Skobeltsyn Institute of Nuclear Physics
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RESULTS OF THE FIRST ORBITAL ULTRA-HIGH-ENERGY COSMIC RAY DETECTOR TUS IN VIEW OF FUTURE SPACE MISSION KLYPVE-EUSO

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for the Lomonosov-UHECR/TLE Collaboration
&
for the JEM-EUSO Collaboration

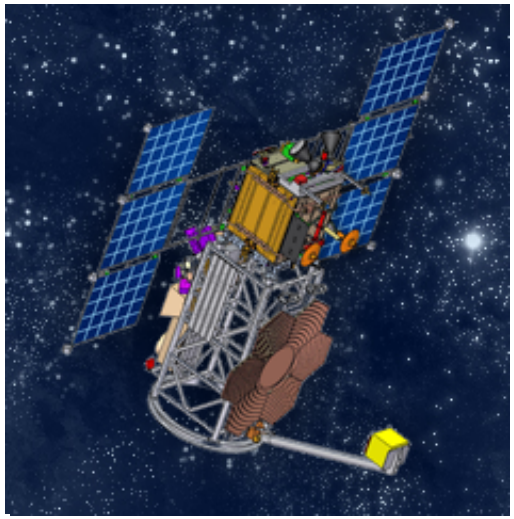
OUTLINE

- Introduction. The TUS detector in the space-based UHECR detectors program
- The TUS detector
- The TUS data and types of events
- Search and analyses of UHECR EAS events
- KLYPVE-EUSO (K-EUSO)
- Conclusions
- Appendix. UHECR space-based detectors and atmospheric science.

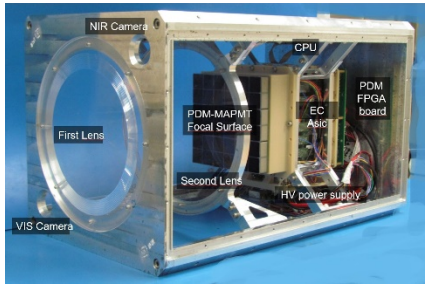
TUS IN THE JEM-EUSO PROGRAM. TOWARD UHECR MEASUREMENTS FROM SPACE

2014 2016 2019 2022

TUS

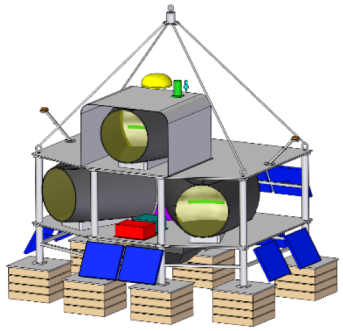


EUSO-Balloon
EUSO-SPB1



Mini-EUSO

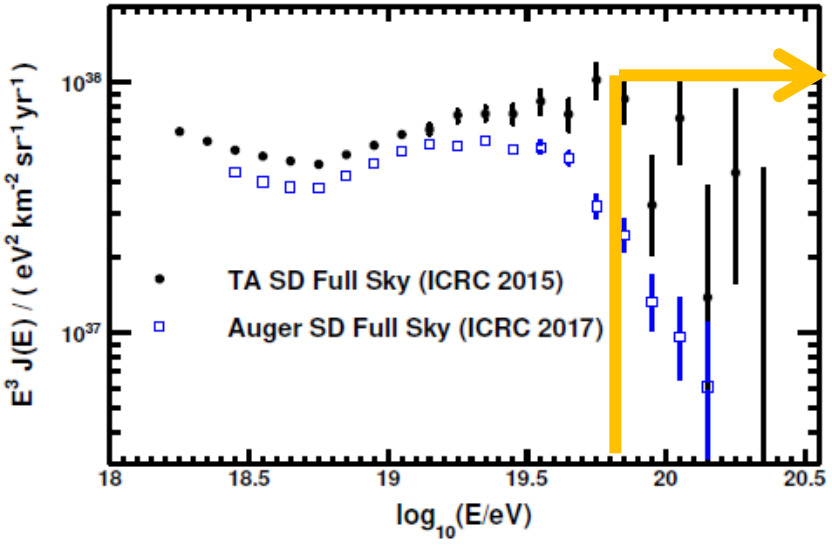
KLYPVE-EUSO



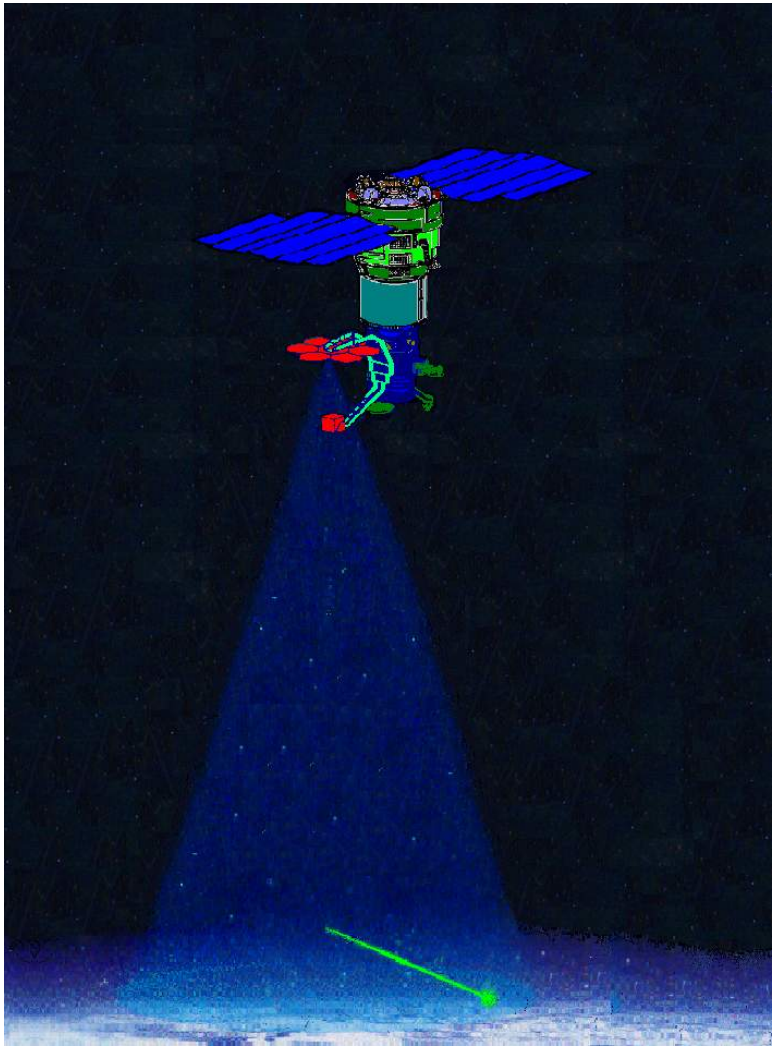
EUSO-SPB-2

SCIENTIFIC GOALS OF THE EXPERIMENT

I. First UHECR measurements from space
II. UV atmospheric radiation and transient atmospheric phenomena study



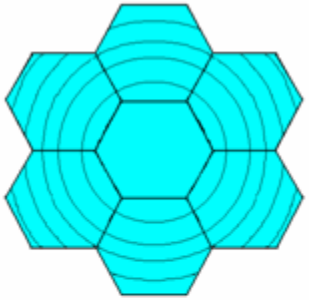
Dmitri Ivanov, PoS(ICRC2017)498

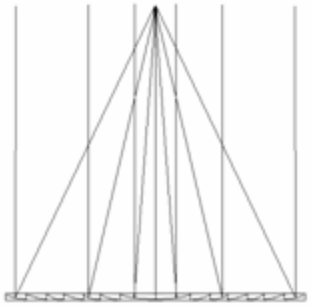


Detector TUS is designed as a multifunctional orbital telescope for various luminous atmospheric processes research.

TUS detector on board the Lomonosov satellite

Fresnel type mirror-concentrator





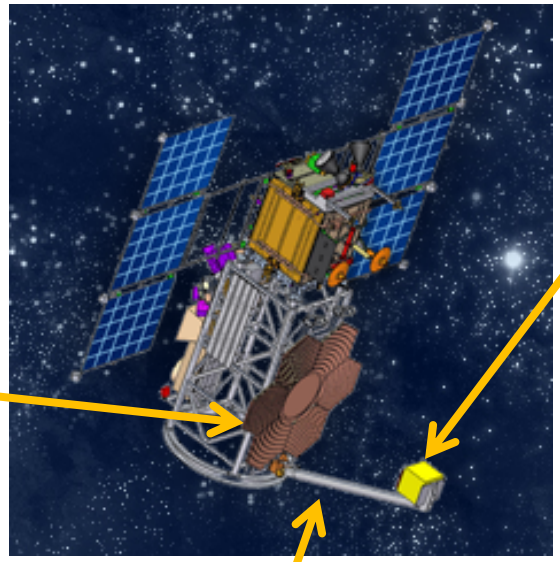
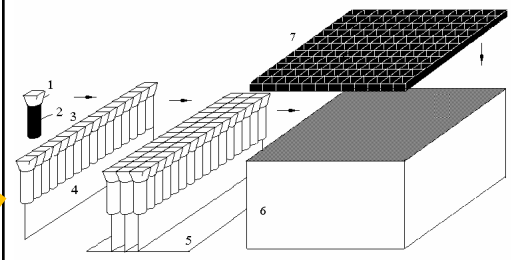


Photo receiver moving system



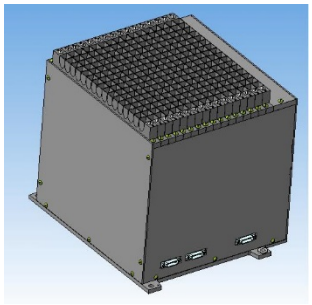
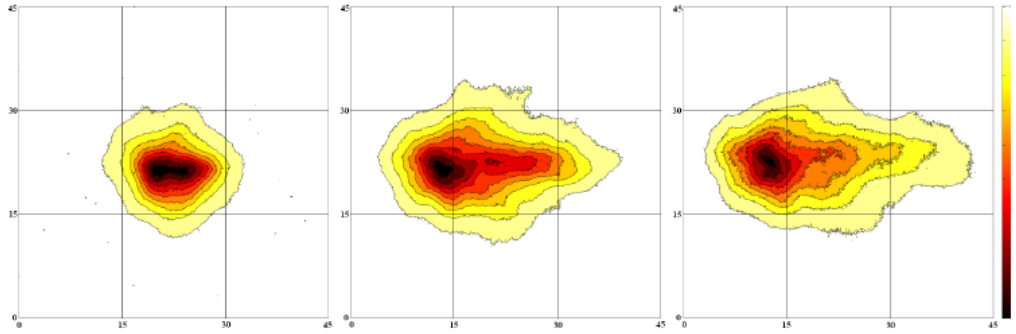


Photo receiver

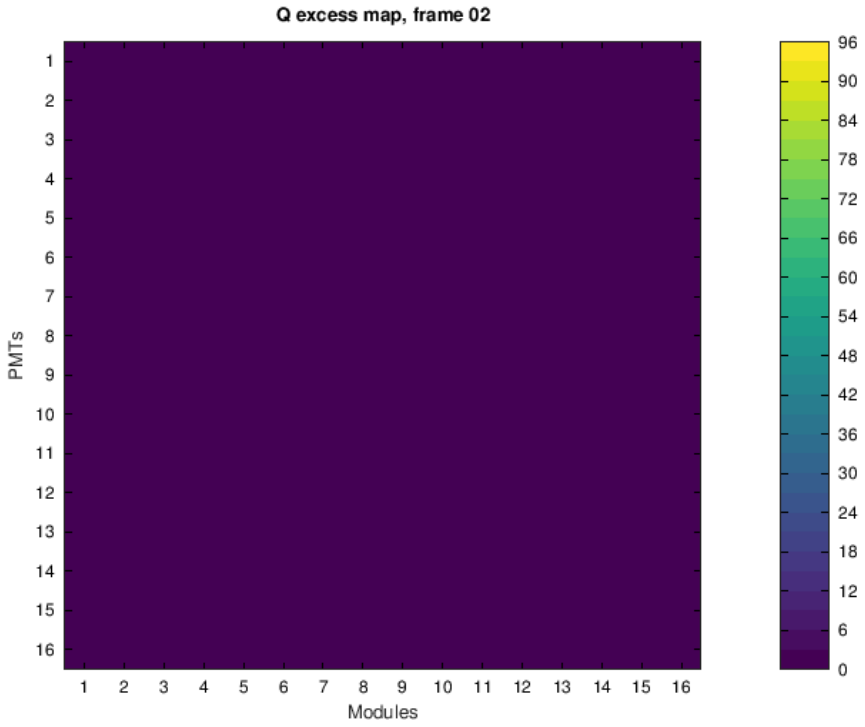


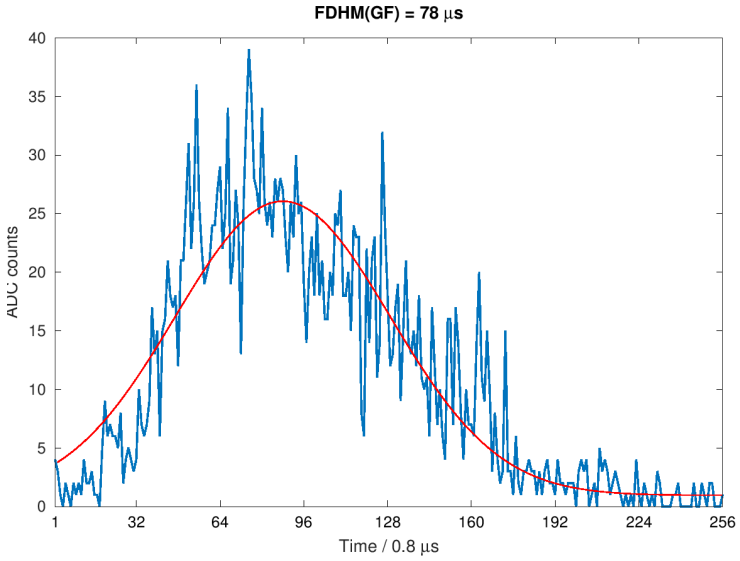
Mass	60 kg
Power	65 W
FOV	±4,5 degree
Channels	16 modules of 16 PMTs
Pixel size	10 mrad (5×5 km)
Mirror area	~2 m^2
Duty cycle	30%

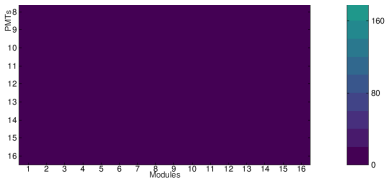
TUS detector trigger and modes of operation

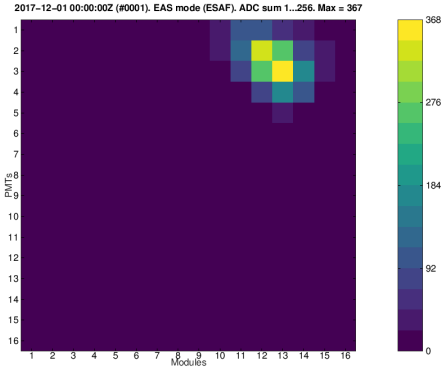
Phenomena	Time sample	Integration time	Oscillogram length
EAS	$\tau = \tau_0 = 0.8$ μs	$t = 2^4\tau = 12.8$ μs	$\Delta T = 256\tau = 205$ μs
Short TLE (elves)	$\tau = 2^5\tau_0 = 25.6$ μs	$t = 2^3\tau = 0.2$ ms	$\Delta T = 256\tau = 6.6$ ms
Long TLE (sprites, jets)	$\tau = 2^9\tau_0 = 0.4$ ms	$t = \tau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

EAS SIMULATIONS FOR TUS









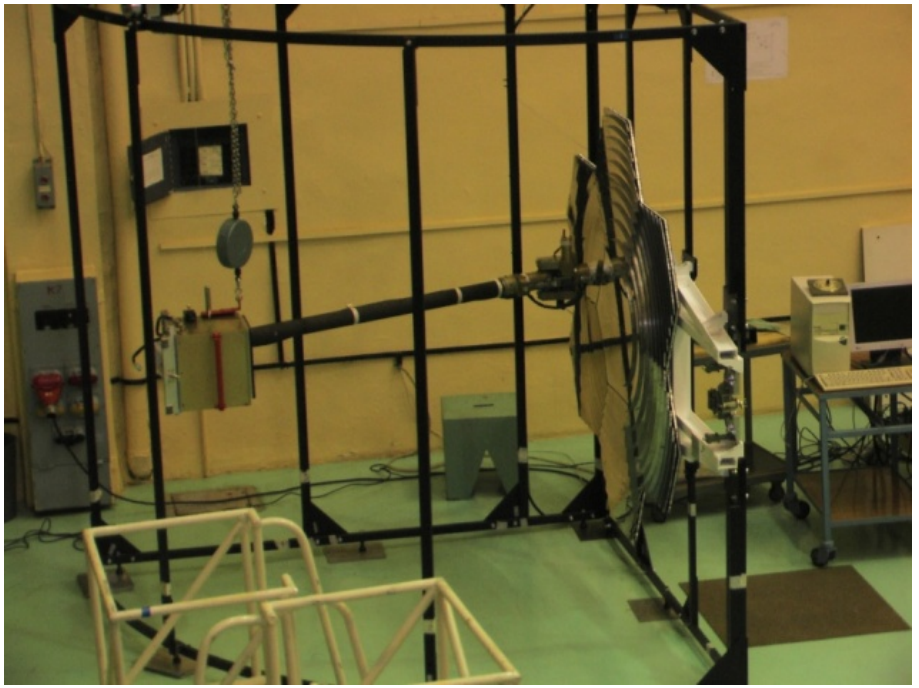
θ = 60°

E=200 EeV

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

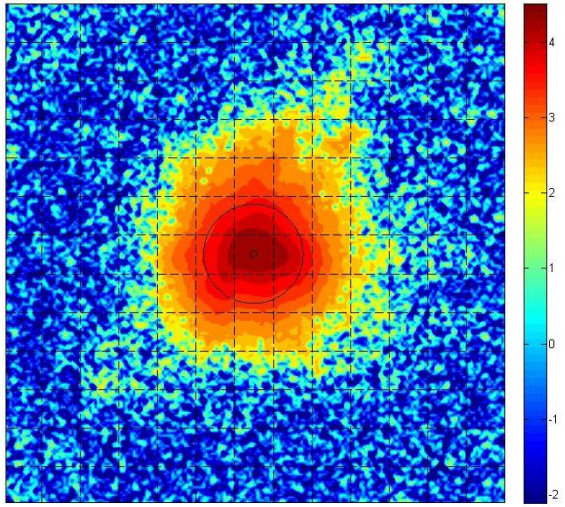
C. Berat, S. Bottai, D. De Marco et al., *Full simulation of space-based extensive air showers detectors with ESAF*, *Astroparticle Physics* **33** (May, 2010) 221–247

