Conference materials
UDC 537.591.15
DOI: https://doi.org/10.18721/JPM.161.263

Design of an optical concentrators array for the camera of a small-size Cherenkov gamma-ray telescope

A.S. Antonov[1]✉, A.A. Bogdanov[1], A.M. Krassilchtchikov[1]

[1] Ioffe Institute, St. Petersburg, Russia

✉ andrey.antonov@mail.ioffe.ru

Abstract. Quantitative modeling of a system of optical concentrators based on an improved design of Winston hexagonal cones, providing a possibility of using light filters and intended for the registration camera of a small-size Cherenkov gamma-ray telescope, has been performed. The transmission of the cones is calculated, and the intensity distributions of the photon flux in the detector plane are given. Based on the results obtained, an optimal configuration of optical concentrators is proposed with an account for design features of the TAIGA-IACT mount, mirror, and camera, as well as of new detector units. The results obtained for the considered system are compared with the previously published models.

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

Funding: This research has been supported by the Russian Science Foundation via grant 19-72-20045. The results of the presented research will be also used at UNU “Astrophysical complex MSU-ISU” (the complex is supported by the agreement 13.UNU.21.0007 between the ISU and the Ministry of Science and Higher education of Russia).

Citation: Antonov A.S., Bodganov A.A., Krassilchtchikov A.M., A Design of an optical concentrators array for the camera of a small-size Cherenkov gamma-ray telescope, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.2) (2023) 417–422. DOI: https://doi.org/10.18721/JPM.161.263

Материалы конференции
УДК 537.591.15
DOI: https://doi.org/10.18721/JPM.161.263

Разработка системы оптических концентраторов для камеры малоразмерного черенковского гамма-телескопа

А.С. Антонов[1]✉, А.А. Богданов[1], А.М. Красильщиков[1]

[1] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия

✉ andrey.antonov@mail.ioffe.ru

Аннотация. Выполнено количественное моделирование системы оптических концентраторов на основе массива шестиугольных конусов Уинстона, предназначенной для камеры регистрации малоразмерного черенковского гамма-телескопа. Определена трансмиссия конусов, а также распределение интенсивности потока фотонов в плоскости детектора.

Ключевые слова: черенковский гамма-телескоп, конус Уинстона, численное моделирование, TAIGA-IACT

Финансирование: Авторы благодарят Российский научный фонд (РНФ) за поддержку в рамках проекта 20045-72-19.

Ссылка при цитировании: Антонов А.С., Богданов А.А., Красильщиков А.М. Разработка системы оптических концентраторов для камеры малоразмерного Черенковского гамма-телескопа // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.2. С. 417–422. DOI: https://doi.org/10.18721/JPM.161.263

Introduction

Currently, Cherenkov gamma-ray telescopes are the main type of astronomical instruments in the energy range above 0.1 TeV. Having a very large (~10^4–10^5 m^2) effective detection area they make it possible to measure rather weak fluxes of teravolt range gamma radiation from a number of cosmic sources (see, for example, [1, 2]). Such a large detection area is due to the fact that observations are carried out not by a direct method but by registering Cherenkov radiation of electrons and positrons of extensive air showers (EAS) initiated by primary cosmic gamma rays during their interaction with the Earth's atmosphere. The characteristic transverse size of an EAS is of the order of 200–500 m. The large detection area and the relatively low cost of Cherenkov gamma-ray telescopes provide such significant competitive advantages that, most likely, in the foreseeable future they will remain the main instruments of gamma-ray astronomy in the energy range above 0.1 TeV. Projects of new (IV) generation Cherenkov telescopes [3, 4] are in an active phase, and the existing (III generation) Cherenkov telescopes are being continuously modernized [5, 6].

Since 2019 a team from the Ioffe Institute is carrying out a project aimed at upgrading the camera of the TAIGA-IACT Cherenkov gamma-ray telescope (SINP MSU, Irkutsk University) [7, 8]. The main goal of the project is the development of new detector clusters for the TAIGA-IACT camera based on silicon photomultipliers (SiPM), which would improve the efficiency of this telescope by reducing the threshold detection energy and increasing the duty cycle [9, 10]. The detector cameras of Cherenkov gamma-ray telescopes usually consist of several hundred photomultipliers (PMTs) [11, 12], each equipped with a light concentrator (usually, a Winston cone) which performs several functions [13, 14], such as:

1) transition from the pixel size which is determined by the size of the focal plane area where the image of a Cherenkov flash is formed, and the number of camera pixels, to the size of the input window of the selected photocell, i.e., the additional concentration of source photons;

2) transition from the pixel shape (usually, a hexagon), which should ensure filling of the detector plane without gaps and overlaps in order to reduce the area of "dead" (non-recording) areas of the camera, to the shape of the input window of the selected photocell (in the case of a traditional vacuum PMT, it is usually a circle)

3) reduction of the noise background made of photons from the night sky and reflected background photons.

