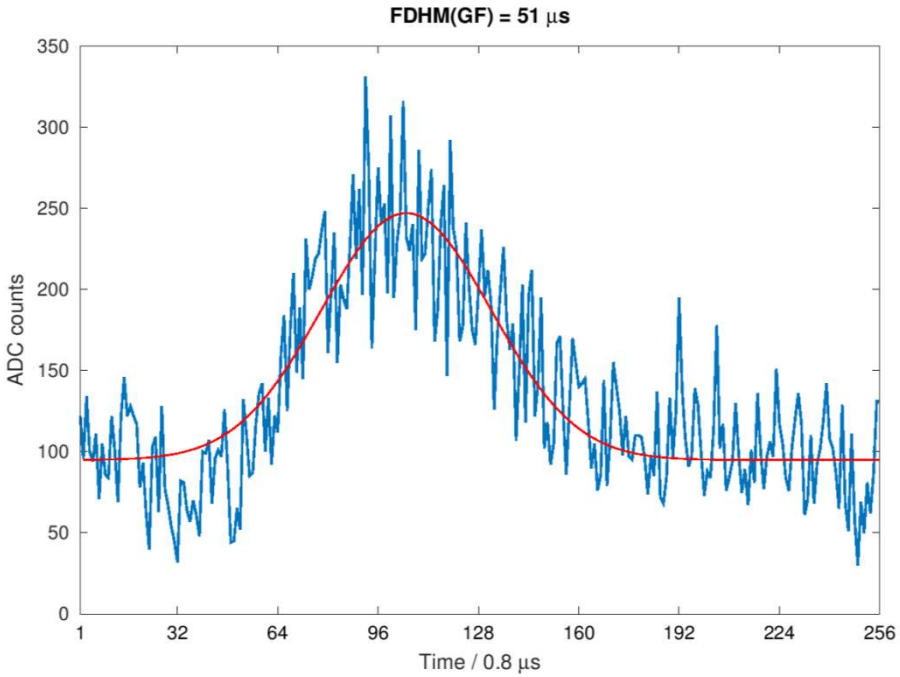
Multi level selection algorithm

- First level – online TUS trigger.
- Second level (analogous to TUS trigger but with additional conditions): the ADC threshold, adjacency length, signal location and duration within waveform)
- Third level – event by event study, reconstruction, atmospheric conditions analyses etc.

Event 03.10.2016 05:48:59UTC



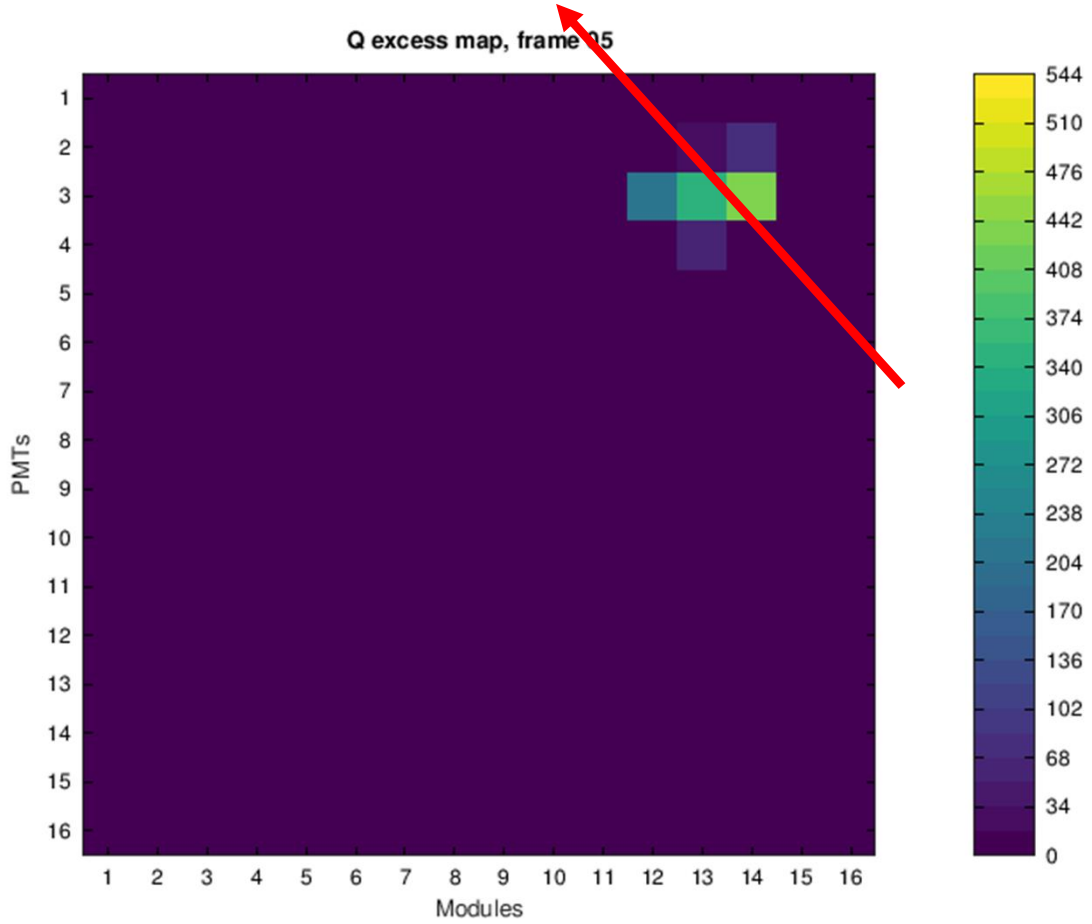
ADC counts in active channels



Sum of ADC counts in active channels

Strong EAS candidate with expected spatial and temporal signal structure (waveforms and pixel map).

Pixel map and signal movement



Linear Track Algorithm (LTA)

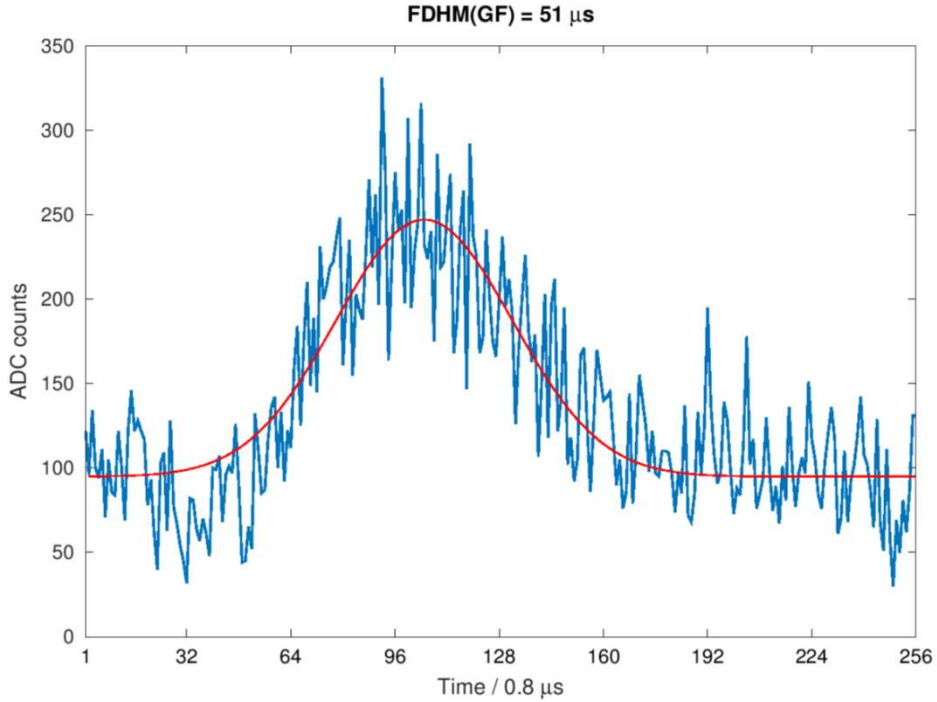
$$x(t) = x_0 + u_x(t - t_0), \quad y(t) = y_0 + u_y(t - t_0)$$

$$\phi = \arctan(u_x/u_y), \quad \theta = 2\arctan(fRu/c)$$

$$(\theta, \phi) \approx (44°, 49°)$$

Kinematic analyses

The TUS event



md/ch	T_m, μs	$T_{1/2}$, μs	A_{max}
13/4	72.3	36.5	57.6
13/3	75.4	44.7	335.0
14/3	79.2	47.1	30.9
12/3	83.7	56.7	79.3
13/2	86.5	50.3	87.8
13/1	87.9	46.9	23.7

