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Space experiment "TUS" for study of ultra high energy cosmic rays and the KOSMOTEPETL collaboration

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Abstract. The telescope with mirror area 1.5 m^2, focal distance 1.5 m, with retina of pixels (photomultipliers) in its focal plane is designed for observation of the Earth fluorescence from orbit of the space platform "Resurs DK1" (apogee height- 600 km, perigee height 350 km). Cosmic ray particles of ultra high energy (energy more than $2 \cdot 10^{19} ev$) produce fluorescent tracks in atmosphere that will be detected by the telescope. The goal of the experiment is to study ultra high energy cosmic rays and to reveal their sources.

1 Introduction

For solution of the fundamental problems put by the present day data on ultra high energy cosmic ray (UHECR), Nagano and Watson (2000), experimental arrays of gigantic geometrical factor S (km^2) Ω (sr) multiplied on the duty cycle T ($years$) are needed — $S\Omega T > 10^5\ km^2\ sr\ years$. One approach to the problem is an observation of UHECR events from the Earth satellites. The original idea was suggested by Linsley (Linsley and Benson , 1981) and was developed in several space projects. In this approach the fluorescent track of the shower initiated by the UHECR primary particle in atmosphere is observed from space by the detector of the Fly's Eye type (Baltrusaitis et al , 1985). From a satellite orbit with distance to the Earth atmosphere R the optical detector with field of view (FOV) Ψ will observe a large atmosphere area $S = (R/2 \tan \Psi/2)^2$ due to large distance R. Estimates of the energy threshold for observations from distance $R = 400 - 500\ km$ with the camera using the mirror of diameter $3\ m$ show that the threshold energy is of about 10^{19} eV. For threshold energy $E = 10^{19}\ eV$ the UHECR intensity is large enough for effective observations with a "telescope" of comparatively narrow FOV $\cong 15^0$. With this FOV the observed atmosphere area is $S = 10^4 km^2$ and the rate of UHECR events is thousands events per year even for a telescope duty cycle 20%. FOV of 15^0 is characteristic to a simple optics of the parabolic mirror "telescope". To make area S larger either FOV should be increased (more complicated optics for wide FOV detectors has to be developed) or a satellite orbit should be higher. These two options are 2 directions of the space UHECR detector development: 1. detectors of wide FOV type- OWL project (Streitmatter et al , 1998), EUSO project (Scarsi et al , 2000) and 2. detectors of "telescope" type (KLYPVE project (Alexandrov et al , 2000), the Kosmotepetl program (Khrenov and Panasyuk , 2001). In a telescope option the mirror area could be constructed larger than an aperture in the wide FOV option. With large telescope mirror area ($400 - 1000\ m^2$) particles of the highest energies of about $10^{21}\ eV$ could be studied from the orbit of height $R \simeq 36000 km$, in area $S \simeq 10^7 km^2$ (almost all area of the Earth disc), see (Khrenov and Panasyuk , 2001). We plan to start measurements with a small telescope prototype (the TUS project, mirror area $1.5\ m^2$) launched as an additional payload on one of the commercial satellites (Resurs DK1).

Experience in construction and operation of the TUS telescope will allow to design larger mirrors: of ten—hundreds m^2 area and to launch special devices to orbits of $R = 400 - 600\ km$ for study of UHECR of low energy threshold ($10^{19}\ eV$ for $S = 10 m^2$, $2 \cdot 10^{18}\ eV$ for $S = 400 m^2$). A search for neutrino of energy $\geq 2 \cdot 10^{18} eV$ generated in proton-"relic" photon interactions of energy $\geq 5 \cdot 10^{19} eV$ is of special interest.

2 Telescope parameters. Scientific goals

The TUS telescope on the Resurs DK1 satellite is shown in fig. 1.

