Письма в ЭЧАЯ. 2013. Т. 10, № 1(178). С. 84–93

МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

THE TUS FRESNEL MIRROR PRODUCTION AND OPTICAL PARAMETERS MEASUREMENT

G. Garipov [b], *A. Grinyuk* [a], *V. Grebenyuk* [a], *P. Klimov* [b], *B. Khrenov* [b], *S. Porokhovoy* [a], *A. Puchkov* [c], *S. Sabirov* [a], *O. Saprykin* [c], *S. Sharakin* [b], *A. Skrypnik* [a], *M. Slunecka* [a], *A. Tkachenko* [a], *L. Tkachev* [a], *I. Yashin* [b]

[a] Joint Institute for Nuclear Research, Dubna

[b] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow

[c] Space Regatta Consortium, Korolev, Russia

The TUS space experiment is aimed to study energy spectrum, composition, and angular distribution of the Ultra-High Energy Cosmic Ray (UHECR) at $E \sim 10^{20}$ eV. The TUS mission is planned for operation at the end of 2012 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. Production of the flight model of the optical system is in progress. Status of the Fresnel mirror production, the method, and results of their optical parameters measurement are presented.

Космический эксперимент ТУС предназначен для изучения энергетического спектра, состава и углового распределения космических лучей сверхвысоких энергий (КЛСВЭ) при $E \sim 10^{20}$ эВ. Запуск ТУС запланирован на конец 2012 г. на спутнике «Михаил Ломоносов». Детектор ТУС будет измерять флуоресцентное и черенковское излучения света, испускаемые широкими атмосферными ливнями (ШАЛ) в области КЛСВЭ, с помощью оптической системы — семи модулей зеркал-концентраторов Френеля общей площадью ~ 2 м^2. Изготовление полетных модулей оптической системы находится в стадии производства. В работе представлены статус процесса изготовления зеркал Френеля, методика и результаты измерений их оптических параметров.

PACS: 95.55.K; 95.55.Vj; 29.40.-n

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 $E > 7 \cdot 10^{19}$ 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 SINP MSU (main investigator), JINR, and Consortium «Space Regatta» together with several Korean and Mexican Universities are collaborating in the TUS detector preparation. The TUS mission is now planned for operation at the dedicated «Mikhail Lomonosov» satellite shown in Fig. 1.

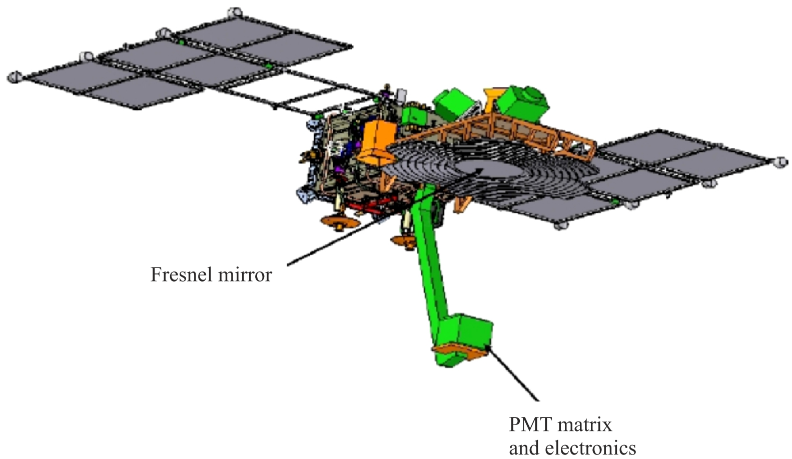

Fig. 1. The TUS detector at the «Mikhail Lomonosov» satellite

Main TUS parameters are: mass < 60 kg, power consumption ~ 65 W, data rate 200 Mbytes/day (1 EAS event contains ~ 80 Kbytes), Field-of-View $\pm 4.5°$, number of pixels 16×16 (Hamamatsu type R1463 PMT: 13 mm tube diameter, multialcali cathode, UV glass window), pixel FOV $\sim$10 mrad, Fresnel mirror area is 1.8 m^2, focal distance — 1.5 m.

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 orbit height of 500 km). The digital integrators allow us to use the same photo detector to study different phenomena in the atmosphere in a wide time interval: from ~ 100 μs (EAS) to 1–100 ms (transient luminous events, TLE) and up to 1 s (micrometeors). A prototype of such photo detector was tested during 2 years of «Universitetsky-Tatiana» mission [1].

