The TUS orbital detector optical system and trigger simulation

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Abstract. The TUS orbital experiment is aimed to study energy spectrum, composition and arrival directions of the Ultra High Energy Cosmic Rays (UHECR) at $E \sim 10^{20}$ eV. The TUS mission is planned for operation at the dedicated “Mikhail Lomonosov” satellite. The TUS detector will measure the fluorescence and Cherenkov light radiated by EAS of the UHECR using the optical system - Fresnel mirror-concentrator of 7 modules of ~2 m$^2$ area in total. Status of the Fresnel mirror production, its optical parameters measurement and the TUS trigger system simulation are presented.

1. Introduction

The TUS project task is an experimental study of UHECR. The fluorescent and Cherenkov radiation of Extensive Air Showers (EAS) generated by UHECR particles will be detected at night side of the Earth atmosphere from the space platform at heights 400-500 km. It will make possible to measure the CR spectrum, composition and arrival directions at $E > 10^{20}$ eV beyond the GZK energy limit. There are two main parts of this detector: a modular Fresnel mirror and a matrix of PMTs with corresponding DAQ electronics. The TUS mission is now planned for operation at the dedicated “Mikhail Lomonosov” satellite shown in figure 1.

Figure 1. The TUS detector at the “Mikhail Lomonosov” satellite.
Photo detector and electronics consist of 256 PMT pixels with the time resolution 0.8 μs and the spatial resolution 5×5 km (for the initial orbit height of 500 km). The digital integrators allow us to use the same photo detector to study different phenomena in the atmosphere in wide time interval: starting from ~100 μs (EAS) to 1 ms – 100 ms (transient luminous events, TLE) and up to 1 s (micrometeors).

The Fresnel mirror module prototypes were produced and tested in 2008-2009. The mirror module consists of the multilayer carbon plastic and aluminum honeycomb support to keep its properties stable in the day and night part of the space orbit cycle with the temperature difference of ± 80° C. The optical parameters measurement is the important part of the TUS preparation program because their results will be used in future data analysis, especially for an evaluation of the systematic uncertainties. The special procedure was elaborated to measure the mirror module optical parameters including the PSF (point spread function) measurements of the lateral and central TUS Fresnel mirror modules [1].

A set of the programs for TUS are produced for the event simulation based on ESAF program package developed previously for JEM-EUSO experiment with expected TUS optical parameters. Trigger efficiency simulation and on board data processing programs are in preparation.

In the TUS photo detector box the pinhole camera is added for study of TLE. The JEM-EUSO UV sensor will be tested in TLE data taking by the pinhole camera [2].

2. The TUS Fresnel mirror measurements

The PSF measurements were performed for each lateral and central Fresnel mirror modules. In the left part of the figure 2 the two-dimensional x, y-coordinate plot of the simulated parallel light beam images are presented on the focal plane of ideal mirror that is exactly 1500 mm from the mirror profile. The light beams were simulated at the different azimuthal (φ) and the TUS FoV polar (θ) angles respect to the optical axis of mirror. The PSF dependence of angles is important for the EAS track image reconstruction on the PMT matrix.

An example of such dependence for the measured TUS mirror is presented in the right part of figure 2 that was obtained with parallel laser beams. The x, y coordinates of the central spot correspond to the beam that is parallel to the mirror optical axis. The other spots correspond to PSF positions of beams at different azimuthal angles and θ = 0°, 1.5°, 3°, 4.5°. There is naturally no φ-dependence due to small differences between lateral mirror modules. Simultaneously absence of the φ-dependence confirms correctness of a procedure of the PSF angular dependence evaluations. There is obvious difference with the same angular dependence for the ideal Fresnel mirror. The PSF parameters are by the definition RMSx and RMSy of the light spot distribution which are equal 5.08 and 4.27 for central spot and which are inside of the photo receiver pixel size that is 15x15 mm².
Figure 2. The PSF angular dependence of the Fresnel mirror. Left – ideal mirror, right – TUS mirror after correction of optical parameters.

In the figure 3 an example of UHECR EAS event is shown of the $E \sim 2 \times 10^{20}$ eV energy as it looks at the TUS photo detector but without background light for ideal mirror (left) and for real TUS mirror (right). The percentage of EAS photons is shown for each PMT pixel.