Such a device is typically an off-axis paraboloid of revolution, which collects a set of rays, allowing the off-axis rays to repeatedly reflect when passing from the entrance to the exit aperture. At present, Winston cones with windows in the shape of regular hexagons are used in the TAIGA-IACT telescope cameras, the exit window size (the diameter of the inscribed circle) is about 14.8 mm, which corresponds to the size of the 15 mm round entrance window of the XP1911 PMTs [15]. The planned modernization of this camera involves the employment of an assembly of four OnSemi MicroFJ-60035 SiPMs with a square-shaped entrance window with a size of about 12.8 mm as photocells [9]. Such differences would require the development of new light concentrators. In order to assess the need for changes in the design of light concentrators (Winston cones) for the upgraded TAIGA-IACT camera compared to those currently used, preliminary modeling of Winston cones was carried out using the ZEMAX package [16]. Some results of these simulations are presented below.

Materials and Methods

The main characteristic of a Winston cone is the viewing angle θ equal to the angle of inclination of the parabola axis to the axis of the cone. This value determines the area of transmission of the cone in the space of angles, as well as the ratio of the areas of the input and output windows. A simplified (polygonal) construction of cones, consisting of a set of parabolic surfaces, is considered. Thus, the inlet and outlet of the cones are polygons. Fig. 1 shows a drawing of a modified design of an array of Winston cones with flanges for attaching light filters. The prototype of these cones with a reflective film applied to the inner surface was made for the new TAIGA-IACT camera. Based on the requirements for the design of the telescope registration camera for numerical simulation, hexagonal Winston cones were chosen, whose characteristics are close to the ideal case of a paraboloid of revolution. The calculations of [18] showed that the transmission of a hexagonal Winston cone does not differ significantly from its axisymmetric counterpart at cone angles of about 30 degrees or more. The transmission of a cone refers to the percentage ratio of the number of photons that have passed through the cone to the number of photons that have arrived at the input window of the cone.

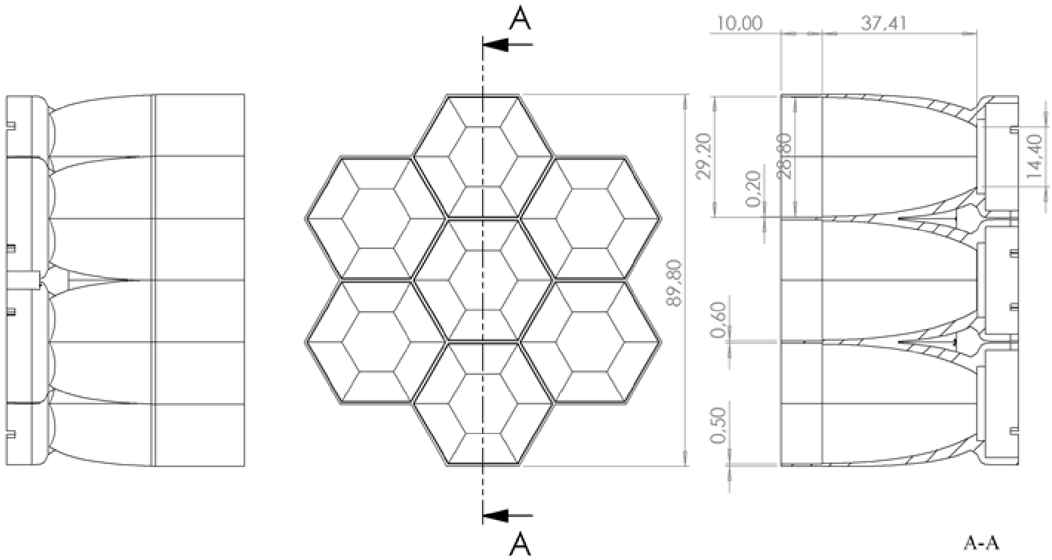

Fig. 1. Design of an array of modified Winston cones

Numerical simulations were carried out using the ZEMAX software package designed for the calculation of optical systems and optoelectronic devices. To solve problems of geometric optics, this package employs Monte Carlo ray tracing, the essence of which is to track the trajectory of rays and calculate interactions with the objects lying on the trajectories. According to the specification, the reflection coefficient of the inner surface of the Winston cones must be at least 0.95 in the wavelength range of 300–700 nm. This is the value used in the simulations.

