Hybrid method for study multi TeV gamma rays in the TAIGA astrophysical complex: methodics and results.

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The TAIGA astrophysical complex includes now 3 IACTs at the distance 300-500 m between each other and 1km2 area wide-angle timing array TAIGA-HiSCORE. At energies above 40 TeV, a hybrid approach to the detection of gamma-rays becomes possible - the detection of EAS by both IACTs and the TAIGA-HiSCORE installation. The main advantage of the joint operation of the IACTs and timing is their good gamma/hadron separation, even by only few telescopes on the large area, by image parameters information and EAS another parameter (core position, direction and energy) that can be better reconstructed by the timing array. In this paper the following topics of a hybrid method are discussed: data processing and analysis, a comparison experimental results with Monte-Carlo simulations, selection of the first events with the energy more than 100 TeV from Crab Nebula in 250 hours of observation. The data were taken during the period of installation deployment, with one IACT in operation and half of the area of TAIGA-HiSCORE installation.
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1. Introduction

Gamma-ray astronomy is a promising field of research of galactic and extragalactic sources of gamma radiation. Modern studies show that galactic objects, such as the Crab Nebula, are capable of generating radiation with energies above 100 TeV (HAWC [1], LHAASO [2]). But the origin of radiation (electromagnetic or hadronic) is not understood yet. Until now, most of gamma-ray quanta with energies above 100 TeV are detected only by ground-based observatories that register the charged component of the EAS. This is due to the fact that such instruments are capable of conducting observations regardless of weather conditions and seasons. Observatories that register Cherenkov radiation of the EAS are able to work only on clear moonless nights and it is necessary to have a high effective area to accumulate significant statistics. The aim of TAIGA gamma-ray observatory is to detect gamma rays with energy more than 100 TeV by Cherenkov light with increasing the effective area of installation [3, 4].

2. TAIGA gamma-ray observatory

Currently, on an area of ~1 km², the TAIGA Astrophysical Complex [5] (Fig. 1) includes three atmospheric Cherenkov telescopes of the TAIGA-IACT installation [6] (Imaging Atmospheric Cherenkov Telescope), wide-angle Cherenkov detectors of the TAIGA-HiSCORE installation [7, 8] (High Sensitivity COSmic Rays and gamma Explorer) and other installations.

Fig. 1. TAIGA gamma-ray observatory

To cover the entire energy range available for observation, the TAIGA experiment uses three modes of registration of Cherenkov radiation of EAS: monoscopic, stereoscopic and hybrid (Fig. 2). The monoscopic mode is used to register gamma quanta with energies of more than 3-5 TeV with only one IACT. To detect gamma quanta with energies above 10 TeV, it is possible to use a stereoscopic approach - the EAS is recorded by two or more IACTs of the TAIGA–IACT installation.
The hybrid approach combines data obtained by TAIGA-IACT and TAIGA-HiSCORE installations. This method is unique for modern gamma experiments and is aimed to register gamma quanta with energies of more than 40 TeV. An energy, an arrival direction and the position of the axis of the EAS are reconstructed by analyzing the data of the TAIGA-HiSCORE installation. A type of primary particle is determined by the image parameters detected by the TAIGA-IACT telescope [5].

2.1 TAIGA-HiSCORE

The TAIGA-HiSCORE installation is a network of 120 wide-angle Cherenkov detectors (stations) located on an area of 1.1 km², grouped into 4 clusters and designed to register Cherenkov radiation of EAS. The distance between the detectors is 106 m. Every i - station measures a signal amplitude Am(T), Cherenkov light flux Q(i), and time T(i) with nano second accuracy. Primary reconstruction of the EAS zenith (θ) and azimuth angle (φ) is done by fitting time, T(i), with plane model of the shower front. Reconstruction of the shower core position (X0, Y0) is done by fitting Am(i) of the data with the amplitude distance function (ADF) [6]. Final reconstruction of (θ, φ) with known core position X0, Y0 is done by fitting T(i) with the curved model of shower front [6]. This step results to significant improvement of angular resolution. Fitting Cerenkov light Q(i) by lateral distribution function [6] one can measure energy of EAS. The accuracy of arriving direction reconstruction is estimated as 0.1°-0.4°, of core position as 10-40 m, of energy estimation as 0.05-0.2 (in log scale) in dependence on number of hit stations [6].