dt ~ 40 μs
FDHM ~50 μs

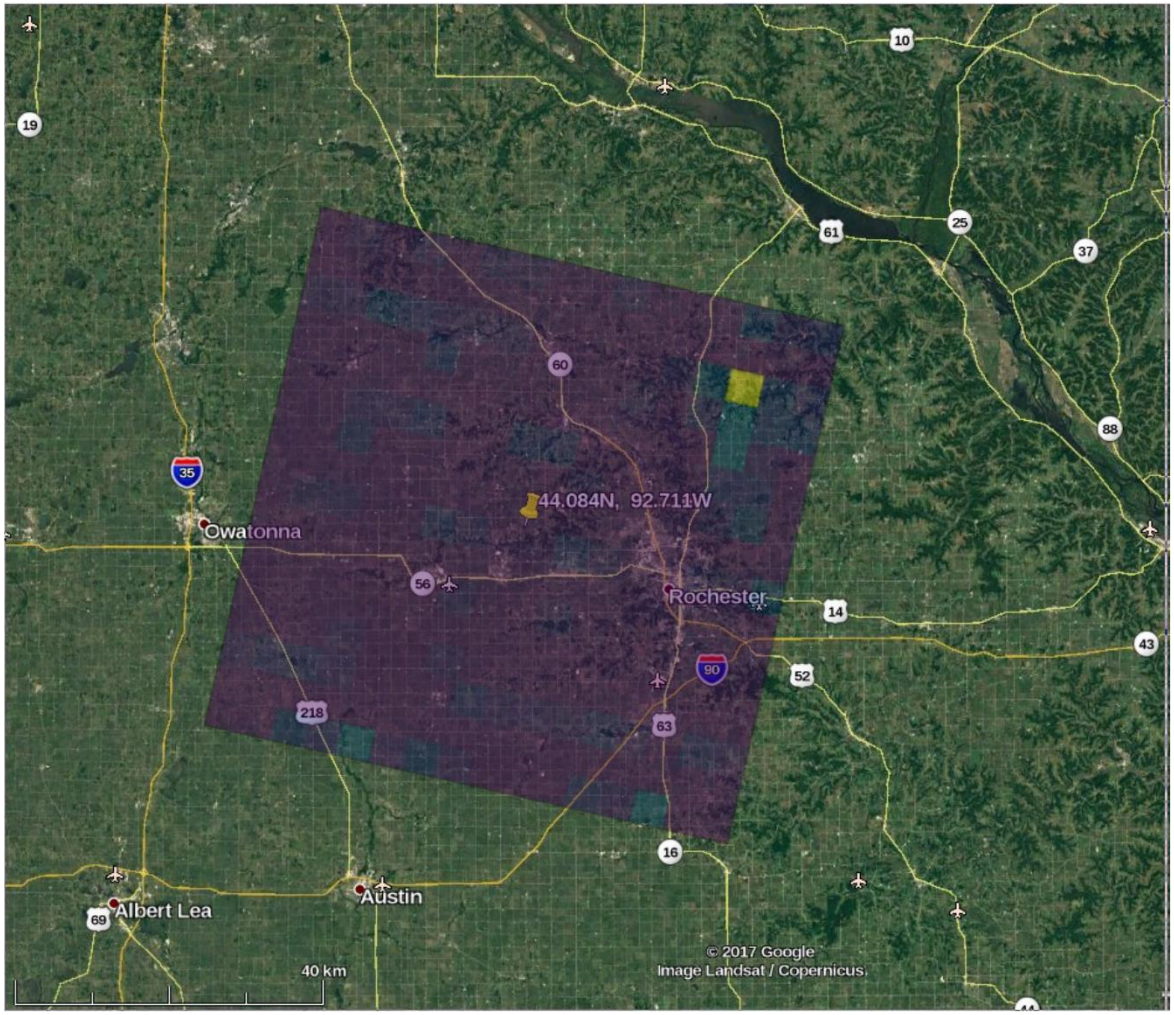
Simulations

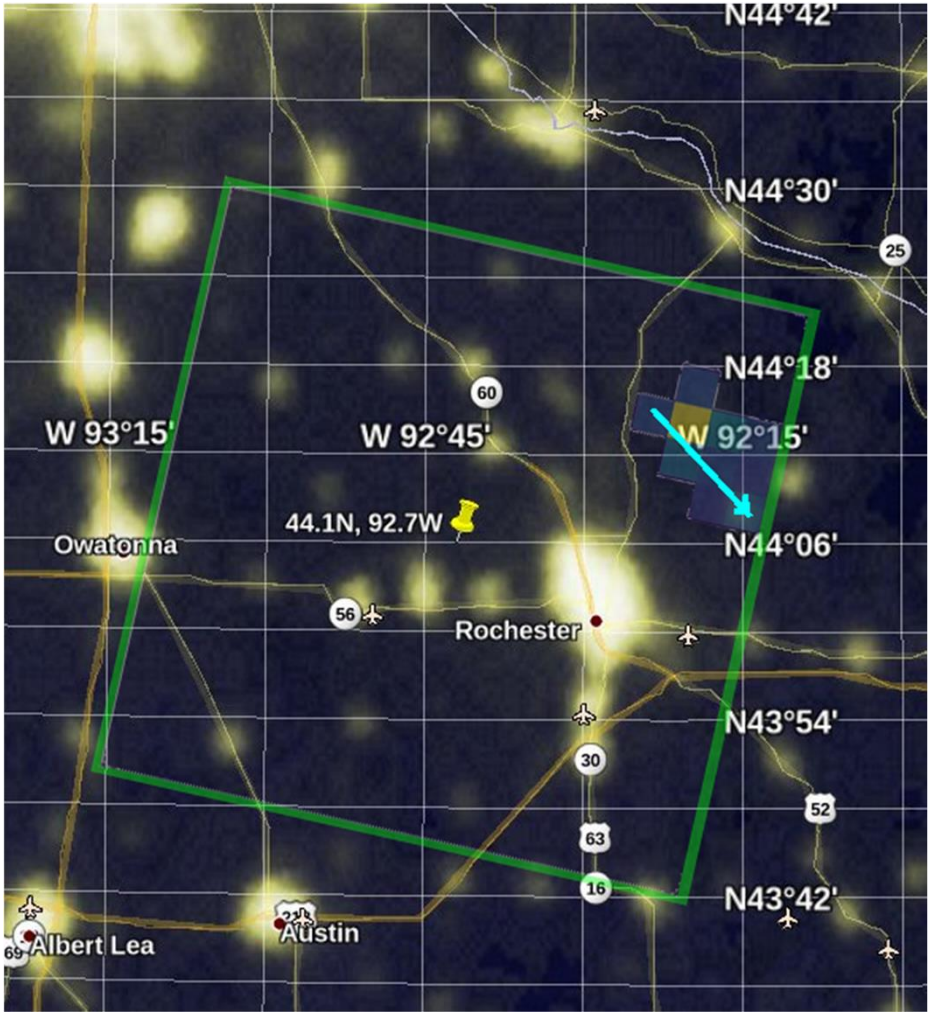
E, EeV	$\langle dt \rangle$, μs, noise 24 γ/μs
100	29
200	**36**
300	**41**
400	44
500	45
600	47
700	48
800	50
900	52
1000	54

θ,°	$\langle dt \rangle$, μs	$\langle$FDHM$\rangle$, μs
35	23	41
40	28	46
45	**36**	**52**

- ✓ The absolute calibration and energy problem: ground based PMTs adjustment doesn't work because of HV algorithm error during first days of flight.
- ✓ The event is too bright to be a ~100-300 EeV EAS

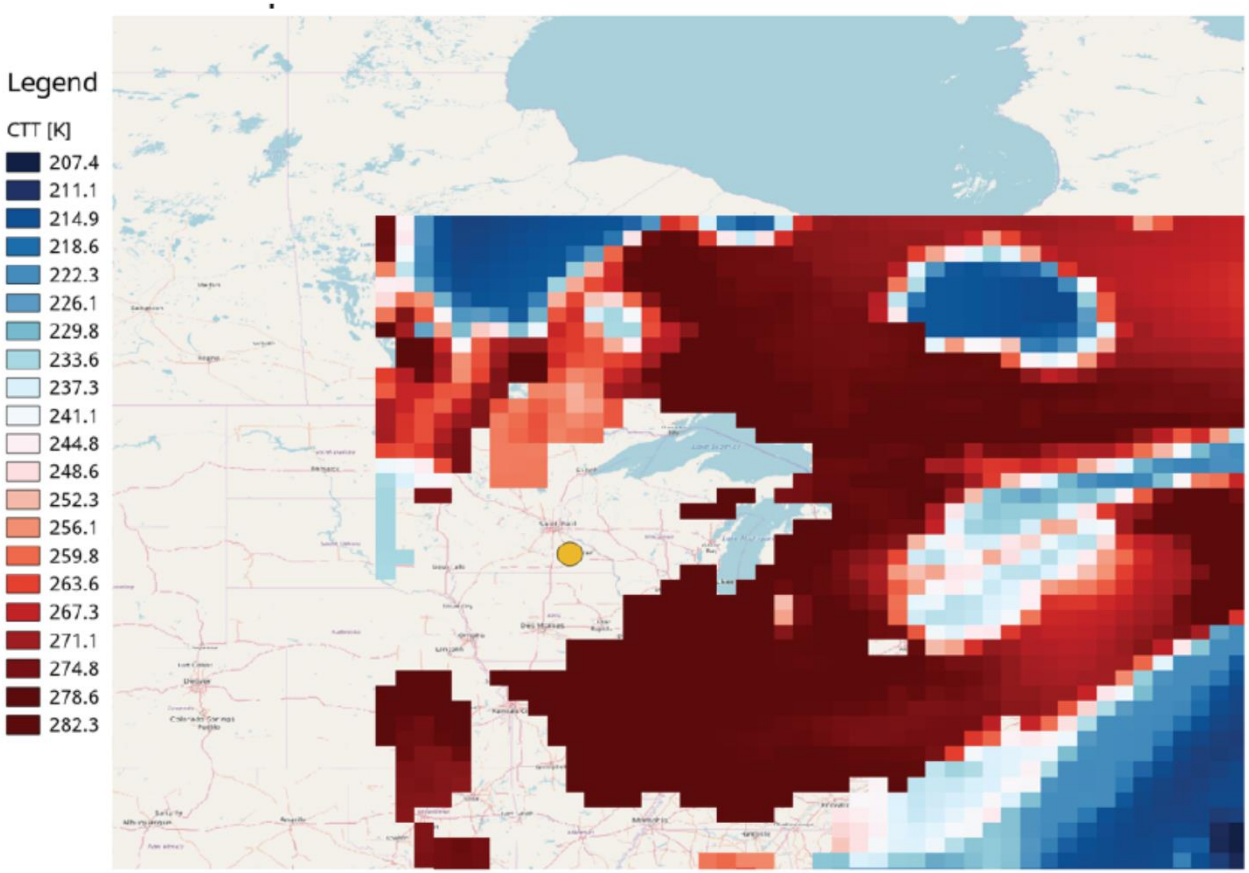
EAS candidate measurements conditions





Google Earth map with the TUS field of view and the event

EAS candidate measurements conditions



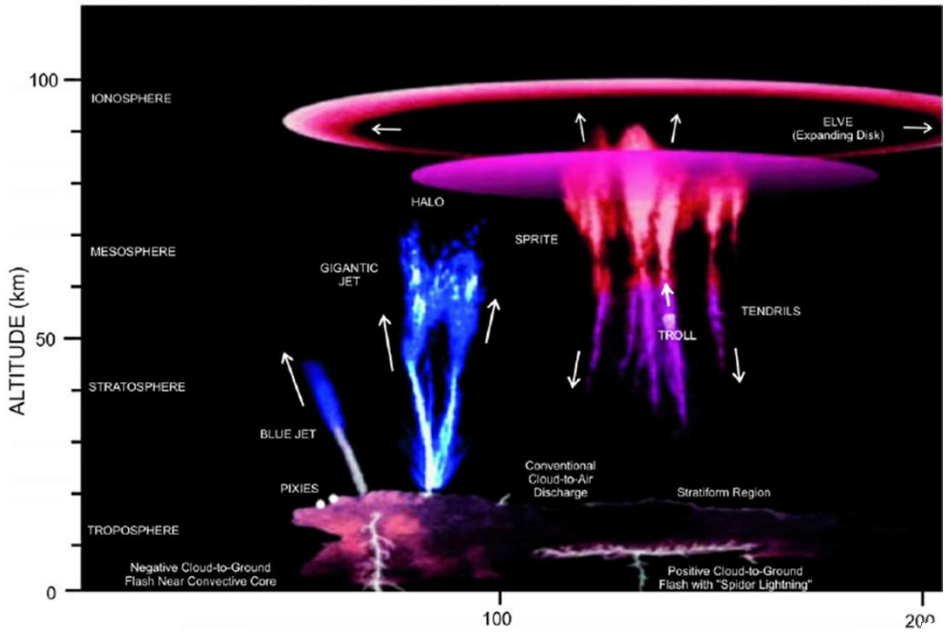
Data of MERRA-2
Provided by
R. Cremonini and M. Bertaina

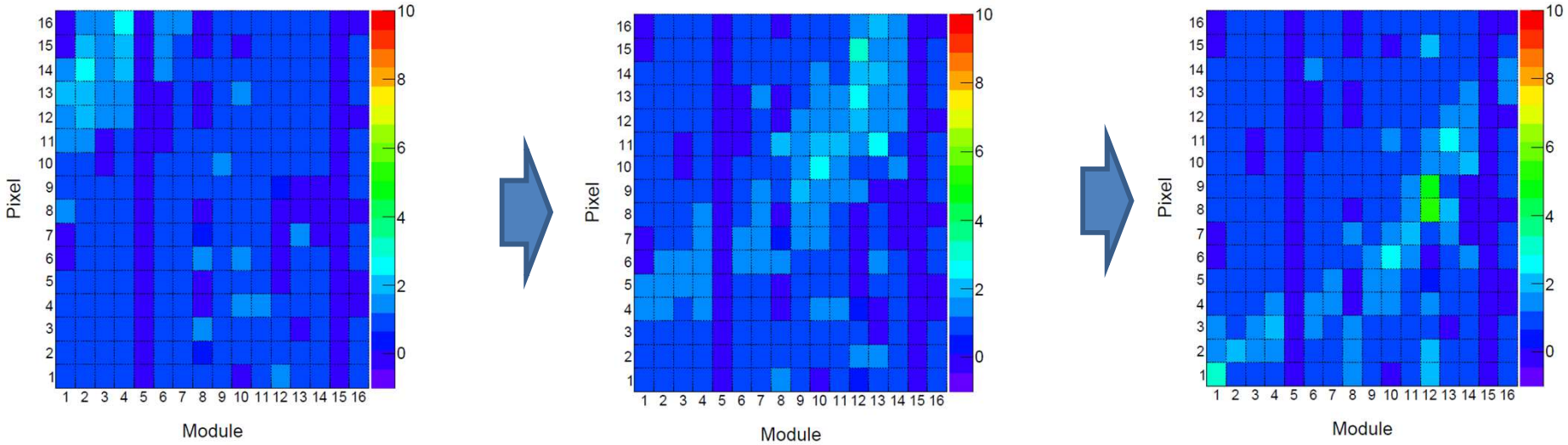
The Vaisala GLD360 ground based lightning location network did not register any lightning strikes in a region with radius of 930 km and during 10 s period around the time of the TUS event.

