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The IACT Optical System of the TAIGA Observatory Complex

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Abstract—TAIGA (Tunka Advanced Instrument for Gamma Astronomy) is designed for studying gamma rays and charged cosmic particles in the energy range of 10^{13}–10^{18} eV. The staff of the Joint Institute for Nuclear Research is now working on the design and fabrication of Cherenkov telescope elements (IACTs). The IACT field of view is ~10° × 10°, due to a Davis–Cotton optical layout with 34 mirrors 0.60 m in diameter, a focal length of 4.75 m, and 560 XP1911 PMT camera. The first IACT was commissioned in 2016 in the Tunka Valley. The second IACT is now being prepared for operation. The steps of PMT alignment and the results from its calibration are thoroughly described along with the fabrication of a mirror and its optical parameters. The technique for adjusting the mirror is presented as well. It replaces the conventional visual assessment of the image with pattern recognition software that is applied to a screen shot of the calibration source. This software ensures highly precise calculations of the mirror's adjusting screws to obtain a correct image.

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INTRODUCTION

In recent decades, many researchers have focused on identifying cosmic ray (CR) sources and understanding the mechanisms of their acceleration and propagation. The Galaxy is expected to contain objects that can accelerate CR to energies above 10^{15} eV (Pevatrons), though there is still uncertainty about their nature. Since CR acceleration obeys hadron kinematics, these objects must also emit gamma rays at energies of up to 100 TeV and have to be measured in order to univocally identify the pevatron sources. Data on CRs above 100 TeV are available through ground-based extensive air shower (EAS) experiments. Despite the large volume of available information, the origin and propagation of CRs remain in question. Sources of gamma radiation with energies above 100 TeV are still unknown, due to the limited light-gathering capability of existing gamma observatories. To solve this problem, the TAIGA collaboration has developed a hybrid setup composed of different types of detectors that cover an area of more than 1 km^2. As part of this array, the IACT will improve the sensitivity of the entire system and improve the efficiency in distinguishing gamma and hadron–nuclear CR components. This hybrid technique will therefore improve the efficiency in pevatron detection as well.

THE TAIGA-IACT PROJECT

IACT setups are state-of-the-art tools for TeV gamma ray astronomy that allow us to measure gamma radiation spectra. The gamma ray energy is determined by processing images acquired by the IACT photodetector. With stereoscopic systems composed of several IACTs that ensure EAS monitoring from different viewing angles, the location of the shower axis and the distance from the telescope to the axis can be determined via simple geometric reconstruction. For singular IACTs, the distance to the shower axis can be found by analyzing the Cherenkov image using the set of HiSCORE detectors that are part of the TAIGA system.

The main shortcoming of experiments with the IACT–HESS [1], MAGIC [2], and VERITAS [3] instruments is their poor sensitivity to gamma rays with energies $E > 15$–20 TeV, due to the small effective area of the setups (0.1 km^2). This prevents us from detecting gamma rays with energies on the level of ~100 TeV. To solve this problem, the TAIGA complex includes HiSCORE wide-angle Cherenkov detectors with viewing angles of around 0.6 sr and EAS angular resolutions of 0.1°–0.2°, along with several IACTs that improve the low-energy sensitivity, allowing high angular resolution to be retained [4].

The benefit of using IACTs in combination with the HiSCORE array is more accurate gamma hadron separation with respect to the EAS image, while the position, direction to, and energy of the EAS axis can be reconstructed by the HiSCORE detector system (Fig. 1). The IACT/HiSCORE hybrid approach ensures better results than each individual component, allowing the background hadron showers of CRs to be suppressed

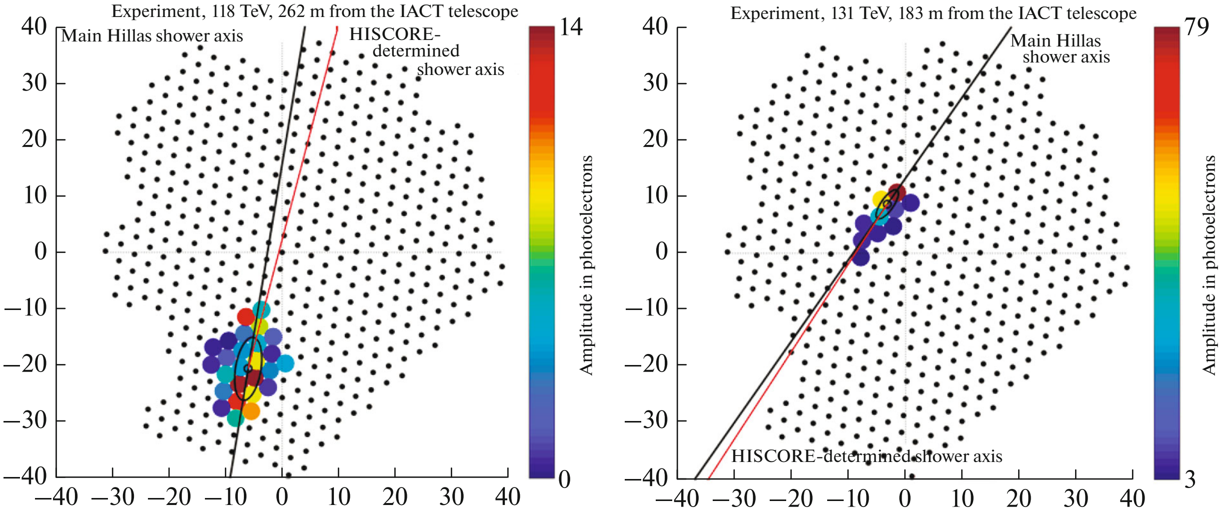

Fig. 1. EAS patterns obtained by an IACT camera with a fixed position and direction of the axis.


