

Ultra high energy cosmic rays detector TUS on-board Lomonosov satellite

P.A. KLIMOV¹, G.K. GARIPOV¹, A.A. GRINYUK², B.A. KHRENOV¹, M.I. PANASYUK¹, V.S. MOROZENKO¹, S.A. SHARAKIN¹, A.V. SHIROKOV¹, L.G. TKACHEV², A.V. TKACHENKO², I.V. YASHIN¹ FOR THE TUS COLLABORATION

¹ Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

² Joint Institute for Nuclear Research, Dubna, Russia

pavel.klimov@gmail.com

Abstract: Orbital ultra high energy cosmic ray (UHECR) detector TUS (tracking ultraviolet set-up) is prepared for launching on-board Lomonosov satellite. The TUS space experiment is aimed to study energy spectrum and arrival distribution of UHECR at energy range above $\sim 10^{20}$ eV. Detector contains a large Fresnel-type mirror-concentrator ($\sim 2 \text{ m}^2$) and photo receiver placed in its focal plane (matrix of 16×16 PM tubes with a spatial resolution in the atmosphere near 5 km). In 2012 - 2013 TUS apparatus tests were done in assemble with Lomonosov space platform. The preflight tests, development of trigger simulation, data analysis programs are in progress.

Keywords: ultra high energy cosmic rays, GZK cut-off, orbital fluorescent detector

1 Introduction

Recent results obtained at ground-based experimental arrays do not give clear answers to the most important questions in the field of UHECR physics: mass composition and possible sources of the most energetic particles. Statistics beyond the GZK limit is still very low. The new method of UHECR observation by fluorescent detector on board a satellite, having high and uniform exposure, was suggested by Linsley and Benson in 1981 [1]. Now this idea is close to fulfilment in several projects (TUS, JEM-EUSO, KLYPVE). The main concept of TUS (Tracking Ultraviolet Set up) was developed in 2000-2001 [2, 3, 4] as the first stage of larger detector KLYPVE (Russian abbreviation of UHECR). Later on TUS detector was modified for launching on-board of various satellites [5, 6, 7], and recently is planned for launching on-board Lomonosov satellite [8]. The view of TUS detector on-board Lomonosov satellite is shown in figure 1. The scientific payload of Lomonosov satellite consists not only of fluorescence detector of cosmic rays TUS, but also detectors of x-ray and gamma radiation, wide angle cameras for GRB search in optical wavelengths, fast UV telescope for early GRB UV photons measurements [9]. The satellite will also provide monitoring magnetosphere particles and radiation.

2 Instrumentation overview and recent results

Detector TUS consists of the following parts: mirrorconcentrator, photo receiver, photo receiver moving system and solar light sensor. Fresnel type mirror-concentrator focuses UV light generated by EAS particle disc to photo receiver, which consists of 256 PM tubes and support electronics. Photo receiver moving system changes position of receiver from transportation to operation mode. It is also capable to remove receiver out of mirror focus in case of danger from concentrated sunlight. Alarm signal for removing receiver comes from directional solar light sensor.



Figure 1: Detector TUS on-board Lomonosov satellite.

Detector parameters are presented in table 1.

Image of EAS particle disc moves along photo receiver pixels and produce sequent in time signals in one or more pixels. Event with many "hit" pixels is considered as inclined EAS event. In vertical EAS only one or two pixels are informative. Data on space-time EAS signal distribution give information on direction of primary particle, its energy and position $\sim X_{\text{max}}$ of EAS maximum. In vertical EAS all data is concentrated in a few pixels and information on primary particle direction is poor. Triggering by inclined and vertical EAS are done separately, see below subsection 2.3.

Overview of the separate parts of TUS is presented in the following subsections.

2.1 Optics

Fresnel-type mirror-concentrator is designed as complex of the central parabolic mirror and 11 parabolic rings focusing a parallel beam to one focal plane. In this design thickness of the mirror construction is small (3 cm) which is important





Figure 2: PSF measurements results. Zenith angle: 0° , 3° , 4.5° . Dimensions are in millimeters. A square 15×15 mm corresponds to one pixel of TUS photo detector.