PreConclusions

- The TUS detector measured the event that looks like EAS, but too bright to be considered as EAS with energy around 100-300 eV.
- Two major problems:
  - Variable and complicated background (with many natural and anthropogenic sources) → TUS gives an important information about this factor of measurements
  - Low sensitivity and FOV of the detector to measure a number of reliable EAS events → new projects are started to be developed: K-EUSO

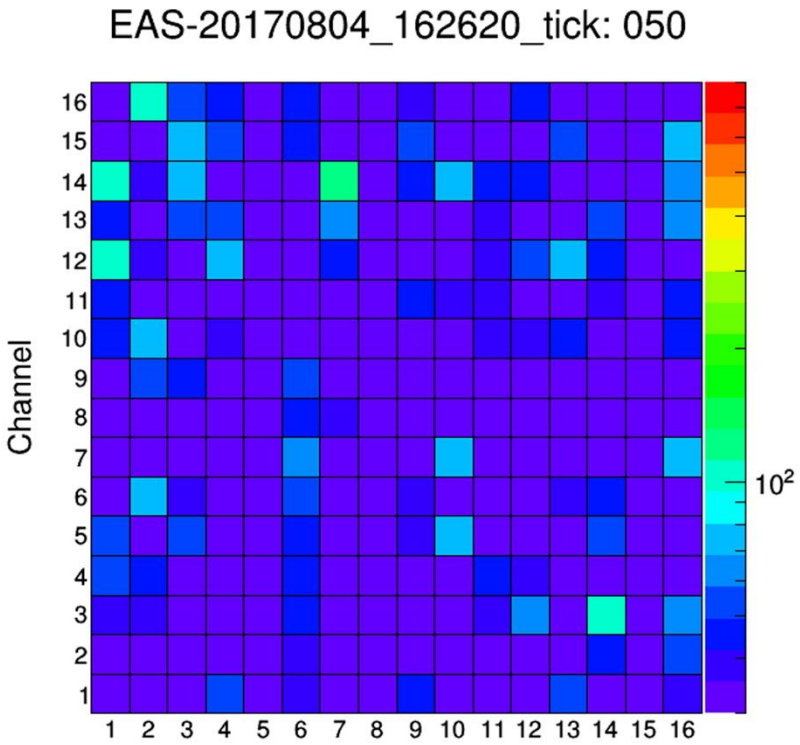
Transient luminous events I

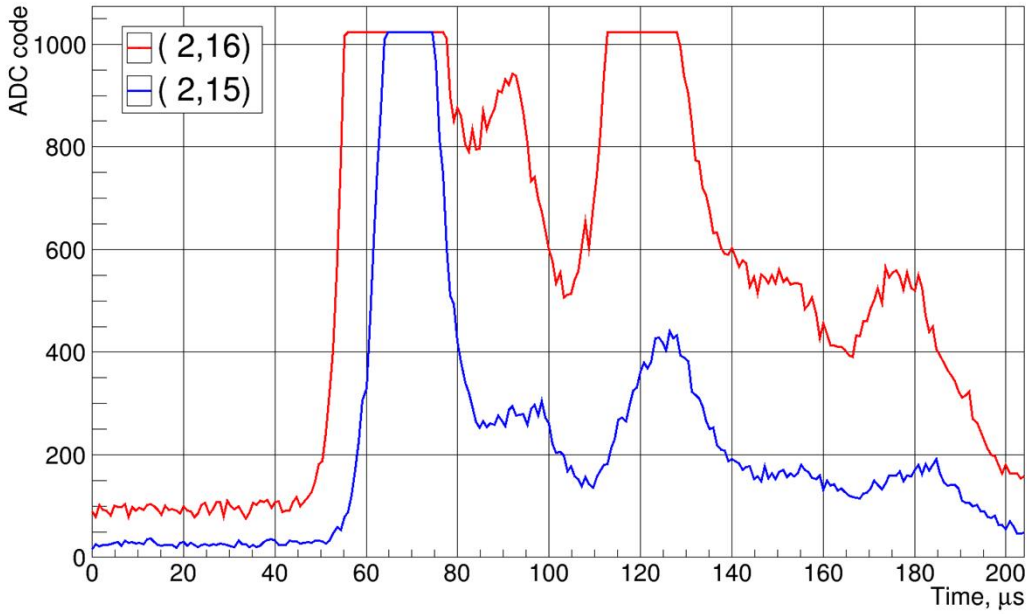


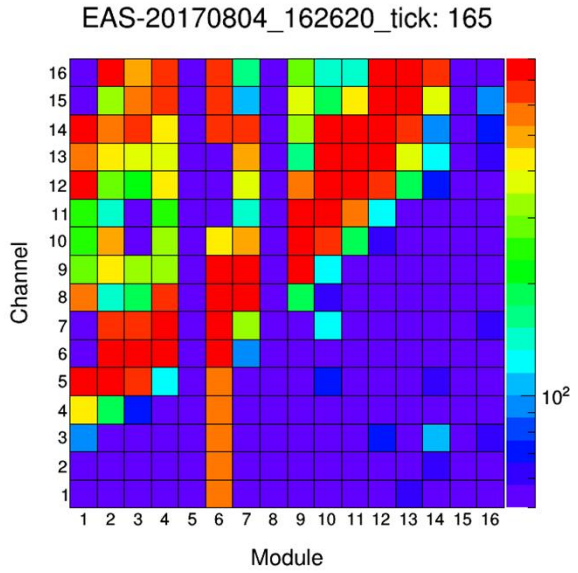


TUS event 18.09.2016, 9.66S, 17.14W

Transient luminous events II

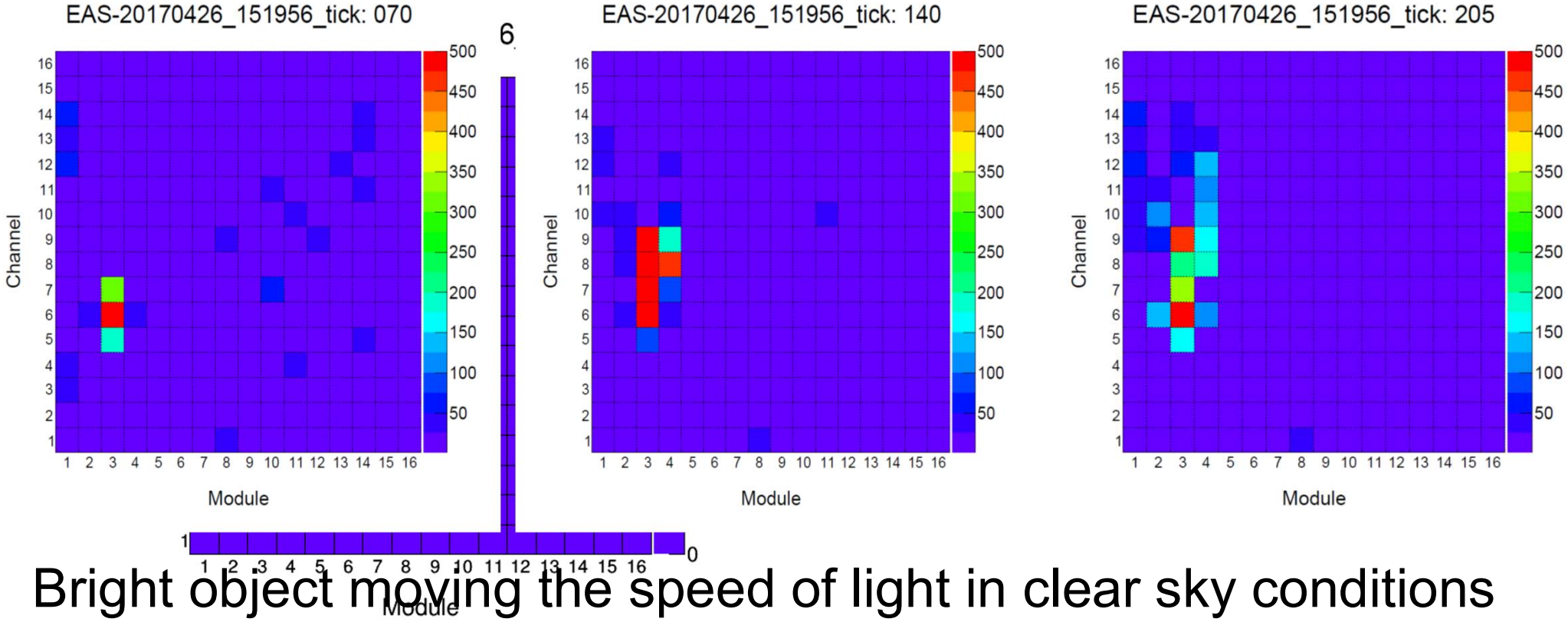




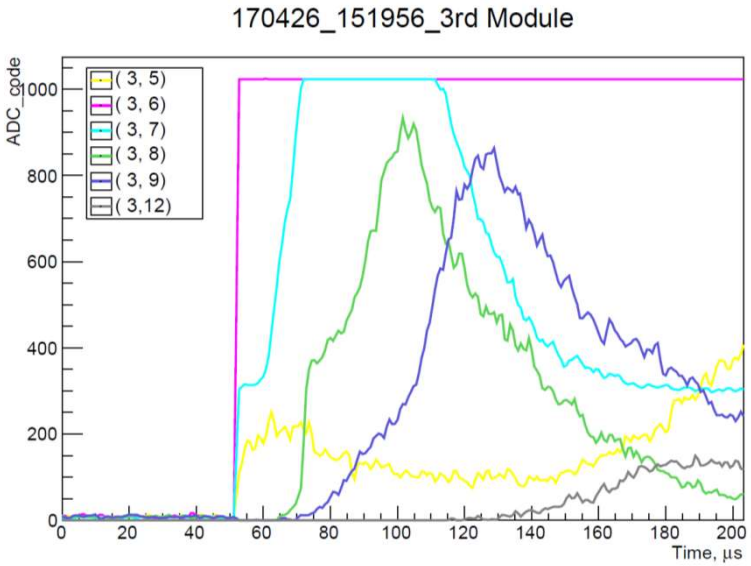


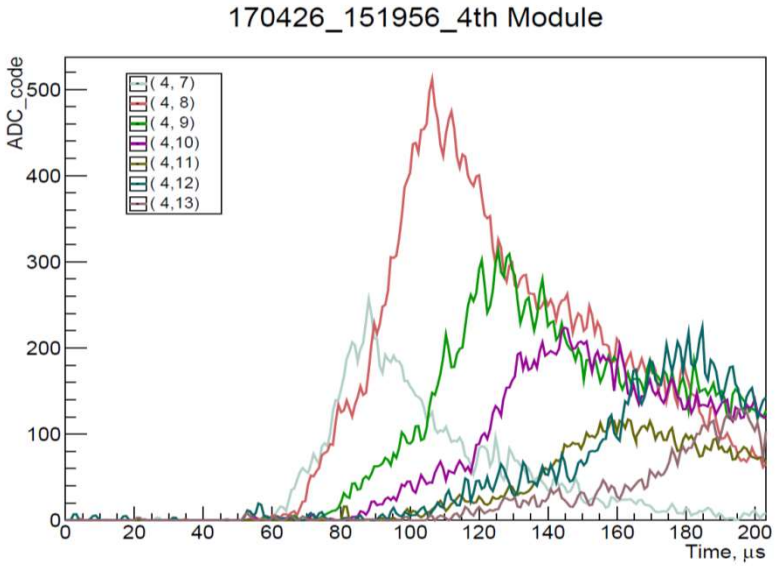
Multiple ELVE

Marshall, R. A., C. L. da Silva, and V. P. Pasko (2015), Elve doublets and compact intracloud discharges, Geophys. Res. Lett., 42