The numerical model included a parabolic telescope mirror, a single Winston cone, and a set of 4 detectors located near the exit window of the cone. The geometrical parameters of the telescope mirror were taken as follows: the radius of the mirror, 2.16 m, and the focal length, 4.75 m. 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 a square with a side of 6.33 mm. When determining the geometric parameters of the cone, the following relations were used:

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

where R_1 and R_2 are the radii of the inscribed circle for the input and output windows respectively, θ is the angle of the cone, h is the height of the cone.

Results and Discussion

Three variants of the cone design were considered, differing in the angle θ equal to 26.56, 30 and 35 degrees, respectively. In particular, when the angle $\theta = 30°$, the ratio of the areas of the input and output windows of the cone is 4. Based on the simulation results, the angular size of a pixel of the telescope mirror and a single cone system was determined, which is a hexagonal area on the celestial sphere with an inscribed circle angular radius of 10.8′.

In the numerical simulation, the photons started from plane 2 (Fig. 2) in the direction of the telescope mirror with a uniform distribution in the coordinate space within the region bounded by a circle with a radius equal to the radius of the telescope mirror, and in the space of angles within a circle with an angular radius of 10.8′. This value corresponds to the found angular size of the pixel of the telescope mirror and a single cone system. The detectors were located at a distance of 1 mm from the output window of the cone, which made it possible to minimize signal losses. Due to the imperfection of the cone, namely to the polygonal structure, some of the photons did not pass through it and were reflected in the opposite direction. These photons were recorded on plane 2 (Fig. 2) which made it possible to determine the signal loss caused by the imperfection of the cone. Calculations have shown that the best transmission is obtained in the case of a cone angle of 30 degrees. The most significant reason for the decrease in the signal was the loss of photons in the area of the detectors. Losses due to reflection from the inner surfaces of the cones were 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 less than the radius of the inscribed circle of the input hexagon), noticeable losses in the photon flux were associated with their reflection in the opposite direction.

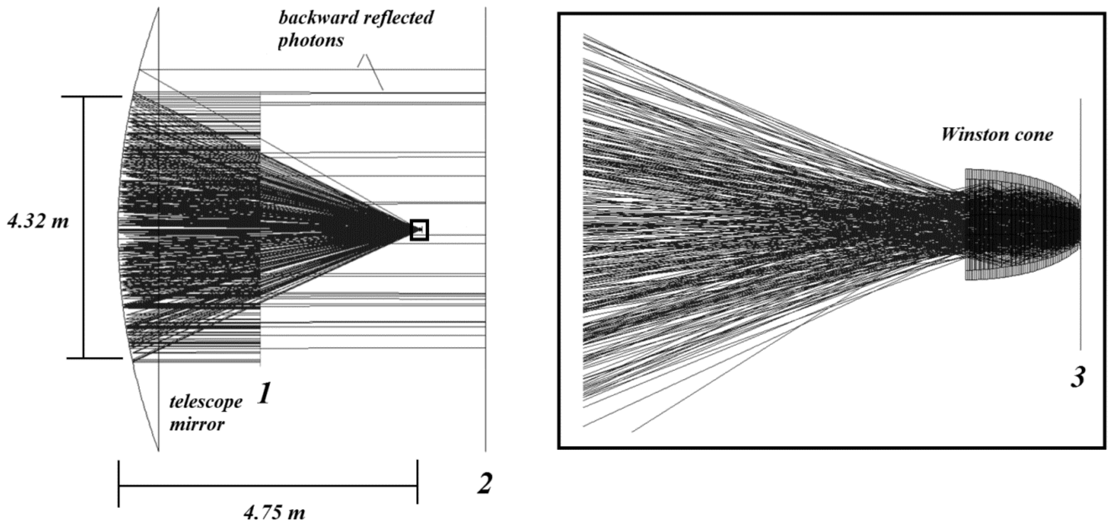

Fig. 2. Numerical model in the Zemax package including a telescope mirror and a single Winston cone: *1* is the plane of the start of photons, *2* is the plane of registration of photons reflected in the opposite direction, *3* is the plane of the detectors

The calculation of the normalized intensity distribution of the of the photon flux in the plane of the detectors (Fig. 3, *a*) showed that, despite the hexagonal shape of the cones, this distribution is generally symmetrical with respect to the axis of the cone. The intensity distribution of photons reflected in the opposite direction in plane 2 is shown in Fig. 3,*b*.

