Study of anomalous events in TUS experiment

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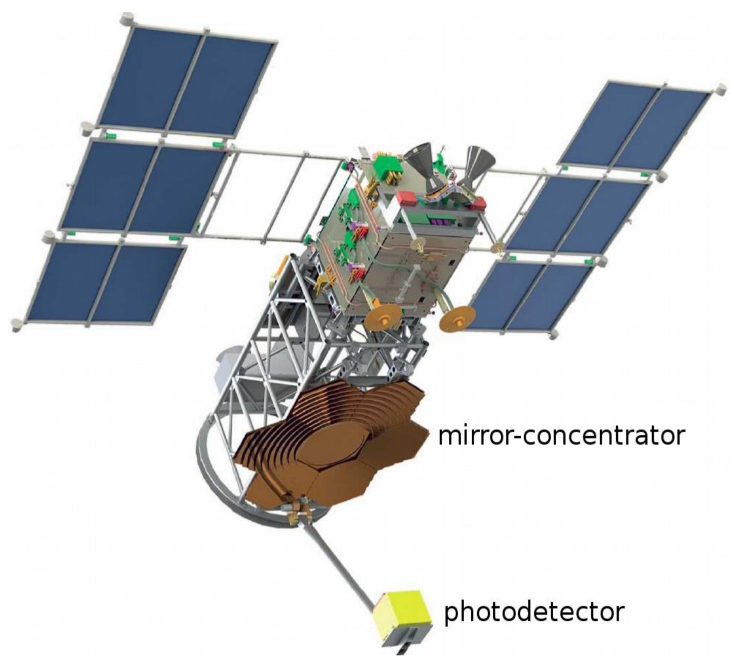
Measurement of the spectrum, mass composition and anisotropy of Extremely High Energy Cosmic Rays (UHECR) at energy of E ~ 10^{20} eV and the search for UHECR sources are one of the most important tasks of modern high energy astrophysics. The TUS detector aboard the Lomonosov satellite was launched into a sun-synchronous orbit with an altitude of about 500 km on April 28, 2016 and was the first experiment to measure the fluorescent and Cherenkov radiation of Extensive Air Showers (EASs) from space orbit. The main goal of the TUS experiment was to study UHECRs with energies of E > 70 EeV. At the same time, the TUS detector has registered dozens unusual events, the origin of which is unclear. Unique and unlike EAS anomalous events are the subject of the study presented in this paper. Events of the cosmological gamma-ray burst (GRB) type, as well as out-of-aperture lightning flashes, are considered as their possible sources.

Detector TUS

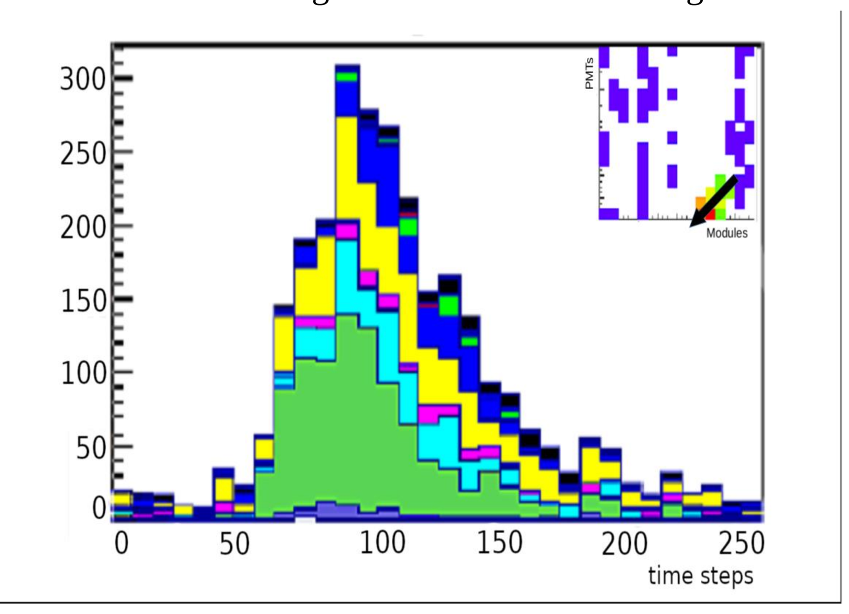
The multifunctional "Lomonosov" satellite, with the TUS detector on board, was launched from the newly built Cosmodrome Vostochny on April 28, 2016. The satellite has a solar-synchronized orbit with an inclination of 97˚, a period of ~94 min, and a height of about 470-500 km. The TUS detector consists of two main parts: a modular Fresnel mirror-concentrator and a photo-receiver matrix. A PMT quantum efficiency is ~20% for the wavelength of 350 nm. The TUS electronics can operate in four modes intended for detecting various fast optical phenomena in the atmosphere on different time scales (1 time step): 0.8μs, 25.6 μs, 0.4 ms, 6.6 ms.