TESTS IN MSU AND NIIEM



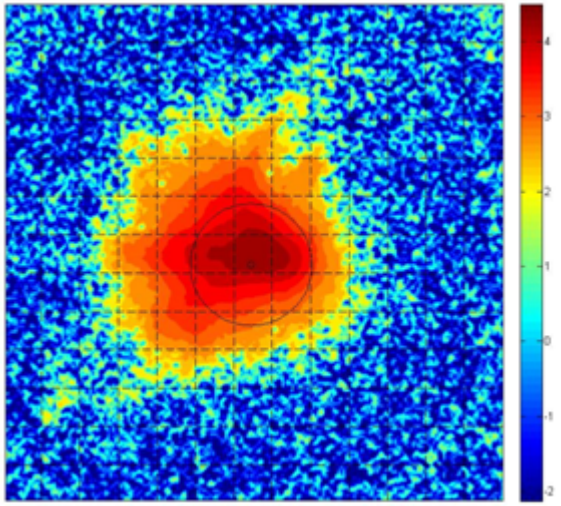
PSF measurements in NIIEM, Istra

θ = 0°

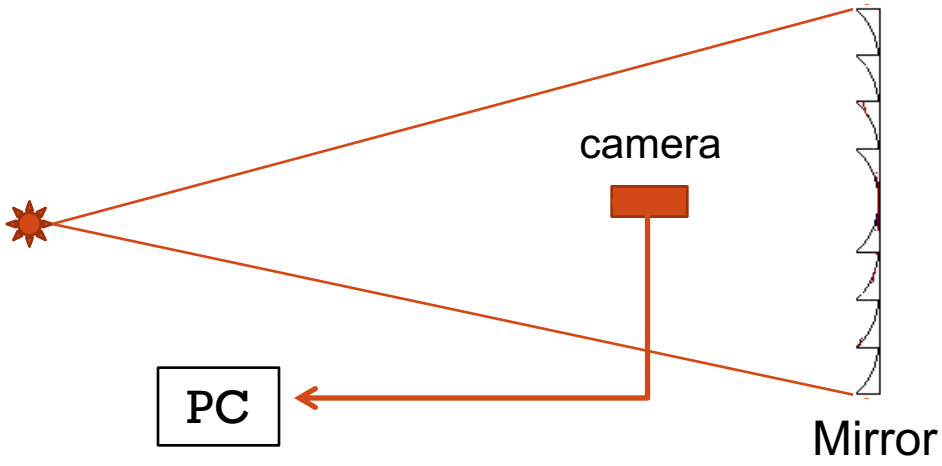


$D_{1/2}$ = 11 mm, D_{70} = 20 mm

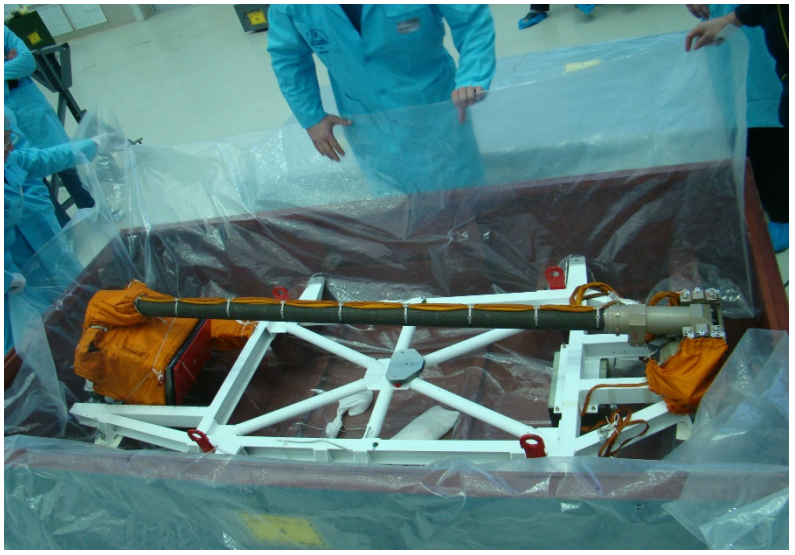
θ = 3,5°

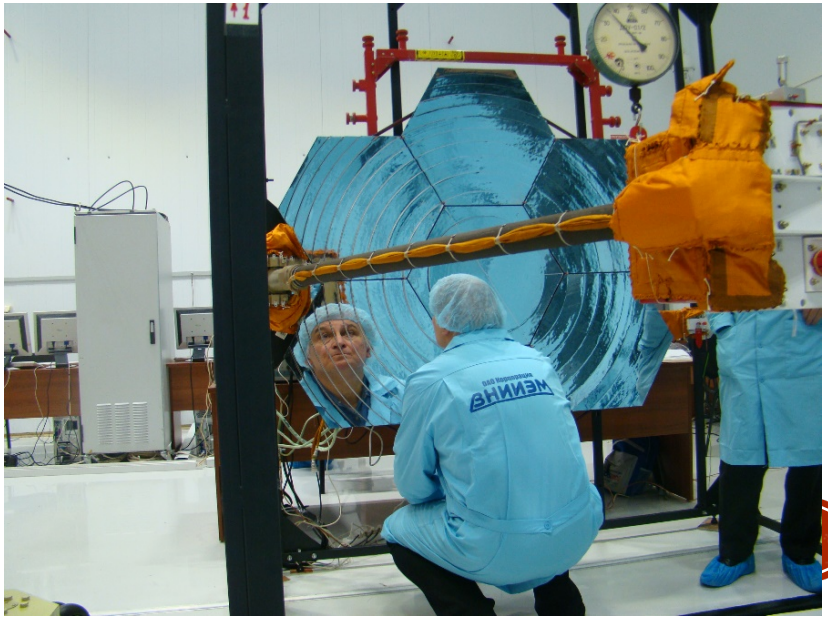


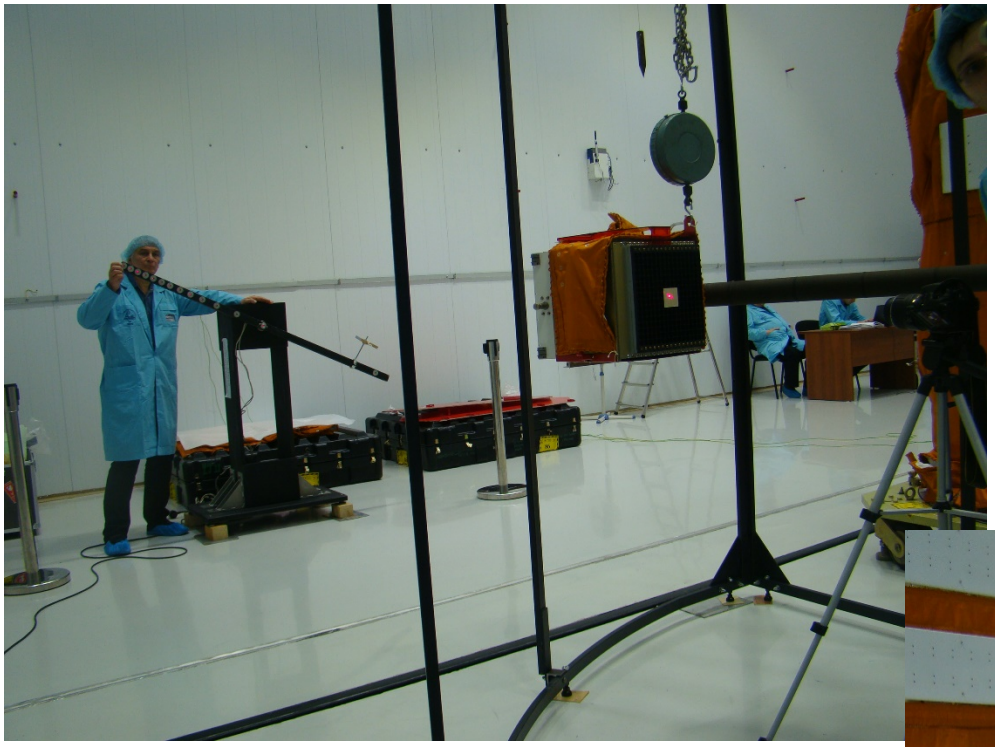
$D_{1/2}$ = 15 mm, D_{70} = 27 mm

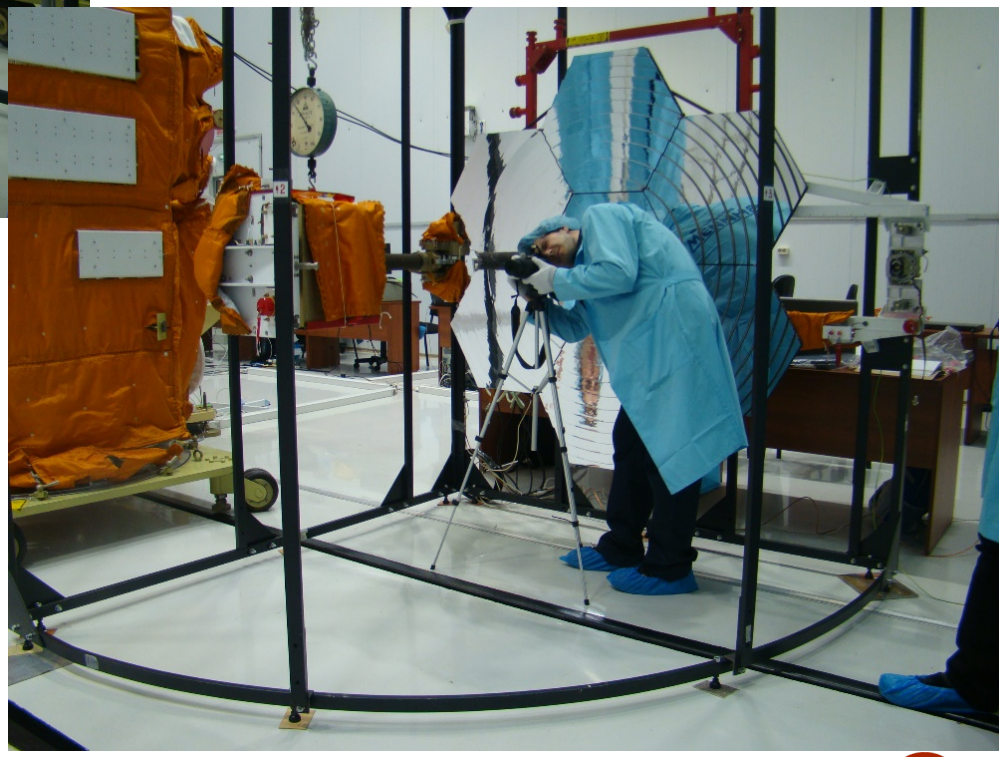


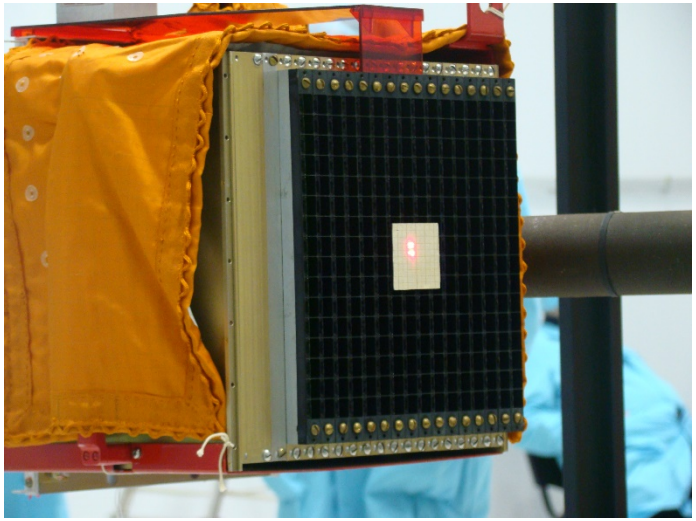
PREFLIGHT TESTS ON THE COSMODROME VOSTOCHNY

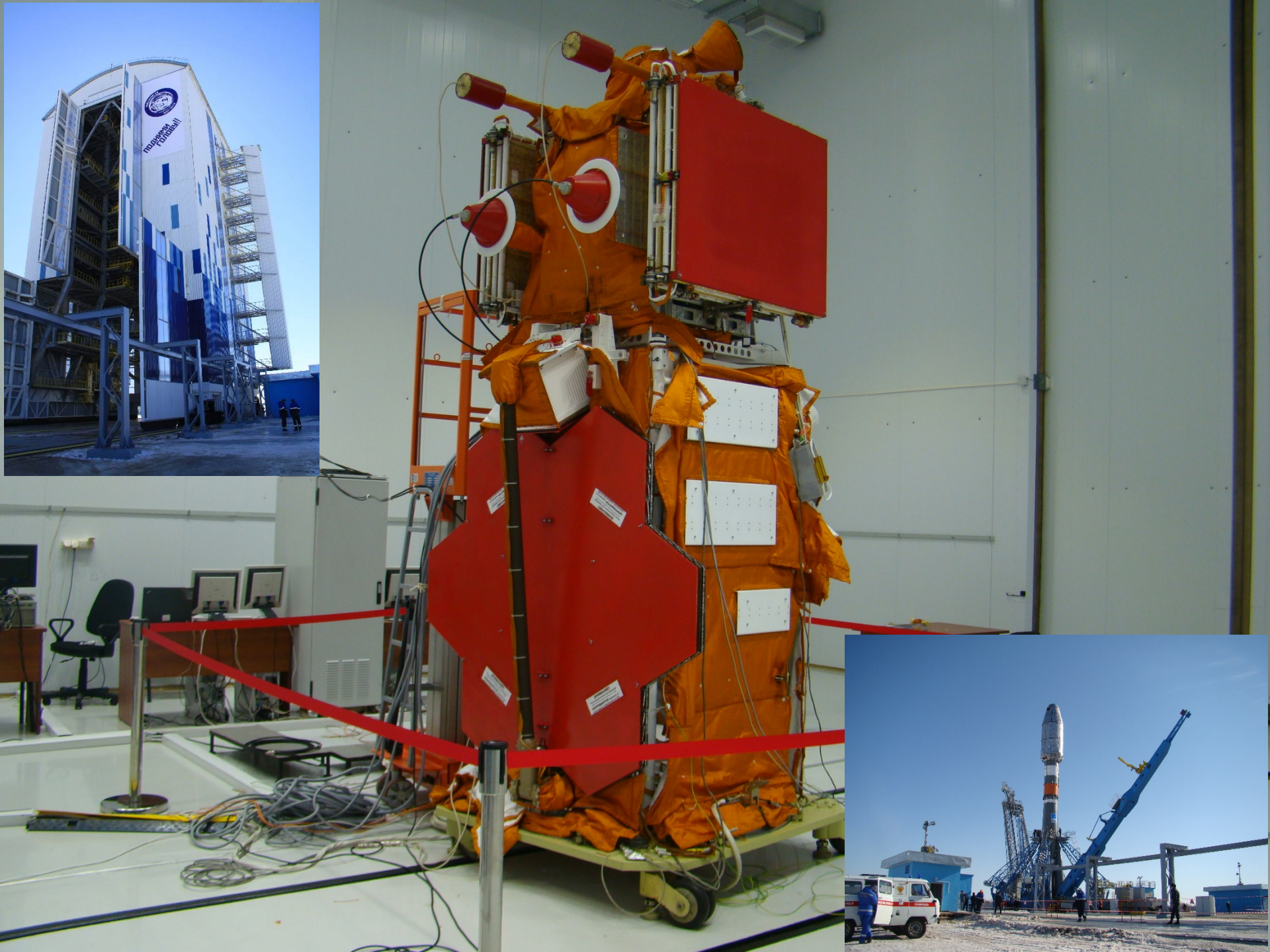






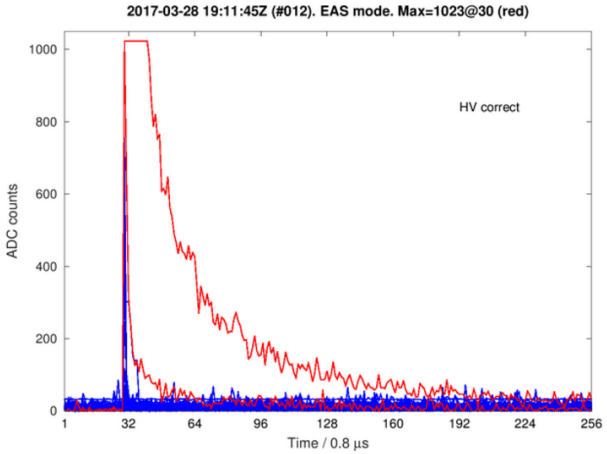


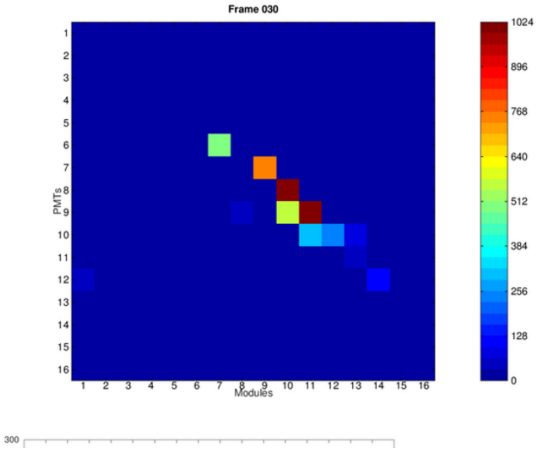





April, 28 2016

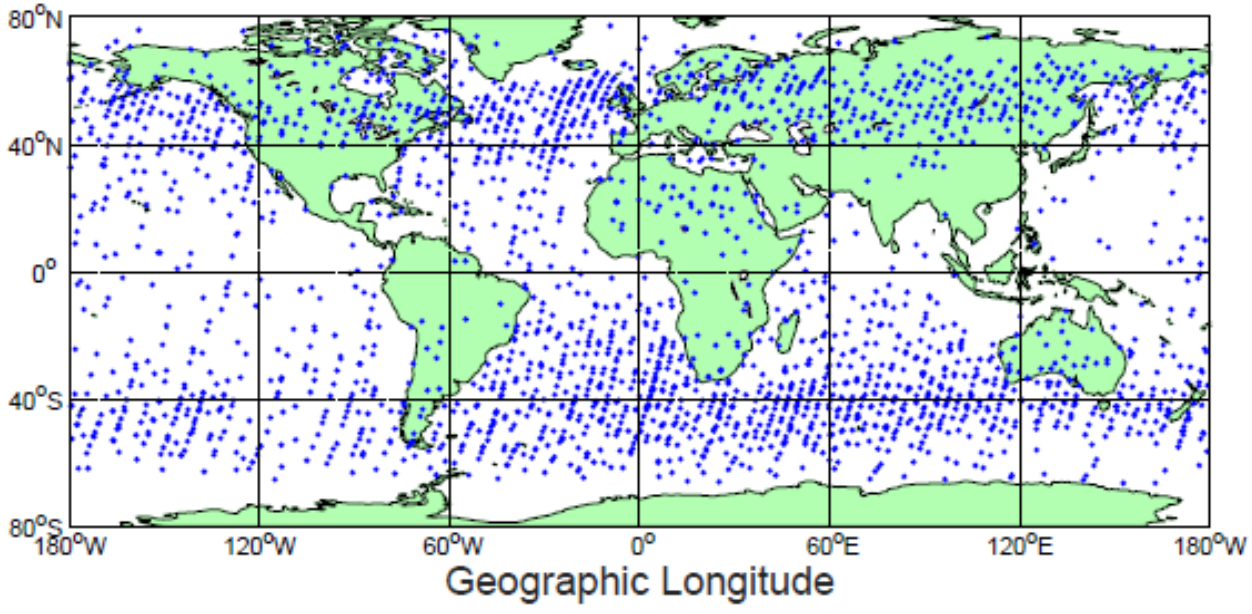
SHORT PULSES, LESS THAN 1 μs (CHARGE PARTICLES TRACKS)

