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Modeling of optical concentrators for the upgraded camera of the TAIGA-IACT Cherenkov gamma-ray telescope

© A.S. Antonov, A.A. Bogdanov, A.M. Krassiltchikov, E.E. Kholupenko

Ioffe Institute,
194021 St. Petersburg, Russia
e-mail: andrey.s.antonov@gmail.com

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A quantitative simulation of a system of optical concentrators based on Winston's hexagonal cones, intended for the registration camera of the TAIGA-IACT Cherenkov gamma-ray telescope, has been performed. The data on the transmission of the cones are obtained; the distributions of the photon flux intensity in the plane of the detector are given. On the basis of the results obtained, an optimal configuration of optical concentrators is proposed, taking into account the design features of the mount, mirror and TAIGA-IACT camera, as well as the features of its new detector units.

Keywords: Cherenkov gamma-ray telescope, TAIGA-IACT, Winston cone, numerical simulation.

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Introduction

Currently, Cherenkov gamma-telescopes are the main type of astronomical instruments in the energy range above 0.1 TeV. Having quite a significant ($\sim 10^4-10^5$ m^2) effective detection area, they allow measuring sufficiently weak flows of teravolt gamma-radiation from a number of cosmic sources (see, for example, [1,2]). Such a large detection area is due to the fact that the observation is carried out not by a direct technique, but by registering the Cherenkov radiation of electrons and positrons of extensive air showers (EAS) initiated by primary cosmic gamma-quanta when interacting with the Earth's atmosphere. The typical transverse size of the EAS is about 200–500 m. The large detection area and relatively low cost of Cherenkov gamma-telescopes provide such significant competitive advantages that, most likely, in the foreseeable future they will remain the main instruments of gamma-astronomy in the energy range above 0.1 TeV. The projects of the Cherenkov telescopes of the new (IV) generation [3,4] are in the active phase, and the existing Cherenkov telescopes of the third generation are constantly being upgraded [5,6].

Starting in 2019, a project aimed at upgrading the Cherenkov gamma-telescope TAIGA-IACT is being implemented at the Ioffe Institute of Physics and Technology (NIIYaF MGU, Irkutsk University) [7,8]. The main goal of the project — is to develop new detector clusters for the TAIGA-IACT camera based on silicon photomultipliers (SiPM), which will increase the efficiency of this telescope by reducing the threshold energy of observations, increasing the duty cycle duration, etc. [9–11].

The detector chambers of Cherenkov gamma-telescopes usually consist of several hundred photomultiplier tubes (PMT) [12,13], each of which is equipped with a light concentrator (usually a Winston cone) that performs several functions [14,15], such as:

1) the transition from the pixel size, which is determined by the size of the focal plane area where the Cherenkov EAS flash is formed, and the number of camera pixels, to the size of the input window of the selected photocell, i.e., in fact, the implementation of an additional concentration of photons of the useful signal;

2) the transition from the pixel shape (usually a hexagon), which should ensure that the detector plane is filled without gaps and overlays in order to reduce the area of the „dead" (non-registering) camera areas, to the shape of the input window of the selected photocell (in the case of a traditional vacuum PMT, as a rule, a circle); 3) reduction of the background noise of photons from sources located on the earth's surface and the background of photons of the night sky reflected from the earth's surface. This device is an off-axis paraboloid of rotation and collects a set of rays, allowing off-axis rays to carry out repeated reflections when passing from the input aperture to the output.

Currently, the camera of the TAIGA-IACT telescope uses cones with windows in the form of regular hexagons, the size of the output window is about 14.8 mm (the diameter of the inscribed circle), which corresponds to the size of 15 mm round input PMT windows XP1911 [16]. The modernization plan for this camera involves the use of an assembly of four SiPM OnSemi MicroFJ-60035 with a square-shaped output window with a size of about 12.8 mm [9] as photocells. Such differences may require the development of new light concentrators. In order to assess the degree of necessity and the scale of changes in the design of light concentrators (Winston cones) for the upgraded TAIGA-IACT camera compared to those currently used, a preliminary modelling of Winston cones was carried