In the TUS photo detector box, the pinhole camera is added for study of TLE. The pinhole camera consists of multianode PMT and a hole at the focal distance from the PMT cathode. In design of the camera, the multianode PMT of JEM-EUSO type is used [2]. The JEM-EUSO UV sensor will be tested in TLE data taking by the pinhole camera.

STATUS OF THE TUS FRESNEL MIRROR PRODUCTION AND TESTS

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. At the first stage, the blank mirror modules are produced at Consortium «Space Regatta» using two types of the moulds for lateral and central modules, respectively. At JINR, the blank modules are covered by ~ 120 nm layer of pure aluminum and 40 nm protective layer of MgF_2 in process of evaporation in vacuum chamber.

In Fig. 2 the technological Fresnel mirror module and the fiducial net are shown inside the thermovacuum camera during tests at temperature ± 80 °C and pressure of 0.02–1.0 atm. The fiducial net reflection was used to check the mirror optical quality. The tests gave a positive

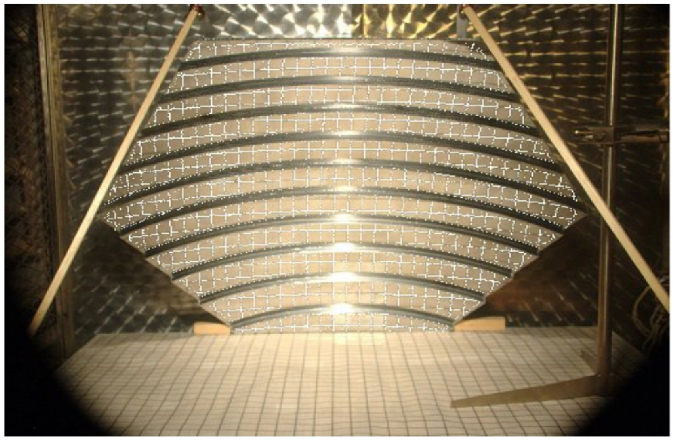

Fig. 2. The mirror module test in thermovacuum camera at temperature ±80 °C and pressure of 0.02–1.0 atm

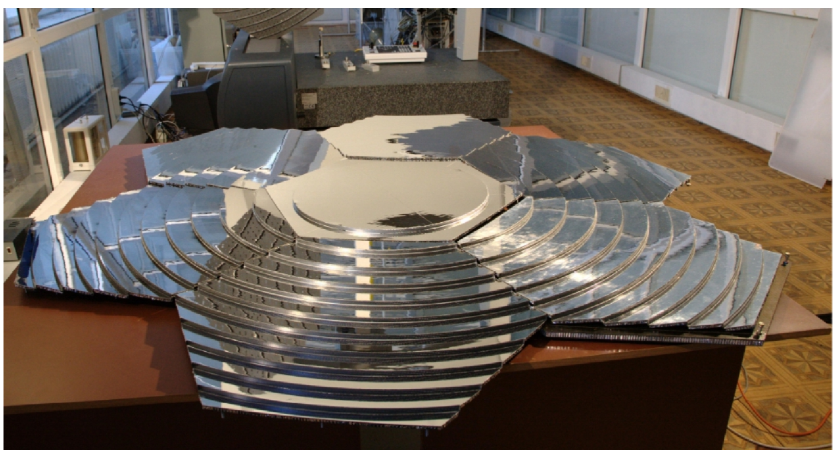

Fig. 3. Technological Fresnel mirror

result — no essential difference in the mirror properties was found. The image lines were obtained by the off-line reconstruction of reflected fiducial net lines.

The technological prototype of the segmented 7-module Fresnel mirror produced in 2010 is shown in Fig. 3. The mirror was successfully tested according to the space qualification requirements. Test devices with the mirror are presented in Fig. 4.

One of the main TUS collaboration tasks in 2012 is production of flight model of the Fresnel mirror. The work is in progress: eight lateral and two central modules were fabricated and covered by reflective aluminum and protective MgF_2 layers. Various measurements of the optical parameters of the mirror modules were fulfilled. At the moment, the flight TUS Fresnel mirror production is at the conclusive phase.

