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The SPHERE Project: Developing a Technique for Reflected Cherenkov Light

E. A. Bonvech[a, *], D. V. Chernov[a], V. S. Latypova[b], C. Azra[b], V. I. Galkin[a, b], V. A. Ivanov[b], D. A. Podgrudkov[a, b], and T. M. Roganova[a]

[a] *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*

[b] *Faculty of Physics, Moscow State University, Moscow, 119991 Russia*

**e-mail: bonvech@yandex.ru*

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Abstract—Further development of the way of studying primary cosmic rays by detecting the reflected extensive air shower Cherenkov light is planned, based on the successful implementation of the SPHERE-2 aerostat experiment. The possibility of simultaneously detecting direct and reflected Cherenkov light from extensive air showers is demonstrated. Prospects for creating a new SPHERE-3 detector are discussed and the first results from modeling are presented.

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INTRODUCTION

A change in the slope of the energy spectrum of primary cosmic rays (PCRs) by ~3 PeV was discovered more than 50 years ago, and new features in the ultrahigh-energy (above 1 PeV) cosmic ray spectrum continue to be found. These inhomogeneities can be attributed to changes in the composition of PCRs, which can in turn provide important information about mechanisms of the acceleration of cosmic rays and the structure of their sources. The question of the composition of ultrahigh-energy PCRs has yet to be answered [1–4]. The team at the KASCADE-Grande experimental array has managed to identify the spectra of two groups of nuclei [5], but a more detailed classification is hampered by the uncertainty of the strong interaction model. Results from different experiments on the average mass number logarithm at energies of ~10 PeV differ nyseveral times [4–8].

Cosmic rays in the ultrahigh energy region are studied at large ground-based facilities using indirect means based on components of extensive air showers (EAS), including Vavilov–Cherenkov and Cherenkov radiation. In the Cherenkov parts of the TAIGA [9], LHAASO [10], and NICHE [11] facilities, the average logarithm of the mass number is estimated from calculated depth $X_{\max}$ of the maximum shower development, which is in turn found from shower characteristics observed directly using modeled dependences. Quantity $X_{\max}$ thus serves as a parameter intermediate between measured values and the mass of a primary particle, which inevitably affects the error of estimation. In addition, the mass estimate obtained in this way depends on the nuclear interaction model used in the calculations.

In the SPHERE project, cosmic rays with energies of 1–1000 PeV are studied by detecting the EAS Cherenkov light reflected from snow. The SPHERE project's technique is based on Chudakov's idea of detecting EAS Cherenkov light reflected from the Earth's surface by photodetectors raised above the surface by aircraft [12]. The history of this technique was described in [13]. The first successful use of the technique was the SPHERE-1 experiment, which allowed us to test its applicability and measure the PCR spectrum [14]. A further development of the technique was the SPHERE-2 experiment [15], the main physical results from which were reported in [13]. In this work, the idea of simultaneously detecting direct and reflected Cherenkov light from the same EAS is formulated and the fundamental possibility of such measurements is demonstrated. We plan to create a new SPHERE-3 detector to develop the technique.

In contrast to confined ground-based facilities, where the distance between Cherenkov detectors is rarely less than one hundred meters, the observing area of a SPHERE facility is continuous and the full flux of the EAS Cherenkov light is detected. This reduces systemic errors in determining the energy of primary particles.

On the other hand, the SPHERE project measures the spatial distribution of EAS Cherenkov light, especially the intensity of light in the paraxial region, which is a characteristic of shower development that is sensitive to the type of primary particle. The way of building a criterion for separating the primary mass

