Optics development of ultra high energy cosmic rays detector KLYPVE on-board ISS

S.A. SHARAKIN[1], V. BATSHEV[2], B.A. KHRENOV[1], P.A. KLIMOV[1], I.V. YASHIN[1]

[1] *Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow, Russia*
[2] *Bauman Moscow State Technical University, Moscow, Russia*

sharakin@mail.ru

Abstract: High energy cosmic rays detection from low earth orbit (for example TUS and JEM-EUSO projects) requires development of special optic systems (OS). Characteristics of these OS largely differ from astronomical cosmic telescope ones: wider field of view, relatively lower angular resolution, a few numbers of optic components. New Russian project on board of International Space Station - KLYPVE - aims to spectral measurements of transient luminous events as well. In this paper we offer one (generalized Davies-Cotton systems) and two components OS allowing to realize such multipurpose research

Keywords: Optics, KLYPVE, space detector, UHECR.

1 Introduction

Ultra high energy cosmic ray (UHECR[1]) study by registration of fluorescence signal from Extensive Air Shower (EAS) has both the own *history* - fluorescence detectors Fly's Eye and HiRes, and the *present* - ones at AUGER and Telescope Array. All these detectors operate at ground looking up to the atmosphere (really looking aside at elevation angles 0-30°). The *future* of this method is associated with the imposition of the instruments into the earth orbit: for UHECR physics the most important parameter of the fluorescence detector is area of the atmosphere covered by observation. It determines statistics of the highest energy events and today it is too small for obtaining final results on origin of UHECR. Larger area of the atmosphere covered by fluorescence detectors could be achieved by detectors looking down to the atmosphere from satellite board. In this case fluorescence detector operates as a Space Cosmic Rays Telescope (SCRT) covering by one instrument area of tens thousands of square km in the atmosphere from orbit heights 400–500 km. Nowadays the original idea of Linsley [1] has being developed into projects of cosmic rays telescopes for International Space Station (ISS): JEM-EUSO - to be installed on the Japanese experimental module [2] and KLYPVE - on the Russian ISS segment.

SCRT is not the "astronomical" type of telescope although the main telescope conception remains valid: it is used for observation of remote weak signal. Object of observation is moving disc of charged particles generated by UHECR in the Earth atmosphere: the charged particles ionize and excite molecules of atmosphere which radiate "fluorescence" in tens of nanoseconds in near UV band of wavelengths (300–400 nm). Typical size of EAS disc are: transverse diameter ~ 1 km, thickness ~ 0.1 km, EAS length - 20–100 km (depending on EAS zenith angle), and the fluorescence light can be observed from large distance as a point source moving in the atmosphere with light velocity. So the main components of SCRT - Optic System and Photo Detector - should have sufficiently high angular and temporal resolutions.

In UHECR experiment "high" angular resolution is determined as accuracy resolving dimensions of source (0.1–1 km) from distance to telescope of 400–500 km, i.e. accuracy has to be better than 1 mrad (3–4 minutes of arc). This accuracy is much higher than already achieved in ground based fluorescence detectors (~ 30 minutes of arc) but is very rough to compare with astronomical telescopes (cf. with 0.5 seconds of arc of the Large Synoptic Survey Telescope). Telescope field of view (FoV) has to cover at least one full event with length in atmosphere of about 50 km (angular length ~ 0.1 rad $\sim 6°$).

Design of SCRT optics should meet the following requirements.

1. Optical systems must be composed of minimal element number, typically one or two. In this case it is easier to minimize light losses and to adjust optical elements and photo receiver in space (automatically or manually by astronaut).

2. It should have very large primary concentrator with entrance pupil diameter $D = 3$–5 m as efficient EAS signal collector ($D = 3.6$ m for KLYPVE SCRT and $D = 1.6$ m for its prototype TUS detector, see below).

3. The relative aperture ($A = D/f$, f - focal distance) should be near 1 ("fast optics") because of constrains to photo receiver size and pixels number.

4. It should have a wide FoV ($\pm 5°$ for UHECR threshold energies of about 10–20 EeV and $\pm 30°$ - for the higest energies > 100 EeV) for reasons of high UHECR statistics.

5. The angular resolution could be several minutes which corresponds to spatial resolution of about 1–2 km in the atmosphere near the Earth surface.

Optic System of SCRT can be developed in two designs: a) telescope-reflector as in KLYPVE project and b) telescope-refractor as in JEM-EUSO.