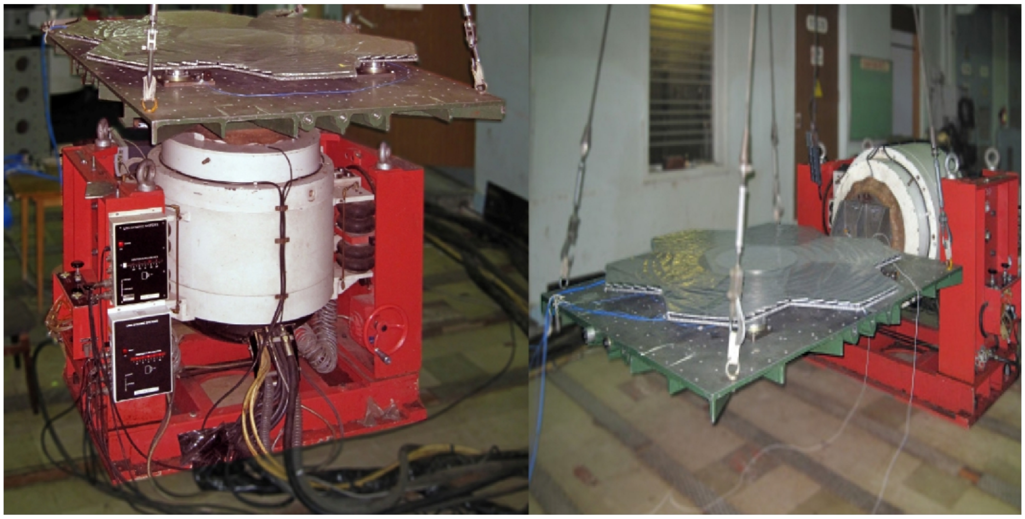

Fig. 4. The technological Fresnel mirror at space qualification tests

THE OPTICAL PARAMETERS MEASUREMENT

The optical parameters measurement is the important part of the TUS preparation programme. Results of this measurement are very important for future data analysis, especially for an evaluation of the systematic uncertainties. Also in this measurement the best mirror modules are selected among all produced ones.

The special procedure was elaborated to measure the mirror module optical parameters. The Eclipse 700/1000 coordinate measuring machine from Carl Zeiss, complimented by a laser head and a web camera, shown in Fig. 5, were used for the PSF (point spread function) measurements of the lateral and central TUS Fresnel mirror modules. Homogeneous parallel light flux was simulated by moving the laser beam across the mirror along the prescribed trajectory controlled by PC. The laser beam was reflected from the mirror on the screen that was located at 1500 mm distance — at the mirror focal plane. The angle between laser beam and mirror support was fixed in every run of measurements to simulate homogeneous parallel light flux on the mirror and to get a possibility to measure PSF. The measurements were made at the different angles to obtain the angular PSF dependence.

The screen images with the laser beam spot were written on-line by the web camera on another PC with the fixed frequency frame rate 15 frame/s. A special measurement was done to check mutual correspondence between laser beam location on the mirror and its reflected image on the screen. For such a purpose the plane optical mirror was used.

With the same procedure as for the plane mirror, a point-to-point correspondence was obtained between the laser beam on the TUS mirror module and its screen spot location. The speed of the laser beam movement and the frequency frame rate were selected and fixed to get 3.5 mm distance between the measuring points on the mirror. Obviously such a procedure provides a PSF measurement locally for separate mirror areas which is useful due to possibility of the module surface adjustment.