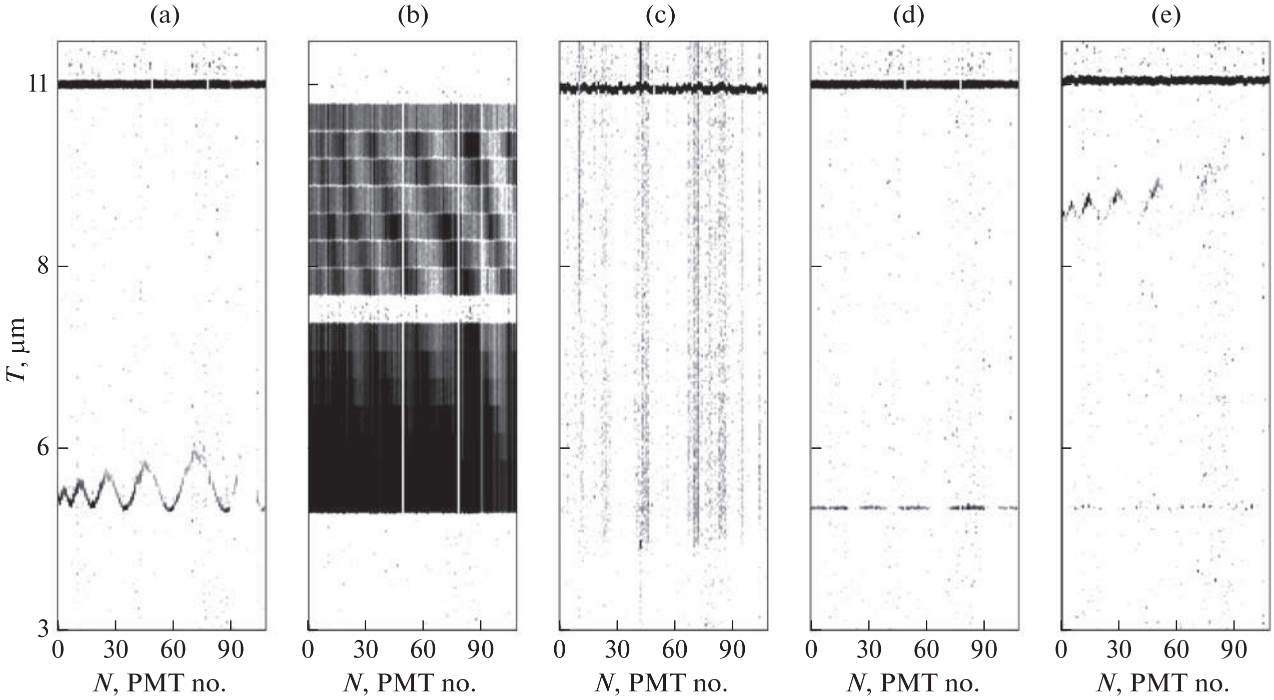

Fig. 1. Examples of events detected in the SPHERE-2 experiment: (a) reflected EAS Cherenkov light, (b) calibration event, (c) long noise event, (d) short noise event, and (e) event with direct and reflected Cherenkov light.

used in the project [16, 17] is based on the shape of directly measured distributions, so the criteria depend weakly on the nuclear interaction model, which reduces systemic experimental errors of determining the mass composition of PCRs as well. To effectively use this criterion, we must approximate the function of the spatial distribution of EAS Cherenkov light that would accurately describe the distribution of light near the shower's axis. Such a function is described in this article.

CLASSIFYING EVENTS IN THE SPHERE-2 EXPERIMENT

Measurements on the SPHERE-2 facility [15] were made over the snow-covered surface of Lake Baikal in 2008–2013 [18]. The facility was lifted on a tethered balloon to a height of 300–900 m above the lake surface. The EAS Cherenkov light reaching the Earth's surface was reflected diffusely from the snowy surface as from a white screen. The SPHERE-2 facility raised on a tethered balloon detected some of the light reflected in its direction by a mosaic of 109 FEU-84-3 photomultipliers. In the period of 2011–2013, 32000 trigger events were detected.

The total time of the saved oscillogram of the amplitude profile of the signal for one event is 12 μs with a resolution of 12.5 ns, including 5 μs before each trigger. A calibration LED sync pulse is sent 6 μs after a trigger, which also falls into the event digitization window. Figure 1a presents a typical time scan of the reflected EAS Cherenkov light detected by the SPHERE-2 facility. It is a characteristic snake of pulses of average length of no more than 300 ns in each measuring channel. The way of presenting such an event was described in [13].

Since 2012, each trigger event has been accompanied by a calibration event [19]. The mosaic of photomultipliers is illuminated by LEDs 12 μs after the trigger is activated, and a calibration frame is formed. Figure 1b shows a typical calibration event accompanying a trigger.

Short and long noise events are detected in addition to the useful ones described above. In long events (Fig. 1c), the signals in the measuring channels last more than 7 μs and end outside the event digitization window. Such events can be interpreted as some electrical phenomena, e.g., static voltage discharges on photocathodes of photomultipliers.