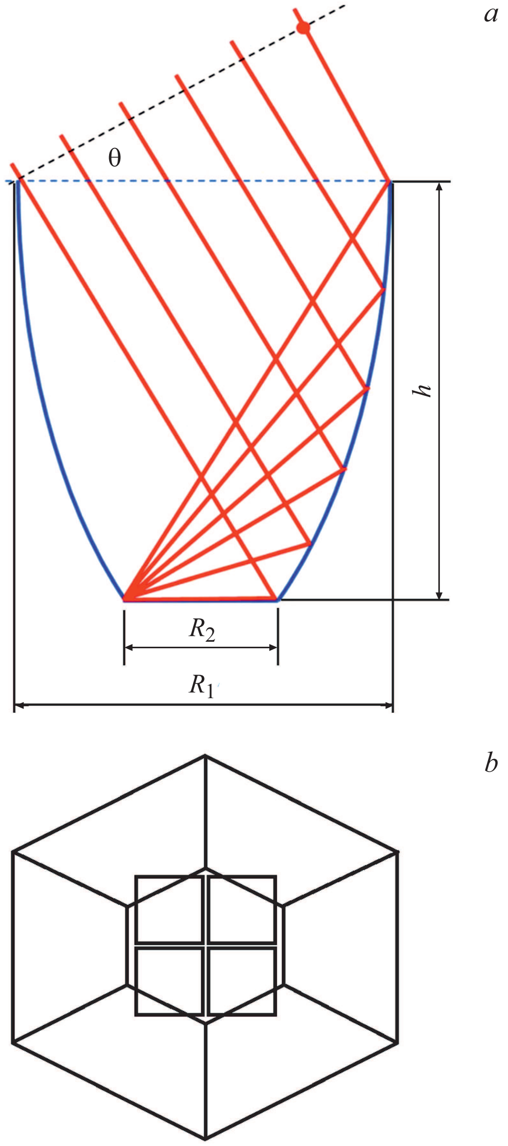

Figure 1. Winston cone diagram; *a* — side view [18], *b* — top view. The squares indicate the position of the detectors.

out using the ZEMAX [17] package. This paper presents the results of this modelling.

1. Problem formulation

The main characteristic of the Winston cone is the viewing angle θ, equal to the angle of inclination of the axis of the parabola to the axis of the cone (Figure 1). This value, on the one hand, determines the transmission area of the cone in the space of corners, and on the other — the ratio of the areas of the input and output windows.

In this paper, we consider a simplified (polygonal) construction of cones consisting of a set of parabolic surfaces; thus, the inlet and outlet openings of the cones are polygons. Figure 2 shows a general view of a prototype of a hexagonal Winston cone with a reflective film applied to the inner surface, manufactured for the new TAIGA camera.

Based on the requirements for the design of the telescope registration chamber for numerical modelling, hexagonal Winston cones were selected, which in their characteristics are close to the ideal case of a paraboloid of rotation. The calculations given in the study [19] showed that the transmission of the Winston hexagonal cone practically does not differ from its axisymmetric counterpart at cone angles of about 30 degrees or more. The transmission of a cone means the percentage ratio of the number of photons that have passed through the cone to the number of photons that have entered the input window of the cone.

Numerical modelling was carried out in the ZEMAX software package designed for calculations of optical systems and optoelectronic devices. To calculate the problems of geometric optics, this package employs ray tracing using the Monte-Carlo procedure, the essence of which is to track the trajectory of rays and calculate interactions with objects lying on the trajectories. Modelling of Winston cones was carried out in the mode of inconsistent ray tracing, which implies that rays can hit any surface of any object in an arbitrary sequence, can hit the same object several times or not at all. In the modelling process, the trajectories of the movement of light rays in the optical concentrator system were calculated, taking into account the reflection from the inner surfaces of the cone. Prior to conducting numerical modelling for the optical concentrator system, a technical specification was drawn up, according to which the reflection coefficient of the inner surface of Winston cones should be at least 0.95 in the wavelength range of 300–700 nm. This value was used in the modelling.

The numerical model included a parabolic telescope mirror, a single Winston cone, and a set of 4 detectors

Figure 2. Prototypes of Winston hexagonal cones with a reflective film applied to the inner surface.

Table 1. Geometric parameters of Winston cones with different angles θ

Parameters	$\theta = 26.56^\circ$	$\theta = 30.00^\circ$	$\theta = 35.00^\circ$
R_1, mm	15	15	15
R_2, mm	6.50	7.50	8.60
h, mm	44.77	38.97	33.70
Distance to detectors, mm	1	1	1

located at the cone's output window (Figure 2). The geometrical parameters of the telescope mirror were taken as follows: the mirror radius — 2.16 m, focal length — 4.75 mb. The geometric parameters of the cones are given in Table 1. Each of the 4 detectors has the shape of a square with a side of 6.13 mm, the centers of the detectors are located in the corners of the square with a side of 6.33 mm.

When determining the geometric parameters of the cone, the following relations were used:

$$\frac{R_2}{R_1} = \sin\theta,$$

$$h = \frac{R_1 + R_2}{\operatorname{tg}\theta},$$

where R_1 and R_2 — the radii of the inscribed circle for the input and output windows, respectively, θ — the angle of the cone, h — the height of the cone (Figure 1).