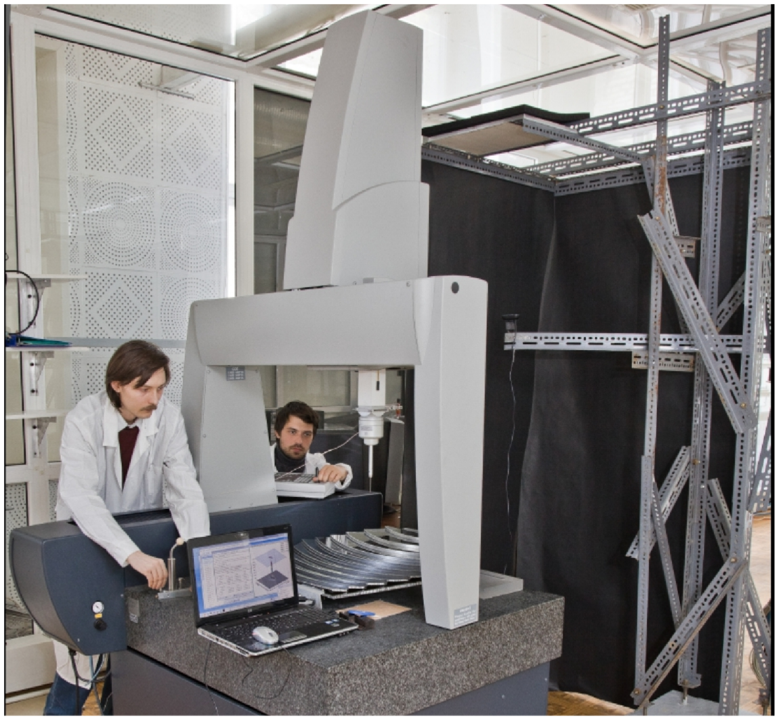

Fig. 5. Eclipse 700/1000 coordinate measuring machine. The web camera and screen are located on the right support structure

In this preliminary analysis the Fresnel mirror shape is assumed to be ideal with 1500 mm common focal distance, and z-coordinate on its surface is calculated according to the measured x and y coordinates of laser beam on the mirror. The normal vector components to the mirror surface in the intersection of the beam and the mirror surface are calculated in such a way to get the point x and y coordinates measured on the screen with the web camera.

LATERAL MODULES

An example of the PSF measurement for the lateral Fresnel mirror module is presented in Fig. 6. The two-dimensional x-, y-web camera coordinate plot of the laser beam images on the focal mirror plane is shown. The x axis is parallel to the hexagon bottom side of the mirror module as is shown in Fig. 2 and that is the nearest to the mirror optical axis. The y axis is orthogonal to the x axis and directed outside of the optical axis. The PSF parameters are by the definition RMS x and RMS y of this distribution which are RMS $x \approx 2.8$ mm and RMS $y \approx 4.6$ mm — both are reasonably inside the photo receiver pixel size that is 15×15 mm. The «bad» points outside the RMS ellipse are located on the edges of the mirror rings, those may be seen qualitatively also in Fig. 2 with a deformation of the fiducial net reflection. Besides RMS y is appreciably greater for RMS x for all modules due to displacement of focal points for the different rings.

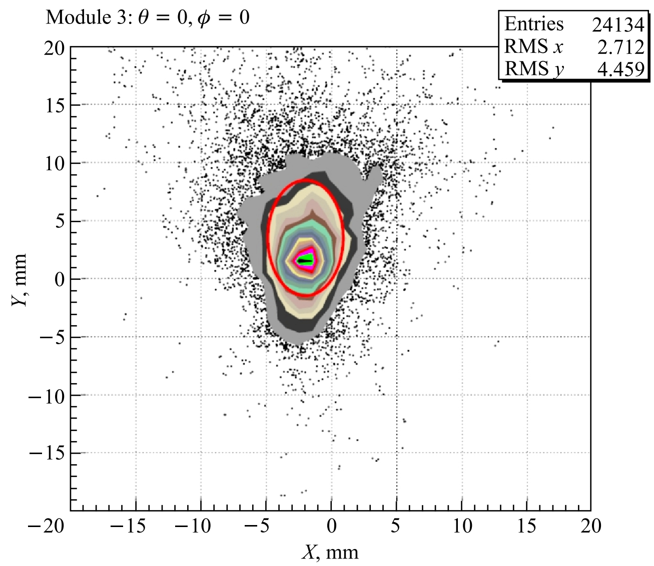

Fig. 6. The laser beam spot image distribution on the focal screen for the lateral Fresnel mirror module

The measurements of the focal point locations of the different mirror modules are presented in Figs. 7, 8. The x vs. y plots of the beam light locations are presented on the focal plane that is exactly 1500 mm above the bottom part of the mirror profile. As is seen, a few mm deviation focal points from $x = y = 0$ zero point exist for all modules systematically. A reason for these deviations is not obvious at the moment but they are good inside the PMT pixel size. The big ellipse axis of each module is always along radial direction of the mirror optical axis.