The telescope consists of 2 main parts:1. the mirror—

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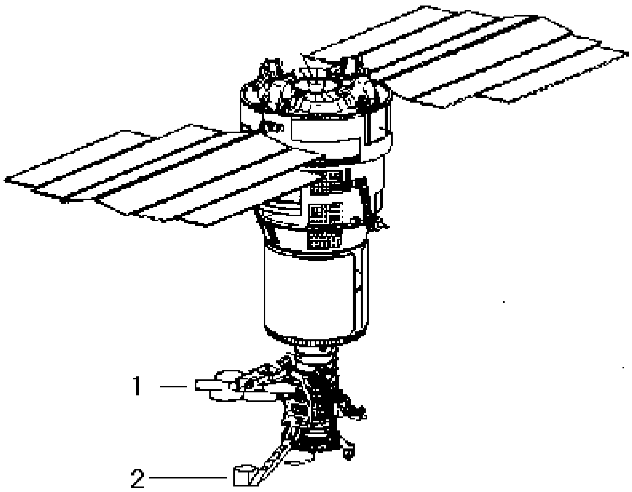

Fig. 1. The TUS telescope on the Resurs DK1 satellite.1- the telescope mirror, the photoreceiver retina

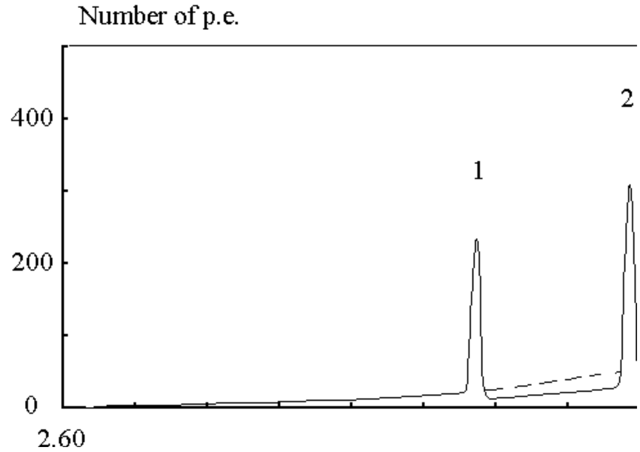

Fig. 2. Pixel signal from the flash backscattered light. Peaks are signals from: 1. upper semitransparent clouds, 2. regular clouds and 3. ground (sea).

concentrator of area 1.5 m^2 with focal distance 1.5 m and 2. the photoreceiver of 256 pixels in its focal plane. Pixels are photomultipliers (PM) with the light guides organising the uniform rectangular retina. Pixel size is 15 mm (angular size 10 mrad). The telescope has a rectangular FOV of 0.12x0.12 rad that corresponds to area in atmosphere of 42x42 km and pixel resolution of 3.5 km at the orbit perigee height (350 km) and to area 72x72 km and pixel resolution 6 km at its apogee height (600 km). Optical aberrations in this narrow FOV are small: a focal spot size is less than 0.3 of the pixel size. Signals from PM tubes go to electronic channels which are FADC with a sampling time intervals of 200 ns.

The movement of EAS particle disc initiated by a UHECR primary particle will be followed as movement of the fluorescent EAS disc image in retina of pixels. The angular image velocity measured in retina allows to determine the direction of the primary particle (when $\geq$ 2 pixels are "hit"). The EAS cascade curve will be measured by brightness of the spot along the track (in time intervals of one pixel signal—for vertical shower, or in time intervals and pixel addresses—for inclined showers).

The light noise of night atmosphere put an energy threshold for the observed UHECR events. The noise is suppressed by using the UV filter adjusted to the wavelength range of atmosphere fluorescence (310-420 nm). For this wavelength range an intensity of night atmosphere glow was measured from the satellite Kosmos 45, Lebedinsky et al (1965). It was $200 - 300 ph/m^2 nssr$ at moonless nights. For moon nights the moon scattered light intensity is expected to be in the range of $10^3 - 3 \cdot 10^4 ph/m^2 nssr$. RMS of the TUS telescope pixel photoelectron number σ in time $t = 12 \mu s$ of the pixel recording a horizontal track is expected to be $\sigma = 7$ p.e.- at moonless nights and $\sigma = 20 - 80$ p.e.- at moon nights. The TUS telescope is designed for operation as at moonless nights so at moon nights. The gain of the PM retina will be changed in several steps corresponding to the level of scattered moon light noise.