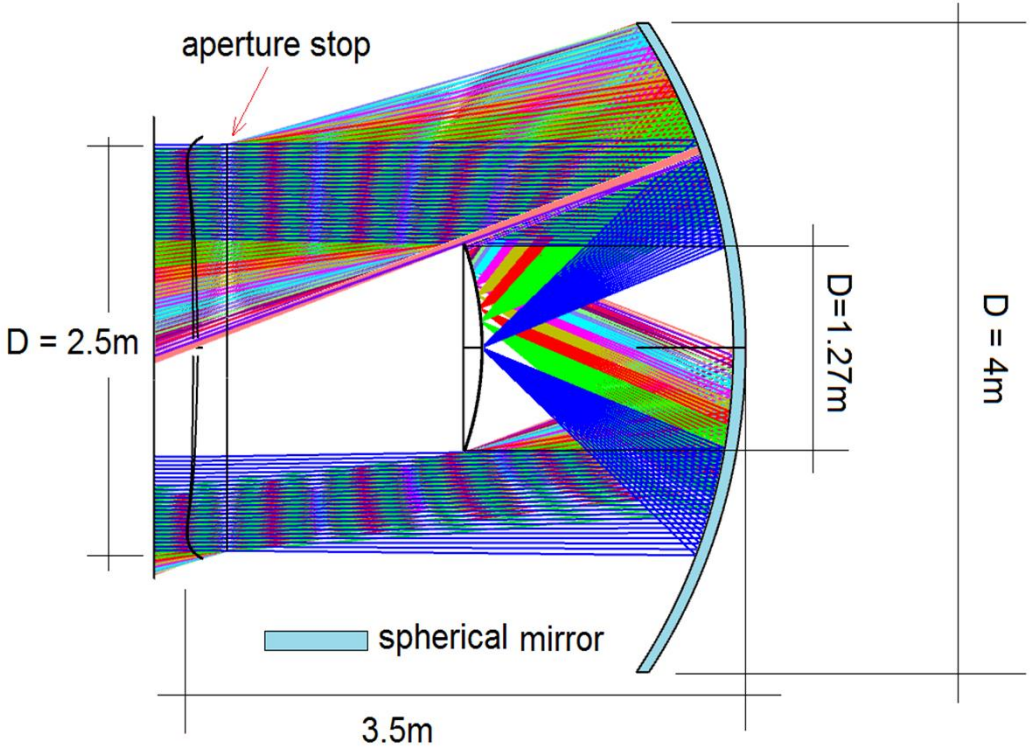
Bright object moving the speed of light in clear sky conditions after the initial flash.

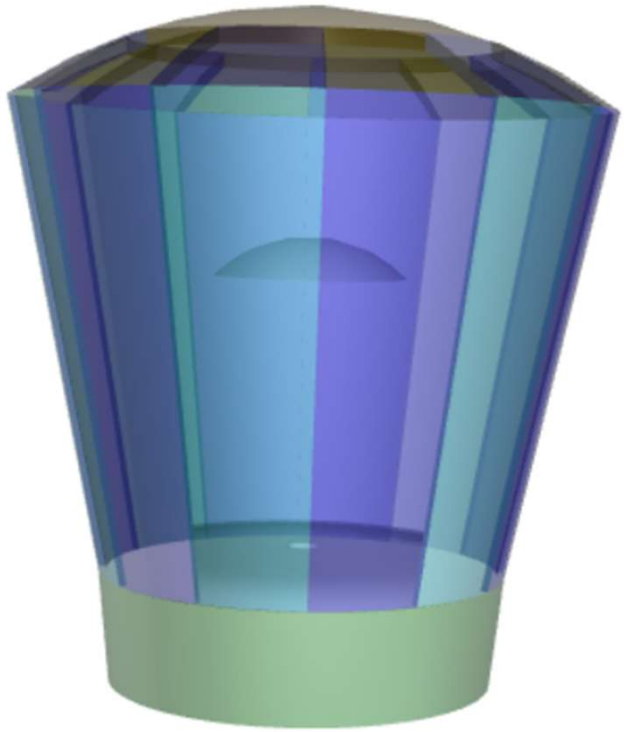




KLYPVE-EUSO – is the next step in orbital UHECR measurements

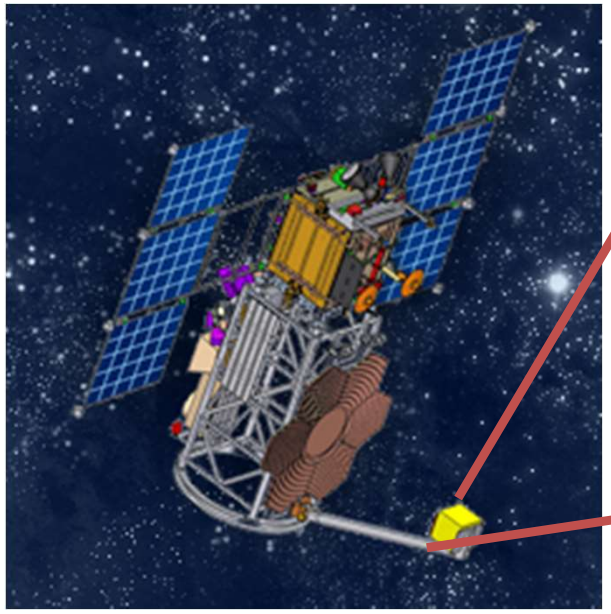
- The large FOV (40°) and large aperture (~5 m^2) Schmidt camera to be installed on boards the Russian segment of the ISS in ~2022