Parameter	Value
Mass	60 kg
Power (maximum)	65 W
FOV	$\pm 4.5^{\circ}$
Number of pixels	256
Pixel FOV	10 mrad (5 \times 5) km
Mirror area	2 m^2
Focal distance	1.5 m
Duty cycle	30 %

Table 1: Detector TUS parameters

for mirror implementation into satellite construction. Mirror focal distance is 1.5 m. The mirror is cut to hexagonal segments with a diagonal 66 cm. Mirror segments are made of carbon plastic strengthened by honeycomb aluminum plate so that the mirror construction is temperature stable in wide range of temperatures. Mirror surface is fabricated as plastic replicas of aluminum mould (one for central mirror part and one for 6 lateral parts). Reflective optics do not produce chromatic aberration, but have large coma and astigmatism for large off-axis angles. Field of view of the detector using this type of optics is determined as the offaxis angle at which parallel beam image size becomes equal to pixel size. Beam image light distribution for various angles were measured to obtain point spread function (PSF) which is important for further data analysis. PSF was obtained by two methods: 1) in independent measurements of each mirror segment by scanning with parallel laser beam; 2) in measurements with distant (\sim 30 m) pinpoint light source. The first method allows to evaluate mirror segments production quality. By the second method final results on full size mirror PSF at various beam angles were obtained. They are shown in figure 2. Results of laser beam technique are discussed in details in [10].

2.2 Photo receiver

Photo receiver comprises 256 pixels combined in 16 clusters. One cluster and whole photo receiver are shown in figure 3. Each pixel contains the photomultiplier tube (PMT) of Hamamatsu type R1463 (13 mm tube diameter, multi-alkali cathode, glass window transparent to UV). In front of PMT the UFS-1 filter is placed to separate radiation with



Figure 3: Photo receiver (left), PMT cluster (right).

wavelength range 240–400 nm from visual light. Light guides with square windows (15×15 mm) are used for having higher fill-in-factor in pixel area. Signals from every PM tube anode are coming to the multiplexer and then to 10-bits ADC. Important feature of TUS electronics is the use of FPGA for digital analysis of the signals after ADC. The fast signals from an UHECR event are collected every 0.8 μ s. Digital integration is used as for selection and measurements of longer EAS signals so for measurements of slower signals from other event types (micro meteors, sub-relativistic dust grains, transient luminous events – TLE). Temporal parameters of detector for various events are presented in Table 2.

Phenomena	Time sample	Oscillogram length
EAS	0.8 µs	205 µs
Dust grain	25.6 μs	6.6 ms
TLE	0.4 ms	105 ms
Micro-meteor	6.6 ms	1.7 s

Table 2: Temporal resolution of TUS detector for various atmospheric phenomena.

Important peculiarity of TUS electronics as well as of UV detectors on Universitetsky–Tatiana [11] and Universitetsky–Tatiana-2 [12] satellites (TUS pathfinders) is in use of PMT high voltage (HV) control system. Electronics always adopt the PMT gain corresponding to constant anode current. Such mode saves power consumption and allows PMT to operate in whole range of UV atmo-



Figure 4: The result of PMT adjustment in one cluster (p - photo cathode quantum efficiency, G - PMT gain, M - DAC code).

sphere radiation intensity (including day time). All PM tubes were tested, qualified and grouped into clusters with similar characteristics. PMTs within one cluster should have identical gain for the whole range of HV control at local night time (DAC codes 160–250). It was obtained by divider resistors selection. After such PMT adjustment tests with reference light source were done. Results of those tests for one PMT cluster are presented in figure 4. It is seen that characteristics of all PMTs within one cluster become similar after adjustment. Remaining difference of PMTs will be removed by software.

2.3 Triggering system

For selection of EAS events two-level trigger is implemented. The first level of EAS selection is done in every pixel as a signal above threshold of 5 standard deviation from average background in integration time of 12 μ s. This selection is done in every PMT by cluster FPGA. Selected first stage events are kept in FPGA operative memory. The second level of EAS selection is done in the central FPGA where data on map of the first level events are analysed. Separate EAS selection is done for two cases: 1) when at least three neighbour pixels are triggered in the first selection level during sequential time intervals of 12 μ s and 2) when signals in one pixel are larger than the first level threshold in three sequential time intervals.