Reflector optics has advantage of a priori large aperture due to construction simplicity of one mirror light collector in space. Large aperture allows to start UHECR measurement with lower energy threshold. Narrow FoV of one mirror optics is compensated by high statistics of cosmic ray

1. primary particles with energy more than 50 EeV $= 5 \cdot 10^{19}$ eV

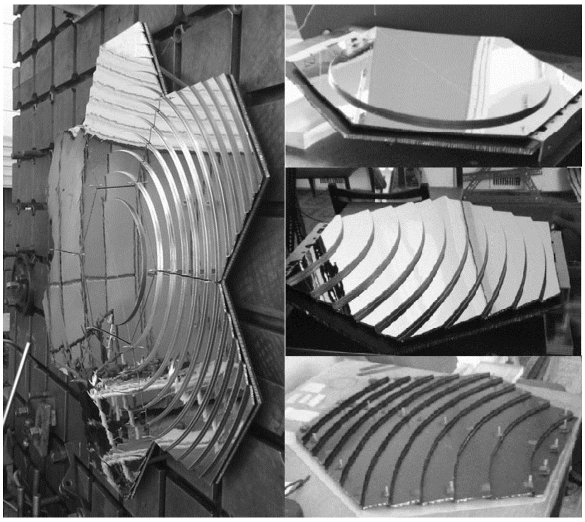

Figure 1: Fresnel mirror of TUS. Right: central segment, one of 6 peripherial segments and its rear surface.

particles at energies close to threshold. On the other hand telescope-refractor optics with less aperture has advantage of a priori wider FoV. In JEM-EUSO wide FoV of $\pm 30^\circ$ allows to observe the atmosphere area 10^5 km^2 needed for UHECR research at energies more than 100 EeV.

2 Pathfinder and OS technical characteristics

The first orbital detector of ultra high energy cosmic rays TUS is prepared now in Russia to be launched on board Lomonosov satellite in 2013 [3]. TUS optical system is a composite (segmented) mirror-concentrator and it consists of one central and six peripheral segments (figure 1, see also [4]). Each segment has hexagon shape. Mirror profile is designed as sum of paraboloids of revolution (with common axis - the main OS axis), projected to the mounting plane. Thus, it is kind of mirror analog of a Fresnel lens (called below as Fresnel mirror) with different radiuses of curvature of each ring correspondent to ideal on-axis focusing (without aberrations). Within one ring its height is fixed and is equal to 1 cm. Fresnel mirror has small total height, which is mostly determined by multilayer carbon plastic structure and presence of bearing surface. Its optical characteristics are similar to ideal paraboloid (within $\pm 4^\circ$ FoV). Side of each segment is equal to 33 cm, an approximate diameter of mirror is $D = 160$ cm. Focal distance is $f = 150$ cm, so the relative aperture is $A = D/f = 1.1$.

TUS detector is a pathfinder for UHECR detector because of its narrow FoV and small mirror size. In 2011, D. V. Skobeltsyn Institute of Nuclear Physics of Moscow State University was initiated preliminary design stage of reflector type SCRT for UHECR measurements from ISS board - detector KLYPVE. It will be located on outer side of Russian ISS segement. The main KLYPVE element is a segmented optical system with large entrance pupil diameter. All parts of telescope have to be transported to ISS by Progress-TM vehicle. It means that dimensions of telescope parts have to be smaller than 60×120 cm. There are also limits for focal distance (4 m) and diameter of the main mirror (3.6 m).

Multicomponent models of optical telescopes were developed before in astronomy, but their manufacturing, delivery to the orbit and further deployment in the open space meet several difficulties. To obtain the large concentrator ones have to fabricate separate segments and components, to assemble them into optical system and adjust it with respect to the photo receiver in open space automatically or by astronaut. Therefore the design should be limited by one or two component optical systems.

Technical characteristics of KLYPVE optical system are the following:

1. OS consists of one primary mirror or from two components (primary mirror and corrective lens).
2. Whole mirror diameter is 360 cm.
3. Overall length of OS is not more than 400 cm.
4. Field of View (half angle) is 7–8 degrees.
5. Image size of point like object should be less than photo receiver pixel (15 mm).
6. Focal photo receiver is flat with diameter less than 120 cm.