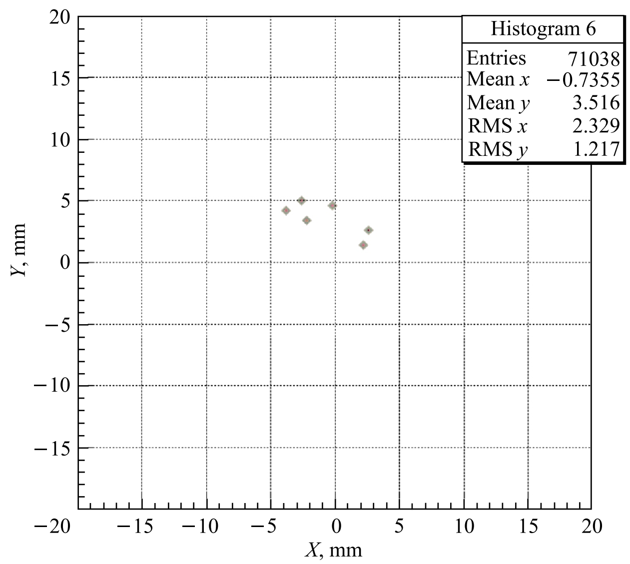

Fig. 7. The focal points of the different lateral Fresnel mirror modules

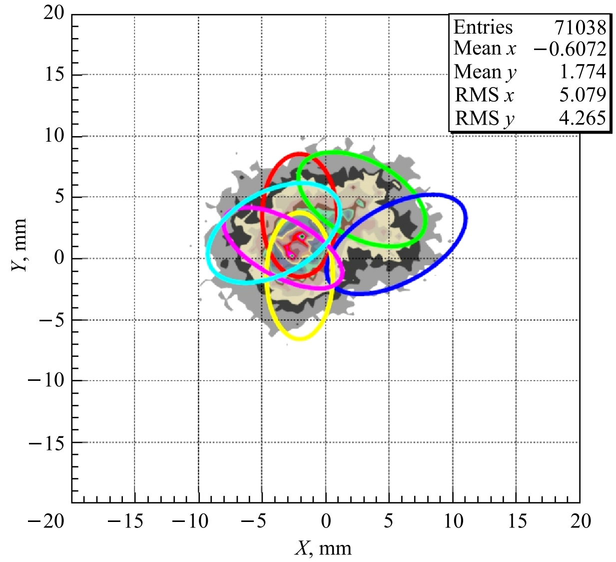

Fig. 8. The PSF ellipses of the different lateral Fresnel mirror modules on the top of the total distribution of the laser beam spot images

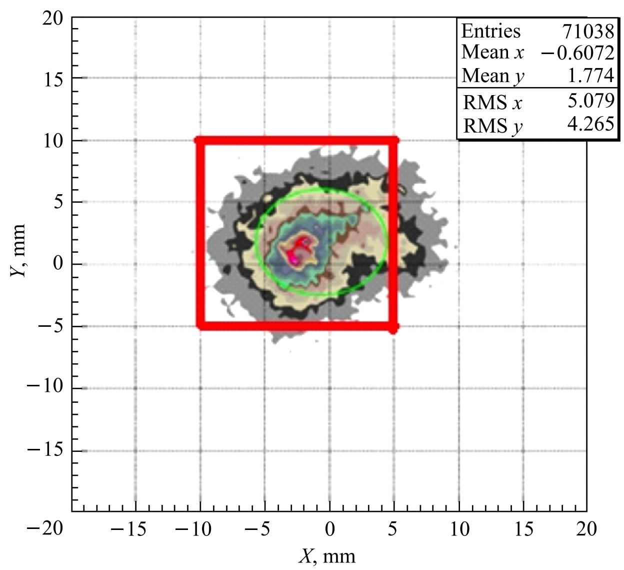

Fig. 9. The PSF ellipse of all the lateral Fresnel mirror modules together with a pixel size of photo receiver on the top of the total distribution of the laser beam spot images

In Fig. 9, the integral PSF ellipse is presented of all the lateral Fresnel mirror modules together with a pixel size of photo receiver on the top of the laser beam spot image distribution. The spot size is in a reasonable correspondence with a pixel size.

