Analysis of the TAIGA-HiSCORE data

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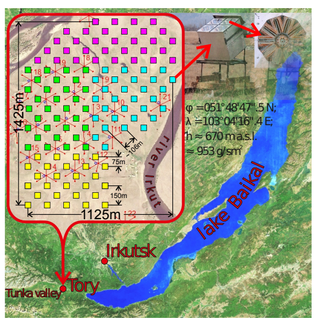
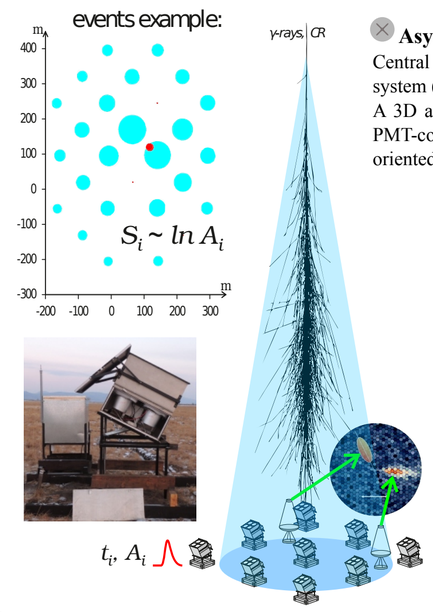
TAIGA-HiSCORE is an extensive air shower array of 121 Cherenkov detectors spread over an area of 1 km^2. It is designed to detect cosmic rays with energies from 50 TeV to 1000 PeV. Also TAIGA-HiSCORE is planned to use for gamma-ray astronomy in cooperation with the other setups of the TAIGA observatory.
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 we propose a method for estimating the signal significance. It takes into account the angular acceptance of the TAIGA-HiSCORE setup. The method is tested on the Monte-Carlo toy model.

TAIGA-HiSCORE array

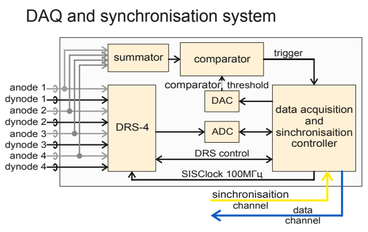
is a part of astroparticle observatory TAIGA [1]. Today the array consists of 80 detectors of air shower Cherenkov emission on an area of Sarr=0.7 km^2. Effective area of one detector is 0.5 m^2, view angle is 0.6 sr. Detectors of the first two clusters are tilted 25° to south. Signal is digitized with 0.5 ns step and timing accuracy of 0.1 ns

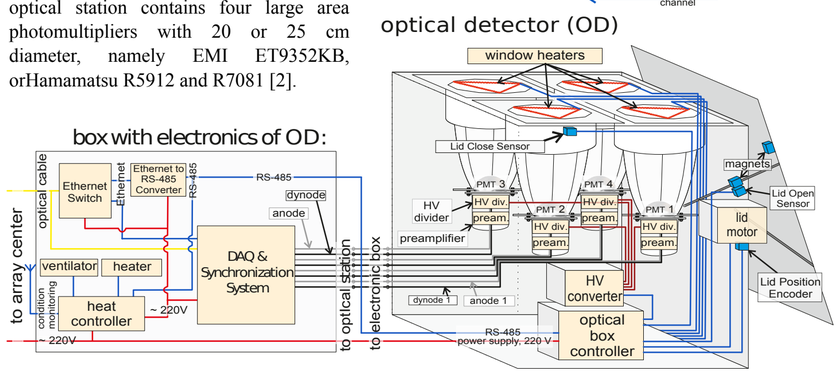




Optical detector

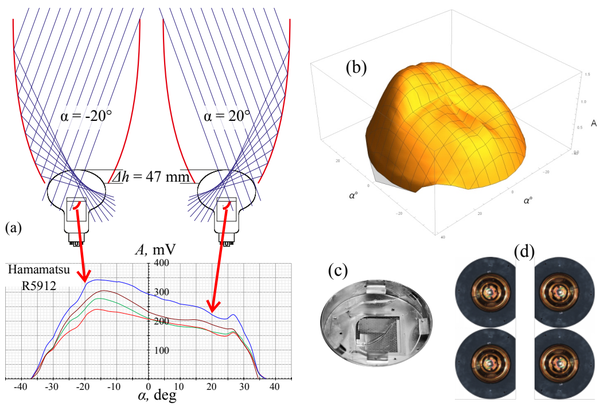
is a metal box (size of 1×1×1 m^3) with remotely-operated lid to protect against sunlight, atmospheric precipitations and dust. This metal box contains the optical station controller, highvoltage power supply unit (HV), heaters for the plexiglass input windows, photomultipliers with voltage dividers and preamplifiers. Each optical station contains four large area photomultipliers with 20 or 25 cm diameter, namely EMI ET9352KB, orHamamatsu R5912 and R7081 [2].





