UHECR energy and arrival direction reconstruction by fluorescence data in space-based detector TUS

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***Abstract*. The space-based fluorescence detector is the new approach to ultrahigh energy (UHE) cosmic rays (CR) measurements. The main problems which should be solved are the energy spectrum in the GZK energy region and CR anisotropy. These tasks require automatic analyses of UHECR events, good accuracy of energy and arrival direction reconstruction. The first Russian space-based fluorescent UHECR detector TUS will have 2 m^2 mirror and 256 pixels with 4×4 km space resolution in the atmosphere. But the good energy and arrival direction estimations are possible even for this chip, small detector. The monocular technique of primary particle parameters reconstruction was developed for detector TUS.**

***Keywords*: UHECR reconstraction, space-based detector**

I. Introduction

Nowadays several orbital ultra high energy cosmic rays (UHECR) detectors are developed (TUS, KLYPVE, JEM-EUSO). These detectors will measure very fast UV fluorescent track of extensive air shower (EAS), produced by energetic particles in the Earth atmosphere. Their main scientific goals are the UHECR energy spectrum and search of astrophysical sources of energetic particles. To achieve these goals ones need to develop methods of primary particle parameters reconstruction for space-based experiments. The first Russian orbital UHECR detector TUS will have 2 m^2 Fresnel mirror and photo detector with 256 pixels. One pixel field of view is 4×4 km when the orbit height is 400 km. (Details about detector TUS in[1]). We develop a primary particle parameters reconstruction technique for this detector.

II. Reconstruction of primary particle arrival direction

The main difficulties of primary particle parameters reconstruction by the orbital fluorescence detector data connected with the following features of experiment:

1) Detector consists of only one photodetector. It makes impossible 3D EAS geometry reconstruction and allow to receive only 2D track, moving on the surface of photodetector. The main measuring parameters are the UV radiation intensity and the velocity of image.
2) The signal from EAS is very low, even in the maxima of shower, so just in few pixels it is higher then noise. As a result, the 2D track is short.
3) The signal from EAS and UV noise are strongly fluctuate. It makes difficult to determine moments of signal start and finish in one pixel.

So, we need a method of arrival direction and energy reconstruction, which will work well for this type of detector.

The primary particle zenith (θ_0) and azimuthal (ϕ_0) angles reconstruction is possible using a velocity of image on surface of photodetector. If one knows the projections of image velocity (v_x, v_y), it is possible to find θ_0 and ϕ_0 using following formula:

$$\theta_0 = 2\arctan\left(\frac{\sqrt{v_x^2 + v_y^2}}{c}\frac{R}{F}\right) + \beta \quad (1)$$

$$\phi_0 = \arctan\left(\frac{v_y}{v_x}\right) \quad (2)$$

where R - the satellite orbit altitude, F - the mirror focal distance, β - the correction angle, which takes into account difference of orbit altitude and distance from EAS maxima to satellite. This angle is maximal ($4.5°$) for EAS in the edge of field of view (FOV), and it is equal to zero for exactly central events. Angle β is calculated on the EAS maximum coordinates on the photodetector and velocity projections.

How to measure the projections of image velocity? If one consider an ideal mirror of detector (without aberrations), the image of EAS in the focal plane will be a point. During EAS development this image will move in a straight line, but the signal will jump from one pixel to another in the moments of image transition from pixel to pixel. So, the velocity projections of signal moving are zero, when image situated in one pixel and have a peak when image moves to another column (v_x) or row (v_y) of pixels. If one measure the average time which image stay in a column (Δt_x) and in a row (Δt_y) it is possible to calculate the image velocity projections by the following formulas ($l = 15$ mm - pixel size):

$$v_x = \frac{l}{\Delta t_x}, \quad v_y = \frac{l}{\Delta t_y} \quad (3)$$

The idea of arrival direction reconstruction is shown in Fig. 1. This method allow to find θ_0 and ϕ_0 without