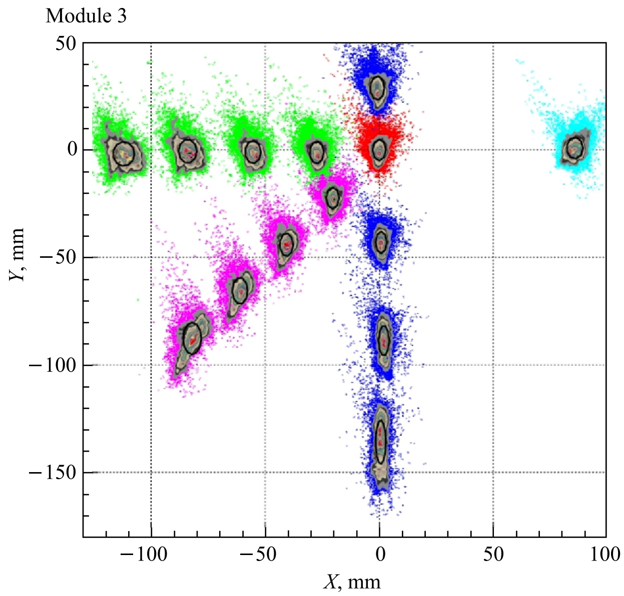

Fig. 10. The PSF angular dependence of the lateral Fresnel mirror module

The PSF dependence of angles between light source (parallel laser beams) direction and the mirror optical axis, that is important for the EAS track image reconstruction on the PMT matrix, was measured. An example of such a dependence for the lateral mirror module is presented in Fig. 10. The x, y coordinates of the central red ellipse in Fig.10 correspond approximately to the mirror optical axis position. The green and magenta ellipses correspond to PSF positions at $\phi = 0°$ and $\phi = 45°$, respectively, and $\theta = 1, 2, 3, 4°$, those are angles between laser beam direction and optical axis, the blue ellipses correspond to PSF positions

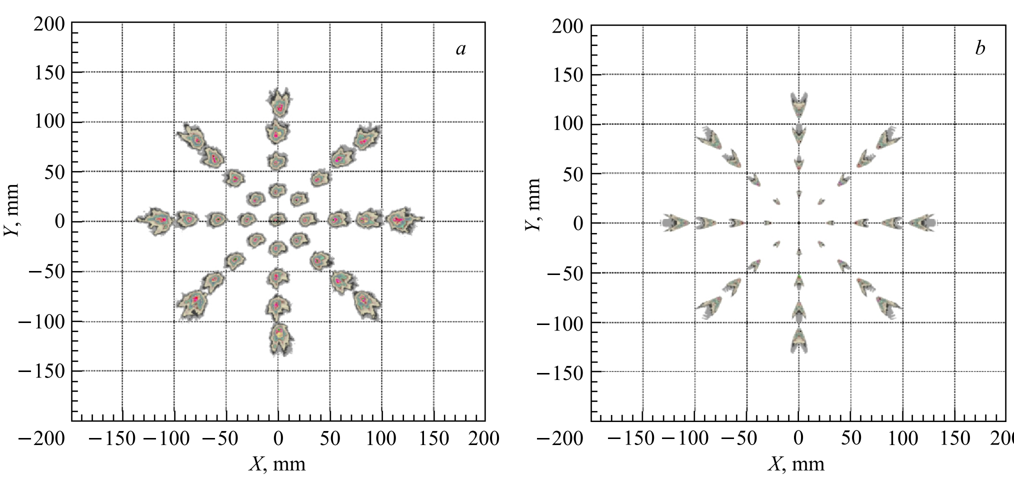

Fig. 11. *a*) The PSF angular dependence of the Fresnel mirror without the central module. *b*) The PSF angular dependence of the ideal Fresnel mirror

at $\phi = 90°$ and $\theta = 1.5, 3.0, 4.5°$, etc. The PSF angular dependences for the other lateral modules are similar.

A knowledge of the mirror module surface and the normal vector components enables us to evaluate the PSF angular dependence of the whole mirror but at the beginning without the central module.

The angular θ dependences at $\phi = 0, 45, 90°$ of PSF are presented in Fig. 11 for the TUS Fresnel mirror without the central module. 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 that is presented in Fig. 10.

MEASUREMENTS OF THE CENTRAL MODULES

A procedure of the optical parameters measurement was essentially modified for the central module. These modifications were due to coincidence of the optical axis with the center of the module axis so the laser head and web camera are on the way of a reflected laser beam. The module was turned at 90° around horizontal axis and mounted on the measurement table vertically, the laser head was moved correspondingly. The web camera was placed after the semitransparent screen. The laser beam scanned along mirror horizontally with the vertical shift of 6 mm between neighbouring scan lines. About 60% of the mirror surface was scanned in such a way due to measuring machine limitation. The measurement was repeated after the 180° turning around the optical axis to cover the whole surface of mirror. The double scanned area is used to connect these two measurements.