2.2 TAIGA-IACT

The methods of identification of primary high-energy gamma quanta above hadron background in ground-based gamma astronomy have been developed during last two decades and reach very high level of efficiency. In experiment TAIGA every telescope has an alt-azimuth
mount, a 4.3 m diameter reflector and a recording camera in focus. The reflector consists of separate spherical mirrors of the Davis –Cotton system with an area of ~10 m² and a focal length of 4.75 m [10, 11]. The cameras of the telescopes provide an angular view of 9.6° and include matrices consisting of 600 PMT (pixels) with a photocathode diameter of 2 cm each (XP1911). Each pixel has an angular size of 0.36° [11].

### 2.2.1 Reconstruction of TAIGA-IACT events

In TAIGA experiment the observations were carried out in wobble mode, using alternating offsets of the pointing positions of ±1.2° to the position of the Crab Nebula pulsar. The wobble direction changes every 20 minutes from +1.2° to -1.2°, that provides the suitable procedure of selection of background pointing. The selection criterion for good-quality data is a cut on the trigger rate of a portion, rejecting those portions with rates larger than an expected zenith angle corrected rate by more than 2 standard-deviations ~7 Hz to 15 Hz.

Data processing of the TAIGA-IACT installation consists of the following steps:

1. Reconstruction of the amplitude matrix Am (Xi, Yi) (Xi, Yi – pixel coordinates): subtraction of the pedestal values in each pixel, recalculation of the amplitude values of the currents into photoelectrons, introduction of corrections for the sensitivity of the PMT.

2. Cleaning procedure – cleaning the Cherenkov image of the EAS in the telescope camera from pixels, the amplitude of the signal in which is associated with fluctuations in the light background.

3. Calculation of the Hillas parameters (parameters of the Cherenkov image of the EAS).

   The selection of events generated by high-energy gamma quanta is carried out on the basis of the analysis of the shape of the Cherenkov image of the EAS according to the method proposed by Hillas [12] (Fig. 3). Depending on the type of primary particle, the images obtained in the telescope camera have a different shape, which allows using simulation to isolate gamma quanta on a hadron background.

4. Formation of hybrid events as events detected by both the IACT and by 3 or more Hiscore stations in 3 mks time window.

### 3. Processing of experimental data

The observation of the Crab Nebula source (RA = 83.63°, DEC = 22.01°) by the TAIGA observatory was carried out for three seasons in the period from 2019 to 2022. The total observation time for hybrid events was ~ 250 hours. Figure 3 shows the distribution of RA and DEC angles, reconstructed from the data of the TAIGA-HiSCORE installation, for hybrid events. The average value of the distribution coincides with the position of the source.
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Fig. 3. Distribution of hybrid events by RA and DEC angles. The red dot is the position of the Crab Nebula source

To separate gamma-like events according to TAIGA-IACT data, the following parameters are used:

- Dist – distances from the center of the ellipse to the point where the source and the anti-source (background point) are located;
- Width – a measure of the standard deviation along the minor axis of the ellipse;
- Size – the total number of photoelectrons in the event.

According to TAIGA-HiSCORE, the following are used:

- Xs, Ys – the restored position of the EAS axis on the ground;
- Rtel – distance from the EAS axis to the telescope;
- Energy – recovered EAS energy;
- dgam – the angle between the direction to the source (background) and the restored direction of the arrival of the EAS. It is the main parameter for evaluating the results obtained.