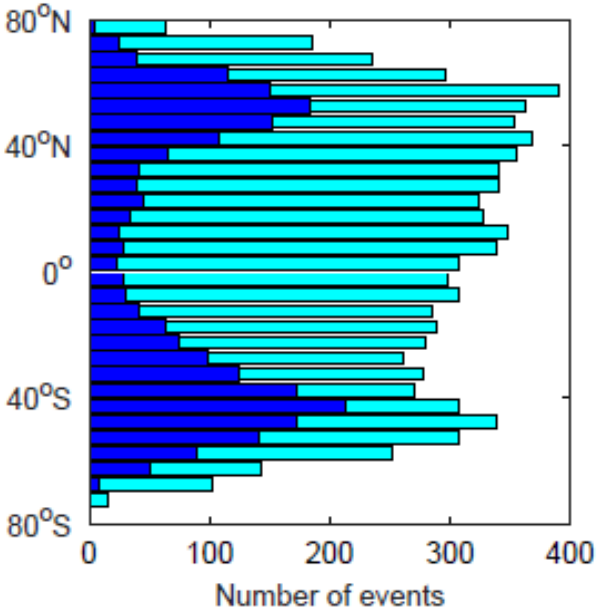




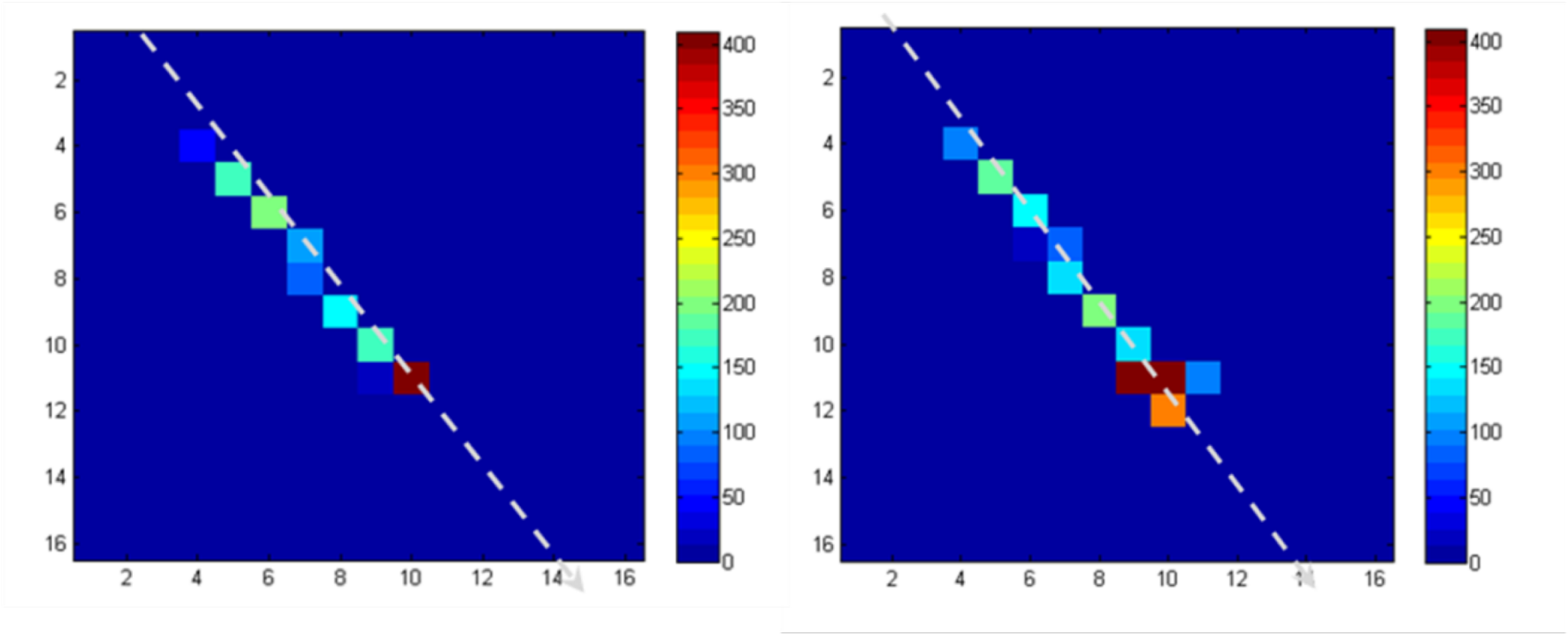
Typical event

Geographical distribution





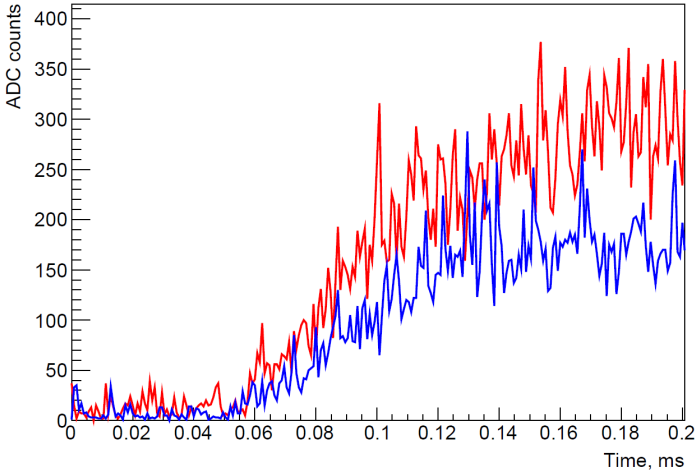
GEANT4 SIMULATION OF SIGNAL FROM PROTONS PASSING UV FILTER IN FRONT OF PMTS

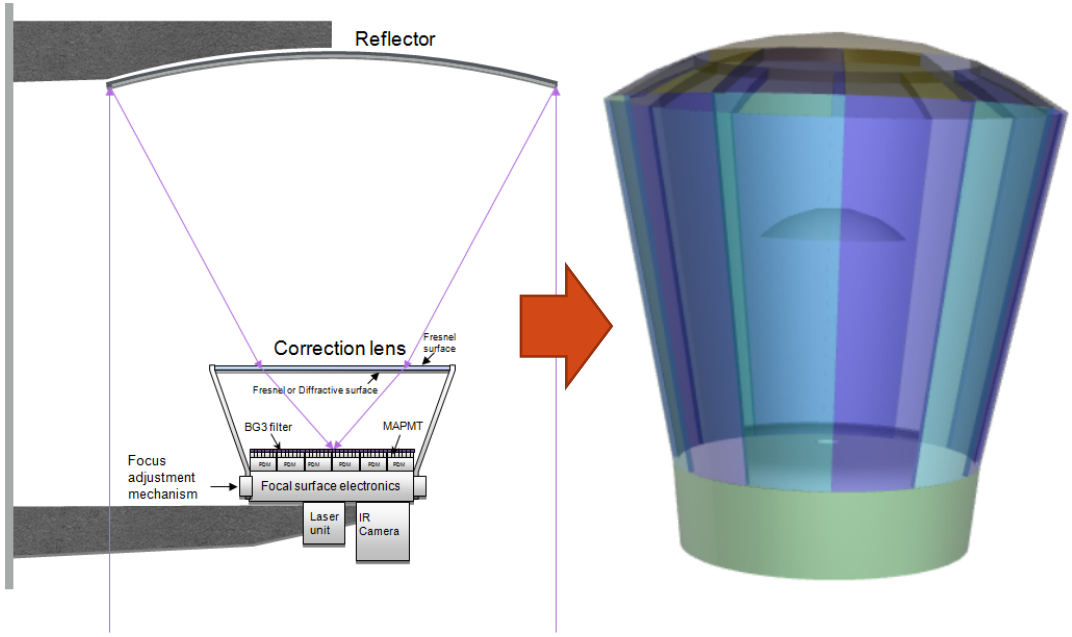


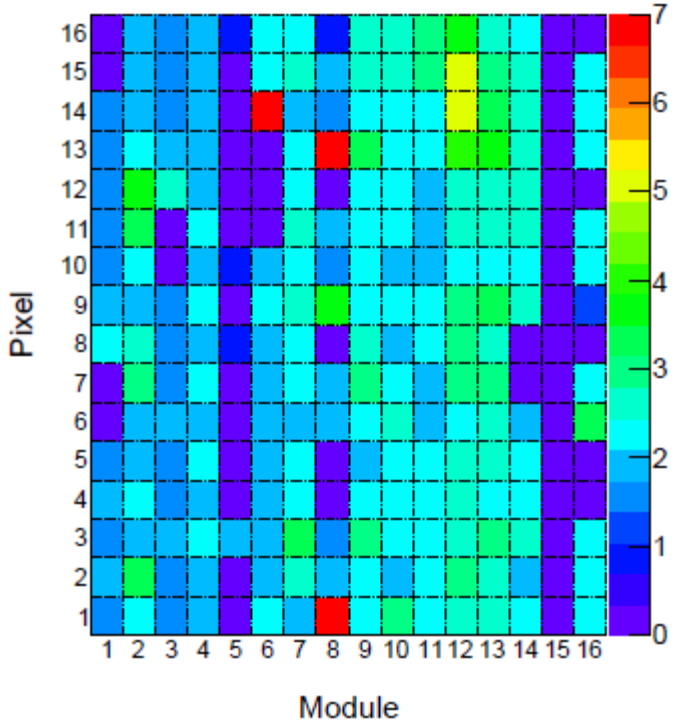
15 % of trigger were caused by this type of events
The anti-trigger was developed (search for instant change of ADC code and trigger blocking for 100 μs) to eliminate them and increase the exposure time.

An important methodical result for K-EUSO trigger system development

THUNDERSTORM SIGNAL IN EAS MODE



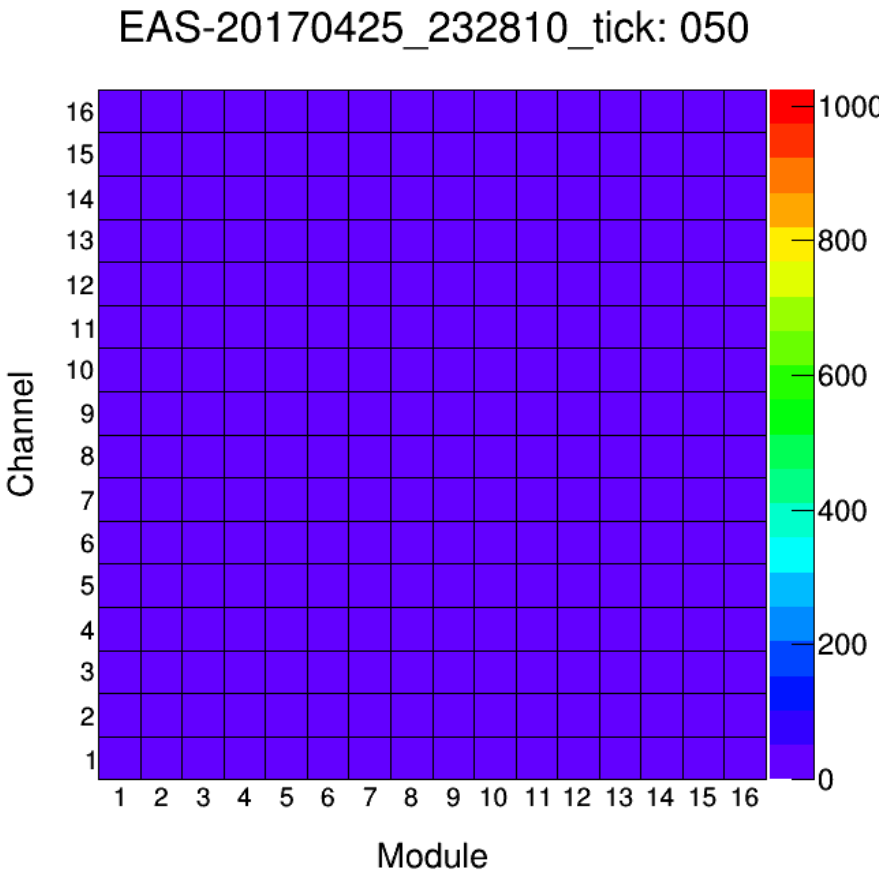


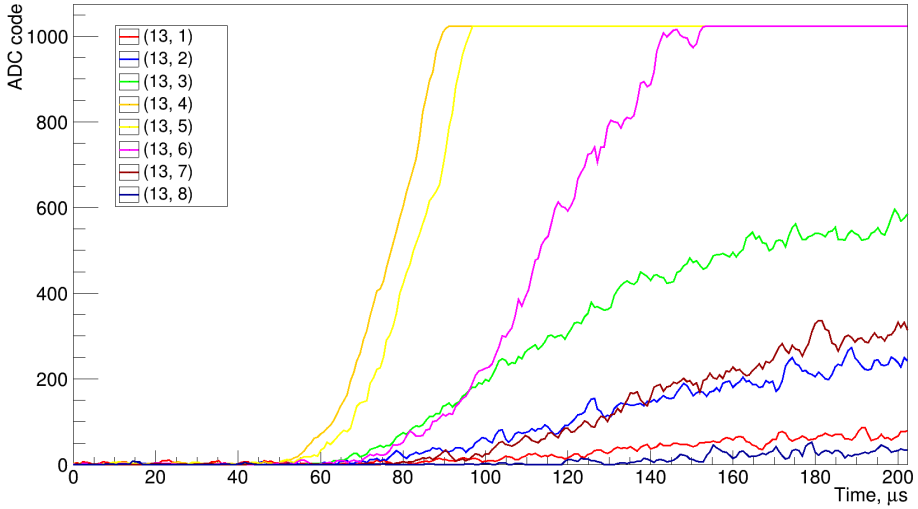


- ✓ “Slow” rising of signal
- ✓ Correlation with thunderstorm regions
- ✓ Stray light outside FOV.

Determined the final chose of K-EUSO optical system

POWERFUL LIGHTNING UV FLASH IN THE FOV OF THE DETECTOR





From database of lightning detection network **Vaisala GLD360**:
Date: 2017-04-25
Time: 23:28:09.417UTC,
Position: 11.2112, -4.6118
Peak curren1t: I_p=+16.9

The event caused EAS trigger but can be distinguish from EAS due to space-time structure. Longer oscillogram will allow to study temporal structure of atmospheric phenomena

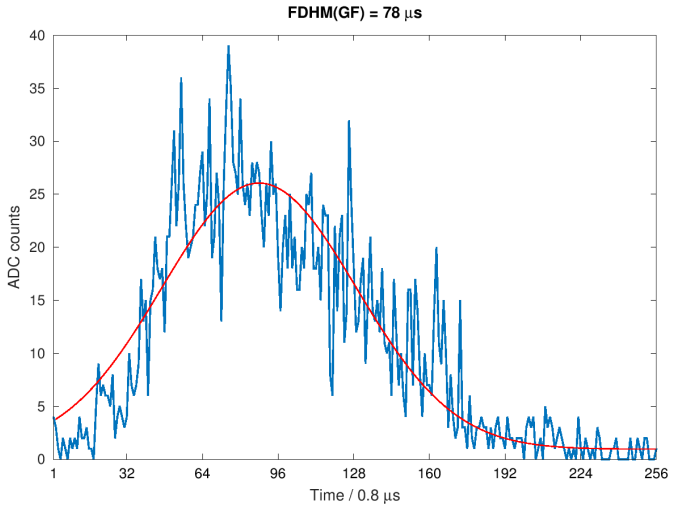
SEARCH FOR EXTREME ENERGY COSMIC RAY CANDIDATES IN THE TUS ORBITAL EXPERIMENT DATA

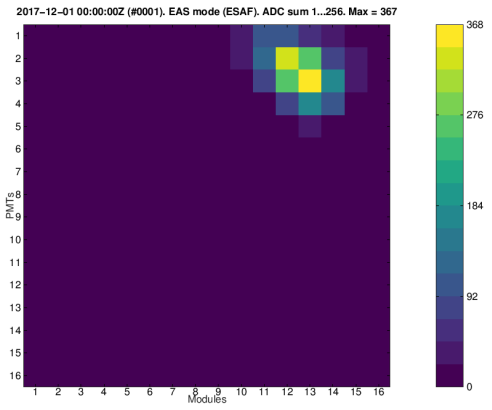
The total exposure of TUS in EAS mode is ~10^3 km^2 yr sr.