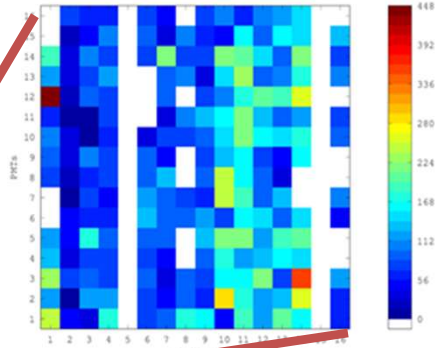


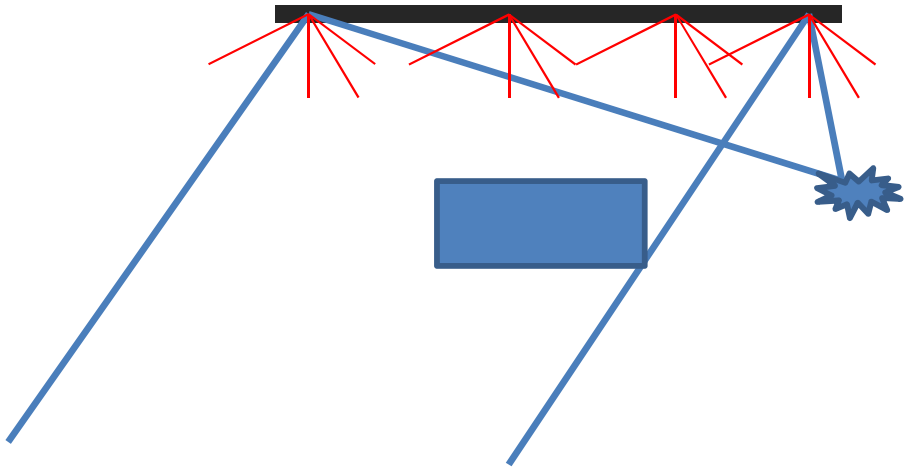


The motivation for Schmidt optics of K-EUSO

TUS

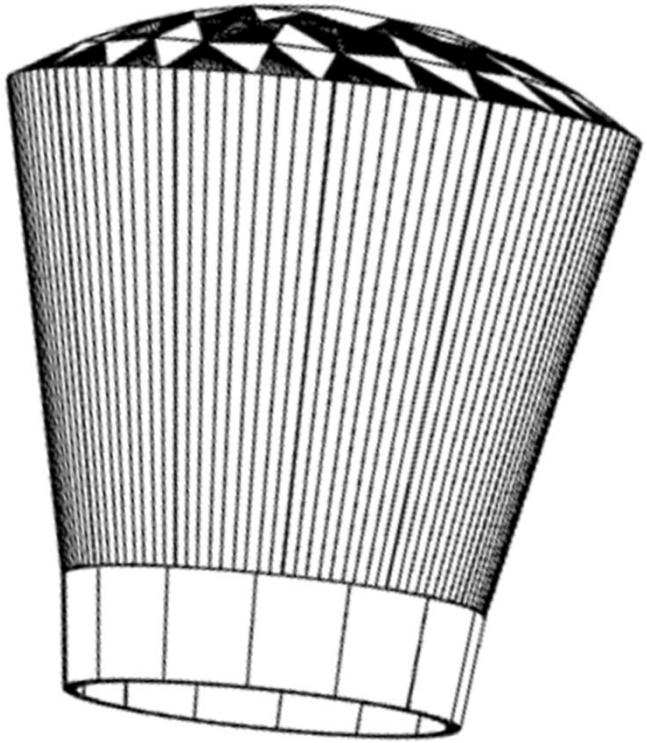






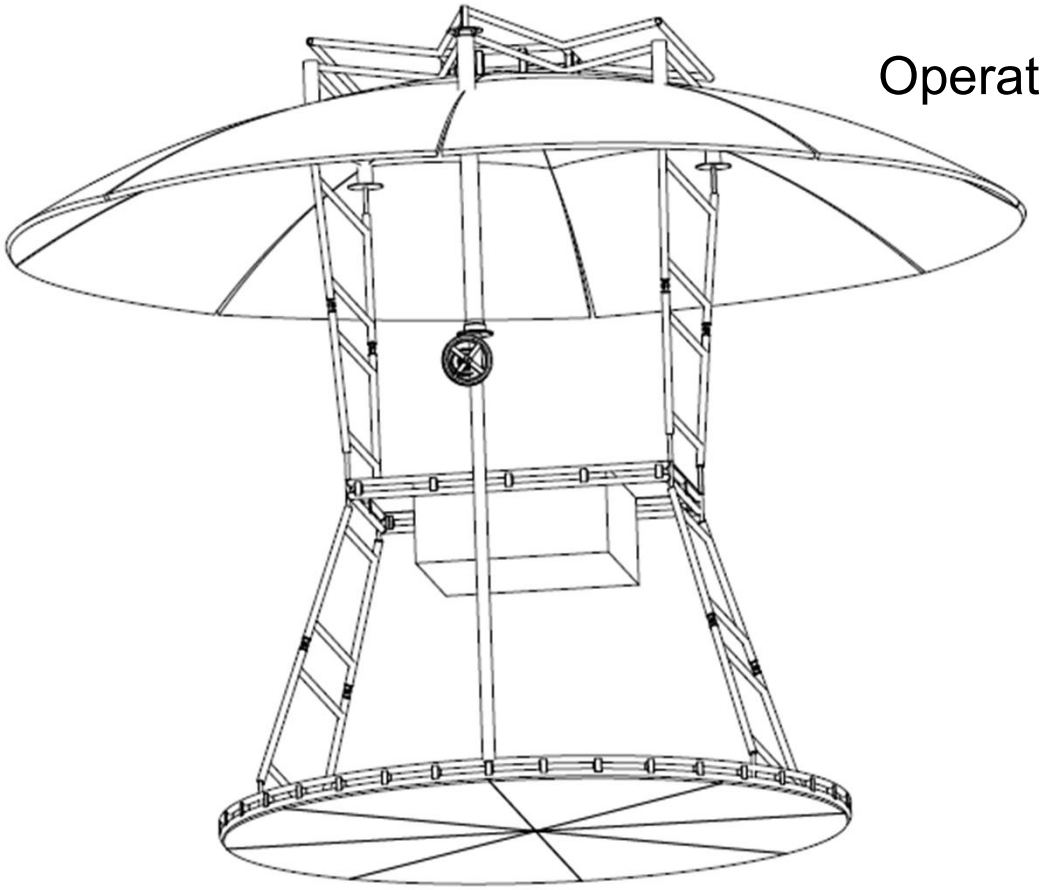
Flash outside FOV

K-EUSO

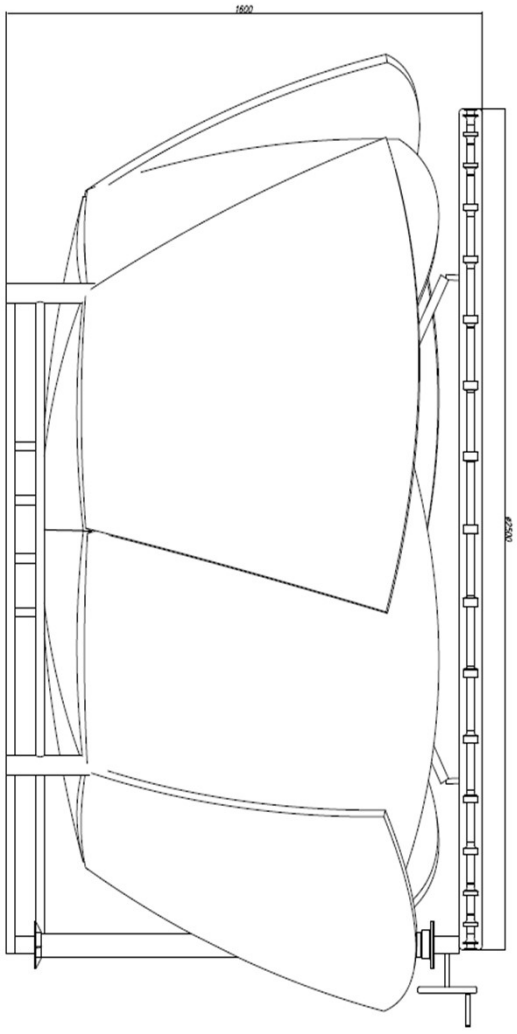


KLYPVE-EUSO. Conceptual design.

Operation mode



Transportation mode



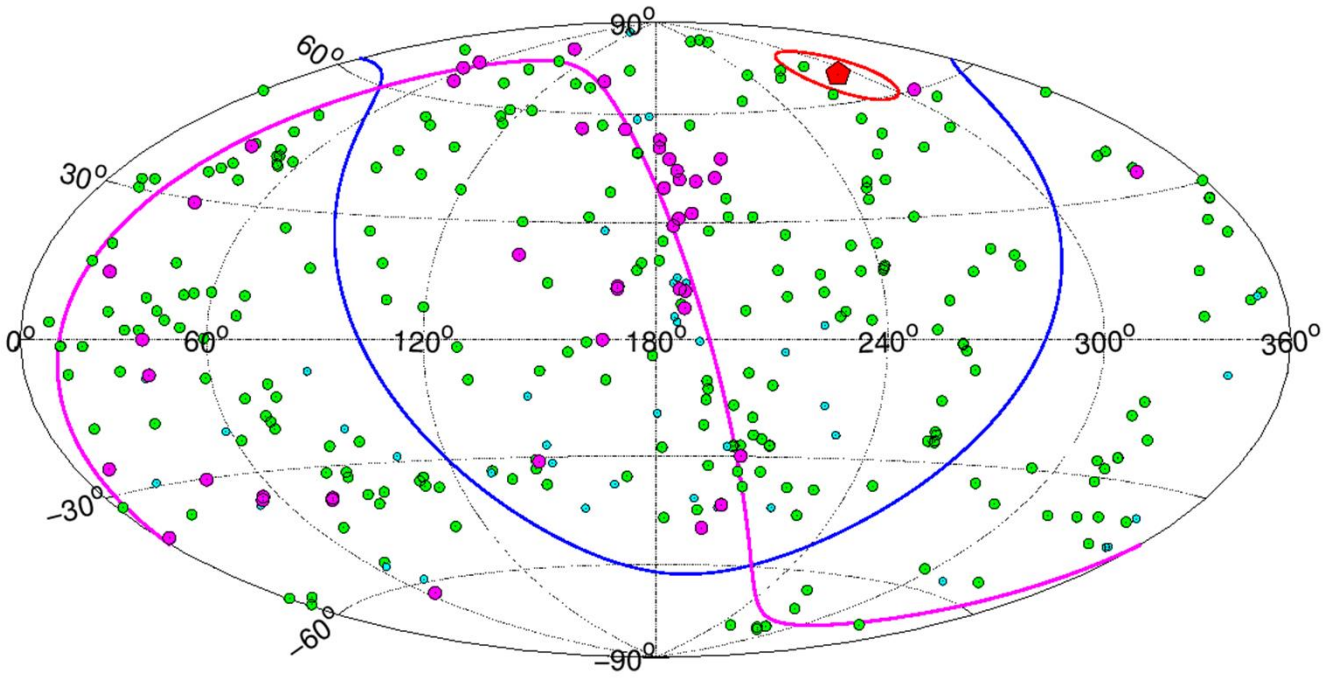
40° FOV
10^5 pixels
1 km spatial resolution
2.5 us temporal resolution
50 EeV energy threshold
~20000 km^2sr yr/yr exposure

Conclusions

- The TUS detector is the first space mission aimed for UHECR EAS measurements. TUS gave important information on the UV background for EAS measurements.
- The TUS detector measured the event that looks like EAS (dynamics and spatial and temporal structure of the signal), but too bright to be considered as EAS with energy ~100-300 eV.
- A variety of atmospheric phenomena are measured by TUS: well known and not explained yet.
- The next mission for UHECR measurements from space is being developed based on the TUS and JEM-EUSO collaboration experience: KLYPVE-EUSO.

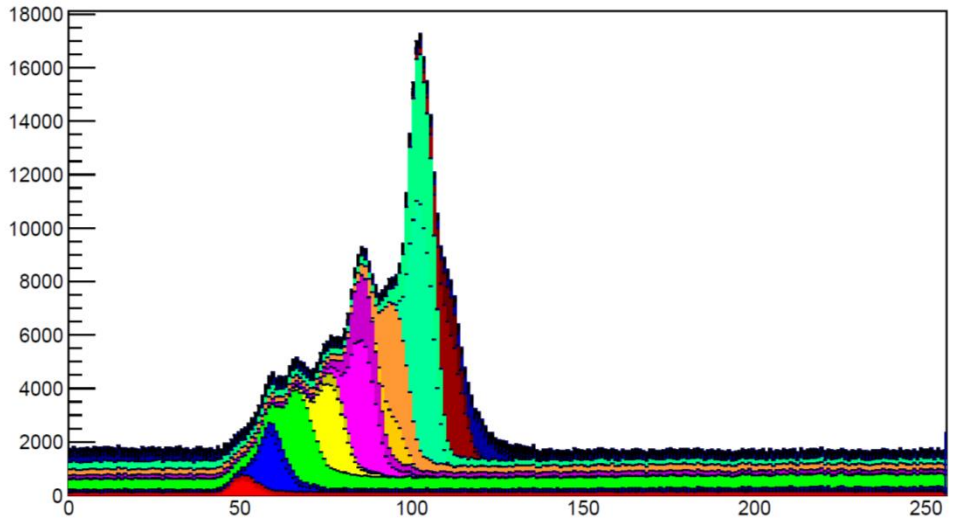

Thank you for your attention!

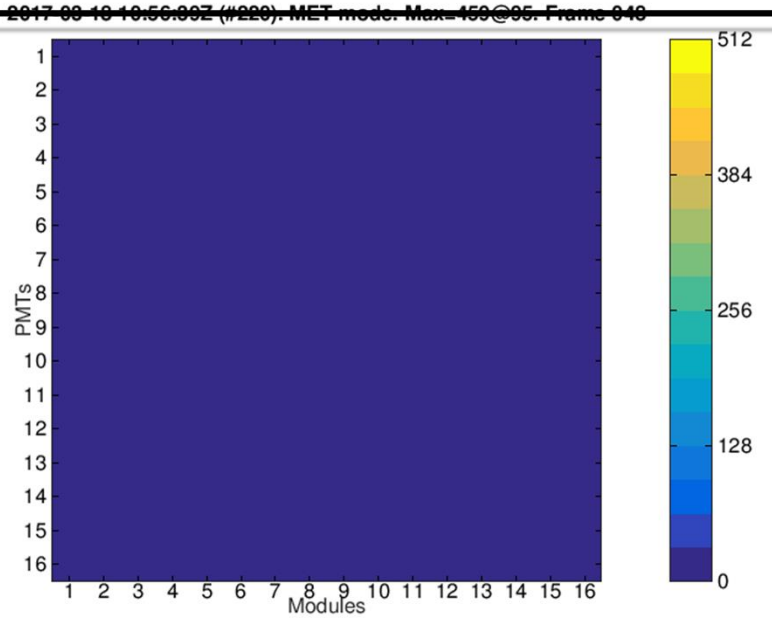
The TUS event position on the sky map.