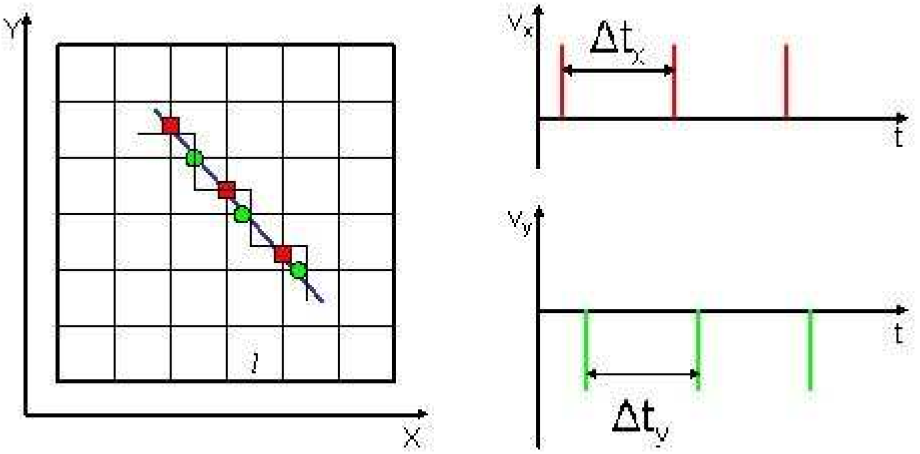

Fig. 1: Left panel: the part of TUS photo detector, straight line - "true" EAS track, broken line - signal moving, squares and circles - moments of signal transition from one pixels row or column to another. Right panel: velocity projection plots.

3D track reconstruction. It use only distances between peaks in the plots of velocity projections.

To apply this method in case of optics with aberrations it is necessary to take into account the image structure. The result of Fresnels mirror simulation is shown in the Fig. 2. The image has a top (apex) which contains more then half of signal, always directed on the photodetector center and corresponds to the non aberration optics (the center of mirror). This image features prompt that one of the best fits to the top of image is the center of the nearest pixel with significant signal. So we use the method described above, using velocity of this point. We simulated 1000 EAS with zenith angle 75° (the middle of measuring range) and various azimuthal angles ($0^\circ - 360^\circ$), energy $E_p = 10^{20}$ eV and found out that average error of zenith angle reconstruction is less then 3°. In this tests we consider the start and finish times of signal in one pixel well known (i.e. at the high signal to noise ratio).

Determination moments of signal start and finish in one pixel is a difficult task for srtongly fluctuated signal. It will increase errors. First estimations show that errors will be $5^\circ - 10^\circ$ and depend on signal to noise ratio.

III. Reconstruction of primary particle energy

The number of electrons in the EAS maxima is determined by the energy of primary particle. Each electron produces UV light in the atmosphere due to nitrogen excitation. The fluorescence yield (Y) is $4.5 - 5$ photons per meter and depends from the atmosphere characteristics (pressure, temperature, humidity) [2],[3]. The UV light from EAS converted into photo electrons in the PMT of photodetector. Number of photo electrons is the EAS energy measure:

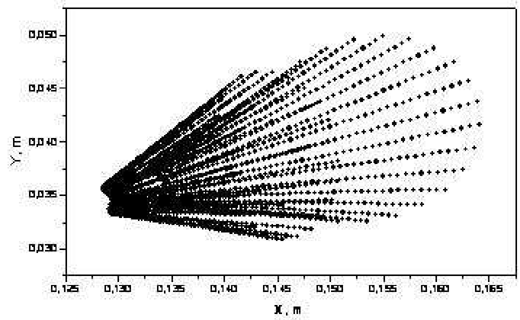

Fig. 2: The image on the surface of photodetector. The apex of image corresponds to the optics without aberrations

$$E_0 = N_{\text{p.e.}} \frac{E_1}{Y c \Delta t} \frac{4\pi R^2}{S} \frac{1}{p \chi \eta} \qquad (4)$$

where $N_{\text{p.e.}}$ - number of photo electrons, E_1 - EAS model parameter (1.4 GeV), $c\Delta t$ - electron way in the atmosphere during measuring time (12 μs - the average duration of signal in one photodetector pixel for horizontal EAS), R - orbit altitude, S - mirror square, p - PMT photo cathode quantum efficiency (0.2), χ - optics efficiency (~ 0.8), η - atmosphere transparency.