2. Results of the numerical modelling

3 options of the cone design were considered, differing in the angle θ, the value of which was taken to be equal to 26.56, 30 and 35 degrees, respectively. In particular, for the case $\theta = 30.00^\circ$, the ratio of the areas of the input and output window of the cone is 4. Thus, theoretically, the flow of recorded photons using Winston cones and a given detector surface area can also be increased by 4 times. However, in practice, this value may be significantly less than - due to various kinds of photon losses, such as losses in reflection from the cone surfaces, as well as losses due to the imperfection of the cone. The numerically found transmission function for a cone with $\theta = 30.00^\circ$ is shown in Figure 4. This function is the ratio of the number of photons passing through the cone to the number of photons hitting the input surface of the cone at a fixed angle of inclination of the photon trajectory to the axis of the cone θ'. When constructing this dependence, numerical modelling of 10 000 000 photon trajectories was performed. The resulting transmission function, in particular, shows the effectiveness of suppression of the background noise of photons (for the angles of inclination of the photon trajectory to the axis of the cone $\theta' > \theta = 30.00^\circ$).

Based on the modelling results, the angular pixel size of the telescope mirror system and a single cone was determined, representing an area on the celestial sphere in the form of a hexagon with an angular radius of an inscribed circle $10.8'$.

In the process of numerical modelling, photons started from the plane *2*, indicated in Figure 3, in the direction of the telescope mirror with a uniform distribution in the coordinate space inside the area bounded by a circle with a radius equal to the radius of the telescope mirror, and in the space of angles inside the area bounded by a circle with an angular radius of $10.8'$. This value corresponds to the found angular pixel size of the telescope mirror system and a single cone.

The detectors were located at a distance of 1 mm from the output window of the cone, which allowed to minimize signal loss.

Due to the imperfection of the cone, namely the presence of a polygonal structure, part of the photons did not pass through it and were reflected in the opposite direction. These photons were recorded on the plane *2* (Figure 3), which allowed us to determine the signal loss caused by the imperfection of the cone.

The results of the transmission calculation for 3 cone options are shown in Table 2. The most significant reason for the decrease in the signal was the loss of photons in the detector area. They are connected, first of all, with the discrepancy between the shape of the detectors used and the output window of the cone, so not all photons that have passed through the cone fall on the detector surface. In general, it can be noted that due to conservation laws, the cumulative photon signal coming to the detectors for the Winston cone ideally depends only on their area and does not depend on the design of the cones. However, this statement is valid only for the ideal case when the reflection coefficient is equal to one, and the shape of the detector coincides with the shape of the output window of the cone.

The reflection losses from the inner surfaces of the cones amounted to no more than 10%. At the same time, for the construction of a cone with an angle of 26.56 degrees (at such an angle, the radius of the circumscribed circle of the output hexagon is 2 times smaller than the radius of the inscribed circle of the input hexagon), noticeable losses of

Table 2. Results of numerical modelling to determine the transmission of Winston cones

Parameter	$\theta = 26.56^\circ$	$\theta = 30.00^\circ$	$\theta = 35.00^\circ$
Photons reflected in the opposite direction, %	7.20	1.45	0.06
Losses at reflection, %	9.92	7.43	5.97
Losses on detectors, %	13.49	17.53	29.38
Transmission cones, %	69.38	72.58	64.43