-During two years of operation, the TUS detector has measured about 200000 events in EAS mode.

- More than 80% of events registered by TUS have noise-like waveforms with amplitudes of all PMTs fluctuating around average values that are close to each other when rescaled according to their individual PMT gains.



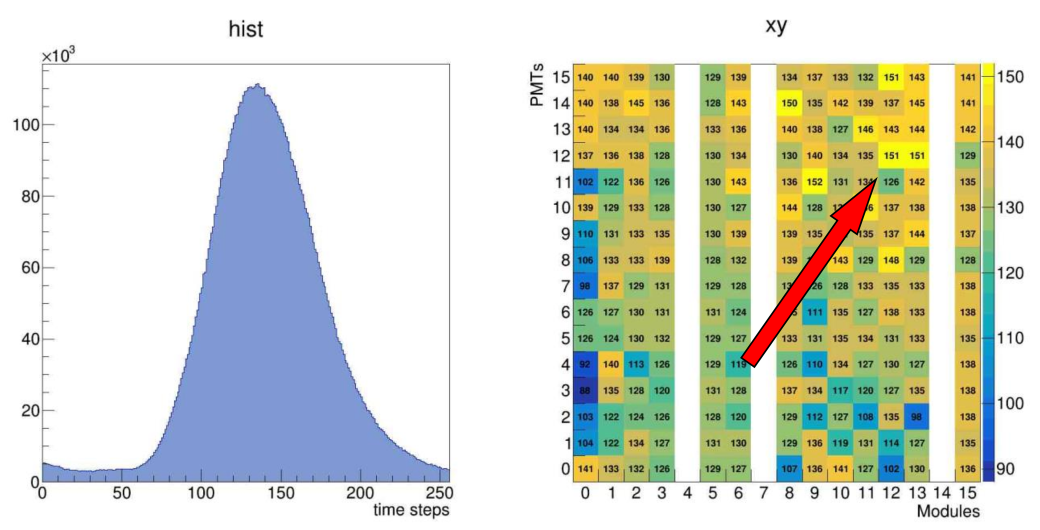
Mass	< 60 kg.
Power	65 W.
Data rate	200 Mbytes/day
Number of pixels	16x16 PMTs
FOV	±4,5 degree.
Duty cycle	30%
Altitude	500 km
Pixel:	10 mrad(5x5 km)
Mirror area	1,8 m².
Focal distance	1,5 m
Period	94 min



EAS-candidate with energy about ~ 100 EeV

Anomalous events

The TUS detector measured an unusual event 170818-101809-072 with an EAS trigger east of New Zealand (40.18° N,176.02°W), that pictured below.