It gives expected number of events with energy threshold 100 EeV:
~0,5 ev/year (PAO spectrum) or ~2 ev/year (TA spectrum)

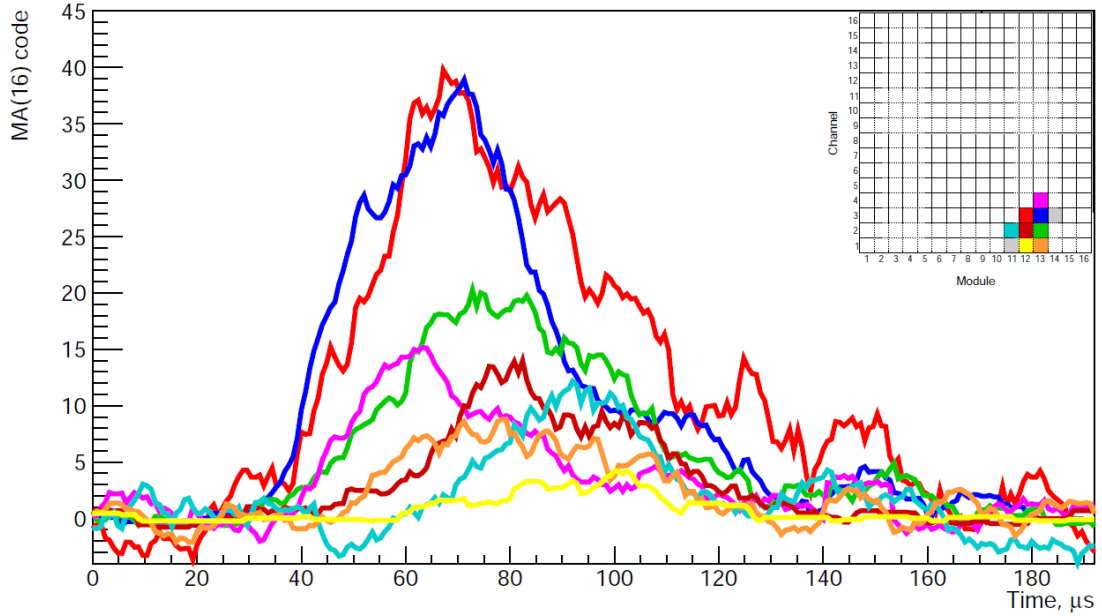
Multi level selection algorithm

- First level – online TUS trigger.
- Second level (analogous to TUS trigger but with additional conditions to select events with expected time-space structure from all measurements)
- Third level – event by event study, reconstruction, atmospheric conditions analyses etc.

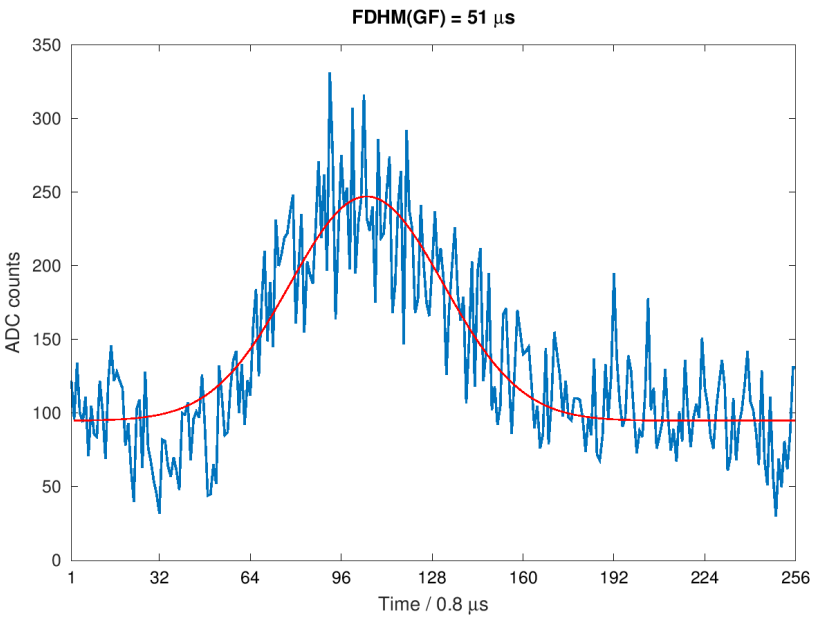




EVENT 03.10.2016 05:48:59UTC



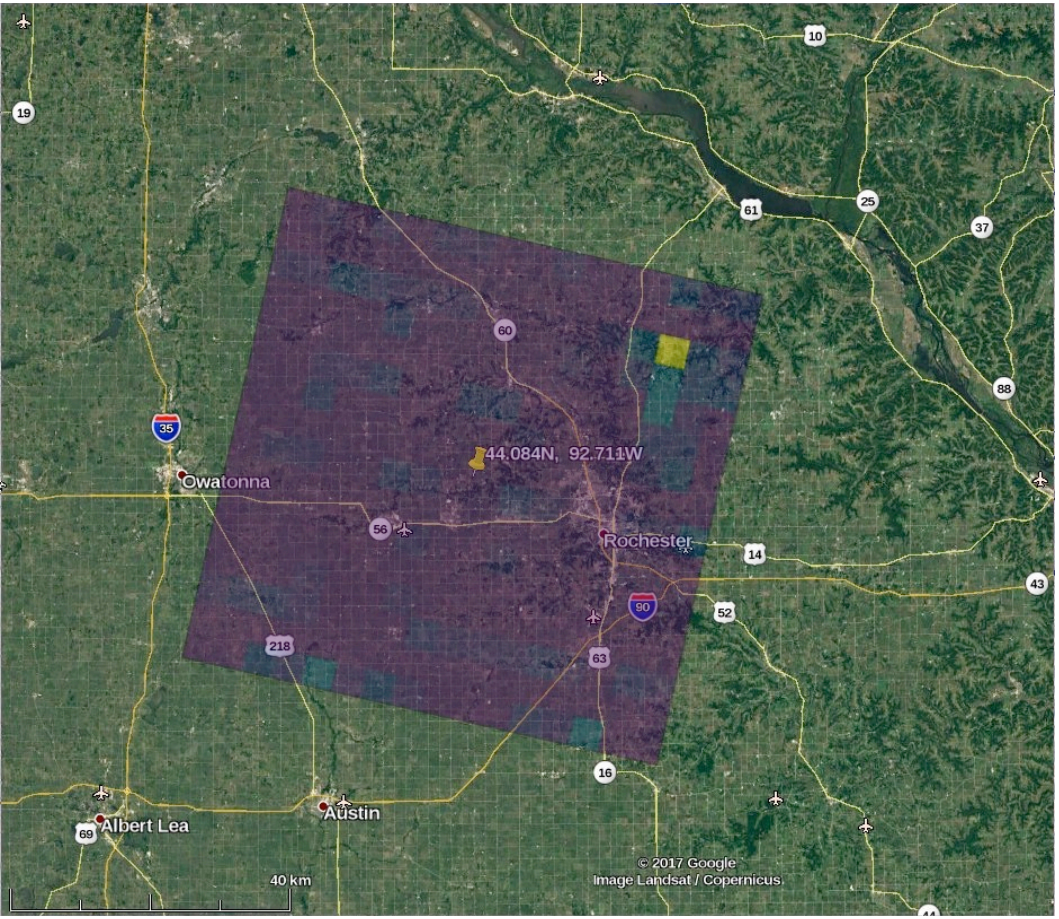
ADC counts in active channels

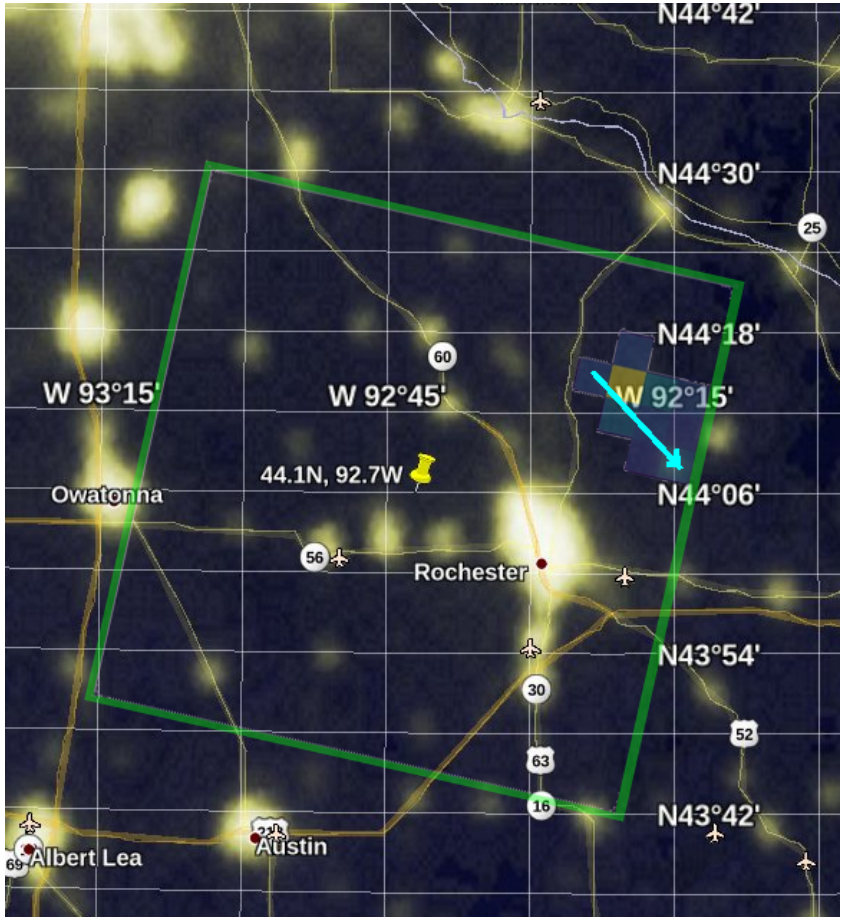


Sum of ADC counts in active channel

The event with expected EAS spatial and temporal signal structure (waveforms and pixel map).

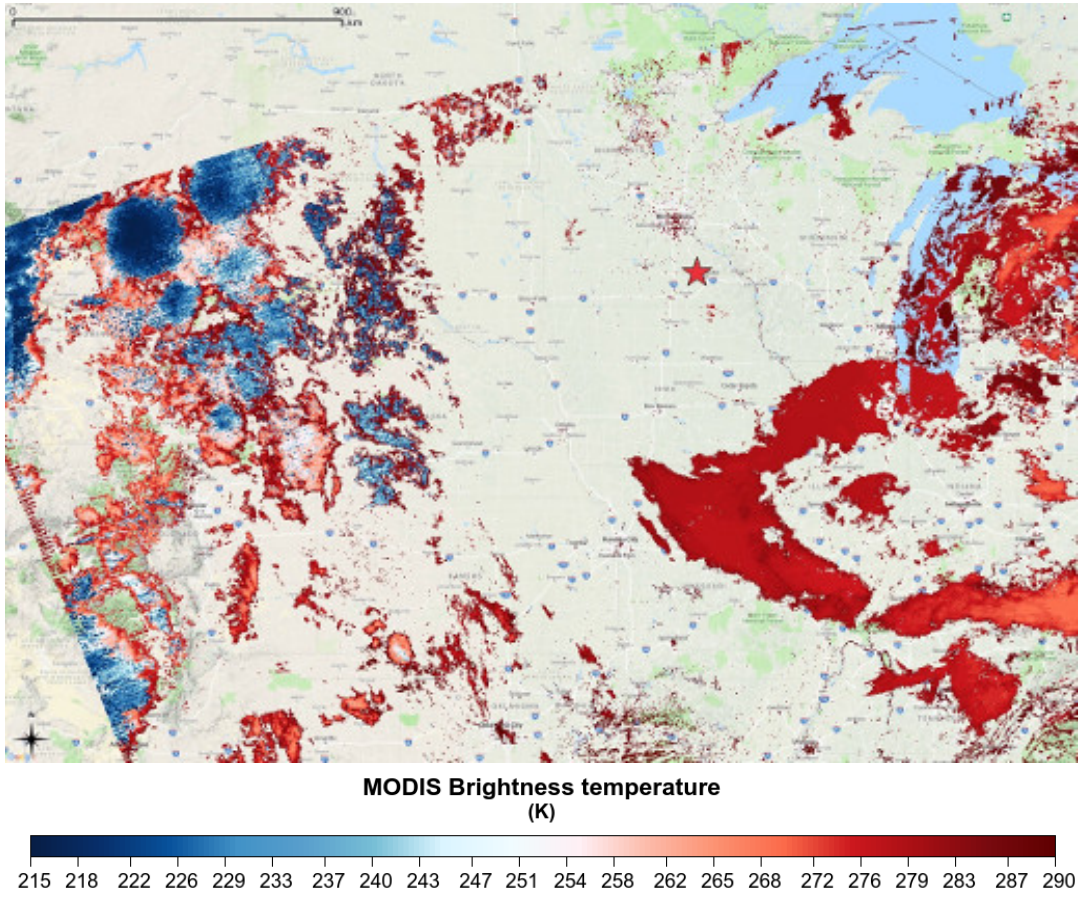
Measurements conditions analyses: anthropogenic sources





Google Earth map with the TUS field of view and the event – no huge anthropogenic light

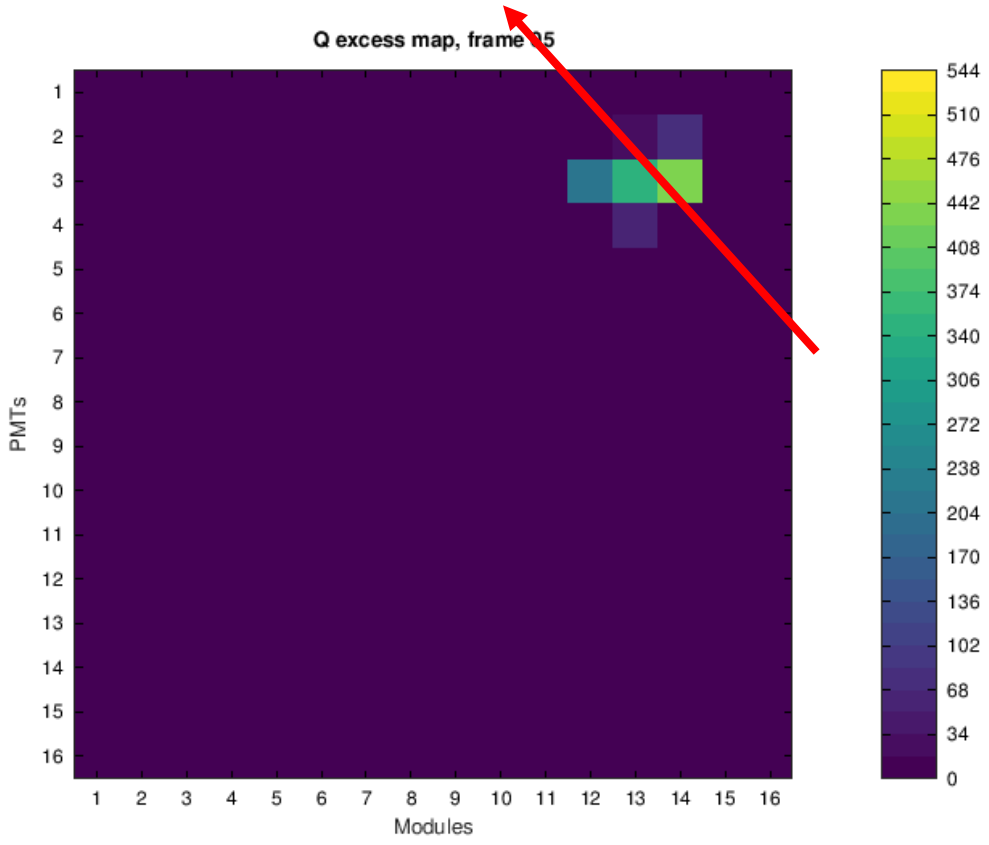
Measurements conditions analyses: thunderstorm activity



Data of MERRA-2
Provided by R. Cremonini

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.

PIXEL MAP AND SIGNAL MOVEMENT. ARRIVAL DIRECTION RECONSTRUCTION



Linear Track Algorithm (LTA)

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

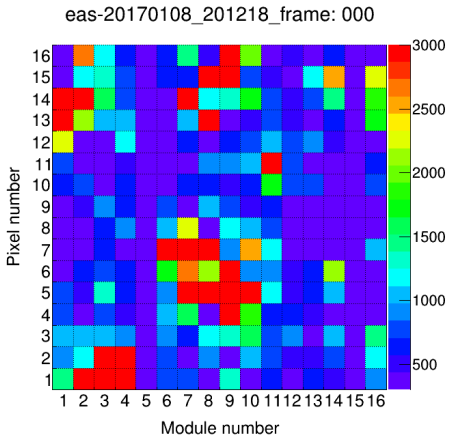
$$\phi = \arctan(u_x/u_y), \quad \theta = 2\arctan(fRu/c)$$

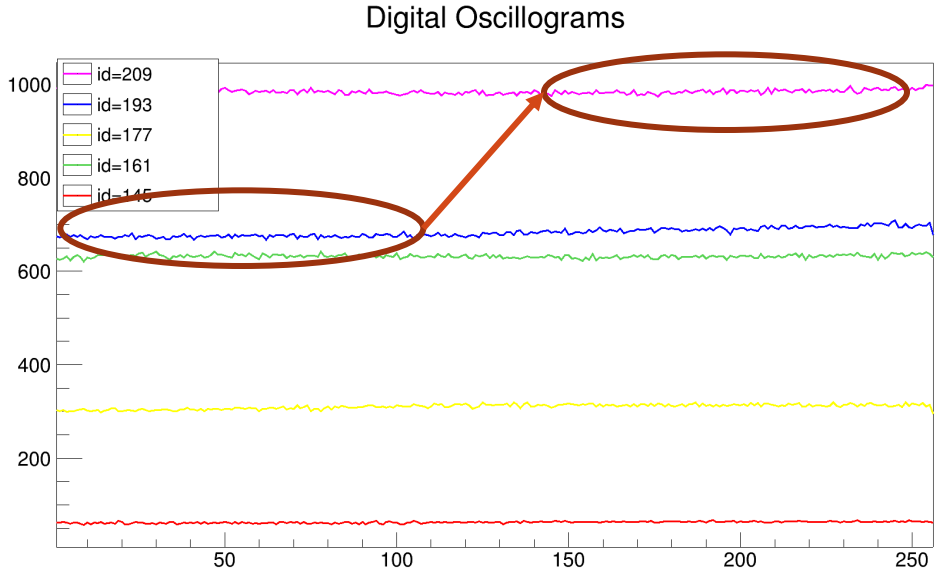
(θ, φ) ~ (45°, 50°)

The LTA method is very sensitive to the chose of hit pixels.
More robust algorithms are under development

ON-FLIGHT CALIBRATION. ENERGY ESTIMATION

$V_{Lomonosov}$





Slow mode of operation is useful for relative calibration and should be implemented in K-EUSO