The laser beam spot image distribution for the central module is presented in Fig. 12. The RMS x and RMS y values of this distribution (RMS $x \approx 5.9$ mm and RMS $y \approx 7.6$ mm) are noticeably larger in comparison with the lateral modules but inside the photo receiver pixel

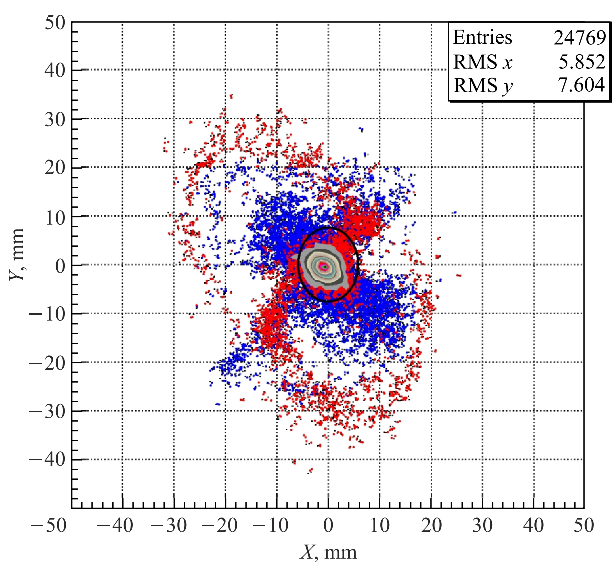

Fig. 12. The laser beam spot image distribution on the focal screen for the central mirror module

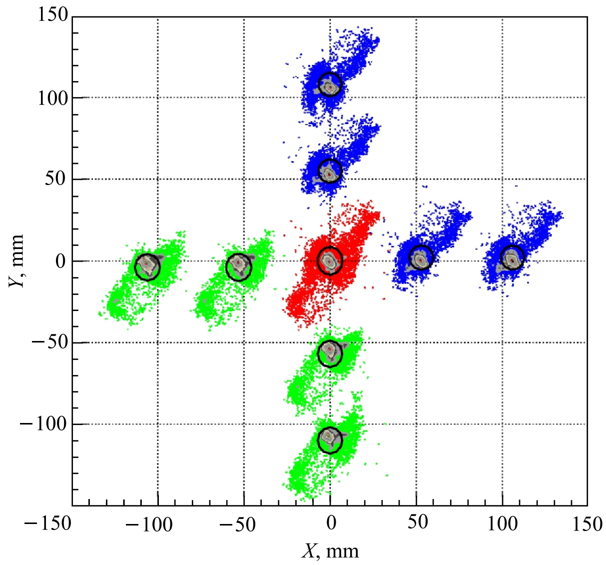

Fig. 13. The PSF angular dependence of the central mirror module

size. It was expected beforehand due to corresponding difference between central and lateral moulds.

The angular θ dependences at $\phi = 0, 90, 180, 270°$ of PSF are presented in Fig.13 for the central mirror module. A small angular dependence is due to deviation of the optical axis direction from the horizontal measuring machine table at the measurements.

CONCLUSION

The technological TUS mirror was successfully tested in 2010 according to the space qualification requirements. It confirms reliability of the mirror composition of the multilayer carbon plastic and aluminum honeycomb. The flight mirror was produced this year and is almost ready for integration at the satellite. According to measurements at «Space Regatta» Consortium, the coefficient of the mirror surface reflection is 0.84–0.87 that is better than was in TUS technical requirements. The optical parameters of the flight mirror are in reasonable correspondence both with the Field-of-View of the TUS photo receiver and with PMT pixel size. The TUS mission is planned for operation at the end of 2012 at the dedicated «Mikhail Lomonosov» satellite for 3 years of data taking [3, 4].

REFERENCES

1. *Sadovnichi V. et al.* The First Results of the «Universitetsky-Tatiana» Satellite // Cosmic Res. 2007. V. 45. P. 273–286.
2. *Takahashi Y. (JEM-EUSO Collab.).* JEM-EUSO Mission // New J. Phys. 2009. V. 11. P. 065009.
3. *Panasyuk M. I. et al.* TUS Mission. Technological Developments in Russia for JEM-EUSO Collaboration. ICRC-2011, ID 1261.
4. *Tkachev L. G. et al.* The TUS Fresnel Mirror Production and Optical Parameters Measurement. ICRC-2011, ID 659.

Received on March 19, 2012.