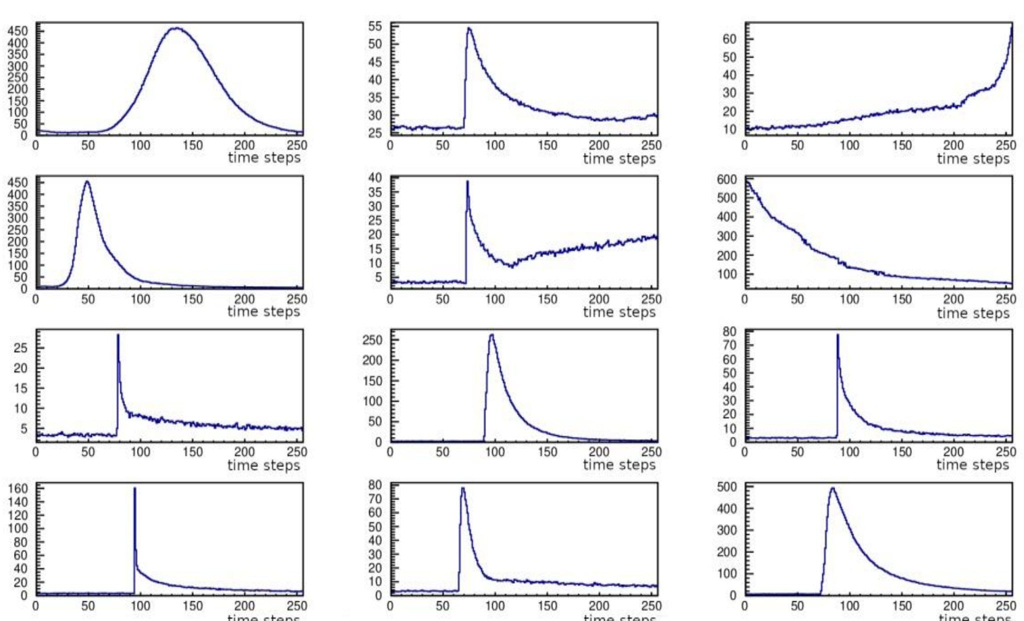


The event was registered in cloudless conditions with a distance of about 900 km to the nearest thunderstorm activity. Unlike EAS candidates event, in the observed event, the same signals appeared in all pixels of the photodetector, which is the criterion for the anomalous event. The source of photons should be either the entire area of 80x80 km², visible by the photodetector from the orbit, or the light source was located on board the satellite and illuminated the entire photodetector matrix. Time shift between earlier and latest maximum is ~Δt = 20 , so we can estimate velocity movement in matrix

Anomalous event 170818-101809-072 . On the left side is the time dependence of the integral amplitudes over all pixels, on the right side is the movement of the signal maximum along the photodetector matrix. The numbers indicate the time of passage of the signal maximum.

$$\mathrm{v} = \frac{\mathrm{S}}{\Delta\mathrm{t}} \approx 80 \cdot \frac{\sqrt{2}}{20 \cdot 0.8 \cdot 10^{-6}} \approx 7 \cdot 10^{-6}\mathbf{km/s}$$

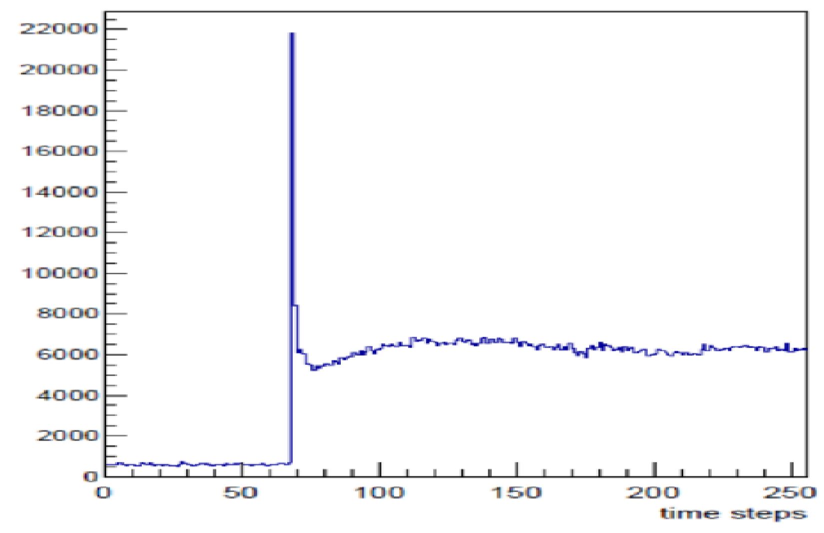
An event of this type could be initiated by the illumination of the entire area observed by the TUS detector with a light wave generated by a short (~200 μs) gamma-ray burst (GRB) of cosmological origin. It is natural to expect a signal to move along the photodetector matrix if the signal originated in the atmosphere in the detector aperture and was initiated by an incident plane wave from a (GRB). If this is a displacement of the line of intersection of two planes, then its speed can be greater than the speed of light , which does not contradict the Lorentz invariance, since there is no superluminal speed of signal propagation.