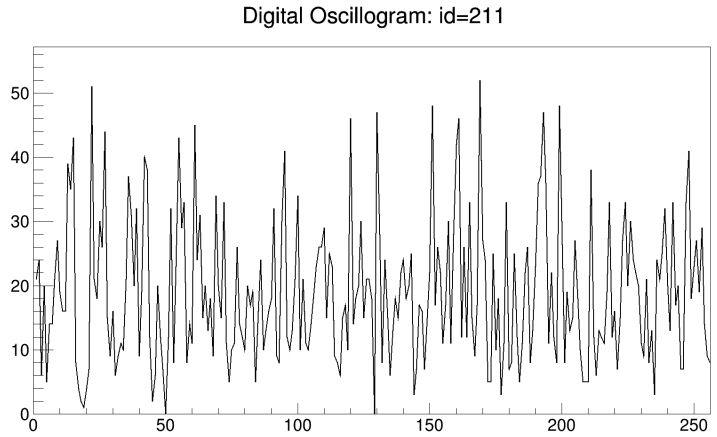
ON-FLIGHT CALIBRATION. ENERGY ESTIMATION

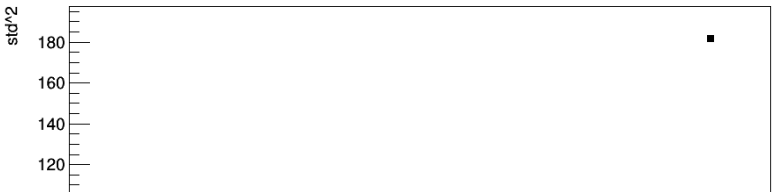
DC-mode of PMT: $A \sim I_{ph} \cdot G$, $\sigma_A^2 \sim I_{ph} \cdot G^2$, so $s_e \sim \sigma_A^2 / A$

$$A = pI \cdot \alpha G q_e R$$

$$\sigma_A = \sqrt{pI/2RC} \cdot \alpha G q_e R$$

$$s_e = p \cdot \alpha G q_e R = \frac{\sigma_A^2}{A} \cdot \frac{1}{2pRC}$$

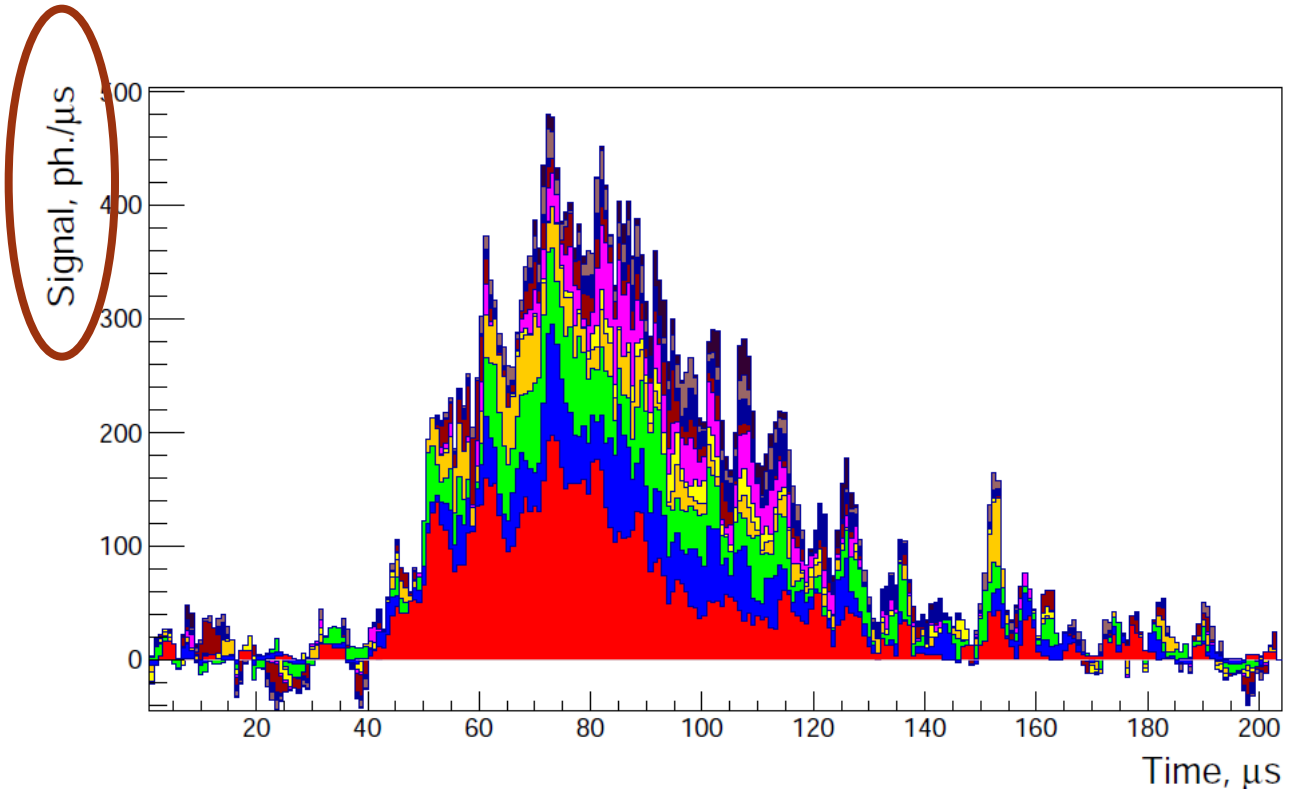




α – Analog-to-Digital conversion coefficient (512 V^{-1}),
C and R – anode capacity and resistance (0.03 nF, 20 kOm, RC = 600 ns)

id (md,ch)	161 (11,1)	162 (11,2)	177 (12,1)	178 (12,2)	179 (12,3)	193 (13,1)	194 (13,2)	195 (13,3)	196 (13,4)	211 (14,3)
s_e, μs	0.37	0.59	0.44	0.76	1.27	0.41	0.66	0.37	0.40	1.78
$s_e/s_e[211]$	0.21	0.33	0.25	0.43	0.71	0.23	0.37	0.21	0.23	1
G, $\times 10^6$	1.14	1.79	1.34	2.33	3.86	1.26	2.00	1.12	1.23	5.42

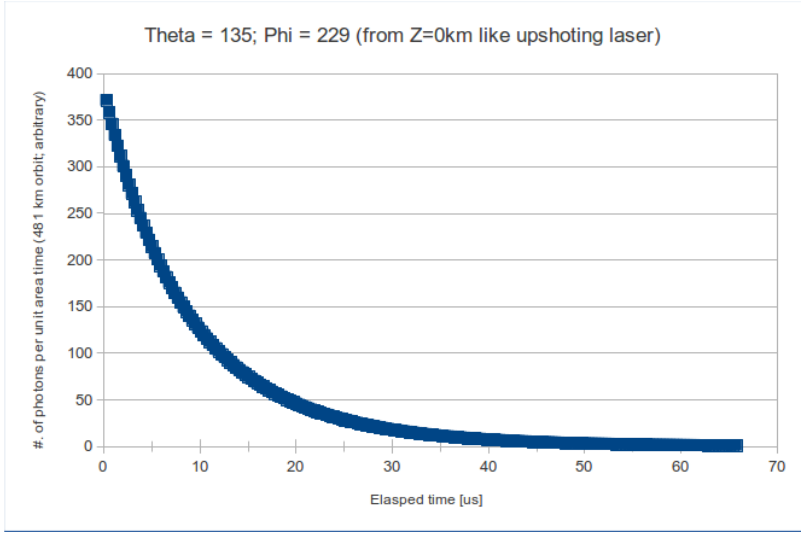
ON-FLIGHT CALIBRATION. ENERGY ESTIMATION



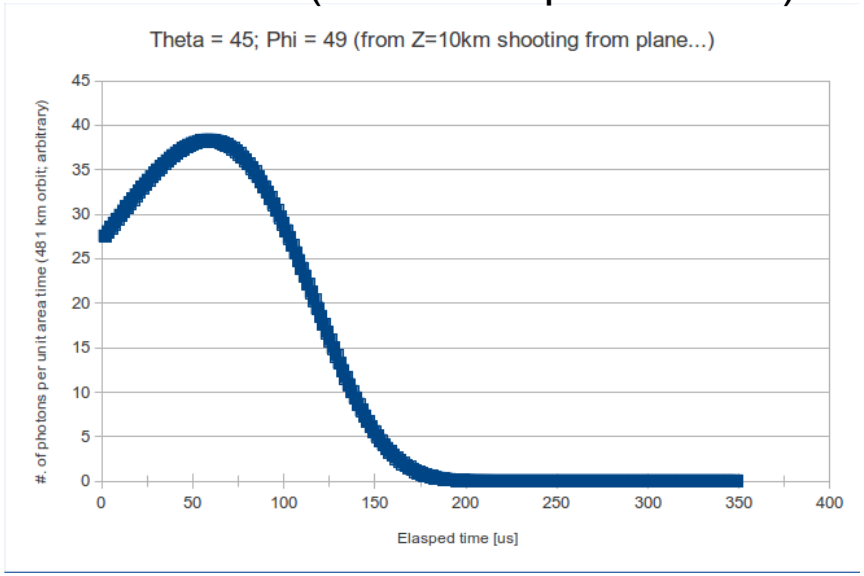
In the assumption of UHECR origin of the event the energy of primary particle is **~10^{21} eV**

MEASUREMENTS CONDITIONS ANALYSES: LASER PULSE?

Upward laser beam signal in TUS



Downward laser beam signal in TUS (case of airplane Lidar)

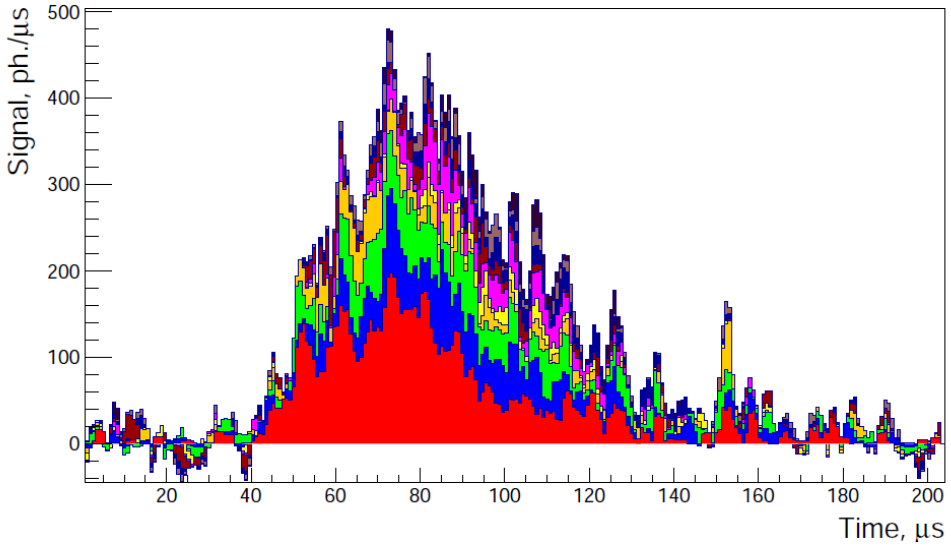


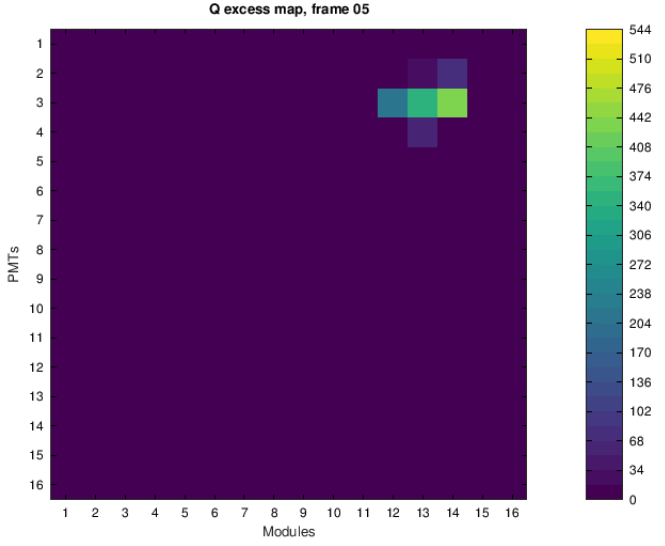
Calculations and plot provided by Kenji Shinozaki

One of the possibilities consistent with the movement downward is a laser shooting from the height of few kilometers, for example, from an airplane.

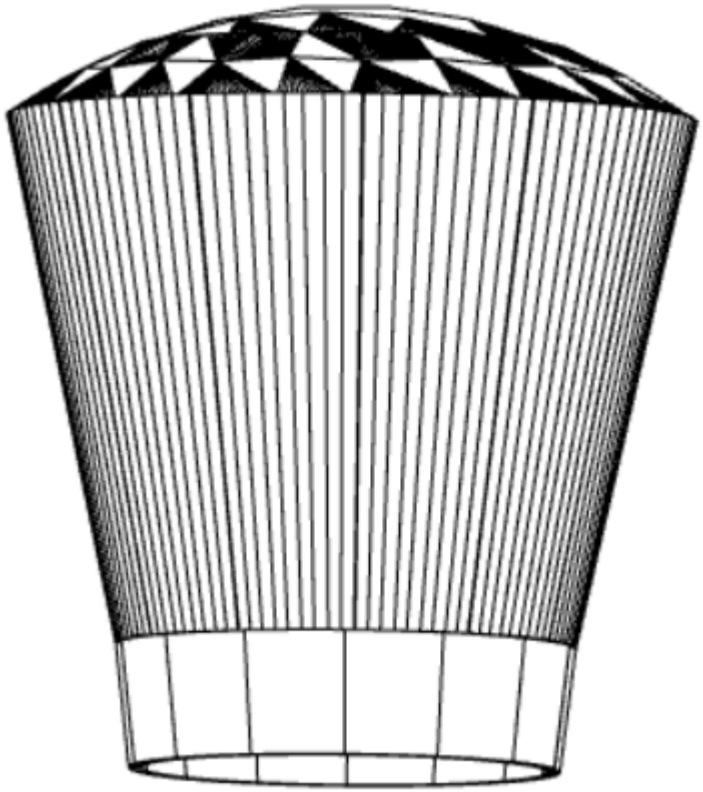
In this case, the light curve has a shape different from the observed one, with an exponential decay or a sharp cut-off as soon as the beam hits the ground.

- 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 registered an event which is analyzed as candidate for the first EAS measured from space. The event has specific kinematics of a UV source moving with a speed of light in the detector's FOV downward to the Earth surface.
- Measurements of TUS are of great importance for the future mission aimed for UHECR measurements from space. Being a pathfinder with a relatively low sensitivity, narrow FOV and only 5 km spatial resolution it proves the possibility of EAS measurements from space and shows the necessary improvements for the next generations missions like KLYPVE-EUSO.





K-EUSO DESIGN



KLYPVE is a wide field of view Schmidt telescope with following key parameters:

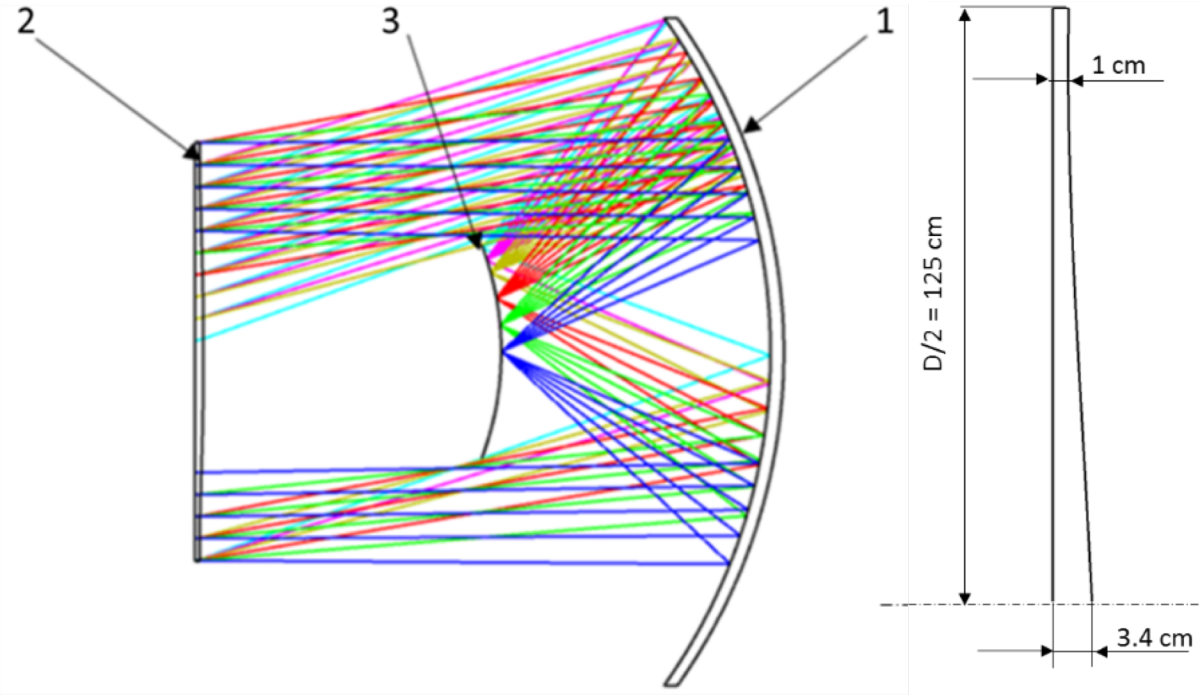
Mirror area	>10 m^2
Entrance pupil area	~5 m^2
FOV	±20°
Angular resolution	~ 1 mrad
Time resolution	1-2.5 μs

The design of the detector should provide measurements of UHECR with a threshold neat 50 EeV with statistics of ~100 events per year.