The quantum efficiency of PMT and optics efficiency of detector are well known parameters, which are measured before launching. The atmosphere transparency of upper atmosphere layers is much more higher than transparency of bottom layers and has less variations. It is one of space-based EAS measurements advantages. Atmosphere transparency depends on the zenith angle of EAS. For the fixed angle the fluctuations

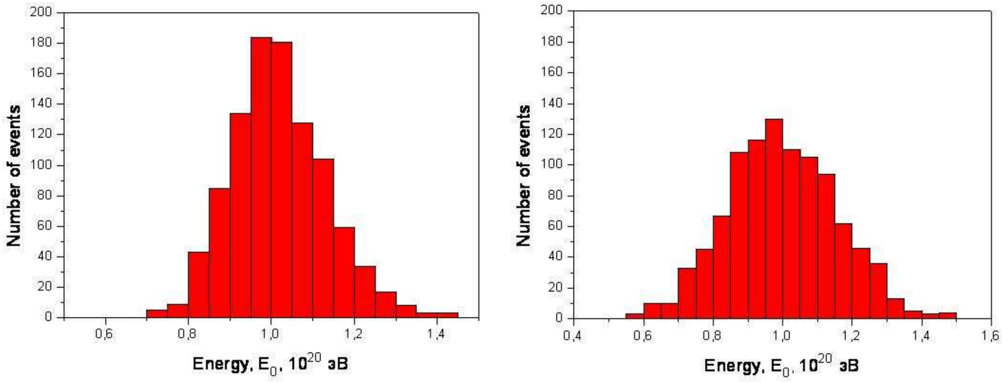

Fig. 3: Distribution of reconstructed energy (1000 EAS, primary particle energy $E_p = 10^{20}$ eV, $\theta_0 = 75°$). Left panel - center of FOV, right panel - edge of FOV.

of η, connected with fluctuations of the EAS maximum depth, are less than 5%.

The main contribution in reconstructed energy error produces signal fluctuations. The average number of photo electrons in maxima for EAS with energy $E_p = 10^{20}$ eV during 12 μs is 300 p.e., so the fluctuation of this signal is 17 p.e. and error 6%.

The accuracy of energy reconstruction strongly depends on the signal to noise ratio. For night with $0-40\%$ moon phase, the intensity of UV radiation is less then 10^8 photon/cm^2 sr s and the threshold of TUS detector is $5 \cdot 10^{19}$ eV[4]. We studied this method in the following conditions: $E_p = 10^{20}$ eV, $I_{UV} = 10^8$ photon/cm^2 sr s, the signal to noise ratio in EAS maximum in this case is high (signal/noise 15 for $12\mu s$). We simulated 1000 EAS with energy $E_p = 10^{20}$ eV, zenith angle $75°$ (the middle of measuring range) and various azimuthal angles ($0° - 360°$). The distribution of reconstructed energies for center of FOV (left panel) and at the edge of FOV (right panel) is shown in fig. 3. In the first case the uncertainty of energy reconstruction is 10%, in the second - 15%.

IV. CONCLUSION

The developed method allow to achieve quite good accuracy of angle determination for space based UHECR detector TUS, which has a rough spatial resolution in the atmosphere. For high signal to noise ratio the accuracy in zenith angle reconstruction is better then $5°$. Energy reconstruction accuracy depends on position of the track in the field of view. In the center of FOV it is near 10%, at the edge $15 - 20\%$.

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