For inclined tracks (zenith angle $\geq 60^0$) the EAS maximum is above the cloud cover so that an EAS maximum signal is not obscured. The transparency of atmosphere above the clouds is high and the UHECR signal is practically not absorbed ($\geq 70\%$ of light signal escapes scattering). For near vertical tracks the light scattering (extinction) is essential. To control the atmosphere transparency and the height of clouds the backscattered light from the satellite flasher will be recorded. Every telescope pixel will receive the backscattered signal illustrated in fig. 2 (the flash covering the telescope FOV has energy $Q = 0.3 J$).

The level of signals "reflected" from clouds or ground will give information on the combined factor: atmosphere transperancy multiplied on cloud (ground) reflectivity. Continuos signal (which is much lower than the signal reflected from the cloud) will give straight data on the atmosphere scattering and instinction coefficient. Timing of peak signals gives the distance between clouds and the telescope (with accuracy better than 300 m– depending on the thickness of the cloud surface reflected the flasher light). For a known satellite height it gives the height of clouds in atmosphere. The flash will be triggered by the UHECR event in the telescope. In comparison of the arrival times of the UHECR maximum signal and of the EAS Cherenkov light scattered back from the cloud (ground) depth X_{max} in atmosphere of EAS maximum will be measured.

At moonless nights the UHECR energy threshold expected to be $2 \cdot 10^{19} eV$ (signal at the EAS maximum equal to $5\sigma =$ 35 p.e.). At moon nights it will rise to $7 \cdot 10^{19} - 2 \cdot 10^{20} eV$. A limited geometrical factor of the telescope and a steep UHECR energy spectrum put an upper limit to the expected highest energy event: $\simeq 10^{21} eV$. Thus the range of expected useful signals (in number of p.e.) is not large: from 7 p.e to $2 \cdot 10^3$ p.e. It allows to simplify the design of the pixel electronics. The operation of telescope not only at moonless nights put a difficult problem for the PM tube retina. As it was mentioned above it is solved by operation of PM tube

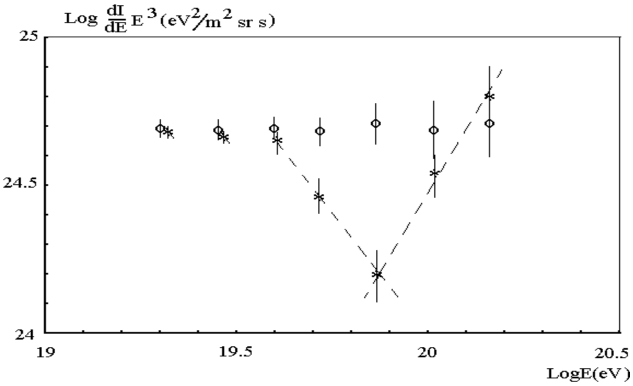

Fig. 3. Expected cosmic ray energy spectrum in 3 years of the TUS telescope operation. Crosses- the spectrum with a cut-off (solid line) and a new cosmic ray component (dashed line) as the AGASA data indicated. Open circles — the power law spectrum.

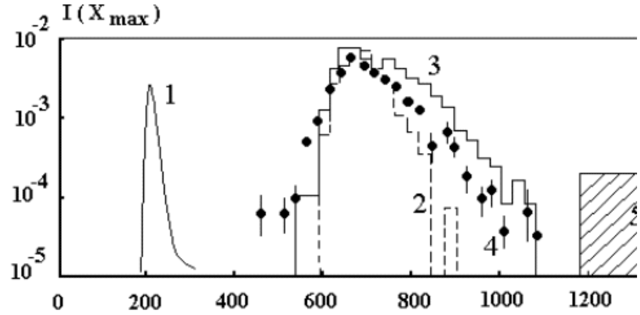

Fig. 4. X_{max} distribution expected for various primaries: 1- dust grains ($\gamma \simeq 10$), 2-iron nuclei, 3- protons, 4- Fly's Eye experimental data, 5- neutrino

with a variable gain. Operation at moon nights allows us to increase the duty cycle up to 25% for the highest energy events. In 3 years of operation the TUS telescope will have the exposure factor of $6 \cdot 10^3 km^2 sryear$ for the UHECR events with energy $\geq 2 \cdot 10^{20} eV$ and will register of about 20 events with this energy threshold (estimation from the AGASA data). Number of registered events of the lowest energy ($\geq 2 \cdot 10^{19} eV$) is expected to be $\simeq 900$ in the same period. With this statistics the first results on energy spectrum, on arrival direction of UHECR particles and composition of UHECR (as they were estimated in Alexandrov et al (2000), Khrenov and Panasyuk (2001) and Alexandrov et al (2001)) will be obtained. In fig 3 the energy spectrum expected in 3 years of the TUS telescope operation is presented. In the range of energies $5 \cdot 10^{19} eV - 2 \cdot 10^{20} eV$ the "GZK cut off" could be revealed due to a high energy resolution of the telescope and a sufficient event statistics.