A short event (Fig. 1d) consists of simultaneous short pulses no more than 60–90 ns long in several photomultipliers in the trigger region. The temporal structure of these pulses, representing the synchronous appearance of short pulses in several channels and their spatial distribution, which represents the appearance of signals in adjacent mosaic channels in the form of a coherent strip, testify to their nonrandom nature. A random pickup on electronic components is associated across electronic boards, but will not appear across different boards as it does in the facility. The pickup on supply cables will be random because the cables were laid in a random order. The impact of particles from a nearby EAS on the photocathode glass will scatter the signals relatively uniformly across the mosaic. The distribution of light in a stripe observed in the short events is more likely to be characteristic of a mosaic illuminated by a short pulse of light through slits in a mirror. The mirror of the facility is discontinuous and consists of several segments [15]. Since the gaps are straight, the illumination should appear in stripes, as is observed. Considering the effect of the gain of photomultipliers and electronic components, the physical light pulse for detected short events should be no more than 10–15 ns. Such a short light pulse is only possible for the direct EAS Cherenkov light incident onto a photomultiplier through slits in the mirror.

SIMULTANEOUS DETECTION OF DIRECT AND REFLECTED EAS CHERENKOV LIGHT

The event shown in Fig. 1d was found among the events classified as short noise. It was recorded by the detector 603 m above a surface of snow. In the trigger region, there are short (50–80 ns) pulses in several photomultipliers characteristic of short events. The reflected Cherenkov light was detected 4 μs after each trigger. In 4 μs, the light traveled a distance of 1200 m. The zenith angle of the axis of this event is 17 deg. This shows that direct Cherenkov light from a shower coming down to the ground was detected in one event. After 4 μs, the Cherenkov light reflected from the snow was detected. Pulse lengths of 50–80 ns are consistent with our modeling of direct EAS Cherenkov light from a 10 PeV proton at an altitude of 603 m above the surface of Lake Baikal.

This double event was detected by chance. The design of the mirror in the SPHERE-2 facility had technological slits through which direct EAS Cherenkov light could reach the mosaic. The possibility of detecting the direct and reflected Cherenkov light of one event will be considered in designing the new SPHERE-3 facility.

ESTIMATING THE PROBABILITY OF THE DOUBLE DETECTION OF LIGHT

To detect the direct and reflected light of one EAS, it must have a zenith angle no larger than the viewing angle of the detector. Otherwise, the axis of a shower passing in the immediate vicinity of the facility will be outside the field of view of the detector on the reflective surface of snow. Let us consider a facility with a half viewing angle of 22° located at a certain altitude above the snowy surface and detecting direct EAS Cherenkov light at distances of up to 150 m from the shower's axis. In the first approximation, we assume it is distributed anisotropically and its density is constant at those distances from the axis. At the level of the snowy surface and within the detector's field of view, we consider a uniform distribution of EAS axes with the zenith angles of 0 up to the maximum angle at which the double detection of a shower is possible, and the azimuth angles uniformly distributed from 0 to 2π. An event is considered detected if its axis passes no farther than 150 m from the detector in the air. We estimated the possibility of double detection under these conditions: 39% for a detector altitude of 500 m, 12% for an altitude of 1000 m, and 6% for an altitude of 1500 m.

To obtain more accurate estimates, we must consider the spatial–angular distribution of photons of the direct Cherenkov light, the shape and area of the entrance hole for the direct Cherenkov light, threshold values for the trigger detection condition, and the angular distribution of the EAS on the Earth's surface. Such calculations are now being made. Detecting the Cherenkov light from one EAS in two different ways will allow us to better estimate the parameters of a primary particle, especially its mass. This statement is based on our earlier studies in the Pamir-XXI project [16, 20], which uses the angular distribution of direct EAS Cherenkov light to separate events according to the mass of primary nuclei. It was shown that using the shape of the angular distribution effectively, the entire mass spectrum can be divided into three groups. Showers from protons are assumed to be from nitrogen nuclei (and vice versa) in no more than 10% of all cases. Similar results were obtained for nitrogen–iron pairs. Of coursr, the partitioning of the entire stream of events into groups is not the final goal, but the criteria for making such a classification contain customized criterial parameters that serve as measures of the primary mass. The idea of using simultaneous measurements of direct and reflected EAS Cherenkov light from snow could greatly improve the telescope's sensitivity to the primary mass. It is too early to speak about the final mass resolution, but this approach certainly has potential.