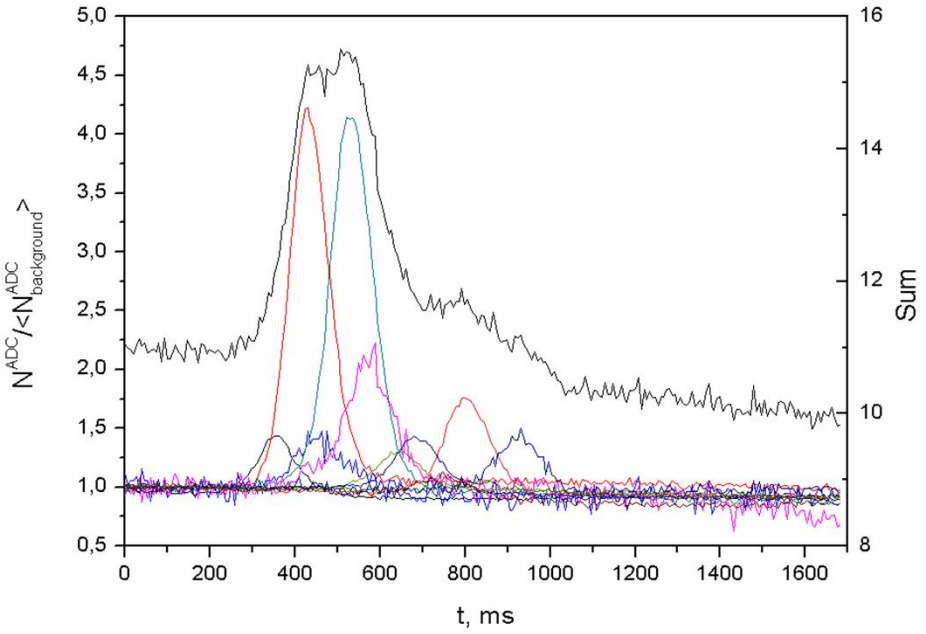


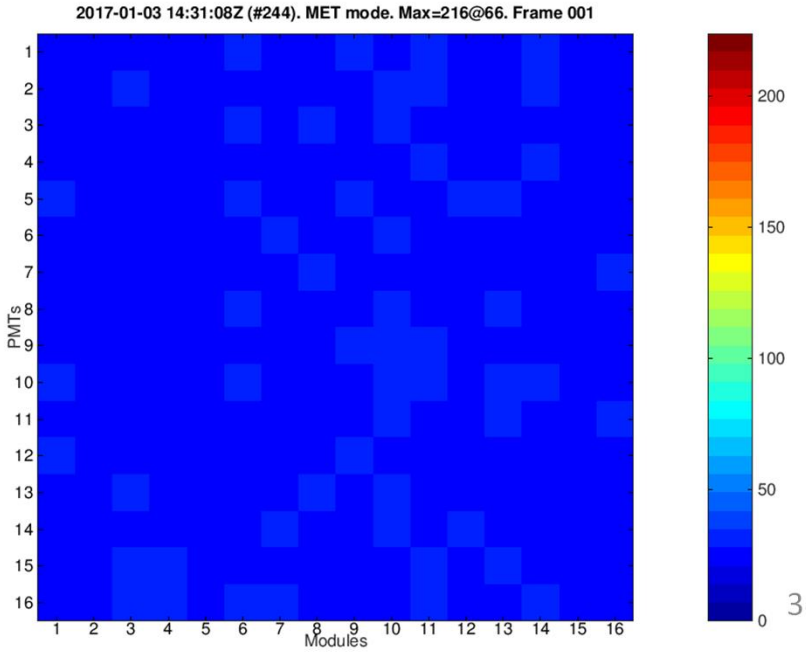
- ✓ Red dot – TUS event
- ✓ AGN van Velzen et al. catalog, less then 20 Mpc (pink), 20-50 Mpc (green), 50-200 Mpc (blue).

Meteor measurements examples (τ = 6.6 ms)



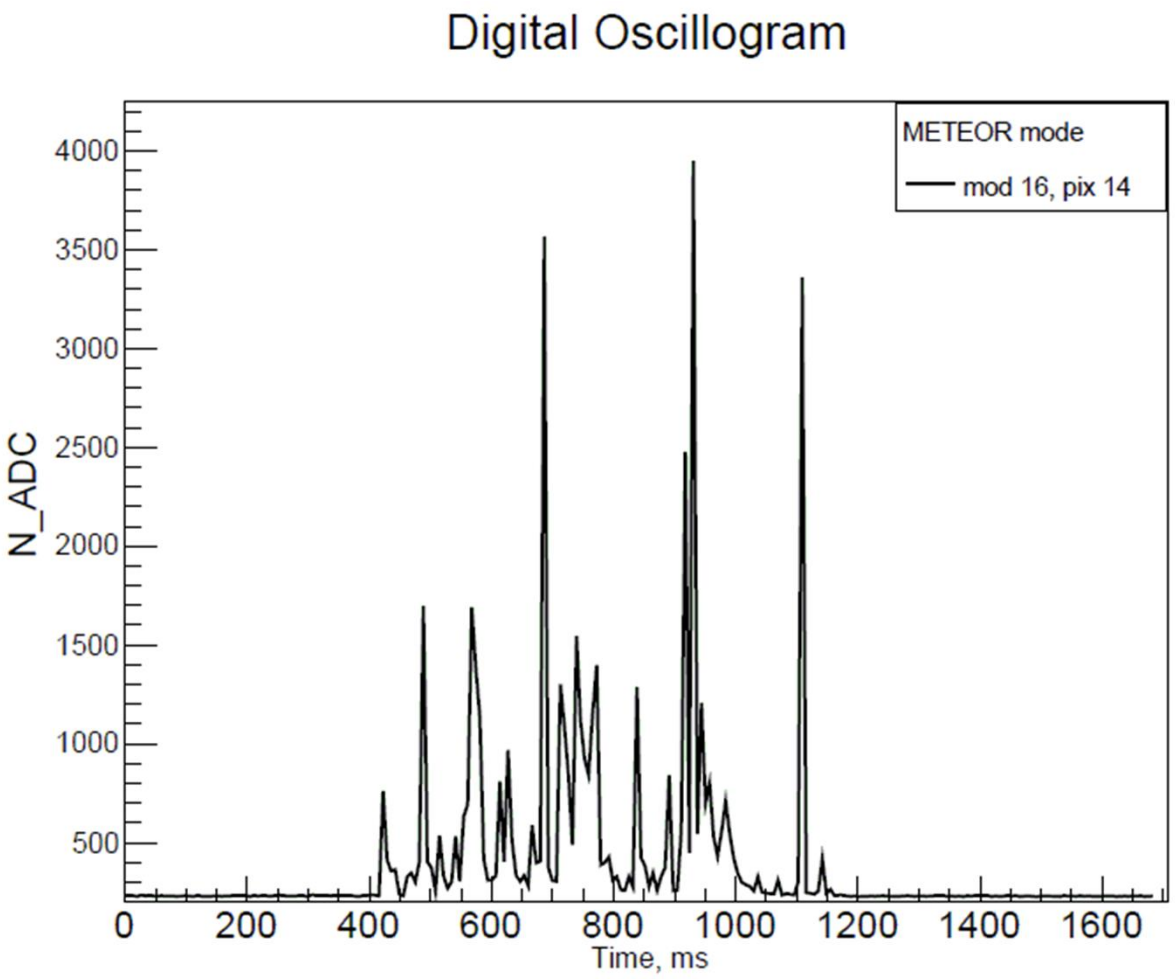




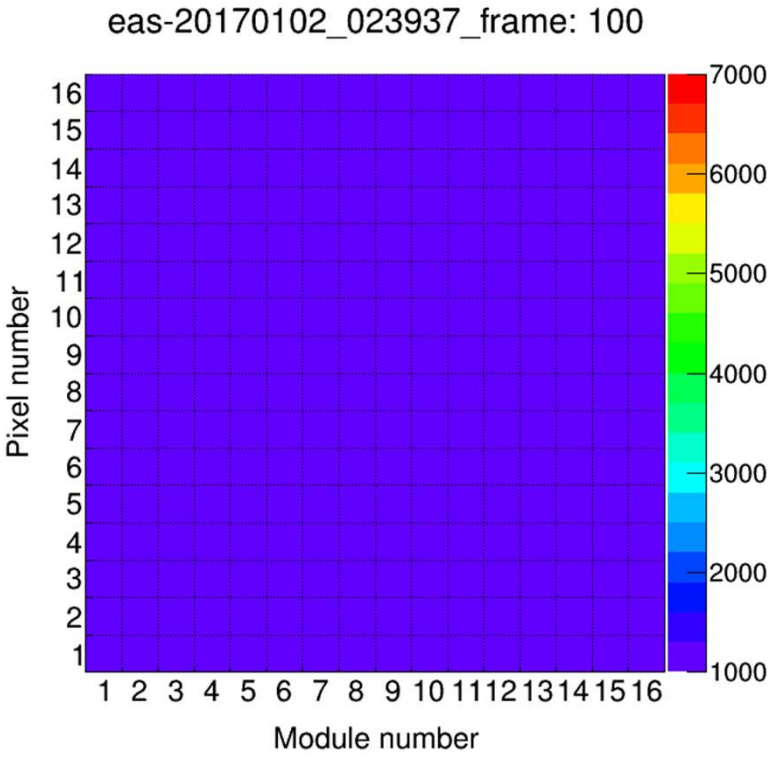


Thunderstorm in Meteor mode (τ=6.6 ms)