Fig. 4. Distribution of source and background positions in celestial coordinates
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To increase the statistical significance of the observed signal, the calculation of which is carried out by the expression \( Li\&Ma \) [13], the assessment of background events (‘off’) is carried out by 9 points. Each background point in the telescope camera was recalculated into celestial coordinates (Fig. 4), which allows using the same background position for two installations, from which the \( dgam \) parameter is calculated.

For identification of gamma-like events there were elaborated cuts, based on MC simulation of both types of detectors: HiSCORE timing array and IACT. The simulations performed in 4 steps. On the first step a shower development in the atmosphere was simulated by CORSIKA; on the second step Cherenkov photons of the shower were traced through the optical system of the IACT and optical system of the every station of HiSCORE, by program TAIGA OPTICA [14], including many details of Cherenkov light tracing in Optic system and registration; on the third step the trigger conditions were included in simulations, on the forth step methods of shower arrival direction, energy and core position reconstruction, used in experiments, were implemented in program. The threshold region of shower detection is most complicated for reproduction in simulation. To adjust little-known parameters we have achieved a satisfactory description of the most important parameters such as a counting rate of 4 and more hit stations, energy and size spectra of different samples of events. Using Monte Carlo simulation, optimal cuts for the different parameters of hybrid events were obtained, when the maximum number of suppressions of the hadron background is reached \( \sim 10^{-4} \), but a suppression of gamma quanta not exceed 50% (Fig. 5). The most effective two cuts are presented in Fig3. The effective area was calculated for these optimal criteria on MC events as \((0.25 - 0.3) \text{ km}^2\) for energy interval 100-1000 TeV.

![Diagram](image.png)

**Fig. 5.** Dependence of the width parameter on size (left); dependence of the dist parameter on the distance from the EAS axis to the telescope Rtel (right);

At the final stage we analyze a distribution by \( dgam^2 \) parameter (\( dgam \) - is the angle between shower axis, reconstructed by HiSCORE data, and direction to Crab Nebular for ‘On’ events or to direction of background positions for ‘Off’ events. Two these distributions are presented in Fig. 6. The maximum difference of ‘On’ and ‘Off’ events is seen in the range up to 0.25°, where the average number of background events is 199 events, the number of events from the source is 224 events, excess is 25 events.
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Fig. 6. Distribution by the $d\gamma m^2$ parameter after suppression of background events

For the selected hybrid events, an energy spectrum was constructed as $F(E)^{on} - F(E)^{off}$ (Fig. 7) for 250 hours of observations. In the energy range up to 100 TeV, the resulting number of gamma quanta contains high uncertainty due to high number of background events. The error bars were calculated in accordance to [13]. The threshold energy estimate for the selected gamma-like events is $\sim 75$ TeV.

Fig. 7. The measured by different methods spectra from the Crab nebula in TAIGA experiments: in mono, in stereo modes from [15] and in hybrid mode, obtained in this work

Figure 7 shows the energy spectrum of gamma-like events from Crab Nebula, obtained during 150 hours of observation in mono and stereo mode in earlier TAIGA work [15], in comparison with world data, and 3 last points, obtained by hybrid mode in this work, are presented. There is a satisfactory agreement with the spectra measured by 3 methods and spectra, obtained in other world experiments.
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Conclusion

In the course of the work a hybrid method for searching for high-energy gamma quanta from the Crab Nebula source was worked out. An energy spectrum in the region of around 100 TeV was obtained. A preliminary estimate of the threshold energy for the selected gamma-like events is \( \sim 75 \) TeV.

Further work involves carrying out more detailed modeling of hybrid events on full HiSCORE area that will give the basis to refine the Crab spectrum in the region \( > 100 \) TeV, which is an important result for the method of registering EAS by detecting Cherenkov radiation.

The effective area for the registration of gamma quanta by the hybrid method at the full HiSCORE area and with five IASTs is expected to be 1.1 km\(^2\) for energy above 100 TeV. It is planned to deploy external HiSCOREc stations with a large distance between optical stations to increase the effective area at an energy above 200 TeV.

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