3 Generalized Davies-Cotton systems

Generally, corrective optics means additional optical elements: corrective mirror or lens. But there is another possibility to improve the image quality in a wide range of field angles – to use additional *degrees of freedom* of the mirror-concentrator itself. It is possible if we make mirror *gross surface* and its *reflective surface* not identical to each other. In these terms the gross surface means surface which determines the total shape of concentrator and reflective surface determines the normal direction in each surface point. So, in the ray tracing the points of reflection lie on the gross surface, but the ray slewing is given by reflective surface. (In fact, TUS Fresnel-type mirror is an example of such "extra degree of freedom" system where the gross surface is flat and reflective surface is represented by the ring structure of paraboloids.)

One of the most well-known examples of this approach is a Davies-Cotton System [5]: the gross surface is a sphere with radius f (f - effective focal distance), but normal of the reflective surface converge at a point, located at a distance $2f$ from the pole. Originally Davies-Cotton systems were developed as solar concentrators, but recently they have been widely used in gamma astrophysics - as the atmospheric Cherenkov telescopes (ACT) [6].

Despite the fact that the bearing surface is a sphere, an additional degree of freedom allows the system to be aberration-free on the axis, as in the case of an ideal parabolic mirror. Davies-Cotton system are used in ACT (for example, H.E.S.S. [7] and Small Size Telescope CTA [8]) because for larger incidence angles this design outperforms the parabolic configuration.

Such OS with two degrees of freedom could not be obtained in class of smooth continuous surfaces, it means that mirror surface has to be with breaks. In the ground based telescopes with Davies-Cotton system it is achieved by a tessellated concentrator. Separate (more often, spherical) mirrors of relatively small size are mounted on the supporting structure so, that center of each mirror situated on the gross surface.

The tessellated structure appears due to economical considerations and the size of each spherical mirror is selected based on the optimization of two factors: focusing quality and total cost of mosaic. In case of SCRT the number of segments and additional work outside ISS should be minimized. Mosaic structure is not suitable for space work and the most acceptable variant of manufacture is axisymmetric: the whole mirror or its large parts (segments) are produced in the form of an annular surface, similar to Fresnel mirror of TUS. But, unlike the TUS mirror, the gross surface can be arbitrary, and not just flat.

Thus, choosing a rather general parametric class for the reference surface and profiles of individual rings, it is possible to select them minimizing the size of image in the focal plane for entire FoV or for any part of its.

We have performed the study in a class of surfaces of conic sections revolution, two-parameter family: R - surface radius of curvature in pole, δ - conic constant. Entrance pupil (with diameter 360 cm) was divided into 11 annular zones, with approximately equal cross section area. The inner edge of each annular zone was beard on the corresponding point on the gross surface. Reflective surfaces of all rings were taken spherical and their radii of curvatures were optimized. The RMSr for 5° incidence angle was taken as a Merit Function.

The parameters of the optimized solution for the system with the relative aperture $A = 0.9$ (i.e. $f = 400$ cm) and its spot size can be found in [9]. Here we only note that the radius of curvature and conic constant of gross surface for this system are 350 cm and -0.5, similar elliptic telescope design was presented early in [10].

This approach allows to expand the FoV up to ±4–5°. But in this case the difficulties with constructional depth arise. The overall height of such system is about 45 cm, while the same parameter for paraboloid is 20 cm, and for classical Davies-Cotton scheme - 40 cm. There are difficulties with these dimensions not only during segments manufacturing stage, but also in a process of their delivery to the orbit. Moreover, this complicated three dimensional system needs the deployment of special large supporting construction.

4 Catadioptric systems

After modeling the one component system it becomes obvious that it is not suitable for KLYPVE project for two reasons: narrow FoV and complicated engineering design. And at the next stage the two component catadioptric systems were investigated. In this case besides the primary mirror the flat Fresnel lens is placed near photo receiver, figure 2. It is important to emphasize that the lens is attached *near* the front surface of the photo detector, because it allows to simplify adjustments of separate components of OS, to reduce the requirements for manufacturing precision and significantly decrease chromatic aberrations. In this scheme lens acts mostly as a *light guide* rather than a real corrective lens.

