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Monte Carlo Simulation of the TAIGA Experiment

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Abstract—The TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) experiment aims at observing gamma-rays in the energy range from 1 TeV to several 100 TeV. The operation of the observatory is based on a new hybrid approach that combines imaging air Cherenkov telescopes (IACTs) and wide-angle Cherenkov detectors (TAIGA-HiSCORE) for measuring times of extensive air shower (EAS) light front arrival. Monte Carlo simulations are compared to real data to determine the performance of the detector setup. Dedicated software and algorithms are described, model parameters are given, and an overview of the current status of model-based performance studies is presented.

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INTRODUCTION

The TAIGA gamma-ray observatory is part of the Tunka Astrophysical Center (Buryatia), which also includes components for studying the physics of high-energy cosmic rays [1, 2]. For gamma-ray astronomy, a network of imaging atmospheric Cherenkov gamma telescopes (IACTs) [3] is used in combination with the TAIGA-HiSCORE network of wide-angle optical stations for measuring the time of arrival of EAS light

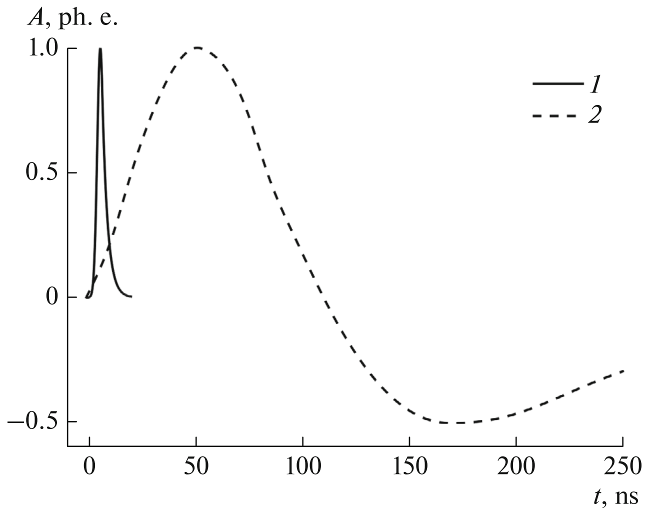

Fig. 1. Simulated form of a single-photoelectron pulse at the output of a pulse shaper: (*1*) fast shaper, the amplitude of whose sum is used in developing a trigger for data collection; (*2*) slow shaper; the amplitude of their sum is determined 35 ns after triggering.

fronts [4]. It is planned to increase the area of the installation to 10 km^2 without using the traditional stereoscopic systems of closely spaced IACTs [5], since good angular resolution helps to suppress the cosmic ray background (~0.1° at an energy of 100 TeV).

The observatory will detect gamma-quanta with energies of 30 TeV and higher (using IACTs in combination with the TAIGA-HiSCORE network) and with lower thresholds of ~1 TeV (in the standalone IACT mode of operation without TAIGA-HiSCORE). Performing these tasks [1, 2, 6] requires careful modeling of its components, i.e., the IACT telescopes and wide-angle optical stations.

SOFTWARE

EASes are modeled using the CORSIKA 7.3500 program [7]. The response of the TAIGA-HiSCORE wide-angle detectors is simulated using special sim_score software [8] based on the IACT/ATMO software package [9]. The response of the IACTs is modeled in two independent ways: using the standard sim_telarray program [9] and the software for simulating the TAIGA telescope developed at the Joint Institute for Nuclear Research (OPTICS-TAIGA) and the Skobeltsyn Institute of Nuclear Physics [10].

PARAMETERS OF THE SIMULATED FACILITY

The telescope consists of 29 mirrors with diameters of 60 cm, arranged according to the Davies–Cotton scheme [11], and a focal length of 4.75 m. In the telescope camera there are 560 hexagonal pixels with angular sizes of ~0.36°. They are composed of photomultipliers (PMTs) and Winston cones [12] that increase the photocathode area of a PMT by a factor of 3. The camera is divided into modules of 28 PMT (4 × 7). The diameter of the telescope camera's viewing angle is 9.6°.

The TAIGA-HiSCORE wide-angle array contains 43 stations (~100 in 2019) in regular grid nodes with steps of 106 m. The stations consist of 4 photomultipliers, the areas of which are quadrupled using Winston cones [12]. The viewing angle is ~ 0.6 sr.

ALGORITHMS

The IACT response is simulated in three steps. First, all EAS Cherenkov photons from CORSIKA are ray-traced [13] with allowance for such factors as absorption in the atmosphere, depending on the wavelength and disregarding multiple scattering; mirror shading; reflection from mirrors according to the laws of classical optics with a reflection coefficient of 0.9 for polished aluminum; random turns of the mirrors, due to their imperfect alignment (blurring of 10 mm at a focal length); random deviation of the direction of the reflected beam, due to the nonideality of the mirror surfaces (blurring of 1 mm at a focal length); the path through the camera protective screen of plexiglass, including the refraction and the input and output reflection coefficients depending on the incidence angle and the wavelength-dependent absorption coefficient in the thickness of the material; and the path through the Winston cones according to their design, and considering only the reflection from an ideal surface with a reflection coefficient of 0.90.