Examples of time dependence of the integral amplitude of anomalous events.

Combined events

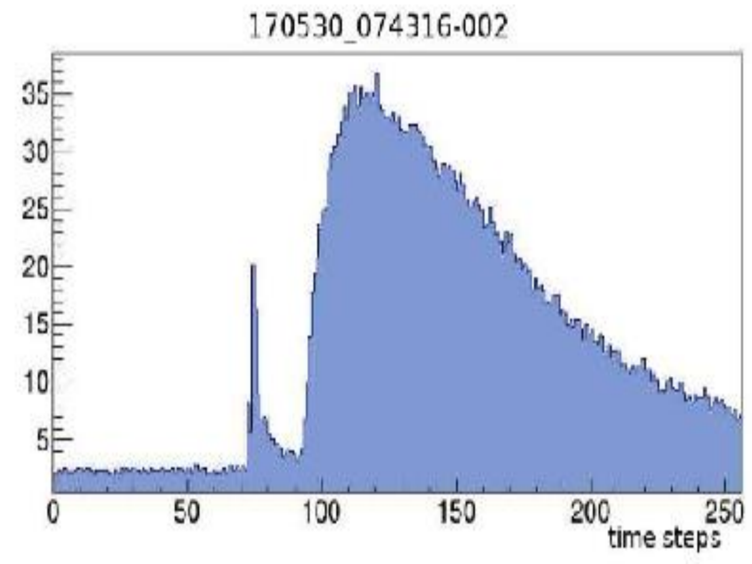
Among the anomalous events, several combined events were found, that arose from a lightning in the atmosphere in the detector aperture, in which both a normal signal, focused by a mirror onto a small locally coupled portion of pixels on a photodetector matrix, and an anomalous signal, diffusely reflected by solar panels to all pixels of the photodetector, are present at the same time. Below you can see an example of such a combined event 160906_020449-129. Since the event is aperture, the sharp peak could initially have arisen from lightning or from Cherenkov and fluorescent EAS light, initiated by an upward high-energy neutrino and focused by a mirror into a small spot of several pixels, as well as diffusely reflected in all pixels. Note that the energy of neutrinos and EASs cannot exceed 100 TeV to pass through the Earth. Currently, due to the lack of a program for modeling of upward EAS, it is impossible to estimate the energy interval of TUS sensitivity to such events.



Hybrid events

The signal is recorded in all pixels, but the time dependences of the amplitudes have a significantly different form. Example of hybrid events is presented below. A narrow, several time-steps peak at the beginning of an event, followed by a wide distribution outside the time window of the event.