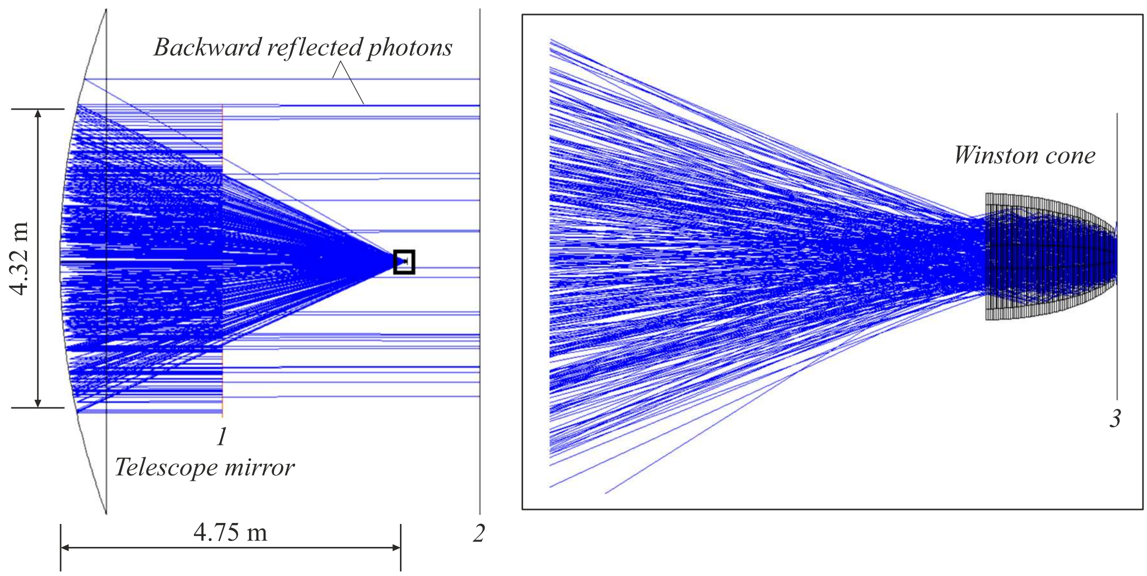

Figure 3. Numerical model in the Zemax package, including a telescope mirror and a single Winston cone: *1* — photon launch plane, *2* — plane of photons recording reflected in the opposite direction, *3* — plane of detectors.

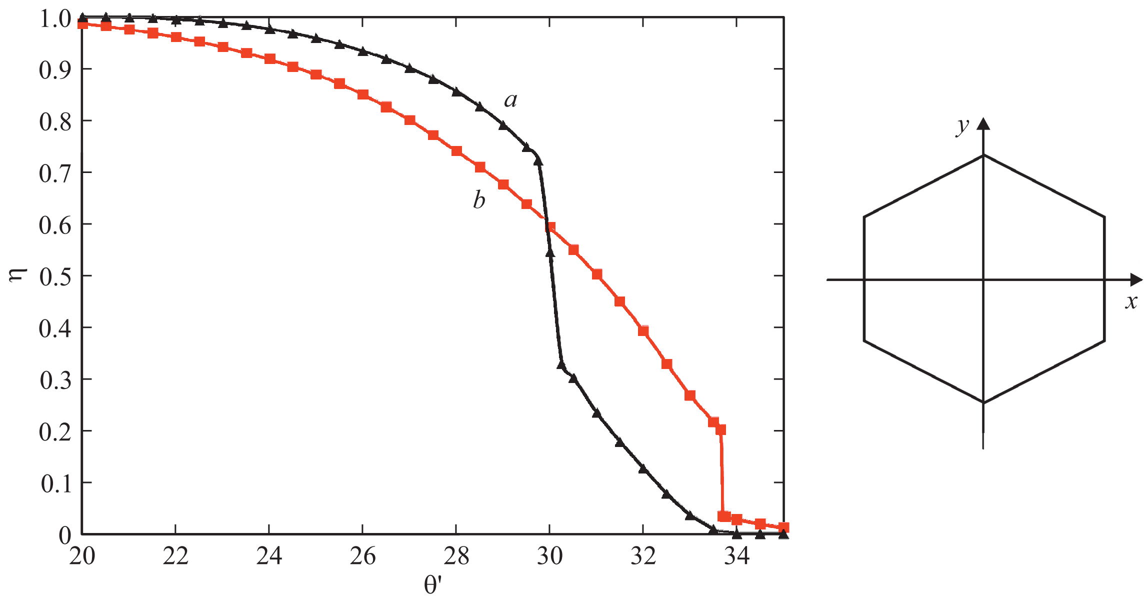

Figure 4. Results of numerical calculation of the transmission function η of the Winston's hexagonal cone at a fixed angle of inclination of the photon trajectory to the axis of the cone θ': a — with respect to the axis x, b — with respect to the axis y.

the photon flux were associated with their reflection in the opposite direction.

The calculation of the distribution of the normalized photon flux intensity in the plane of the detectors (Figure 5, a) showed that, despite the hexagonal shape of the cones, this distribution is generally symmetrical with respect to the axis of the cone. Intensity distribution of photons reflected in the opposite direction in the plane *2*, shown in Figure 5, b. It can be seen from the figure that it is the reflections in the area of the corners of the polygonal structure of the cone that make the main contribution to reducing the intensity of the recorded photons.