APPROXIMATING THE SPATIAL DISTRIBUTION FUNCTION

The aims of the SPHERE project experiments include estimating the mass of primary particles. The criterion used for estimating the mass [21, 22] is determined as a ratio of the integrals of the total number of Cherenkov photons measured from the shape of the spatial distribution of the EAS Cherenkov light in rings with different radii. The criterion itself resembles a boundary parameter separating two class areas. To ensure minimum classification errors when using such a criterion, we must retain important information about the mass of primary particles in the form of the transverse distribution of light near the shower's axis. The function used should therefore approximate the EAS characteristics in the region of 0 to 300 m.

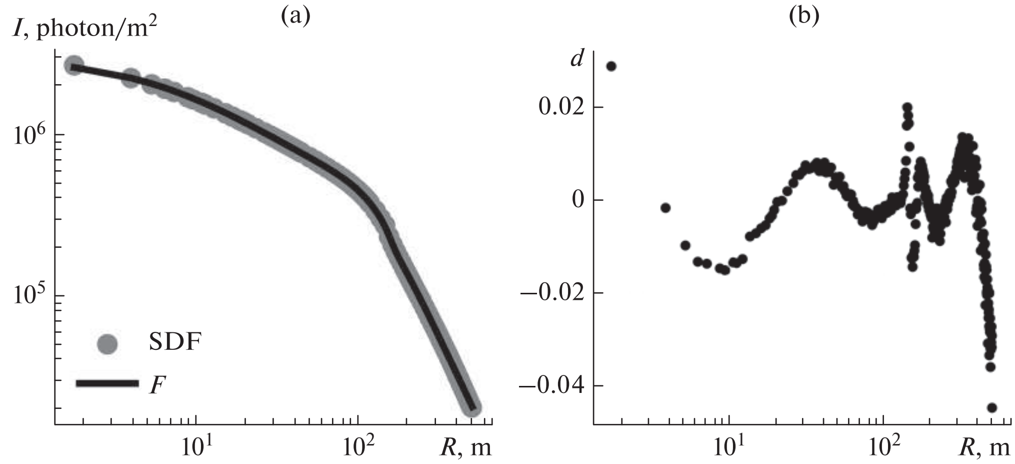

Fig. 2. (a) Spatial distribution function (SDF) of EAS Cherenkov light for an individual EAS event. Simulated $I(R)$ points are marked in grey, and the curve shows function F approximated by formula (1). (b) Relative deviation of approximating curve F from the simulated points.

To model a SPHERE facility, the $I(R)$ distribution of the EAS Cherenkov light on the Earth's surface is approximated by the function

$$F = \frac{p_0}{\left(1 + p_1 R + p_2 R^2 + p_3 R^3\right)} w_1 + \frac{p_4}{\left(1 + p_5 R + p_6 R^2\right)} w_2, \quad (1)$$

$$w_1 = \frac{1}{\left(1 + \exp\left(\left(R - R_{\mathrm{ch}}\right)/s\right)\right)}, \quad w_2 = \frac{1}{\left(1 + \exp\left(-\left(R - R_{\mathrm{ch}}\right)/s\right)\right)}, \quad (2)$$

where R is the distance from the shower's axis; p_1, ..., p_6; and R_{ch} are the chosen parameters.

Function F of the approximation of the spatial distribution of EAS Cherenkov light (Fig. 2a) deviates from the $I(R)$ model by less than 5% at 0–500 m from the shower's axis (Fig. 2b). In the vast majority of cases, the relative approximation error is no more than 2% at distances of 0 to 400 m. This accuracy of the approximation function for the spatial distribution of the EAS Cherenkov light is suitable for using the primary mass criterion. Details of the modeling done to search for this approximation were presented in [23]. Approximation (1) was initially intended to process events from the SPHERE-2 experiment, but it can be applied to any experiment that uses the spatial distribution function of EAS Cherenkov light at the ground level.

DEVELOPING THE SPHERE-3 FACILITY

To further develop the techniques for studying PCRs, a new SPHERE-3 facility is being created and new ways of determining the primary particle type are being sought.