Fresnel lenses are the main part of JEM-EUSO optical system. Its baseline version consists of three curved double-sided Fresnel lenses Poly Methyl Methacrylate (PMMA) material (Mitsubishi Rayon Co., Ltd. product). It is used PMMA material that is more suitable for the near UV ("PMMA-000" grade). It has good UV transmittance (more than 90% for 15 mm thickness layer at wavelength more than 320 nm), refractive index about 1.51 and has been used

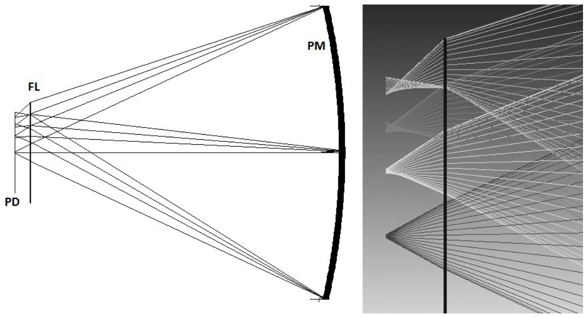

Figure 2: Catadioptric system: PM - primary mirror, FL - Fresnel lens, PD - focal plane of the Photo Detector. Ray tracing through FL is represented at the left (for 0°, 3°, 5° and 7° filed angles).

in space on many occasions. In 2011 The Ohmori Laboratory of the RIKEN Advanced Science Institute (Japan) has done the Bread Board Model manufacturing of the central part of the lenses that has 1.5 m diameter and 10 mm thickness [11]. These lenses have grooves with 1 mm height and a width varying from 50 to 1 mm. Less dimensions of grooves leads to a significant light scattering on the peripheral parts of the lens.

Therefore, as the initial parameters (requirements) of the lens in this project were selected the following:

Material - PMMA-000 (1.20 density g/cm^3).

Thickness - 10 mm.

Grooving height - 1 mm and width - more than 1 mm.

Diameter - no more than 150 cm.

Distance from the lens to photo receiver - no more than 30 cm.

The last parameter was taken 20 cm and the optimization study was carried out in which the remaining parameters of OS were selected: mirror radius of curvature in the pole R_m, and its conic constant δ_m, the same parameters for profile of lens, number of grooves and their sizes. The parameters of one of such optimized OS are shown in the first raw of Table 1 (for spherical grooves applied on one side of flat lens, the second side is smooth). Minimum and maximum groove's width (with 1 mm height) equal to 44.7 and 1.3 mm. The image size for various angles is given in Table 2.

R_m, cm	δ_m	R_f, cm	δ_f	# of grv.	D_L/D_{PD}, cm
807.6	-1	100.0	0	216	124 / 100
608.6	-1	100.0	0	177	113 / 82

Table 1: Primary Mirror and one-side Fresnel Lens characteristics: R_m and δ_m - curvature radius and conic constant of the mirror, R_f and δ_f - corresponding values for Fresnel facet shape, overall number of grooves, lens' diameter and diameter of focal plane if 7° maximum field angle is selected.

As we can see this OS model allows expanding the FoV up to 6–7°, while the image RMSr maintains within one photo receiver pixel. The diameter of the obtained lens is 124 cm. Primary mirror-concentrator has paroboloid shape ($\delta_m = -1$) with focal distance $f_m = R_m/2 = 402.5$ cm, which is exceeds the distance between the mirror pole and focal plane (400 cm).

	RMSr	RMSx	RMSy	R_{70}	R_{90}
$\gamma = 0°$	3.7	2.6	2.6	3.9	4.4
$\gamma = 3°$	6.0	3.8	4.7	5.6	9.1
$\gamma = 5°$	9.5	5.1	8.0	8.3	12.6
$\gamma = 7°$	14.2	6.5	12.6	10.9	21.5

Table 2: Spot radiuses in mm at different field angles (0°, 3°, 5°, 7°) for long-focus sytem with $f = 400$ cm. In addition to the mean-square radii the radii of the spot with 70% and 90% of energy are given in two last columns.

There were considered more general models with a nonparabloic primary mirror and/or aspheric profile of Fresnel facet shape. In all these cases it is possible to achieve insignificant improving of focusing characteristics of OS but with substantial complication of manufacturing. The radius of curvature (R_f) decreasing leads to that grooves width at the edge becomes less than 1 mm, and it strongly reduces optic throughput.

SINP MSU have started new stage of KLYPVE design in 2013. And our designers from TSNIIMASH (Korolev) put some new demands on detector construction, and one of them was to reduce the overall length of the optical system deployable on ISS. The new OS maximal length is 300 cm, so we have to recalculate our models from effective focal length 400 cm to 300 cm. And this is not simple work from optical point of view because it corespondes to changing the relative aperture up to $A = 1.2$. Our prelimenary simulation concludes that one components system (generalised Davies-Cotton) does not suitable in that case - off-axis aberration (mainly *coma* which increases as $\sim A^2$) will be larger than pixel size of KLYPVE photo detector even at 3° field angle. But the catadioptric system is more *tunable* and similar two-component system can be obtain by optimization procedure. The parameters of that short-focus system and spot size characteristics represented in the second raw of Table 1 and in the Table 3 respectively. The diameters of Fresnel lens and photodetector (if 7° maximum field angle is selected) reduce to 113 and 82 cm, minimum groove's width is 1.5 mm.