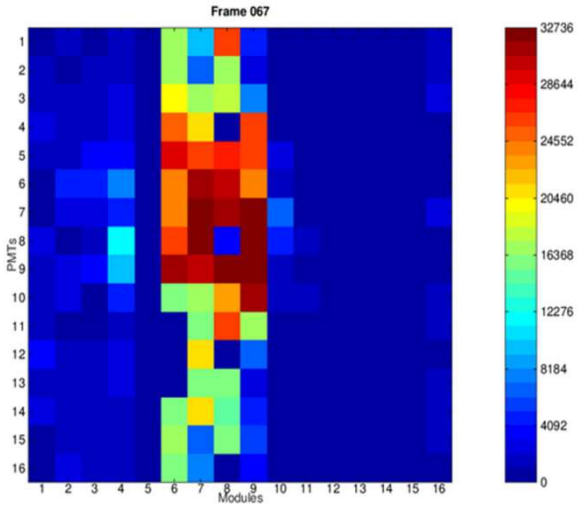
Typical thunderstorm waveform

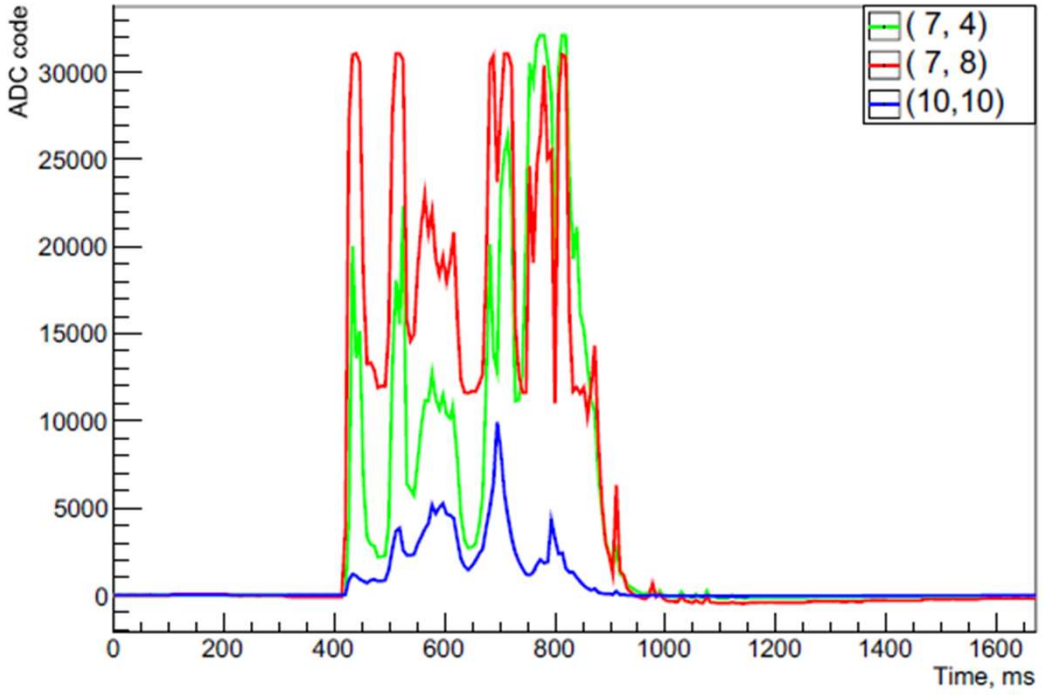


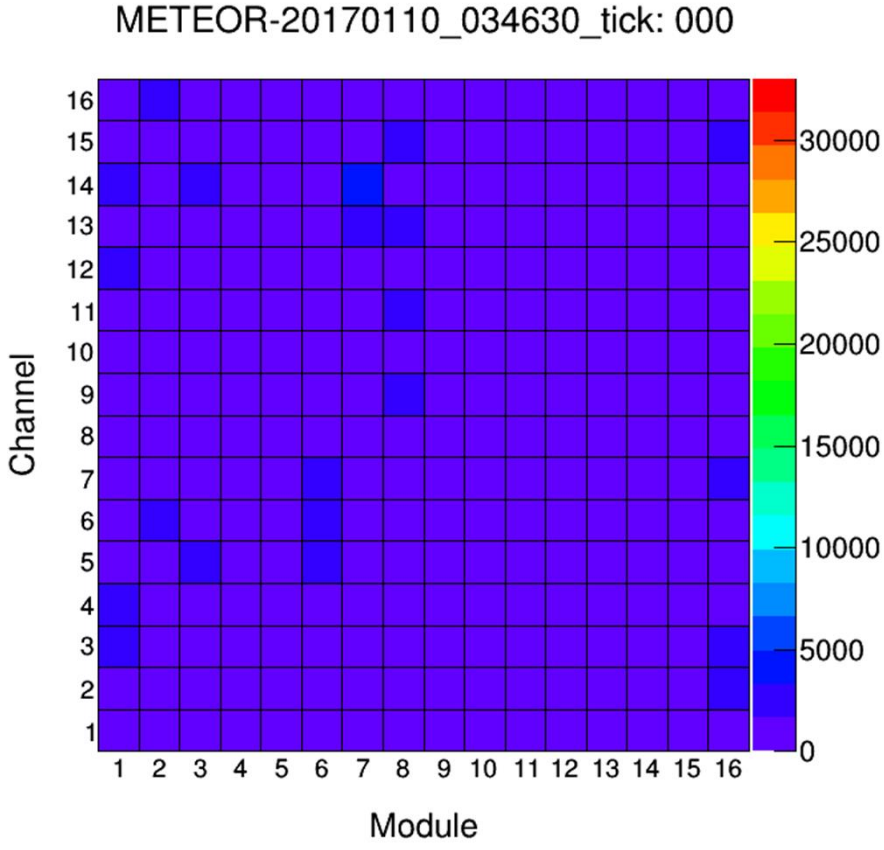
Short pulses – return current



Unusual flashes in Meteor mode

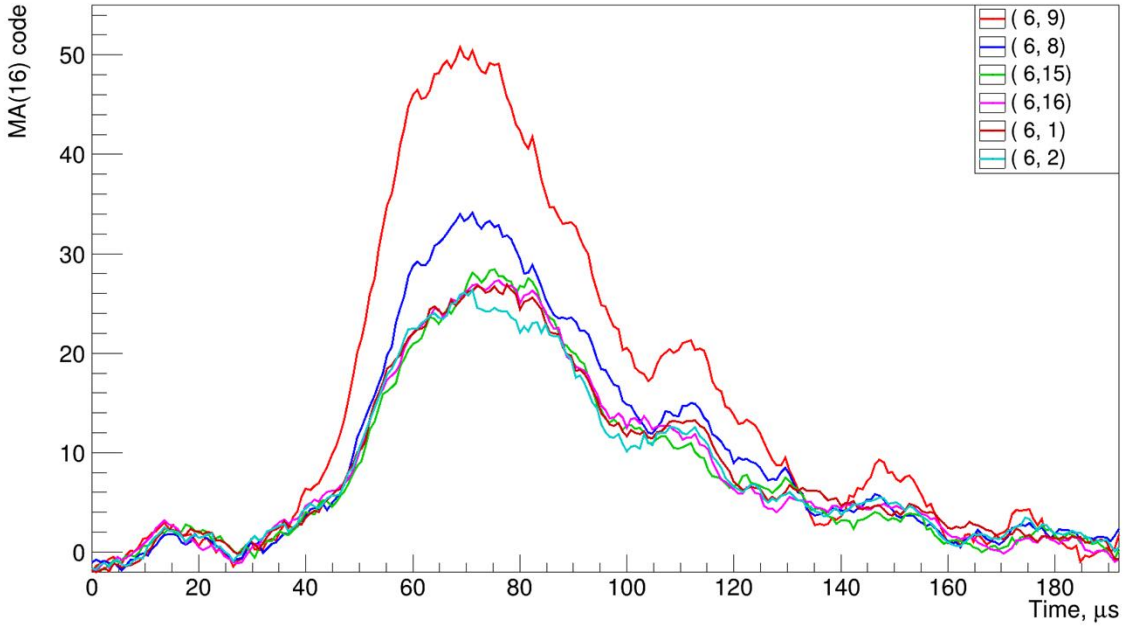


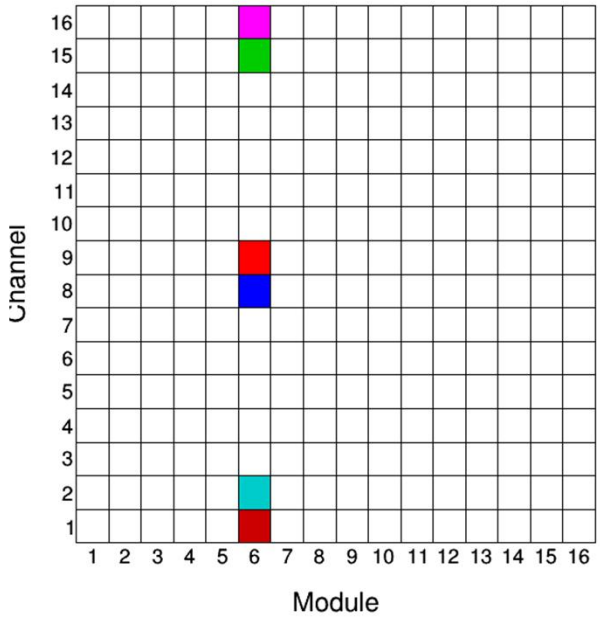


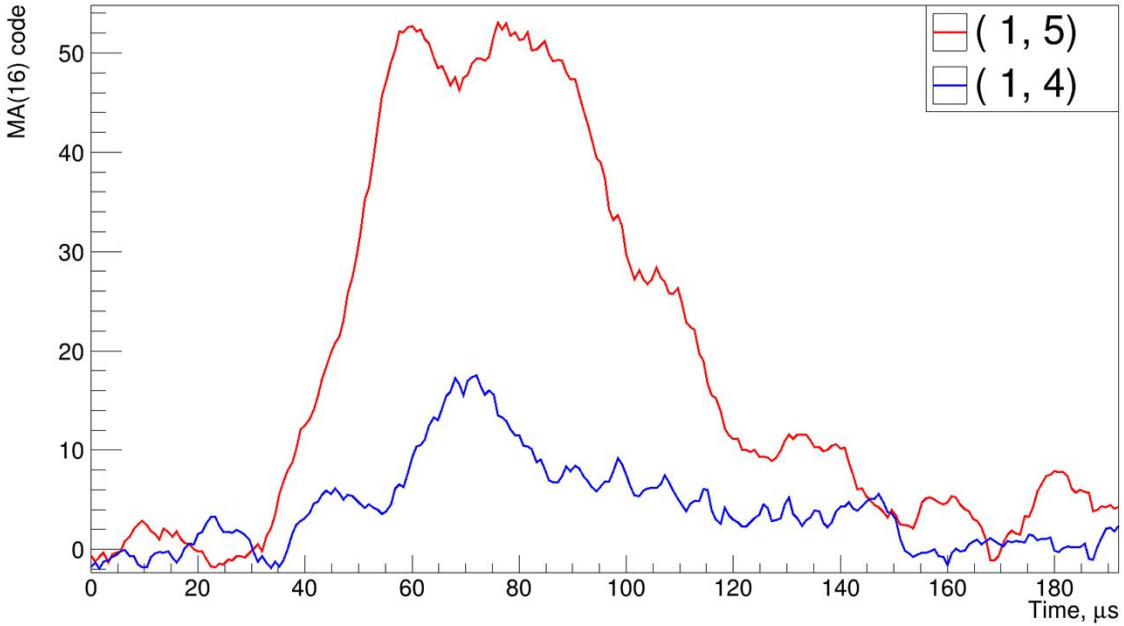


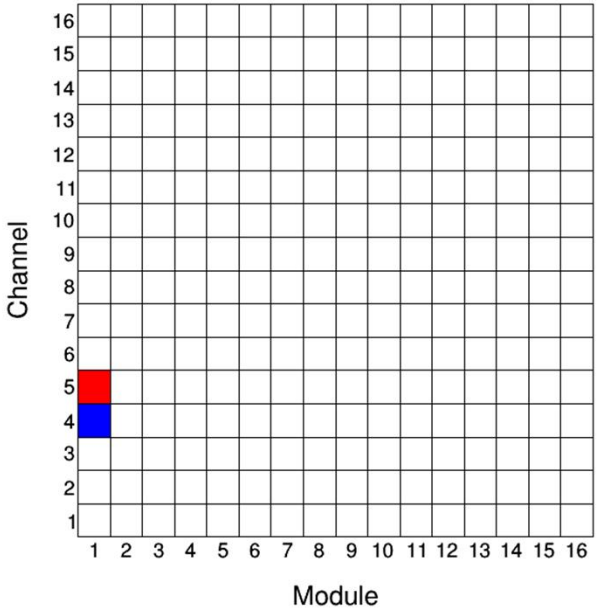
No lightning in radius of 300 km (Vaisala GLD360 data)!