The main function of the new facility is to study the mass composition of PCRs. To do this, we must enhance the spatial resolution and sensitivity of the detector and increase the period of exposure, relative to the SPHERE-2 facility. High spatial resolution will be achieved by using a great number of compact and lightweight silicon photomultipliers (SiPMs). Higher sensitivity will be ensured by a wide-angle Schmidt optical system with a large-diameter mirror and a corrective lens on the window of the entrance diaphragm. The period of exposure can be lengthened by using an unmanned aerial vehicle with a hybrid power plant as a carrier for the detector. To lift the facility to an altitude of up to 2 km, we plan to use a vertical takeoff air vehicle with a hybrid engine that can operate with both batteries and a gasoline generator.

We are currently considering a design of a facility with a sensitive area of the diaphragm entrance window of more than 1 m^2, a mirror diameter of up to 2200 mm, a viewing angle of up to 22°, and a number of SiPMs of up to 3000 in the detector (Fig. 3). To detect direct Cherenkov light, we propose having a lens in the upper part of the mirror. The measuring equipment will be located in the shadow cone of the mosaic. Without batteries, rhe facility will weigh up to 100 kg.

The possibility of using SiPMs was discussed in [24]. A prototype of a SiPM mosaic of the SPHERE-3 facility is used in the SIT facility in the TAIGA astronomical complex [25]. Designs for an SiPM mosaic with segments consisting of seven or nineteen elements are being considered for the SPHERE-3 facility. In the model with a segment of seven elements, 379 such segments fit on the detector mosaic for a total

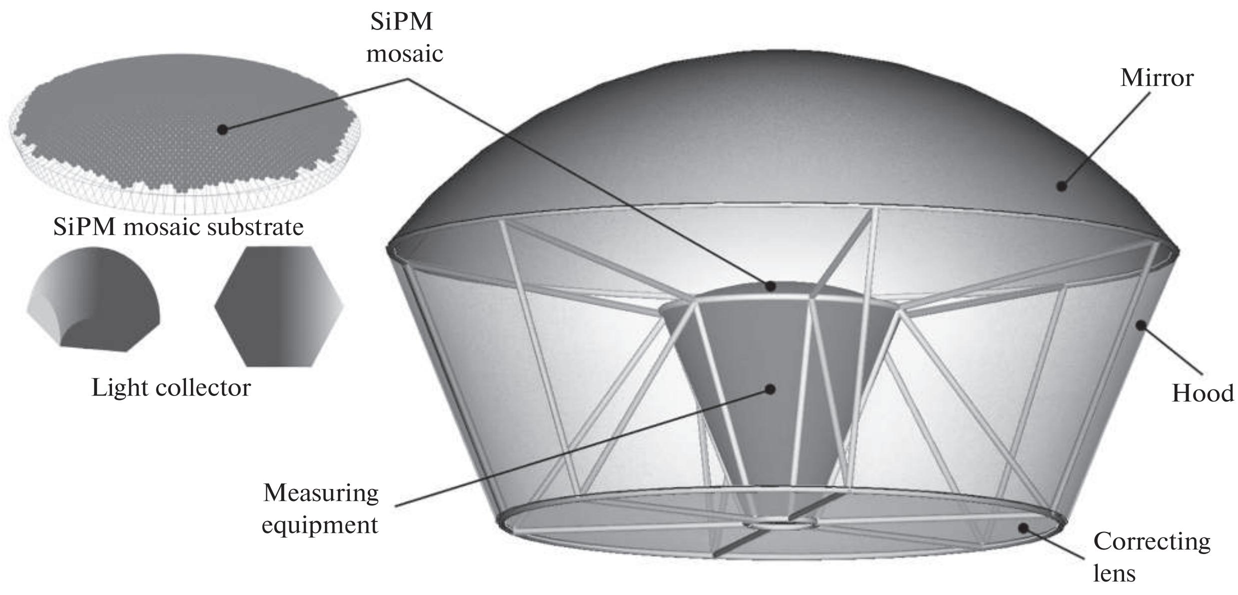

Fig. 3. Preliminary design of the SPHERE-3 detector.