	RMSr	RMSx	RMSy	R_{70}	R_{90}
$\gamma = 0°$	4.3	3.0	3.0	5.3	5.7
$\gamma = 3°$	7.9	4.8	6.3	8.7	10.7
$\gamma = 5°$	12.4	6.8	10.4	12.4	14.3
$\gamma = 7°$	18.0	8.8	15.7	16.1	25.5

Table 3: Spot radiuses in mm at different field angles (0°, 3°, 5°, 7°) for short-focus sytem with $f = 300$ cm. The same characteristics as in the prevous table are presented.

5 Conclusions

We considered one and two component optical systems for SCRT with 360 cm entrance pupil diameter and 400 cm and 300 cm focal distance (long- and short-focus systems). The main purpose of this study is FoV increasing from 3–4° (using just parabolic system) to 7–8° which is necessary for UHECR measurements with high statistics.

In the case of generalized Davies-Cotton model (one component OS) the concentrator structure is not continuous (it has mosaic or ring structure) but it allows applying additional degrees of freedom. The maximum angle at which the signal from distant object is focused in a single photo receiver pixel (15×15 mm) is 4–5° for long-focus system. But this solution can't be apply to short-focus case.

To increase a FoV up to 5–6° and significantly simplify primary mirror construction is possible using two component system. The spot size ($2\sqrt{\text{RMSx} \times \text{RMSy}}$) for field angle 7° is 18 mm, and in the center of FoV - 5 mm. The corrective Fresnel lens is used in this case, mounted close to the focal plane of photo receiver (for the present variant in the 20 cm). The mirror represents the paraboloid of revolution with the focal distance of paraboloid is 403.8 cm for long-focus and 304.4 for short-focus system and relatively small overall height (~ 20 cm). Flat Fresnel lens has about 110–120 cm diameter, grooves with 1 mm height and variable width (1.5–45 mm).

It is important to emphasize that using of large concentrator (≈ 10 m^2 in KLYPVE project) allow to study not only UHECR, but also to provide spectroscopic measurements of Transient Luminous Events (TLE), see [12]. A number of photo receiver pixels is planned to replace by a bunch of fiber light guides, which transfer focused light to a multi anode PMT with 15–20 filters for various spectroscopic channels. These measurements with high temporal and spatial resolution are very important for understanding the nature of TLE and physical processes during the discharge.

So, the KLYPVE is a complex instrument which is designed as a wide angle space cosmic rays detector for UHECR measurements and sensitive spectroscope with high space-time resolution for TLE study for near-Earth orbit.

References

[1] J. Linsley, R. Benson, 17th ICRC Proc. Paris 8 (1981) 145.
[2] Andrea Santangelo, 33d ICRC Proc. Rio De Janeiro (2013) ID0738.
[3] A.M. Amelushkin et al., 33d ICRC Proc. Rio De Janeiro (2013) ID 0339.
[4] A. Tkachenko, A. Grinyuk et al., 33d ICRC Proc. Rio De Janeiro (2013) ID 0423.
[5] D.A. Lewis, Exper. Astronomy 1 (1990) 213–236.
[6] V. Vassiliev, S. Fegan, and P. Brousseau, Astropart. Phys. 28 (2005) 10–27.
[7] K. Bernlohr, O. Carrol, R. Cornils et al., Astropart. Phys. 20(2) (2003) 111–128.
[8] The CTA Consortium, Experimental Astronomy 32 (2011) 193–316.
[9] S.A. Sharakin, B.A. Khrenov, P.A. Klimov et al., Proc. of SPIE 8443 (2012) 84433W-1–84433W-11.
[10] A. Schliesser, R. Mirzoyan, Astropart. Phys. 24 (2005) 382–390.
[11] Y. Hachisu, N. Tone, Y. Uehara, 32d ICRC Proc. Bejin 3 (2011) 179–182.
[12] V.S. Morozenko et al., 33d ICRC Proc. Rio De Janeiro (2013) ID 0519.