(a)
(b)

Fig. 2. (a) First and (b) second IACT telescopes (September 2018).

by approximately 100 times at an energy of 100 TeV for point sources, and the distance between IACTs to be increased to 600 m while retaining EAS precision.

In 2019, there will be 100–120 TAIGA–HiSCORE stations per 1 km^2, and the number of IACTs (Fig. 2) will be increased to three. In the future, the area of the equipment will be expanded to 5 km^2, so the sensitivity at energies of 30–200 TeV will be as high as 10^{-13} erg cm^{-2} s^{-1} over 500 h of observations [5].

TELESCOPE FABRICATION AT THE JOINT INSTITUTE

The elements of IACT gamma telescopes for the TAIGA experiments were produced at the Joint Institute on the basis of a HEGRA telescope. IACTs are atmospheric Cherenkov telescopes with a Davis–Cotton optical layout. It has an alt-azimuth configuration, individual spherical mirror modules 0.6 m in diameter, and a total mirror area of 9.6 m^2. The viewing angle is ±5°, the angle of rotation around the horizontal axis (the zenith angle) is −10° to + 95°, and the one around the vertical axis (the azimuth angle) varies from 0° to 410°. The angular accuracy is 0.01°, and the rate of rotation is 1–2 deg/s. The setup also allows remote PC control over the telescope, and the photoreceiver camera with dimensions of 750 × 750 × 400 mm is a PEM matrix with FE and DAQ electronic elements. The diameter of each PEM element is 15 mm. Each element has a 30 mm Winston cone at its entrance, ensuring IACT angular resolution on the level of 0.36°. A camera with a focal length of 4750 ± 1 mm and as heavy as ~200 kg is mounted in each telescope. The conditions of operation include temperatures of −40 to +30°C at high humidity.

All PEM cameras are calibrated for different modes of operation. Dark currents and gains are measured for different supply voltages. PEMs are grouped in the camera into clusters according to their characteristics, which should simplify the camera settings and signal recovery.

The focusing mirrors are produced at the Joint Institute by bending. A steel mold and a glass blank are heated in a furnace in a controlled manner for 48 h. A glass disk is thus deformed and acquires the spherical shape of the steel mold through gravity. A special mode of temperature variation allows us to achieve a sufficiently smooth surface. Current trials are aimed at increasing the smoothness of a final product in order to avoid polishing the mirror, and to minimize the curvature errors to the values required for the TAIGA–IACT system while retaining a focal spot diameter of 3 mm. It has been proposed that convex shape of the mold be changed to concave. At the same time, the surface of the future mirror is not in contact with the mold's surface. The quality of the glass disk (the uniformity of thickness is around 0.02 mm with a diameter of 600 mm) ensures that molding the mirror's surface minimizes further treatment.

GUIDING AND POSITIONING SYSTEM

Rotation around each axis is provided by Phytron ZSH107/4.200.12.5 stepper motors. Each one is equipped with a planetary gear box (gear ratio, 40; maximum luft, 16'; maximum torque, 17 N m) and a worm gear (gear ratio, 50; nominal torque, 1450 N m). The engine performs a full rotation in 200 steps in the full-scale mode. A telescope thus makes a full rotation in 400 000 steps. The position of the angular axis is controlled by Hengstler absolute encoders (resolution, 17 bit; SSI Grey code). Each axis is also equipped with two limit switchers. The stepper motors, encoders, and limit switchers are connected to a PhyMOTION stepper motor controller. In addition to other functions, the controller supports the step crushing mode to 1/512 of a full step, which can be used in the telescope's anti-aliasing tracking. Remote access to a controller is available through the Ethernet.

The exact orientation of the telescope to the sky can be determined using a Prosilica GC1380 CCD camera. The viewing field of a CCD camera is around ~30° × 20°. The angular resolution is ~83 angular seconds, which allows an image of the sky to be captured with the observed source by the telescope's camera. The sky coordinate system can be linked to the position of the Cherenkov camera. Each CCD camera has a resolution of 1360 × 1024 pixels and contains a 12-bit ADC. The camera can work at speeds of up to 20 frames per second, and the exposure time can be set from microseconds to one minute. Data acquisition and remote control are provided through the Ethernet [6].

MIRROR ALIGNMENT SYSTEM

The mirrors in the telescope are nestled in individual orientation flanges and are aligned manually. The conventional procedure was modified into two-step manipulation to increase the accuracy of alignment. The point source image created by an individual mirror is first displayed far from the focus so it can be associated with a certain mirror. The focal pattern is then captured by the camera, generating recommendations on mirror orientation by dedicated software for achieving highly accurate alignment.

CONCLUSIONS

The first IACT is now operating as part of the TAIGA installation. The elements of the second gamma telescope have been produced and tested at the Joint Institute for Nuclear Research. The second gamma telescope is currently undergoing field trials in the Tunka Valley. The staff of the Joint Institute has developed the technology for the production and control of IACT mirrors. The third IACT telescope is now being designed as well.

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