The X_{max} distribution is of special interest as it may reveal new primary components: neutrino and a dust grain with a low Lorenz factor (Bingham and Tsytovich , 1999). In fig. 4 the expected X_{max} distribution of cosmic ray particles (central block of curves) is accompanied by X_{max} distribution of EAS initiated by dust grains ($X_{max} \simeq 200 g/cm^2$) and EAS from neutrinos ($X_{max} \geq 1500 g/cm^2$).

3 Telescope instrumentation

The main purpose of the TUS experiment is a testing of the space telescope design. The following design features are specially important: stability of the mirror parameters in wide range of temperature ($\pm 150^0$C), uniformity of the pixel retina operating in wide range of noise, low energy consumption of pixel retina with a large number of pixels, stability of the trigger system operating in various local noise conditions (city lights, thunderstorms etc), control of triggering system in analysis of the recorded events.

In the TUS telescope a mirror surface is made on the carbon plastic material mechanically stable in the above range of temperature. It was proved that polishing of carbon is of high quality. The mirror will be done as a segmented Fresnel mirror (Alexandrov et al , 2000) packed in transportation mode.

The TUS telescope electronics was designed as a prototype of a larger telescope electronics, Garipov (2001). Photoreceiver pixels are clustered in lines of the orthogonal retina. In the TUS telescope the number of pixels in a cluster is 16. Hamamatsu PM tube R1463 (multialcali cathode, 13 mm diameter) was chosen for the pixel. It was proved that it operates linearly in various noise conditions of the TUS experiment. For the tube voltage supply a schematic was developed (a common divider is used for a cluster of tubes) that able to keep the tube gain uniform (deviation from a standard gain less than 10%) throughout all retina in the gain range $3 \cdot 10^3 - 3 \cdot 10^5$. In fig.5 schematics of the PM tube cluster voltage supply is shown. In every tube a gain and a slope of voltage-gain relation are adjusted to a "standard tube" by variable resistors. The tube gain in the cluster is controlled by HV_{var} voltage. Every pixel gain is measured during an operation, see Garipov (2001).

Data from PM tubes go in parallel to the FADC channels and to the triggering system. In the FADC channels a multiplexer for every 4 channels is used operating with frequency 20 MHz so that one ADC is used for 4 channels. 8-bit ADC in samples of 200 ns allows to have a needed signal dynamic range for a fluorescence signal time intervals of about $10 \mu s$. FIFO memory keeps the data from every channel during $500 \mu s$. By a trigger signal the data from FIFOs in the time interval around the time of triggered pixels ($\pm 50 \mu s$) go to the TUS computer.

In trigger system the parameters defining the "signal finding algorithm" are controlled from the mission center. The signal finding algorithm operates in two stages. At the 1-st stage a signal is integrated in a controlled time interval $\triangle t$ and events with the signal above a threshold level are selected. In the chosen economical variant of the integration mode an integration is performed in digital form as is shown in fig.6.

An analog signal integrated at a PM tube output with integration time $1 \mu s$ goes to the circuit presented in upper part of fig.6 where it is compared with the signal preceded it by