For a Winston cone with an angle of 30 degrees, a numerical simulation of a modified design with a 10 mm flange was carried out. Two variants of the reflective surface of the flange were considered: an ideally absorbing surface and a surface with a reflection coefficient of 0.95. Calculations showed that in the case of a cone model without a flange, the transmission was equal to 73.57%. At the same time, even in the case when the surface of the cone flange was ideally absorbent the transmission only decreased to 67.91%. In a realistic case, when the reflection coefficient of the cone flange was 0.95, the transmission turned out to be 72.41%.

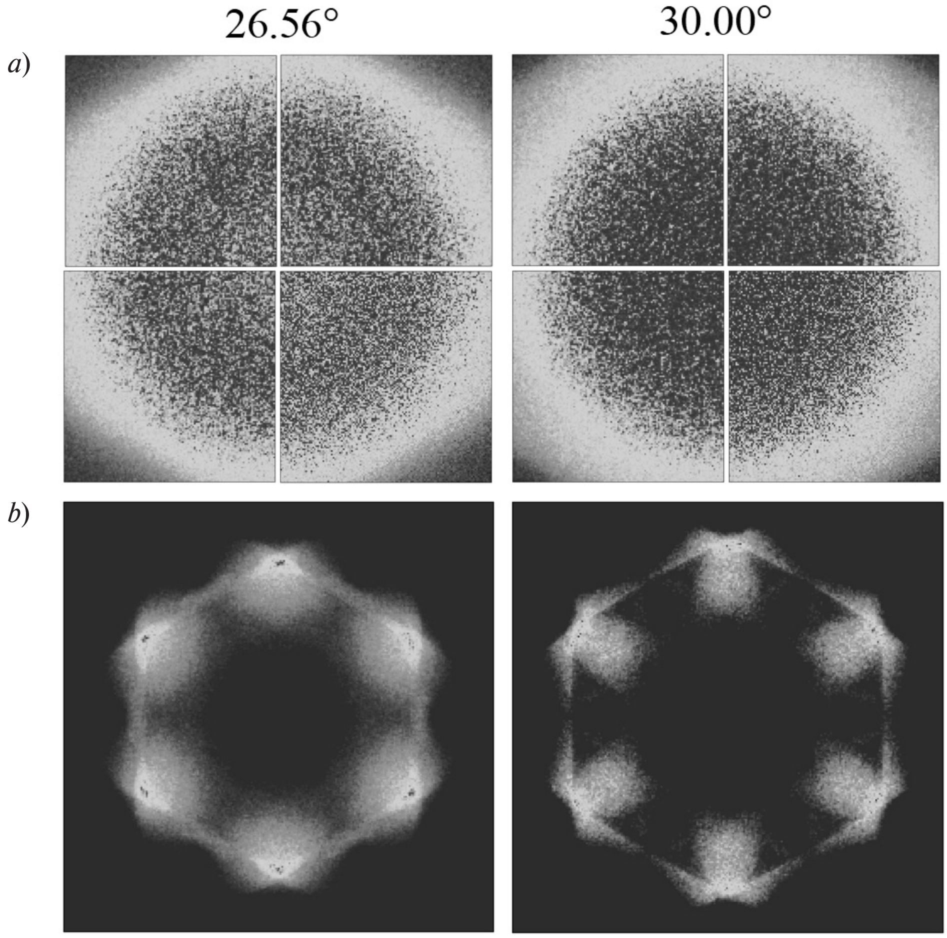

Fig. 3. Distribution of the normalized intensity of the photon flux for different cone angles: in the plane of the detectors (*a*), in the plane of registration of photons reflected in the opposite direction (*b*)

Conclusion

Quantitative modeling of an optical concentrator array based on modified Winston hexagonal cones for a small-size Cherenkov gamma-ray telescope showed that of the 3 designs considered, a cone with a viewing angle of 30 degrees has the best performance when using a given configuration of 4 detectors. According to the results of the numerical simulation, the losses during reflection from the inner surfaces of the cone amounted to 7.43%, and the losses caused by the discrepancy between the exit window of the cone and the detectors amounted to 17.53%. Thus, the numerically found transmission of this cone was above 73%. At the same time, the addition of a filter attachment flange to the design of the cone results in only a slight reduction in transmission.