Conclusions

Quantitative modelling of the optical concentrator system based on Winston hexagonal cones for the Cherenkov gamma-telescope showed that of the 3 considered options, a cone with a viewing angle of 30 degrees has the best characteristics when using a given configuration of 4 detectors. Based on the results of numerical modelling, the losses in reflection from the inner surfaces of the cone were determined, they amounted to 7.43%, the losses caused by the discrepancy between the output window of the cone and the detectors amounted to 17.53%. Thus,

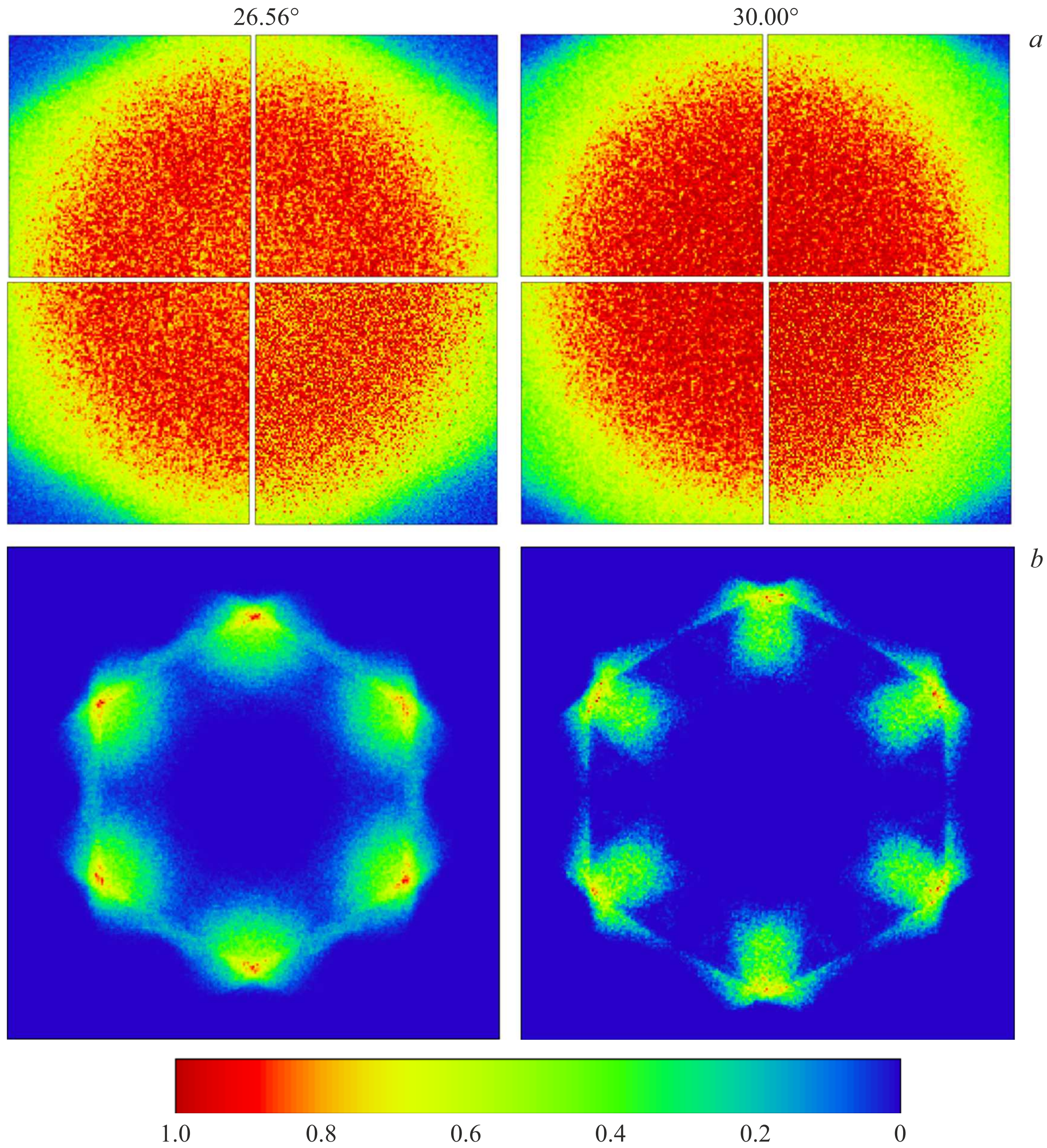

Figure 5. The distribution of the normalized photon flux intensity: *a* — in the plane of detectors, *b* — in the plane of photons recording reflected in the opposite direction.

the numerically found transmission of this cone was more than 72%.

The results obtained for the system under consideration were compared with the published data. In particular, the paper [20] presents the results of numerical modelling for various configurations of the Winston cone, differing in the shape of the input and output windows. Based on the results of the comparison, it can be concluded that the design under consideration has the fastest decline in the transmission function, and, accordingly, the highest efficiency of suppression of the noise background of photons. According to this parameter, the design under consideration is practically not inferior to the Winston parabolic cone.

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Conflict of interest

The authors declare that they have no conflict of interest.

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