Independently of EAS trigger there are other triggers for selection of "slower" events: sub-relativistic dust grains, TLE and micro-meteors. These events are selected with higher integration time (0.2 ms, 0.4 ms and 105 ms). Selection and measurement of dust grains and micro-meteors were discussed in paper [13]. TLE measurements are discussed below, section 3.

To test the EAS trigger system optical simulator of EAS was produced in JINR (Dubna). This device consists of UV laser and fast rotating mirror (10–100 Hz) which produce a moving source of light to illuminate TUS photo receiver. The mirror rotating frequency is selected so that angular velocity of simulator beam corresponds to EAS image movement in TUS detector. Description of simulator and its operation is presented in [14].



Figure 5: Detector TUS in operating position

3 TLE measurements by TUS detector

Transient luminous events (TLE) are recently discovered as very bright and powerful atmospheric phenomena. They are different in space and temporal structure: 1) "elves" are short in time (1 ms) large (up to hundreds km in diameter) rings at altitudes ~ 100 km in the atmosphere (lower ionosphere); 2) "sprites" and "gigantic blue jets" are of tens ms duration structured objects of tens km in size at altitudes of 50-90 km in the atmosphere. Both of them are correlated with lightning and will be measured by orbital detector. These events will occur much more frequently than EAS produced by high energy cosmic ray particles, and will make up a large portion of TUS data. Recent results on UV component of TLE were obtained in Universitetsky-Tatiana-2 experiment [15]. UV detector on-board this satellite selected UV flashes of duration 1 and more ms and measured their temporal structure in 128 ms traces with 1 ms resolution. Their brightness were presented by number of UV photons generated in the atmosphere in the same range of wavelengths planned to be measured in TUS experiment (240-400 nm). Flash event distribution over photon numbers was found changing at photon numbers of $\sim 10^{23}$. Geographical distribution of UV flashes was found different for events with large and small photon numbers: "bright" and "dim" flashes. For photon numbers larger than $\sim 10^{23}$ UV flashes correlate with continents in equatorial regions (as TLE do). They are believed to be initiated by lightning and that is why their distribution is correlated with thunderstorms. Rate of UV "bright" flashes is close to TLE frequency, measured by other space instruments, for example by ISUAL [16]. Flashes with UV photon numbers less than $\sim 10^{22}$ ("dim" flashes) are distributed uniformly, not in correlation with equatorial continent parts. Nature of "dim" flashes is not clear, presumably they are created in the upper atmosphere independent of lightning. The observed rate of TLE-like flashes is large above thunderstorm region (up to $10^{-3} \text{ hr}^{-1} \text{km}^{-2}$) and low out of them $(10^{-5} \text{ hr}^{-1} \text{km}^{-2})$. The rate of "dim" transients is much lower than TLE rate in thunderstorm regions but is comparable to TLE rate out of it. Those not bright UV flashes could be important part of background for UHECR observation. Number of fluorescent photons initiated by EAS of energy $\sim 10^{20}$ eV is $\sim 10^{16}$ - much less than photon number in transients of about $\sim 10^{20-22}$. The expected rate of UHECR events is two order of magnitude less than observed "dim" transient rate, see figure 6. At the same time measurements of "dim"





Figure 6: Comparison of UHECR intensity at primary energies above 10^{20} eV (fluorescent photon numbers more than 10^{16}) with global average intensity of UV atmospheric flashes measured in Universitetsky–Tatiana-2 experiment (photon numbers $10^{20} - 10^{25}$)

flashes by TUS detector will be interesting for physics of the atmosphere as TUS will be the first instrument capable to look for space-temporal structure of such small flashes. Measurements of UV flashes by TUS detector are discussed in [17].

4 Conclusions

Detector TUS is ready for integration at the satellite Lomonosov. It passed all preflight tests. Figure 5 shows TUS in operating position during tests. It will be the first orbital UHECR detector which will test this technique of measurements and give important information for future projects (JEM-EUSO, KLYPVE). In 3 years of operation in space TUS exposure will be $\sim 12000 \text{ km}^2 \text{ year sr} - \text{comparable}$ with the exposure of the largest ground-based detectors.

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