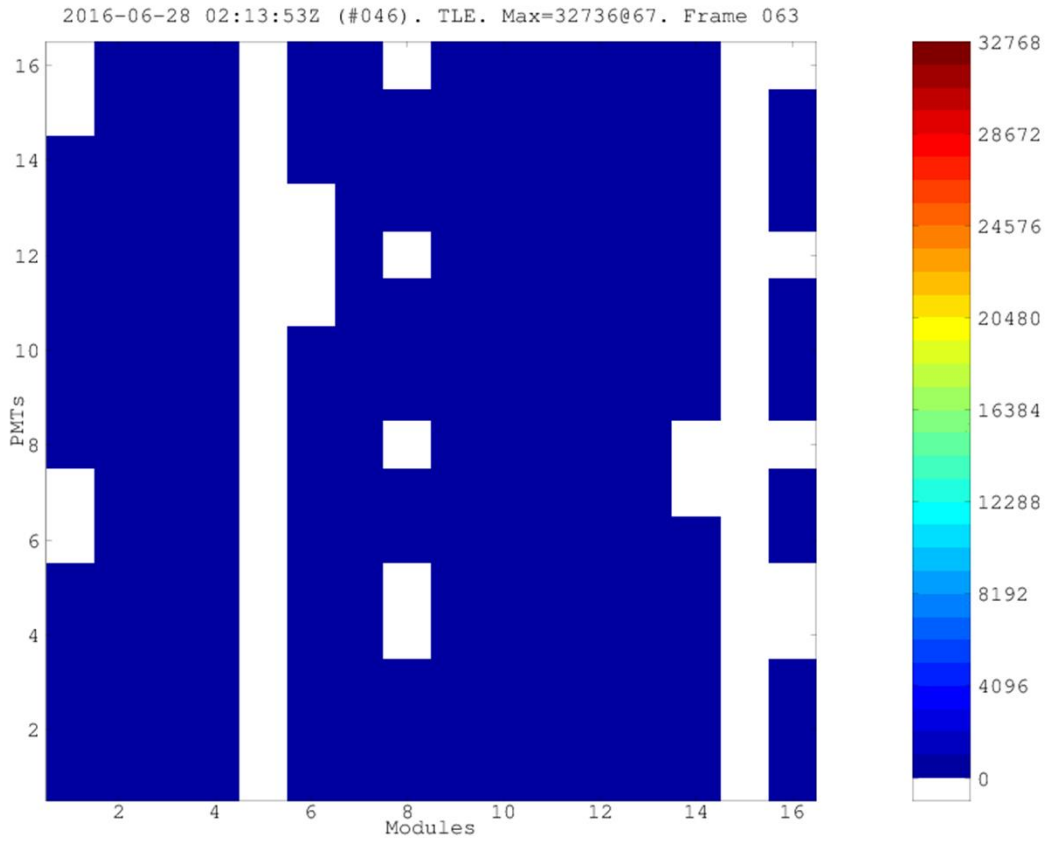
Examples of first two types of events



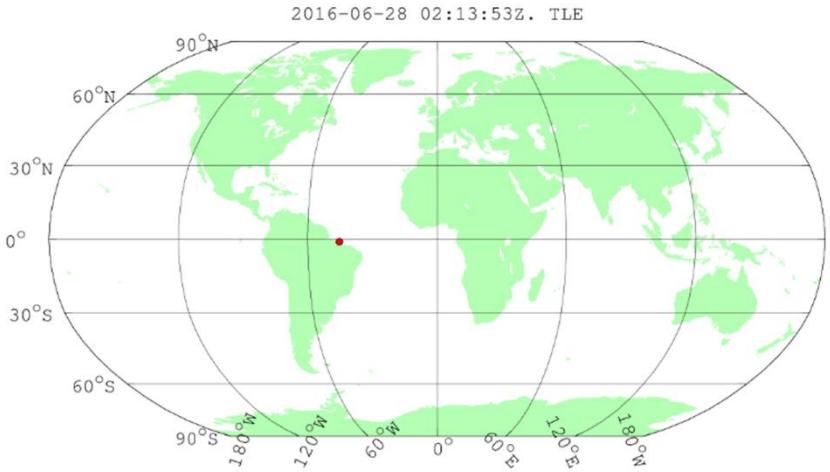








Lightning activity
TLE mode (τ= 0.4 ms)



TUS event

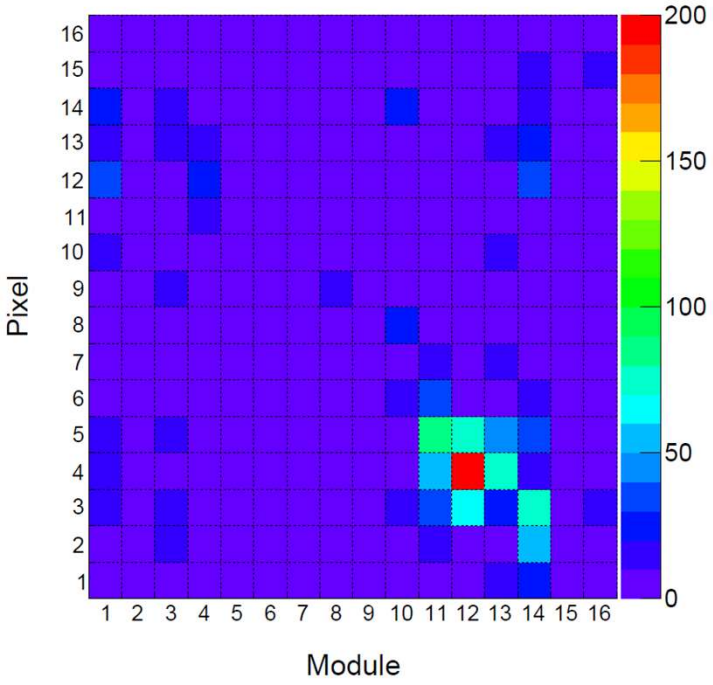
Lat	Long	Date	time
-1.094	-45.328	160628	**02:13:53**

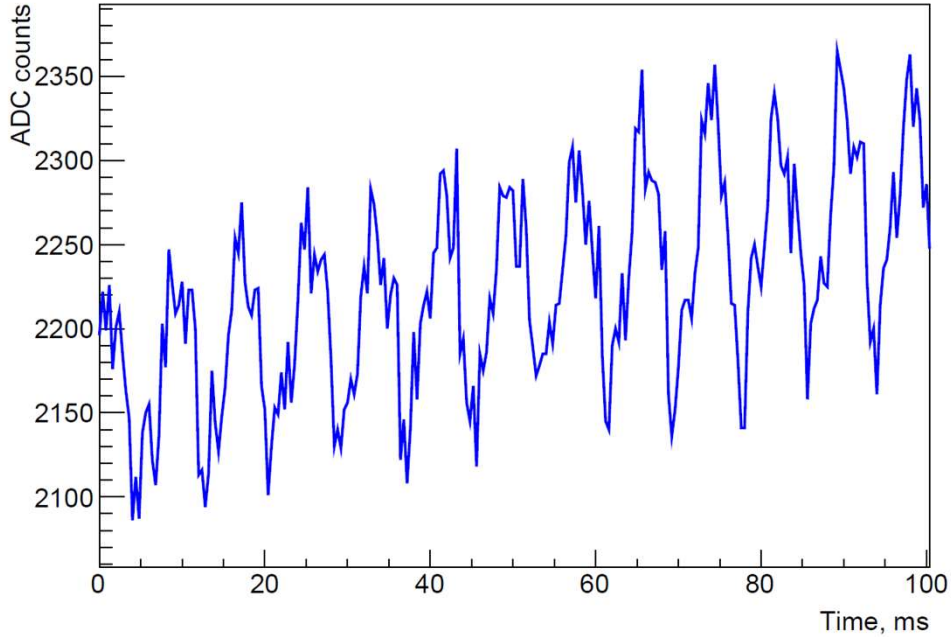
Vaisala GLD360 lightning measurements

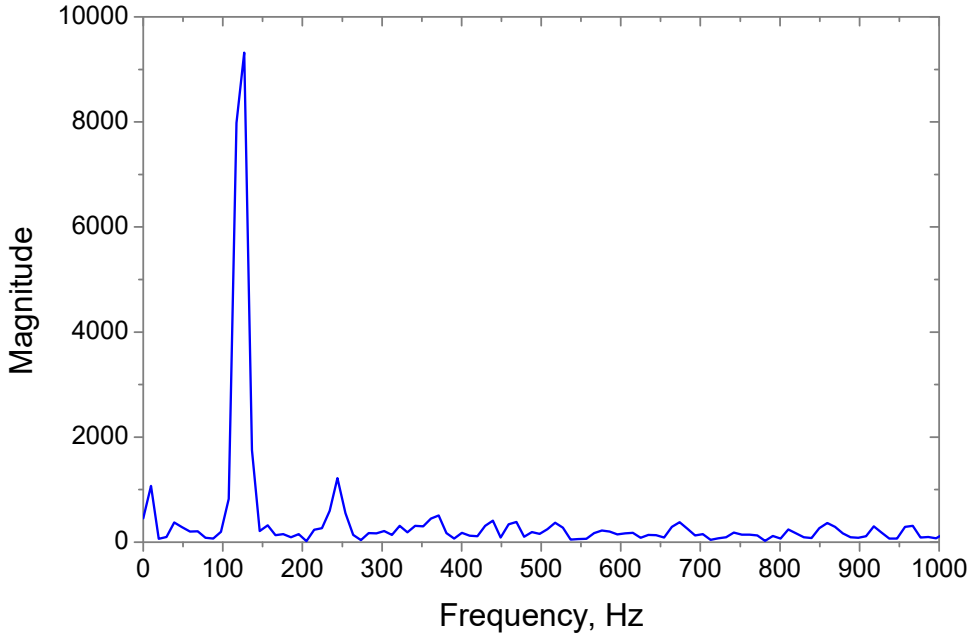
2016-06-28 02:13:53.722119433	**-1.3826**	**-45.4971**	**-44.8**
2016-06-28 02:13:53.756252748	**-1.3955**	**-45.5006**	**+13.8**
2016-06-28 02:13:53.845688510	**-1.4166**	**-45.4738**	**-25.3**
2016-06-28 02:13:53.876783978	**-1.3885**	**-45.4569**	**-22.7**
2016-06-28 02:13:53.918475497	**-1.3878**	**-45.4628**	**-27.6**

Anthropogenic light

- TLE mode (τ= 0.4 ms)



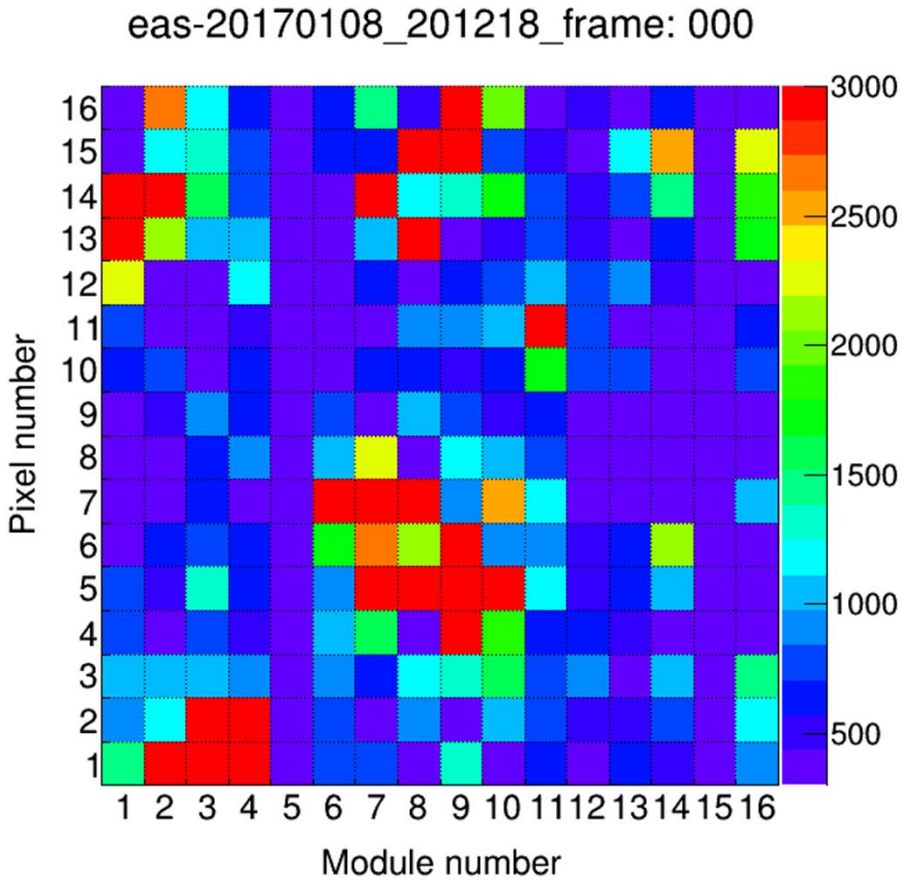




Anthropogenic light

- Meteor mode

(τ=6,6 ms)



$V_{Lomonosov}$

Multi level selection algorithm

- First level – online TUS trigger.
- Second level (analogous to TUS trigger but with additional conditions:
  - moving sum of a waveform in the event exceeded the background level by at least 96 ADC counts (i.e., dQ = 96),
  - the adjacency length L>6
  - additional constraints based on the Gaussian approximation
    - the peak of the signal was located within 72…230 μs from the beginning of the record;
    - total duration of the signal in any active channel was within 27…144 μs;
    - the coefficient of multiple determination $R^2 > 0.8$.
- Third level – event by event study, reconstruction, atmospheric conditions analyses etc.