Analysis of the TAIGA-HiSCORE data

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Abstract. TAIGA-HiSCORE is an extensive air shower array of 120 Cherenkov detectors spread over an area of 1 km\(^2\). It is designed to detect cosmic rays with energies from 50 TeV to 1000 PeV. Also TAIGA-HiSCORE is planned to use for gamma-ray astronomy in cooperation with the other installations of the TAIGA observatory. This work is dedicated to the analysis of the TAIGA-HiSCORE single-mode data. We consider a possibility to detect gamma-ray point source with excess of events from the source direction. For this purpose, a method for estimation of the signal significance is proposed. It takes into account the angular acceptance of the TAIGA-HiSCORE installation. The method is tested on the Monte-Carlo toy model.

1. Introduction
TAIGA-HiSCORE is a part of astroparticle observatory TAIGA [1]. The array consists of 120 detectors of air shower Cherenkov emission on an area of \(S_{\text{arr}}=1\) km\(^2\). Effective area of one detector is 0.5 m\(^2\), view angle is 0.6 sr. The detectors are tilted 25\(^\circ\) to South in order to maximize observation time of Crab nebula. Therefore we can analyze field of view (FoV) of the installation because TAIGA-HiSCORE detectors are pointed in the same direction.

Each detector is equipped with four photomultiplier tubes (PMT) combined with Winston cones – parabolic concentrators of Cherenkov photons [2]. The installation has a specific angular acceptance due to PMT and cone features. The FoV has decreasing sensitivity on the edge (25\(^\circ\)–30\(^\circ\) from the center of FoV) due to the cone and asymmetry on central part due to orientation of the PMT dynode system [3]. In addition, there is a dependence of the sensitivity on the zenith angle due to the thickness of the atmosphere. These properties must be taken into account for data processing. In [3] it is proposed to use the weight functions to compensate the asymmetries.

TAIGA-HiSCORE has no gamma-hadron separation but has good angular resolution at high energies of cosmic ray primary particles (0.1\(^\circ\) at \(E \geq 400\) TeV). There is a possibility to detect gamma-ray sources by excess of number of events from source position above background cosmic ray events. But at lower energies (100-300 TeV) the installation has a worse angular resolution (0.4\(^\circ\) - 0.5\(^\circ\)). In this work a method of signal significance estimation is proposed for this case.

2. Method for signal significance estimation
The arrival direction of the primary particle is reconstructed with an error due to the angular resolution of the installation. Let the spread of the reconstructed directions of events from a point source be determined by the bivariate normal distribution with standard deviations \(\delta_x = \delta_y = \delta\) and angular distance \(r\) from the source to an event. Then the probability that an
event falls into the area of radius $R$ is

$$F(R) = \int_0^R \int_0^{2\pi} \frac{1}{2\pi\delta^2} \exp\left(-\frac{r^2}{2\delta^2}\right) r \, dr \, d\phi$$  \hspace{1cm} (1)

It is proposed to move along the coordinate grid around the source with a given step and to summarize the events from the area with radius $R = 3\delta$ at each point, applying weights $w(r) = \exp(-r^2/2\delta^2)$ to the events. Thus, we get a hypothetical initial signal level $S(x, y)$ at each point $(x, y)$:

$$S(R) = k \int_0^R \int_0^{2\pi} \rho(r) \exp\left(-\frac{r^2}{2\delta^2}\right) r \, dr \, d\phi$$  \hspace{1cm} (2)

where $k$ is normalizing coefficient, $ho(r)$ - event distribution law. In the case of the point source $N_s$ detected events are distributed as

$$\rho(r)_s = \frac{N_s}{2\pi\delta^2} \exp\left(-\frac{r^2}{2\delta^2}\right)$$  \hspace{1cm} (3)

Substituting expression (3) into (2), we obtain initial signal in the source position $S_s = kN_s/2$. It must be equal to $N_s$ therefore $k=2$.

Taking into account the average density of background events $\langle \rho_{bg}(r) \rangle = \rho_{bg}$, we obtain the conditional value of the noise signal $S_{bg} = 4\pi\delta^2 \rho_{bg}$. This value is used to determine the number of events from the source $N_s^{\text{min}}$, required to obtain a valid source signal $N_s \geq 5\sigma$:

$$N_s^{\text{min}} = 5\sqrt{S_{bg}} = 5\sqrt{4\pi\delta^2 \rho_{bg}}$$  \hspace{1cm} (4)

So, for $\rho_{bg} = 10^4/\text{deg}^2$ and $\delta=0.3\ \text{deg}$ we obtain $N_s^{\text{min}}=532$. Figure 1 shows the simulation results for such a case.

![Figure 1](image.png)

**Figure 1.** Monte-Carlo simulation of background (BG) and source (S) events: (a) 2D histogram of BG ($\rho_{bg} = 10^4/\text{deg}^2$) and 550 S events; (b) signal significance of BG+S events distribution.

It should be taken into account that in case of a lack of background events near the source position we need to have $N_s^{\text{min}} > 5\sigma$. For example, if the signal significance of background events is $-3\sigma$ in the source area, it is necessary to have $N_s^{\text{min}} \geq 8\sigma$. 

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This document provides a comprehensive explanation of the methodology used to calculate the signal significance and the minimum number of events required for a valid source signal. The equations and diagrams illustrate the process, and the figures demonstrate the simulation results for a specific case.
3. Application of the method

The proposed signal estimation method was applied on the experimental data of the TAIGA-HiSCORE installation. The events for 3 years of observations (2017–2020) were selected in the area with radius of 5° around the Crab Nebula in several energy ranges from 100 to 300 TeV. For each energy range, correction weight functions were determined in accordance with zenith angle and radial distributions of the events in the FoV of the installation.

Since distribution of detected events becomes more uniform with energy increase [3] correction almost is not required. But on the other hand Crab nebula event flux decreases with energy. Figure 2 shows the results of correction and signal estimation for two optimal energy ranges.

![Figure 2](image1.png)

**Figure 2.** Signal significance of the event distributions: ∼90000 events with $E=100\div125$ TeV without correction (a) and with correction (b); ∼100000 events with $E=125\div160$ TeV without correction (c) and with correction (d).

The influence of the dependence on the zenith angle in the distributions of events without correction is noticeable. After correction, the distribution approaches the normal one within $(-3\sigma, +3\sigma)$.

4. Conclusion

We propose a method for detecting a gamma-ray source by exceeding the number of events from the source direction above the level of background cosmic rays. An estimate was obtained for
the ratio of the number of events from the source to the background to detect the source.

The method is applied on the the TAIGA-HiSCORE experimental data. The data were prepared for the application of the method by leveling the distribution of events around the source using the weighting functions. The functions were obtained from zenith angle and radial distributions of the events in the field of view of the installation.

At the moment, this method has not allowed us to detect the signal from the Crab Nebula due to the insufficient number of detected events. But the obtained results demonstrate the alignment of distributions towards the normal distribution in the range close to (-3σ, + 3σ).

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References
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