Acknowledgments

This research has been supported by the Russian Science Foundation via grant 19-72-20045. The results of the presented research will be also used at UNU “Astrophysical complex MSU-ISU” (the complex is supported by the agreement 13.UNU.21.0007 between the ISU and the Ministry of Science and Higher education of Russia).

REFERENCES

1. **Becherini Y., Djannati-Atai A., Punch M., Bernlцhr K. et al.,** AIP Conference Proceedings 1085 (2008) 738.
2. **Ansoldi S. et al**, Teraelectronvolt pulsed emission from the Crab Pulsar detected by MAGIC, A&A 585 (2016) A133.
3. **Barres de Almeida U.**, Status of the Cherenkov Telescope Array project, Astronomische Nachrichten 336 (8-9) (2015) 795.
4. **Bykov A. M., Aharonian F.A., Krassilchtchikov A.M. et al.**, Journal of Technical Physics 62 (2017) 819–836.
5. **Aleksic J., Ansoldi S., Antonelli L. A. et al.,** Astroparticle Physics 72 (2016) 61-75.
6. **Giavitto G., Ashton T., Balzer A. et al.**, Nuclear Instruments and Methods in Physics Research Section A 876 (2017) 35-38.
7. **L.A. Kuzmichev L.A., Astapov I.I., Bezyazeekov P.A. et al.,** Physics of Atomic Nuclei 81 (4) (2018) 497–507.
8. **Lubsandorzhiev N., Astapov I., Bezyazeekov P. et al.,** In 35th International Cosmic Ray Conference (ICRC2017) 301 (1) (2017) 757.
9. **Bogdanov A.A., Kholupenko E.E., Tuboltsev Yu.V., Chichagov Yu.V.,** Latvian J. Phis. and Tech. Science 1 (2020) 13.
10. **Kholupenko E.E., Krassilchtchikov A.M., Badmaev D.V., Bogdanov A.A., Tuboltsev Y.V., Chichagov Y.V., Antonov A.S., Kuleshov D.O., Khil`kevich E.M.,** The Application Potential of Silicon Photomultipliers for a Camera of a SmallSize Cherenkov GammaRay Telescope for Reducing the Detection Threshold, Journal of Technical Physics 65(6) (2020) 886–895.
11. **Aharonian F.A. Akhperjanian A.G. Kankanian A.S. Mirzoyan R.G. et al**., Proceedings of the 22nd International Cosmic Ray Conference. 11-23 August, 1991. Dublin, Ireland 2, (1991) 615.
12. **Bolmont J., Corona P., Gauron P. et al.,** Instrumentation and Methods for Astrophysics, Res. Sec. A 761 (2014) 46–57.
13. **Aguilar J.A., Basili A., Boccone V. et al**., Astroparticle Physics 60 (2015) 32-40.
14. **Henault F., Petrucci P.-O., Jocou L. et al.,** Proc. SPIE 8834, Nonimaging Optics: Efficient Design for Illumination and Solar Concentration X, 883405 (18 September 2013) 883405.
15. XP1911, product specification, http://www.hzcphotonics.com/products/XP1911.pdf, http://www.isuzuoptics.com.tw/data/product/photonis/pmt/19mm-1.pdf.
16. URL: http://www.zemax.com.
17. **Winston R., Jiang L., Ricketts M.**, Adv. Opt. Photonics 10 (2) (2013) 484.
18. **Coopera T., Dählera F., Ambrosetti G., Pedretti A., Steinfeld A.,** Performance of compound parabolic concentrators with polygonal apertures, Solar Energy 95 (2013) 308–318.

THE AUTHORS

ANTONOV Andrei S.
andrey.antonov@mail.ioffe.ru
ORCID: 0000-0001-9356-5841

KRASSILCHTCHIKOV Alexander M.
kra@astro.ioffe.ru
ORCID: 0000-0001-7681-4316

BODGANOV Alexander A.
Alexander.A.Bogdanov@mail.ioffe.ru
ORCID: 0000-0002-5275-5603

Received 24.10.2022. Approved after reviewing 21.11.2022. Accepted 21.11.2022.