The main task is the energy spectrum and anisotropy measurements **with uniform exposure over the celestial sphere**

K-EUSO OPTICAL SYSTEM

V. V. Druzhin, D. T. Puryaev, and S. A. Sharakin. Optical system for orbital detector of extreme-high-energy cosmic ray. *JOURNAL OF ASTRONOMICAL TELESCOPES INSTRUMENTS AND SYSTEMS*, 4(1):014002, 2018

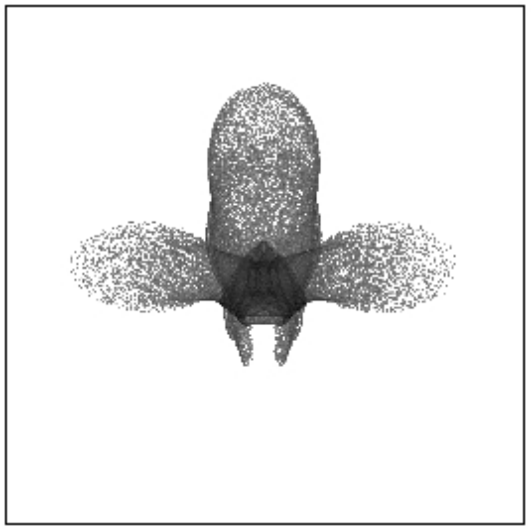


Parameter	Value, cm
Entrance Pupil Diameter	250
Mirror diameter	400
Radius curvature of mirror	345
Radius curvature of FS	180
Axial length	342.6
Distance from M to FS	161.5

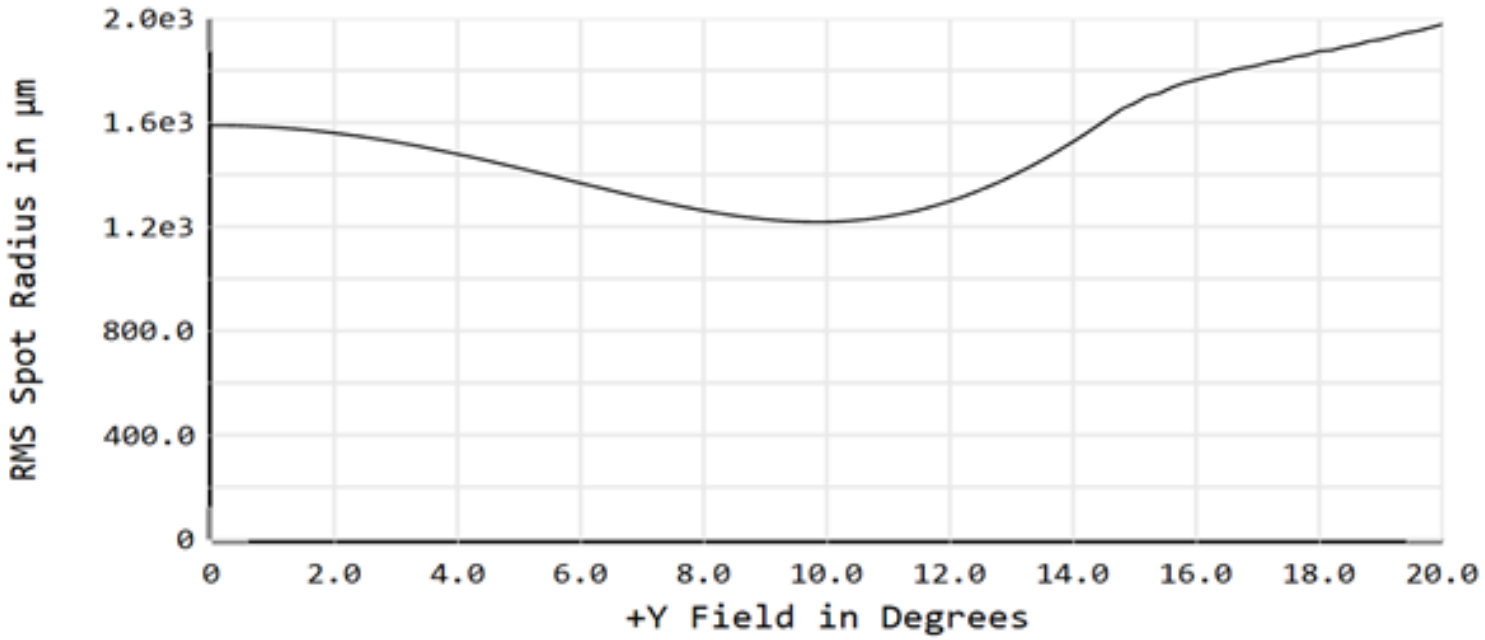
OPTICS PERFORMANCE

Ensquared Energy

Field angle	0°	5°	10°	15°	20°
Energy fraction	0.74	0.92	0.89	0.75	0.55

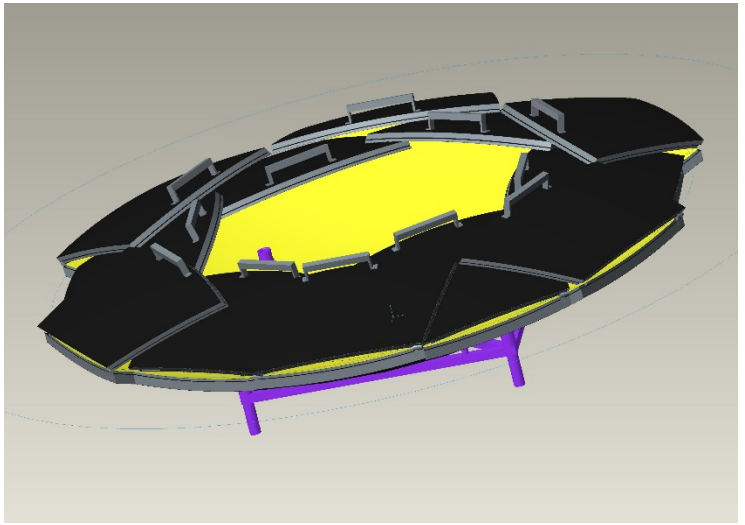


15° spot shape

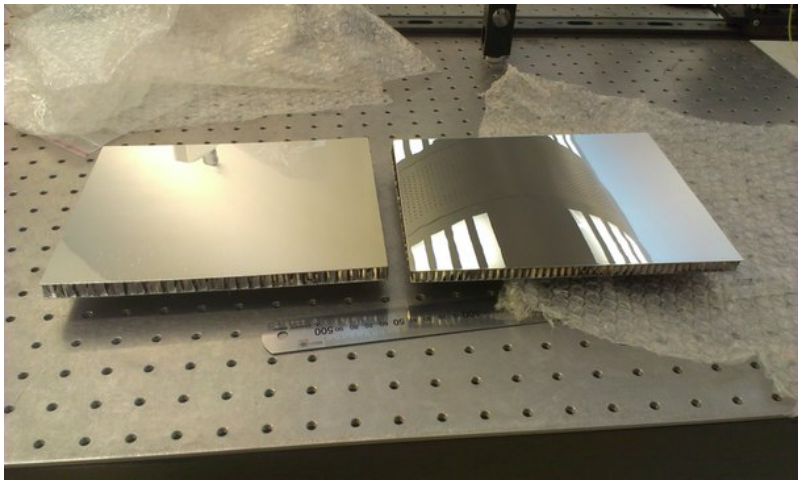


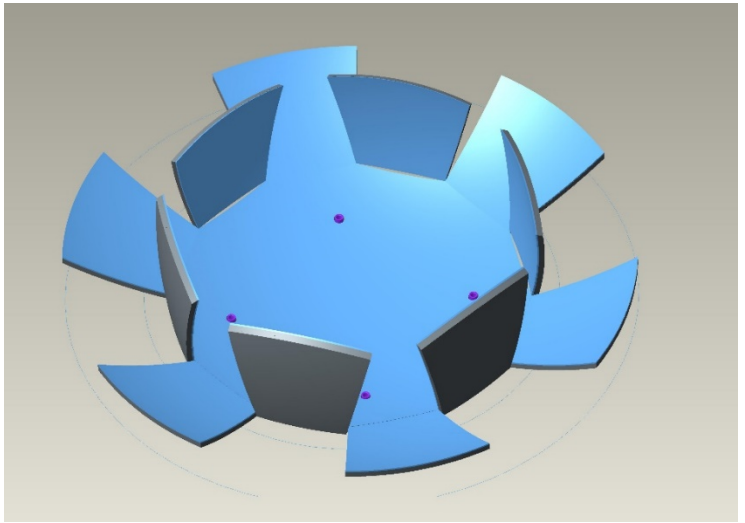
KLYPVE-EUSO MIRROR DEVELOPMENT

- ✓ Space Regatta Consortium is the main designer
- ✓ Two options are considered now



Carbon-plastic mirror samples

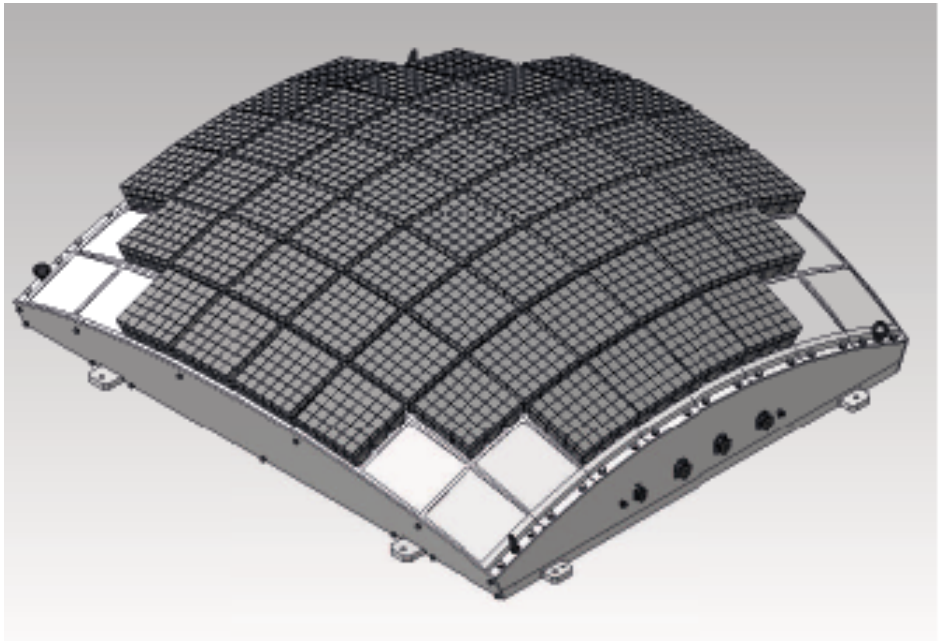


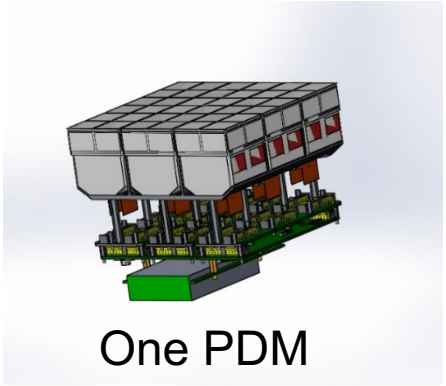


FOCAL SURFACE

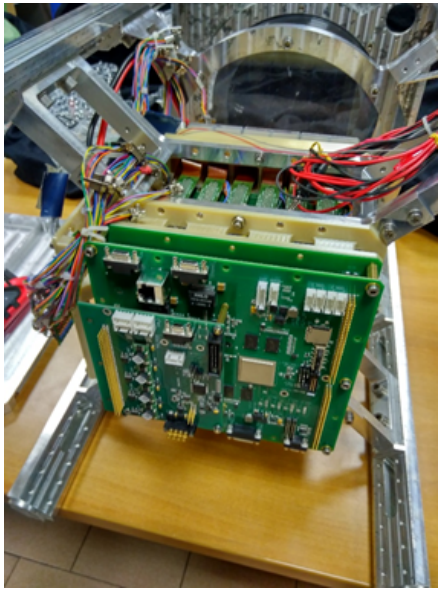
- ✓ 52 PDMs united in a network, 10^5 pixels
- ✓ Each PDM has fact connections to his neighbors
- ✓ 4 PDMs has Ethernet connection with Commutation unit and MDP

PDM design is based om mini-EUSO

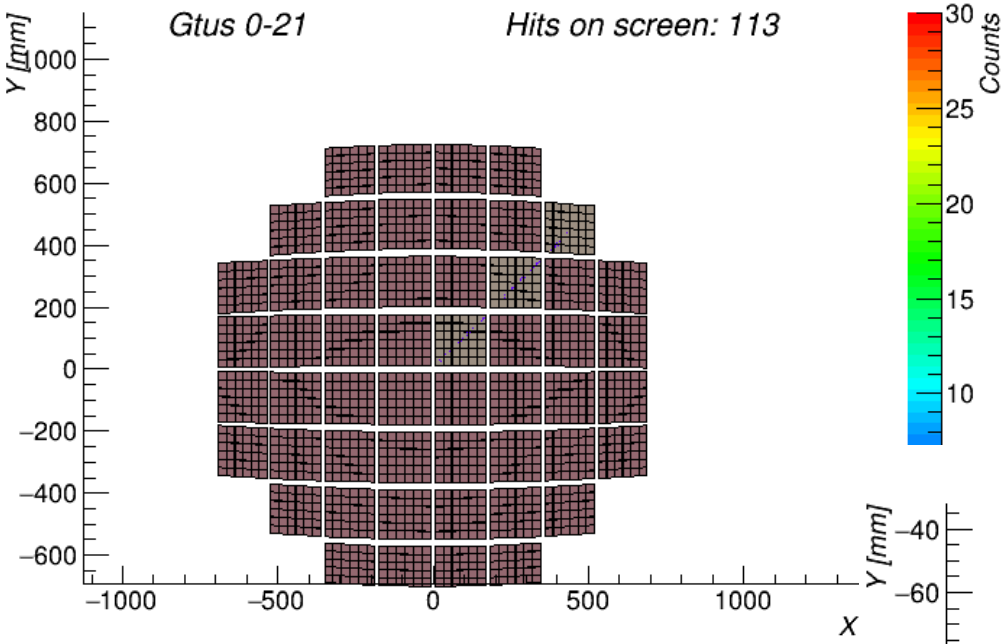


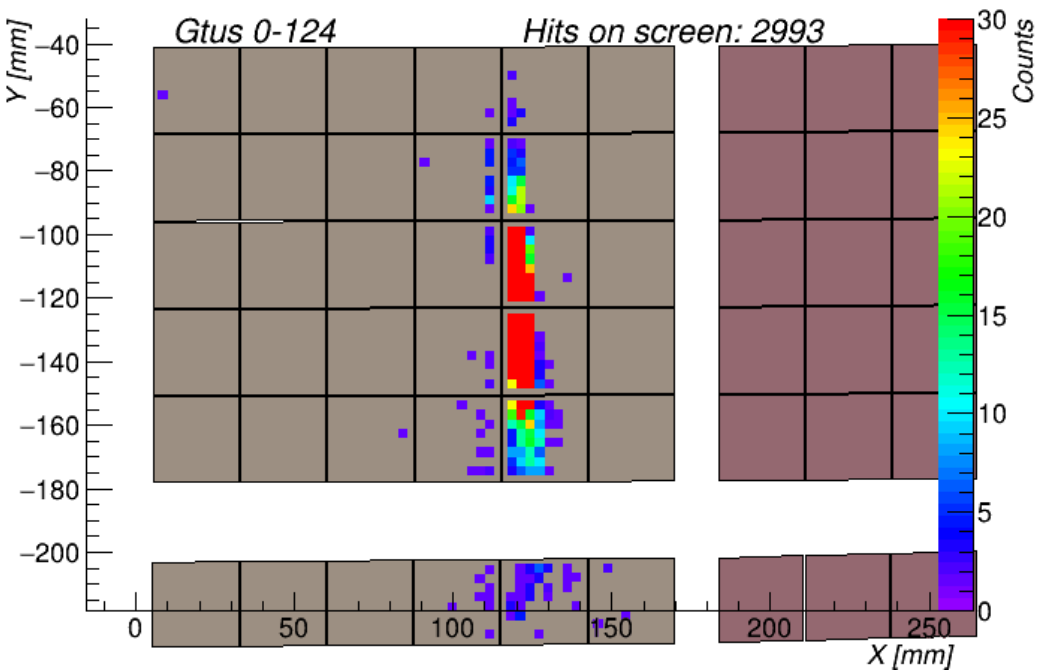


One PDM



CURRENT FS IMPLEMENTATION AND SIMULATIONS IN IN ESAF



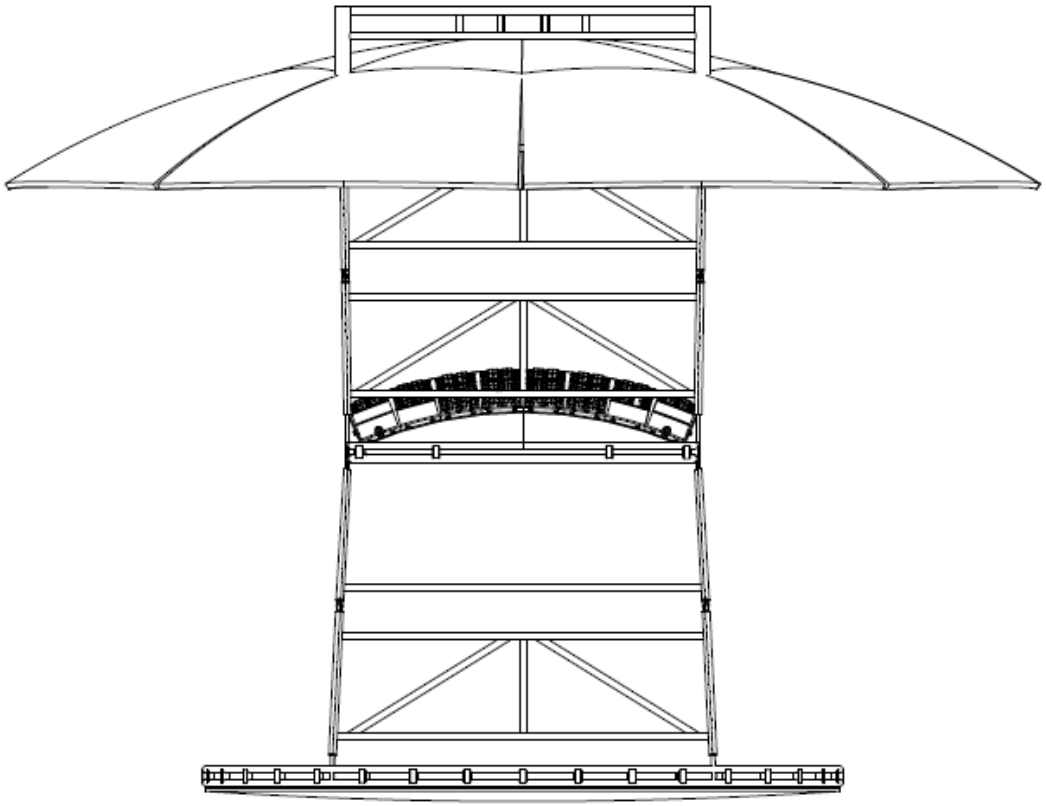


Credits: Naoto Sakaki

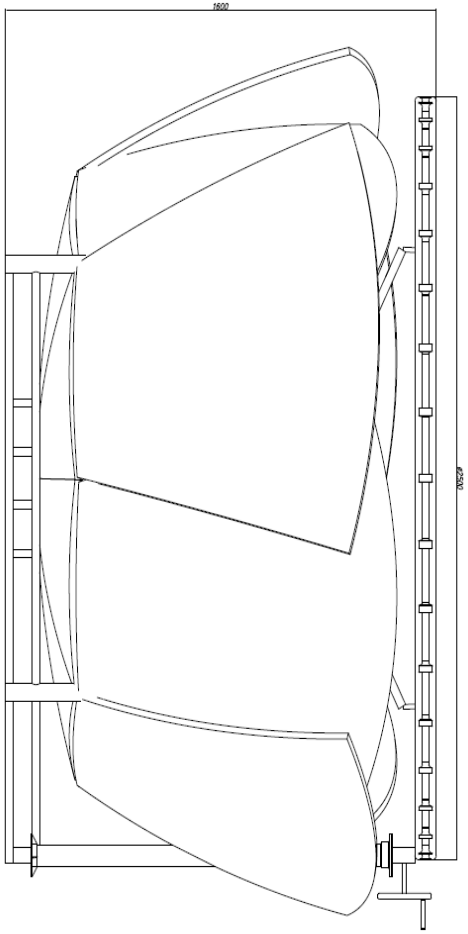
the detailed simulations are ongoing

KLYPVE-EUSO MECHANICS

Operation mode



Transportation mode



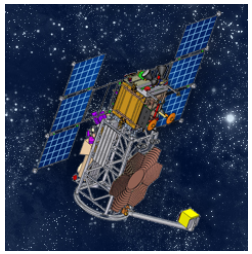
Preliminary K-EUSO mechanics designed by “Ferrit” (Voronezh)

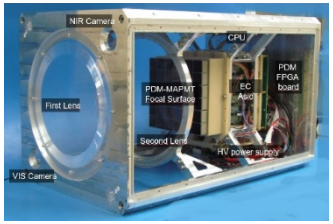
CONCLUSIONS I

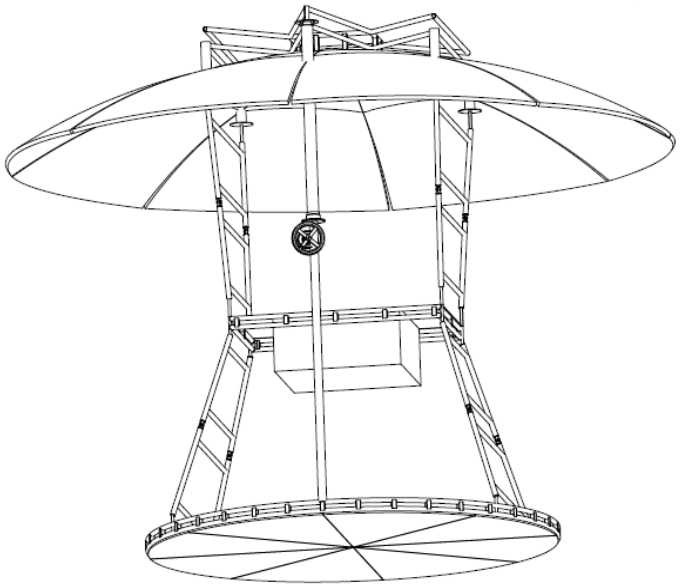
- The TUS detector is the first space mission aimed for UHECR EAS measurements. TUS gave important information on the UV background for EAS measurements.
- The TUS detector registered an event which is analyzed as candidate for the first EAS measured from space. The event has specific kinematics of a UV source with a speed of light in the detector's FOV downward to the earth surface (EAS). The amplitude of the signal corresponds to an energy of cosmic ray particle of the order of 10^{21} eV.
- A variety of atmospheric phenomena are measured by TUS. As an example – multiple ELVE. These data can be used for atmosphere science.