The PMT response is then simulated with allowance for the dependence of the quantum efficiency and the efficiency of electron collection on the photon wavelength, with which the number and time of formation of the photoelectrons in each PMT of the camera are determined. At this stage, the photoelectrons formed by the background light of the night sky are also considered (their number and time of their formation in each PMT are randomized).

A signal processing board based on a MAROC3 specific integrated circuit [14], the trigger conditions for data collection, and the procedure for their analog readout are then simulated. The photoelectron signals at the output of the PMT were spread over time according to the form at the output of the pulse shaper (Fig. 1). The amplitude of the pulses is built from the experimental distribution, including afterpulse [15], after which the pulses at each moment in time are added to the total pulse of one PMT. A trigger in each module of the 28 photomultipliers is activated when the pulse amplitude exceeds the threshold in at least two photomultipliers if the interval between this hap-

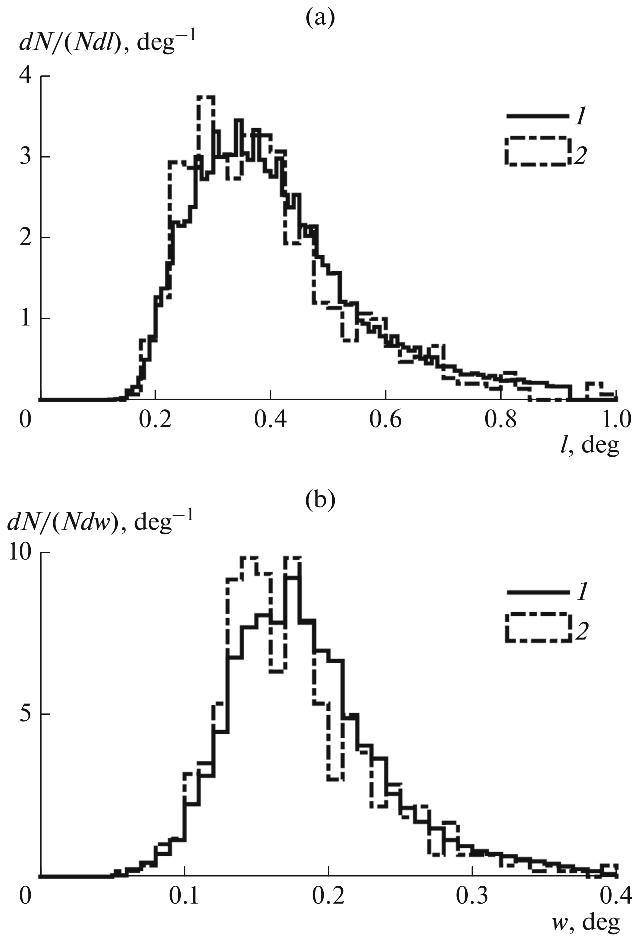

Fig. 2. Distribution of (a) length l and (b) width w of an image in the telescope camera: (*1*) experiment, (*2*) simulation of primary protons with energies of 3–100 TeV under conditions identical to those of the observation in the experiment.

pening in the first and second photomultiplier is less than 15 ns. In all PMTs of the module in which a trigger is activated, the values of the pulse amplitudes at the outputs of the shaper are recorded 35 ns after triggering, in accordance with the results from laboratory measurements.

RESULTS AND DISCUSSION

The described algorithms and software allowed us to collect a simulation databank for refining data analysis and subsequent comparisons with experiments. The databank consists of Monte Carlo simulation of EASes induced by primary gamma quanta with different energy distributions and zenith angles of incidence in the range of 10°–40°, and of EASes from primary protons and nuclei whose angles of incidence deviate from the direction of the telescope's axis by as much as ±10°.

The first results from comparing the model and experiments were published in [1] for a test run of a prototype telescope with six mirrors. For the telescope with 29 mirrors, there was agreement between the model and experimental values of the Hillas parameters [16] (i.e., the length, width (Fig. 2), and total number of photoelectrons of an image [6]). The expected sensitivity of the array in searching for local gamma-ray sources is estimated at $(0.5–1) \times 10^{-13}$ TeV cm^{-2} s^{-1} in the range of 30–200 TeV at 300 h of observing a source [1].

CONCLUSIONS

The TAIGA-IACT and TAIGA-HiSCORE facilities of the TAIGA experiment were modeled in full, with two independent approaches used for the former. The values of the main physical parameters analyzed in the experiment were compared to their model predictions. The model continues to be improved by considering additional factors, comparing it to experiments, and collecting more statistics.

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