Figure 3. Example of an EAS image on the 16x16 photo receiver matrix. Left – ideal mirror, right – TUS mirror after correction of optical parameters.
3. The TUS trigger system simulation

ESAF [4] program package developed for JEM-EUSO experiment was modified for TUS experiment conditions and used for simulation of the TUS trigger efficiency. The simulation of EAS development and propagation of photons through the atmosphere were left unchanged and then all available information about generated shower and array of properties of photons on the detector entrance pupil were saved to a file. Simulation in ESAF was stopped at that. Later the photons from generated files were read by TUS optical system and trigger simulation programs and TUS efficiency was evaluated at various levels of background and trigger thresholds. Reflection by the TUS mirror was done using corrections from measured mirror optical parameters. Besides that the UV filter and PMT lightguides were fully taken into account for each photon on the way to PMT cathode.

The $P = 21\%$ quantum efficiency was taken for each PMT that was obtained at dedicated measurements during PMT calibration. The PMT location in the 16x16 matrix is arranged according to their calibration parameters and these parameters were taking into account in the trigger simulation program.

Average background photon flux is supposed to be $10^6 \text{ph/sr}\cdot\mu\text{s}\cdot\text{m}^2$ that corresponds to $I_o = 160 \text{photons per PMT pixel per 0.8 \mu s trigger time step}$. The following results were obtained for the minimal background photon flux that is about 0.1$I_o$. Total number of EAS photons for $E \sim 10^{20}$ eV on the TUS mirror is only about 4000 photons during 100 μs in comparison with $10^6$ background photons for the same time. Each photon on PMT cathode with a probability $P$ initiates PMT current which is exponentially decreased with time according to RC parameters of the electronic circuit channel.

The severity of a problem to select and to measure such events is obvious. Two-level TUS trigger system was elaborated to do trigger selection more efficiently [5]. At the first trigger level the sliding sum of currents in every PMT pixel is measured during the last 16 substituted trigger 0.8 μs steps and memorized in the 16 PMT cluster board. This trigger level is up if the sliding sum in some pixel is higher than the threshold value that is established beforehand and which is the same for all pixels. In this case the first 16×16 pixel frame is formed in the trigger electronic motherboard memory with marked “hit” pixels. Such three consecutive frames of 16 trigger steps with “hit” pixels in overlapping neighboring vicinities form the second level trigger and elaborate a command to take data in memory.

Such a trigger procedure was realized in the TUSSIM simulation program. As an input the program takes a few thousand ESAF simulated events in $E = 10^{20} - 10^{21}$ eV energy range and arrival zenith angles $10^\circ - 80^\circ$. EAS simulated photons are transferred via TUS optic including of pixel lightguides to the PMT cathods. The background photons are generated inside of TUSSIM program homogeneously in time and photo receiver plane. The threshold value may be put “by hand” or calculated with program which is running for this case with background photons only and without EAS ones. The average number of triggers is calculated for each EAS event for 100-1000 TUSSIM runs with statistically different background photons. It was found that number of triggers are crucially dependent on the homogeneity of the PMT-pixel parameters. In fact the overwhelming part of false triggers is initiated by PMTs with the highest gains.

The relative number of triggers as a function of an EAS energy and a threshold value is presented in figure 4 for real (left panel) and identical (right panel) PMTs. The number is in fact the trigger efficiency after the false trigger number subtraction. The threshold values: 80, 85, 90, 95 correspond to the RMS values 6.0, 6.7, 7.5 and 8.3 respectively for the minimal background photon flux.
Figure 4. Dependence of EAS energy for the relative number of triggers for the minimal background photon flux.

4. Conclusion
The TUS mirror was produced and successfully tested according to the space qualification requirements. The optical parameters of the mirror are in reasonable correspondence as with the Field-of-View of the TUS photo receiver as with PMT pixel size. Preliminary results of the TUS trigger efficiency simulation are presented. The TUS mission is planned for operation at the dedicated “Mikhail Lomonosov” satellite for 3 years of data taking [3].

5. References
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