CONCLUSIONS II

2014 2016 2019 2022



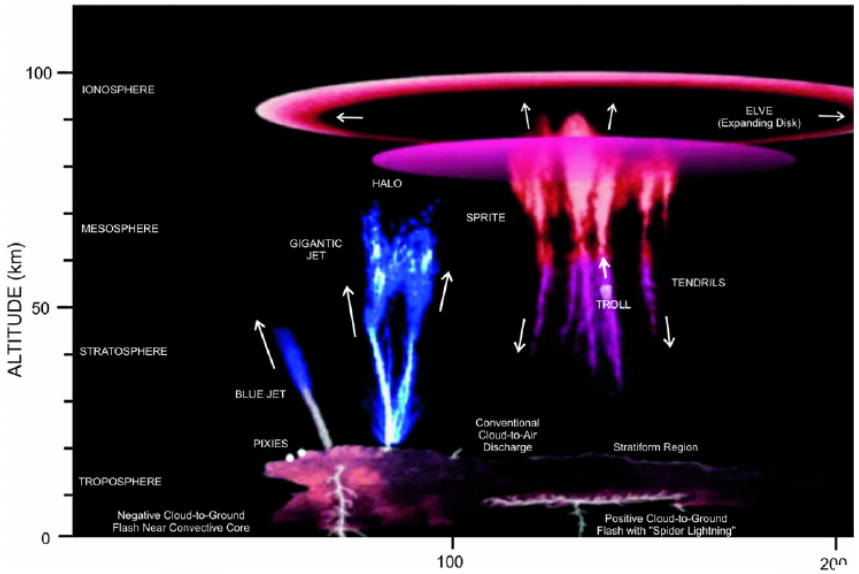


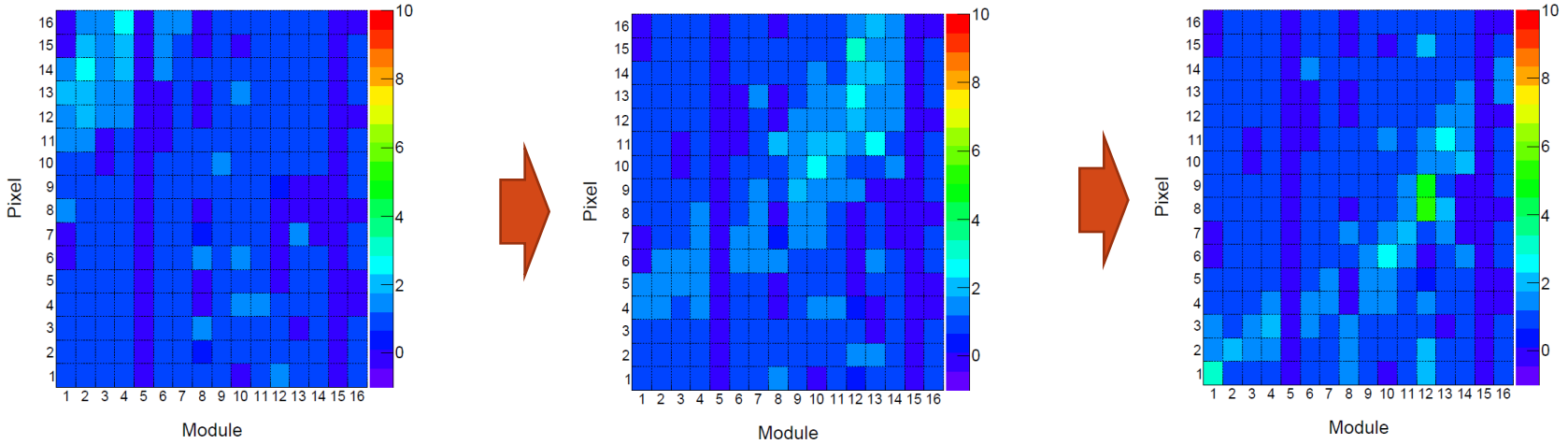


- KLYPVE-EUSO is included into Long-term program of experiments on board the Russian Segment of the ISS. It is the next step of measurements of UHECR from space with statistics ~100 events per year with energy >100 EeV.
- The technique is tested in various pathfinders as EUSO Balloon and TUS.
- 2018 Conceptual design stage with models manufacturing (PDM, mirror, MDP).
- 2020 – Engineering model.
- 2022 – Flight model and launch.


Thank you for your attention!

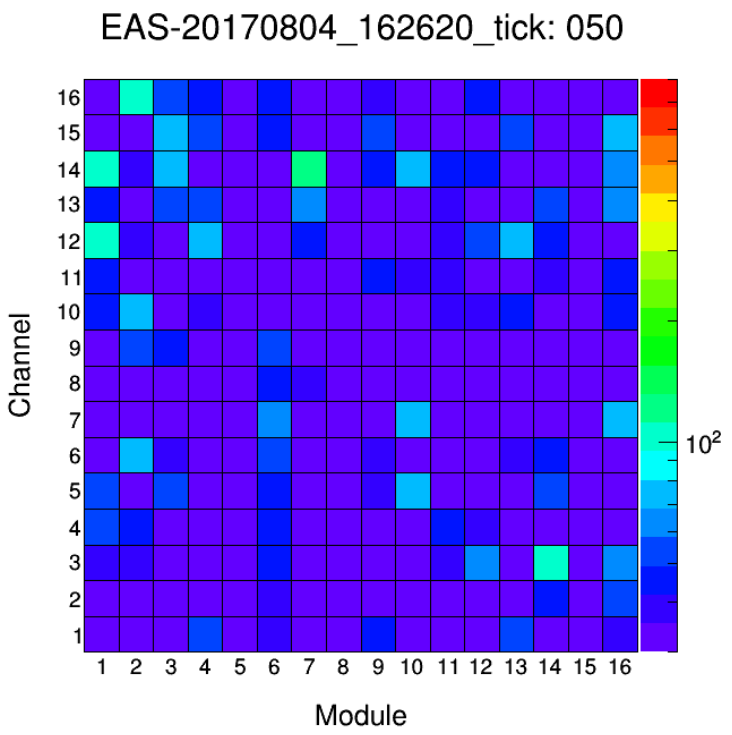
TRANSIENT LUMINOUS EVENTS. ELVE

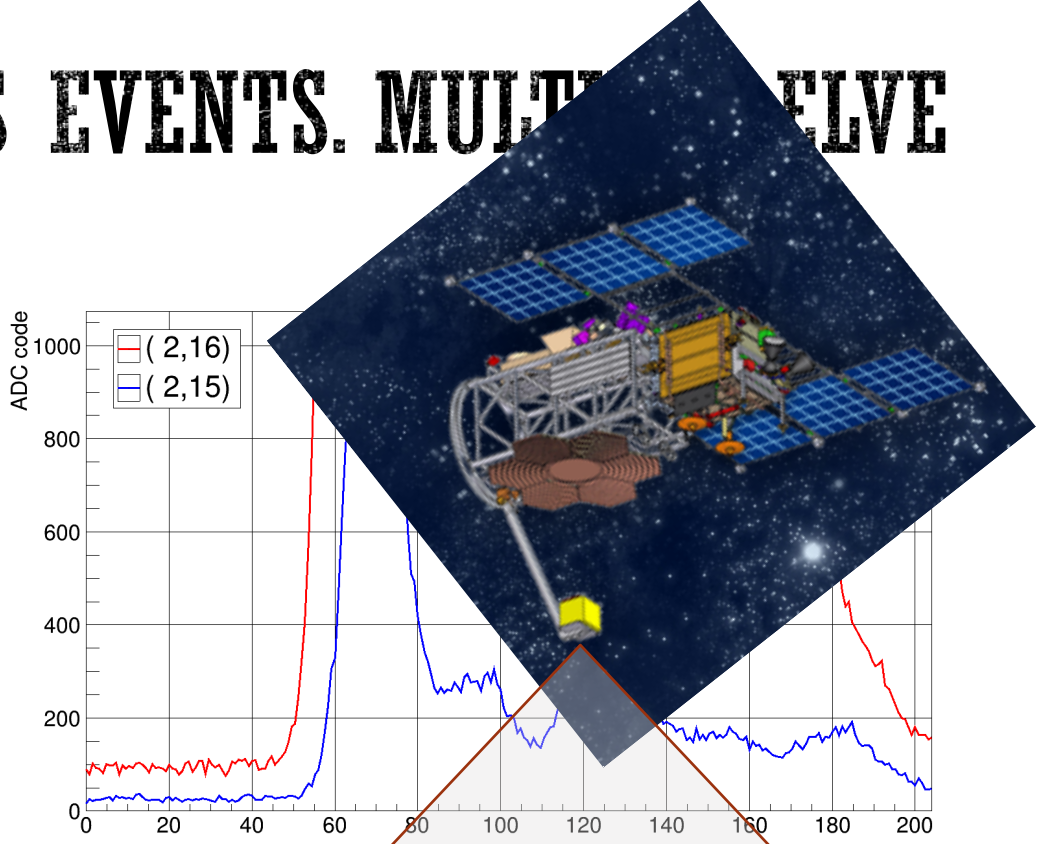


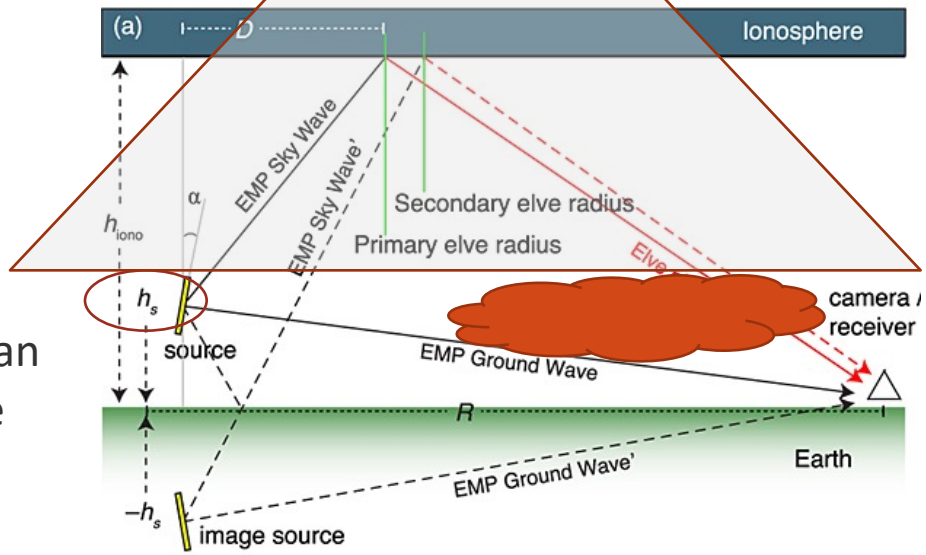


TUS event 18.09.2016, 9.66S, 17.14W

TRANSIENT LUMINOUS EVENTS. MULTI ELVE



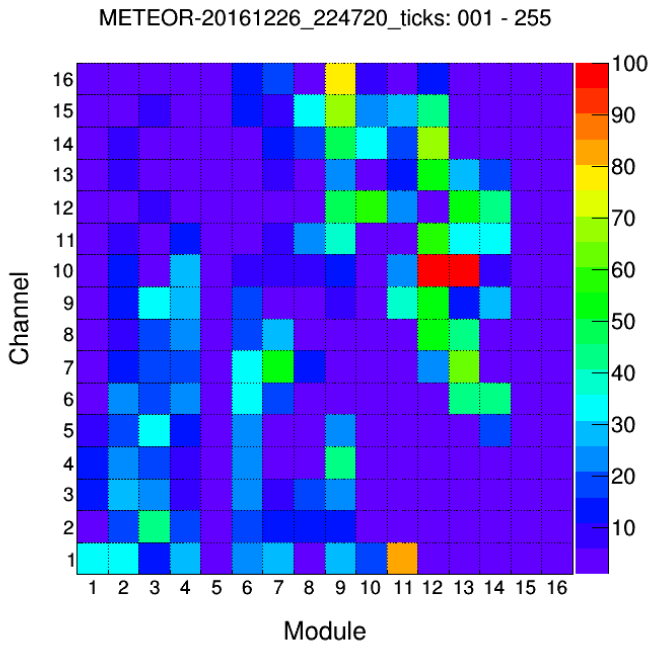


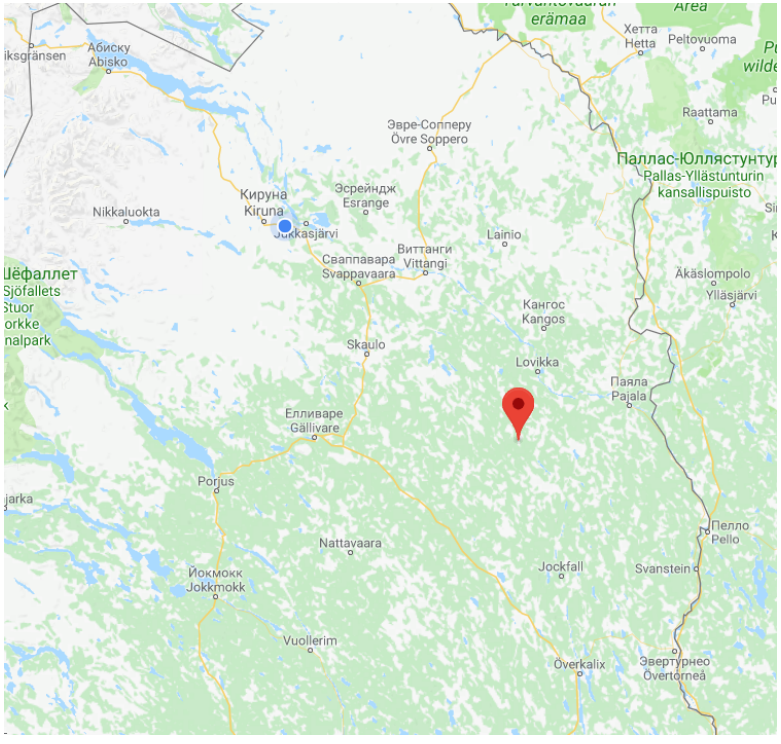


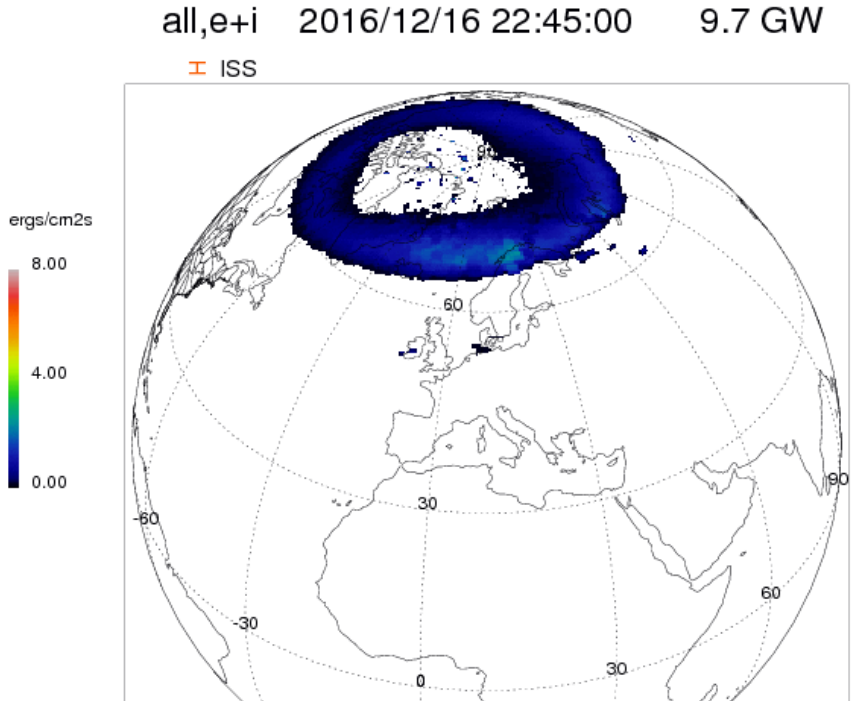
Marshall, R. A., C. L. da Silva, and V. P. Pasko (2015), Elve doublets and compact intracloud discharges, Geophys. Res. Lett., 42

Estimation of intensive intracloud discharges can be made using measurements of ring structure with high temporal resolution.