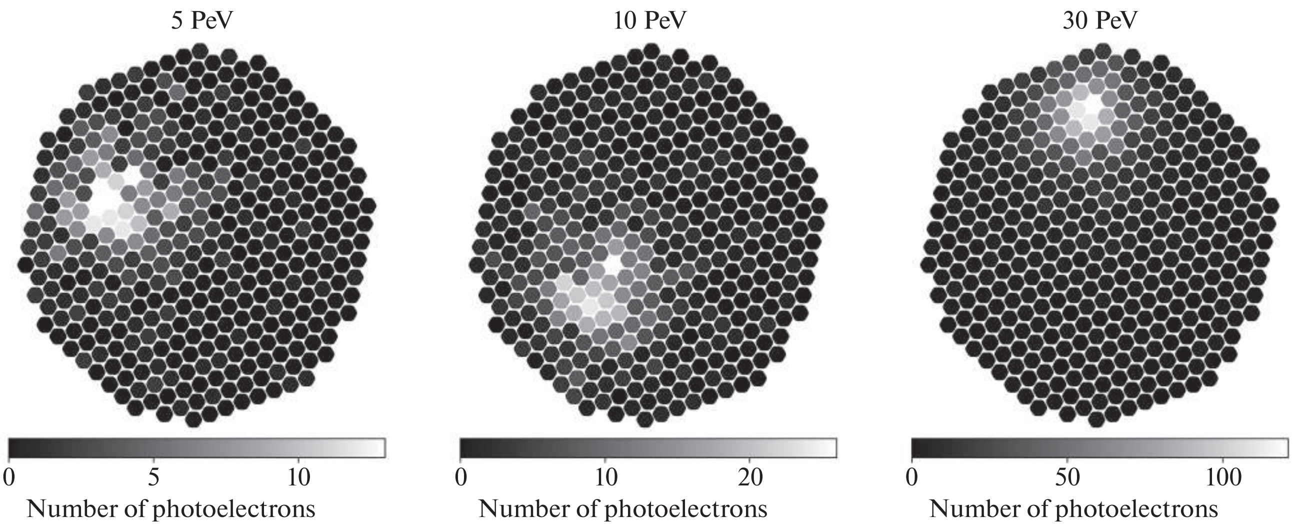

Fig. 4. Calculated distributions of Cherenkov photons on the mosaic of the SPHERE-3 detector from primary protons with energies of 5, 10 and 30 PeV.

of 2653 SiPMs (see this option in Fig. 3). Data on the trajectory and location of the reflection of photons from a snowy surface, obtained in the CORSIKA experiment using algorithms similar to those described in [26], we simulated Cherenkov light images for this model of a mosaic and a spherical mirror with a 140 cm radius of curvature. Figure 4 shows examples of the distributions of Cherenkov photons on the detector mosaic from the EAS with a proton primary particle at energies of 5, 10, and 30 PeV.

Compared to the SPHERE-2 facility, the new detector is expected to lower the event detection threshold by a factor of 3–5 (to 2–3 PeV). This will increase the bank of events by up to an order of magnitude at the same period of exposure. A multiple increase in the period of exposure is expected due to using an unmanned aerial vehicle. All this will allow us to reduce the statistical errors in the measured PCR spectrum of all nuclei and obtain a statistically significant result by analyzing the fractions of groups of PCR nuclei.

To enhance the sensitivity of the detector to the type of primary particle, we are investigating the possibility of obtaining additional data on the intensity of direct Cherenkov light and isolating the fraction of the ultraviolet component of reflected EAS Cherenkov light in the paraxial region, which is sensitive to changes in the EAS cascade from different types of PCR nuclei. This was discussed in detail in [27].

CONCLUSIONS

The SPHERE-2 experiment demonstrated the possibility of simultaneously detecting direct and reflected Cherenkov light from one EAS by raising the facility above the Earth's surface. The new detector of the SPHERE project will provide an option for detecting direct EAS Cherenkov light.

An approximating function was found that allows us to describe the spatial distribution function of the Cherenkov light of individual EASes with an accuracy no worse than 5% at distances of 0–500 m from the shower's axis. The approximation works over a wide range of the primary parameters and can be applied to any experiment that uses the spatial distribution function at the level of the Earth's surface.

The general principles of the optical system and mechanical design of the SPHERE-3 facility were determined, along with the preliminary parameters and dimensions of the detector's components. Preliminary results were obtained from simulating images of the Cherenkov light on the facility's photodetector from an EAS of primary protons with energies of 5, 10, and 30 PeV. Work on finding the optimum parameters of the detector and ways of improving its sensitivity to the type of primary particle continues.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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