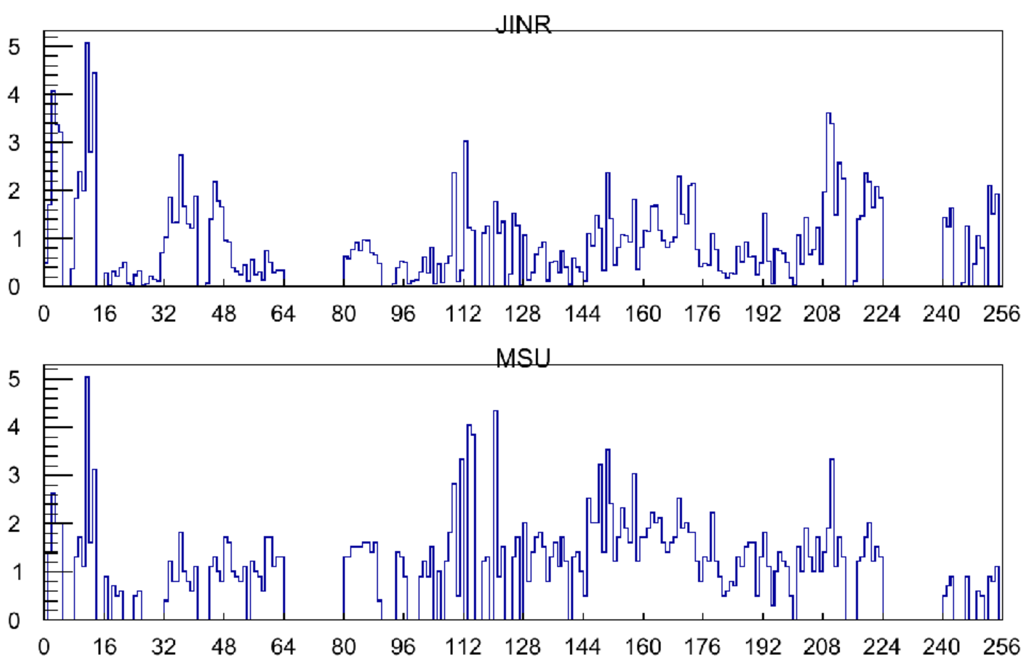
It can be assumed that the narrow peak is a signal of Cherenkov and fluorescent radiation from an upward or horizontal EAS that originated outside the field of view of the detector optics, which then initiated a lightning discharge that triggered the event, and the reflection of which is visible as a following wide distribution. The majority of anomalous events have a sharp leading edge, which may be due to the superposition of the Cherenkov peak from an EAS followed by a signal from a lightning discharge.



Relative calibration of the photodetector

Based on the assumption of diffuse reflection of light from out-of-aperture lightning flashes from solar panels as the cause of anomalous events, it is natural to expect that the same reflected signal is measured in all pixels of the TUS photodetector, which can be used to calibrate the photodetector. If the photon flux density is sufficiently high and spatially homogeneous, then the difference in signal amplitudes in pixels will be due to the difference in their sensitivity and gain factors. Such a calibration can be done using each of the events. The coincidence of calibrations from different events would be a confirmation of the external nature of the events and the correctness of the calibration method. However, this is true only in the ideal case, when all channels of the photodetector have characteristics that are stable over time. In fact, this is not the case due to changes in the physical characteristics of the photodetector channels during the aging, as well as changes in the temperature of the electronics when entering the night part of the orbit, because thermal stabilization of the photodetector was not provided. Such an analysis is currently in progress.

Figure below shows the relative calibration of the photodetector pixels. First, about 40 events were selected in which there is no signal saturation in the pixels of the photodetector, by averaging which the relative calibration coefficients were measured. It can be seen that the relative calibration of the photodetector by anomalous events qualitatively agrees with the previously calibration by analyzing background fluctuations performed by colleagues from SINP MSU .



Possible physical interpretations

1. Gamma-ray burst
   The FERMI-GBM space detector has a time resolution of 2.6 μs, a wide angular aperture, but detects photons starting from the keV range. The SWIFT space detector operates in the energy range from UV to X-ray. The non-observation of similar GRBs during the many years of operation of these and other GRB detectors means, apparently, that such short gamma-ray bursts do not exist.
2. Flashes from out-of-aperture lightning
   We assumed that all anomalous events , except for hybrid and combined events, are caused by light flashes from out-of-aperture lightning, diffusely reflected by the solar panels of the satellite onto the photodetector matrix.
3. Upward going EAS
   For hybrid and combined events we think, that they are produced by upward going EAS. Upward EASs can be initiated as a result of a process called scrambling, when a high-energy τ-neutrino enters the Earth tangentially at a zenith angle θ > 90°, interacts with the nuclei of soil atoms, forming a τ-meson, which escapes into the atmosphere and decays in the hadronic mode, forming upward EAS

Conclusion

1. TUS space detector registred more than 40 of anomalous events.
2. Most probable nature on this events – out-of-aperture flashes from lightning, diffusely reflected by solar panel.
3. Hybrid and combined events probably produced by upward going or horizontal EAS.
4. Calibration of the photodetector matrix based on anomalous events has been created, which is qualitatively consistent with the calibration of the MSU Research Institute of Nuclear Physics.