INTERESTING EVENT IN AURORA REGION 6.6 MS RESOLUTION 26.12.2016

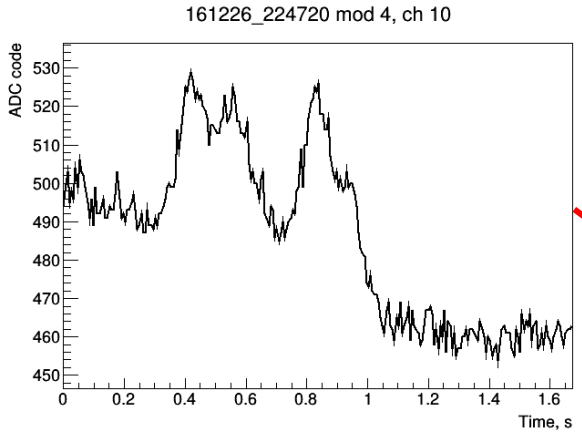


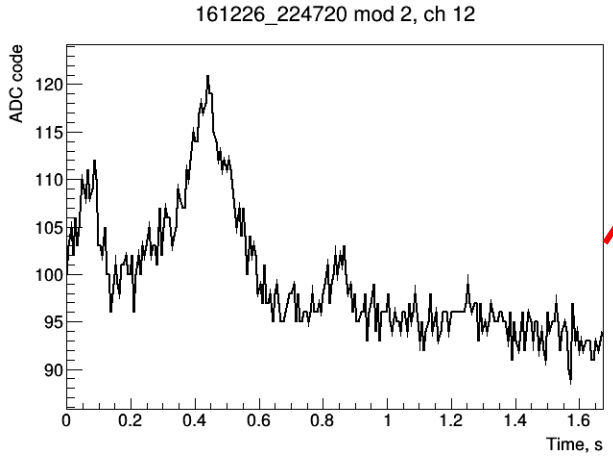


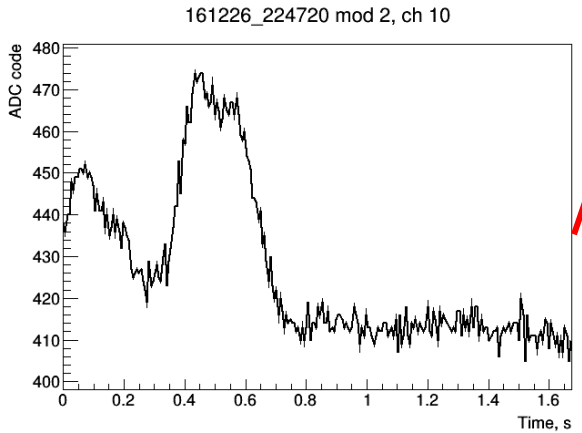


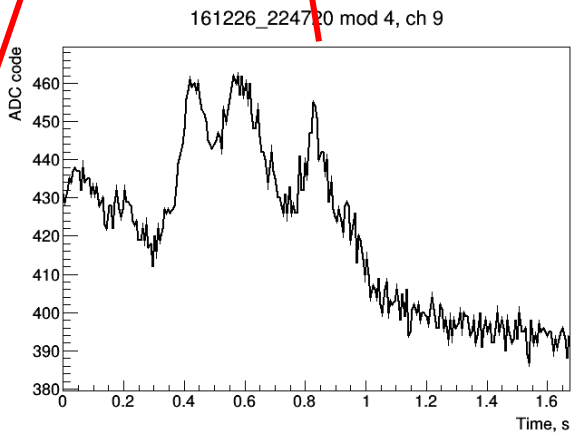
https://iswa.ccmc.gsfc.nasa.gov/IswaSystemWebApp/

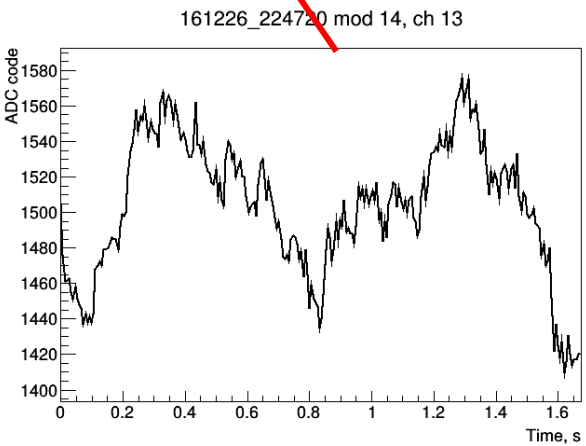
SPACE-TIME STRUCTURE

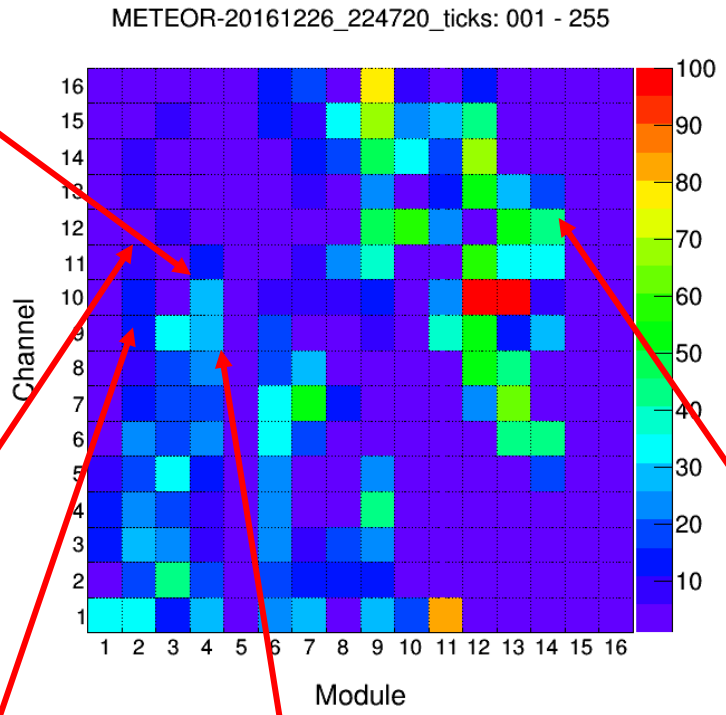




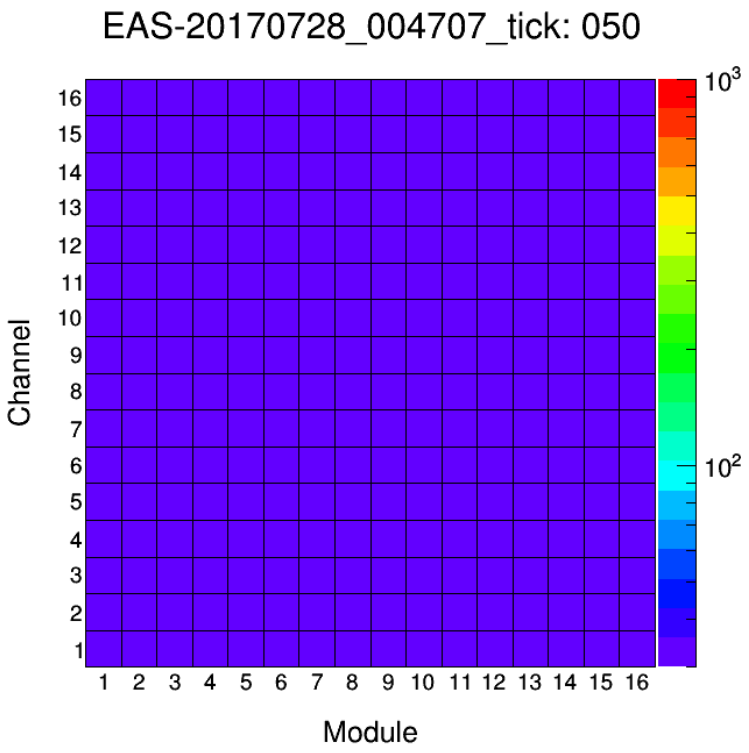


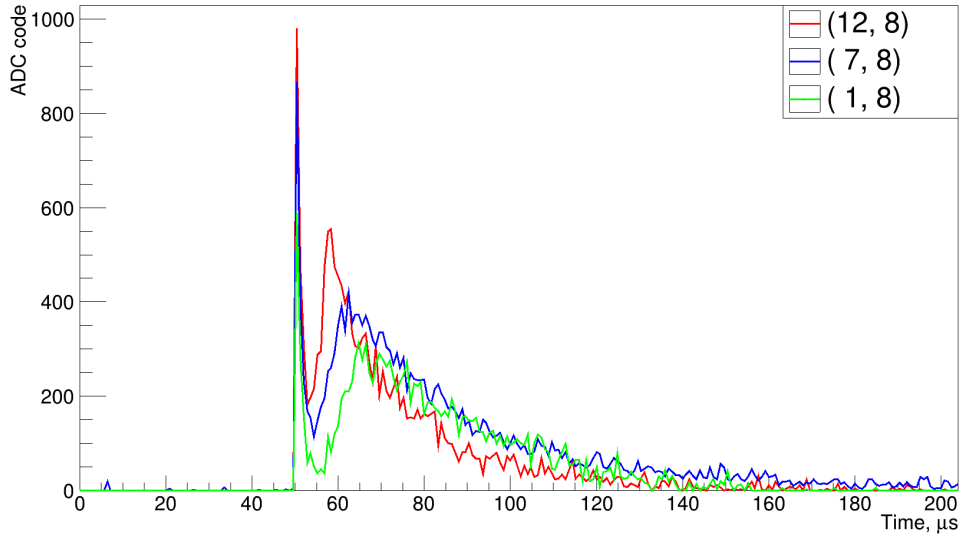


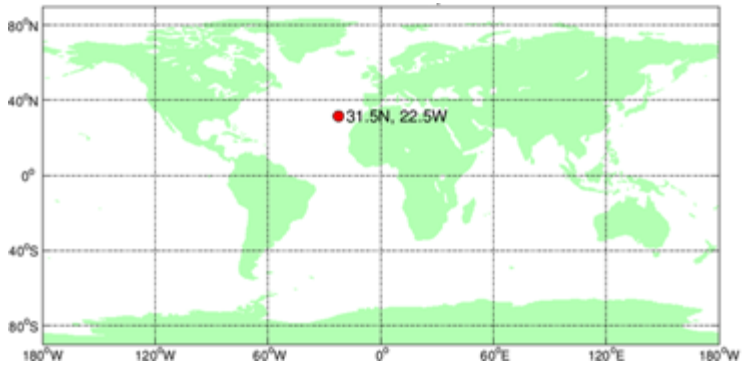




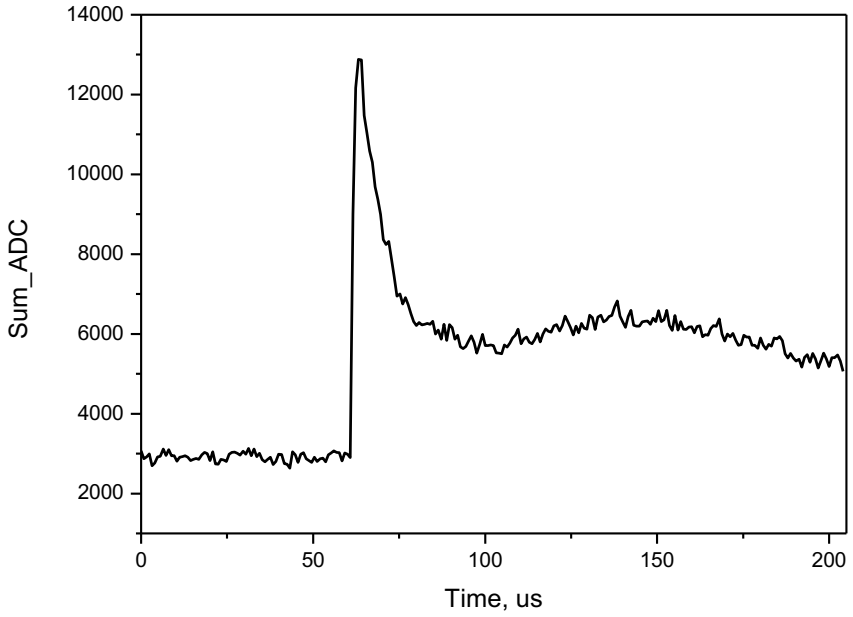
FAR FROM THUNDERSTORM UV FLASH ABOVE THE ATLANTIC OCEAN

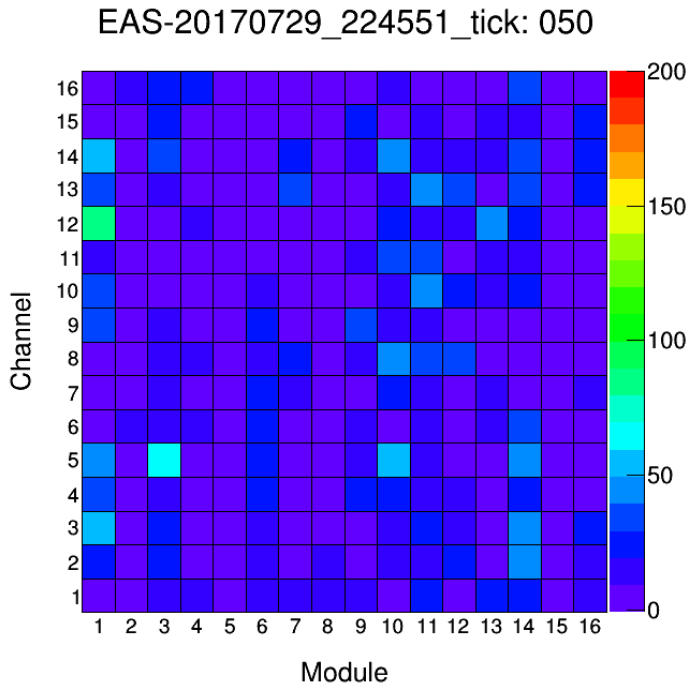




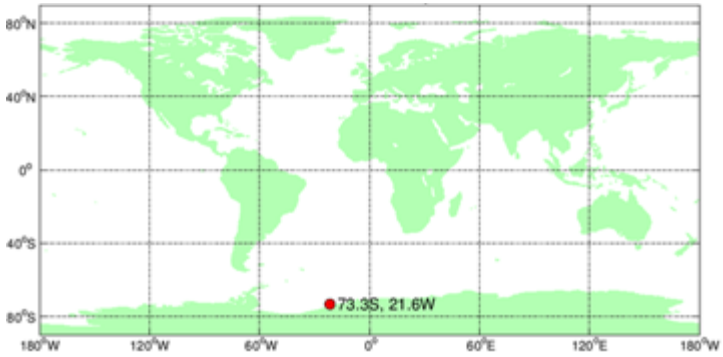


UV FLASH ABOVE ANTARCTICA

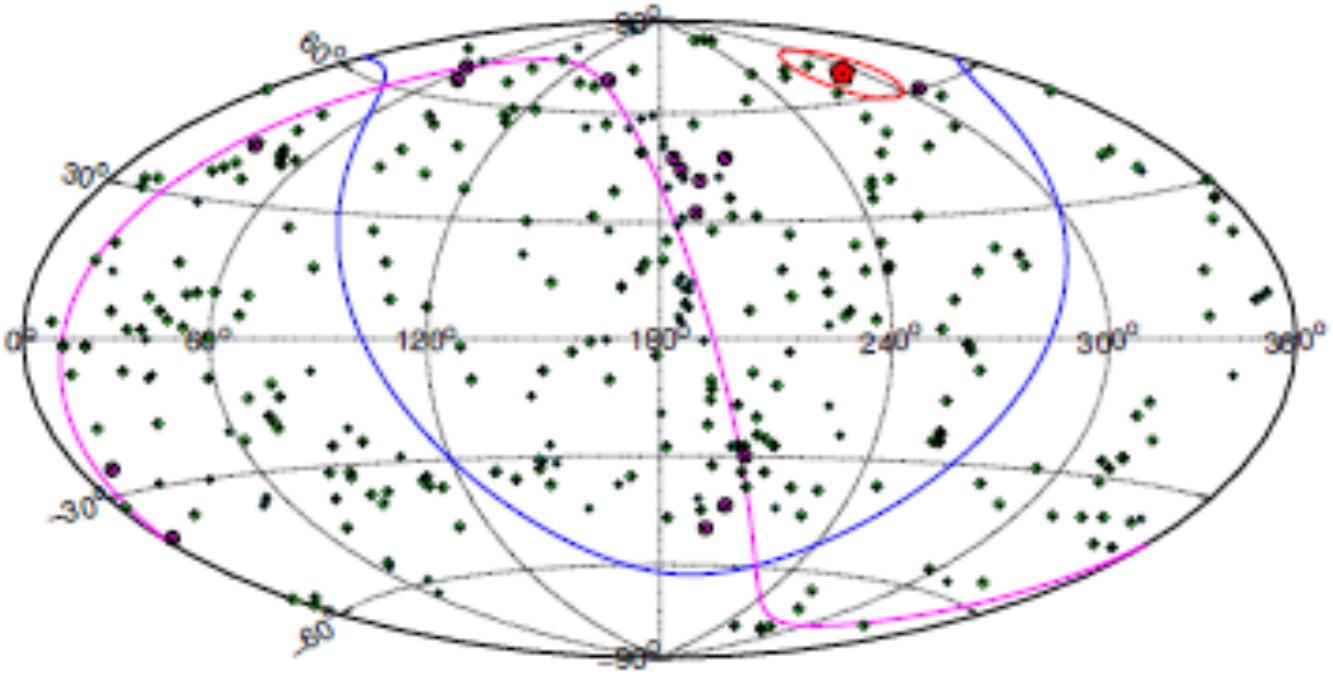




There is a lightning in the conjugate point of geomagnetic field according to Vaisala GLD360.



THE EVENT POSITION ON THE SKY MAP



Arrival direction of the event registered on 3rd October 2016 (the red pentagon) and its 8-neighbourhood. The pink and blue curves show the Supergalactic and Galacticplanes respectively. Also shown are positions of starburst galaxies according to the catalogue* Magenta: D <6 Mpc, green: 6 < D 20 Mpc, cyan: 20 < D 200 Mpc.

*S. van Velzen, H. Falcke, P. Schellart, N. Nierstenh□ofer and K.-H. Kampert, Radio galaxies of the local universe. All-sky catalog, luminosity functions, and clustering, Astronomy & Astrophysics 544 (Aug., 2012) A18.)

with colors denoting distances D to the Solar system