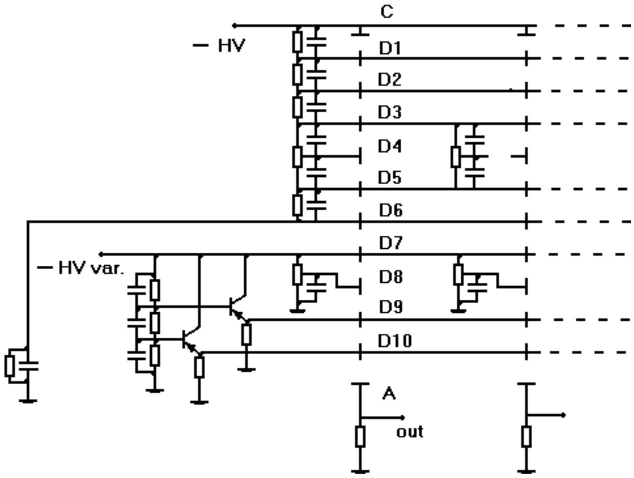

Fig. 5. Diagram of the voltage supply for a PM tube cluster

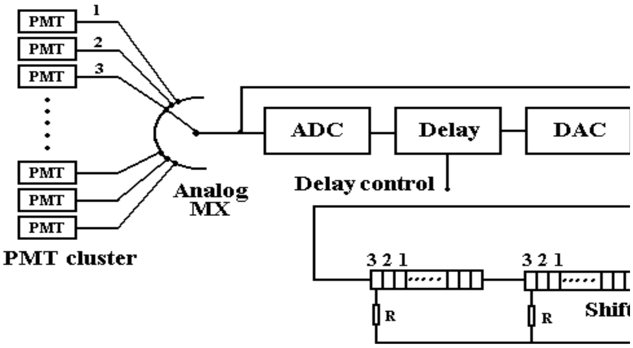

Fig. 6. Diagram of the first stage trigger system

time $\triangle t$ (delay in fig.6). The result of comparison goes to the comparator with a controlled threshold "1". The comparator produces signals "0" (signal below threshold) or "1" (signal above threshold). Digit signals from the comparator are sampled with a controlled frequency F ($F \leq 1$ MHz) and then counted in time interval $\triangle t$. If the number of digits in interval $\triangle t$ is higher than number "N" (threshold "2" in fig.6) the 1-st stage trigger signal goes to the second stage– the triggered pixel map. The use of multiplexer allows to apply one "integration" cirquit for all pixels in the cluster. Such a digitised integration circuit is economical in power consumption. A feature of comparatively large "length in time" of the fluorescent track is used for selection of true events: N repetitions of signals "1" inside time interval $\triangle t$ highly suppresses the noise. Choice of parameters of the trigger in the 1-st stage will depend on experience of the telescope operation in space. In the first approximation they are: $\triangle t = 12$ μs (equal to duration of horizontal track in one pixel) and $F = 1MHz$. With those parameters given the number N determines the rate of accident triggers.

In the 2-nd trigger stage a map of "hit" pixels is considered. The most liberal condition of triggering at the 2-nd stage is a triggering by 1 or more hit pixels. With this condition the accident trigger rate may be above the limit of the data acquisition system. At the same time UHECR events with a single hit pixel have no data on the track direction (one pixel events are expected to be near vertical tracks). Thus a selection of events with number "n" of neighbour hit pixel $n \geq 2$ is preferable. Final trigger condition at the 2-nd stage will be chosen in correspondence to noise conditions in space. Schematics for the FADC channels, triggering system and data acquisition were developed with a low energy consumption. ADC (Analog Device), FIFO (Cypress) and a re-programmable chips of Xilinx type with low current were chosen for the circuitry. The designed PM tube voltage supply for 256 pixels consume less than 10 Wt . All electronics of the TUS telescope in operation mode will consume not more than 50 Wt.

The TUS telescope data flow is restricted to be not more than 100 MB/day. Telescope data will go to the mission center via the fast Resurs DK1 duplex transmission line (commands for control of the telescope operation are available). The useful UHECR data stream is low: at night time (during $\simeq 6$ hours per day) the expected rate of useful UHECR events is not more than 1 per hour. At every trigger the data from all pixels with the data volume of about 0.3 MB are sent to the mission center. The data on backscattered light from a flasher (triggered after every event) add the same volume of data. Thus the full data per trigger are of 0.6 MB. With the above restriction on the data flow the accidental triggering should not exceed the rate of 30 per hour. It is 30 times higher than the rate of UHECR events. With this ratio of accidental to true events the selection of useful UHECR events will be done with a high efficiency.

The TUS project is in the R & D stage that has to be finished in 2001.

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