Asymmetry of angular sensitivity

Central part of angular charactrisctichas asymmetry (a, b) due to the orientation of the PMT dynode system (c). With increasing high voltage, the asymmetry of the central part increases.
A 3D angular characteristic was obtained for one PMT Hamamatsu R5912_SD2886 using optimal PMT-cone mutual position. The two upper and two lower PMTs in each station are oppositely oriented (d). Therefore, the angular characteristics of these pairs are mutually compensated.



Signal estimation method

It is assumed that events coming from a point source are recorded by the setup with a certain error due to its angular resolution. Let the spread of events be a bivariate normal distribution with standard deviations $\delta_x=\delta_y=\delta$ and angular distance r from the source to an event:

$$f(r) = \frac{1}{2\pi\delta^2}\exp\left(-\frac{r^2}{2\delta^2}\right) \quad (1)$$

Then the probability of an event falling into a circle of radius R is

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

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 $R=3\sigma$ at each point, applying weights $w(r)=\exp(-r^2/2\sigma^2)$ to the events. Thus, we get a hypothetical initial signal level $S_{(x,y)}$ at each point (x,y):

$$S(R) = k\int_0^{2\pi}\int_0^{R}\rho(r)\exp\left(-\frac{r^2}{2\delta^2}\right) r\,dr\,d\phi \quad (3)$$

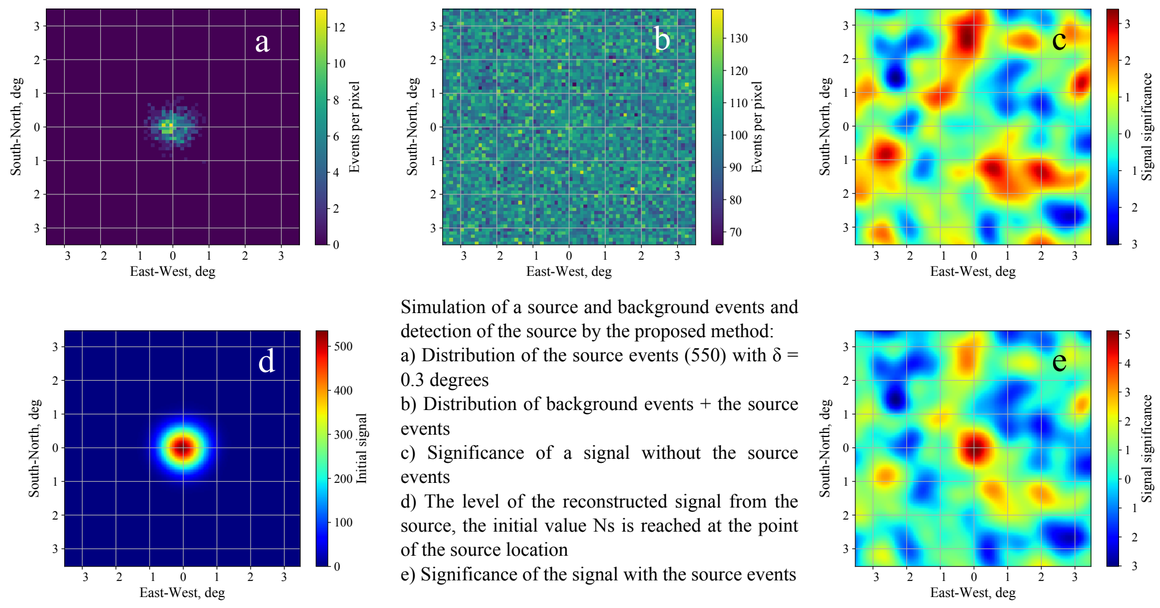
where k - normalization factor, ρ(r) - event distribution law.
In the case of the point source, Ns registered events are distributed as

$$\rho(r) = \frac{N_s}{2\pi\delta^2}\exp\left(-\frac{r^2}{2\delta^2}\right) \quad (4)$$

Substituting expression (4) into (3), we obtain $S_S = kN_S/2$, then $k = 2$.
Taking into account the average density of background events $\rho(r)=\rho_{bg}$, 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, required to obtain a valid signal (5σ):

$$N_s = 5\sqrt{S_{bg}} = 5\sqrt{4\pi\delta^2\rho_{bg}} \quad (5)$$

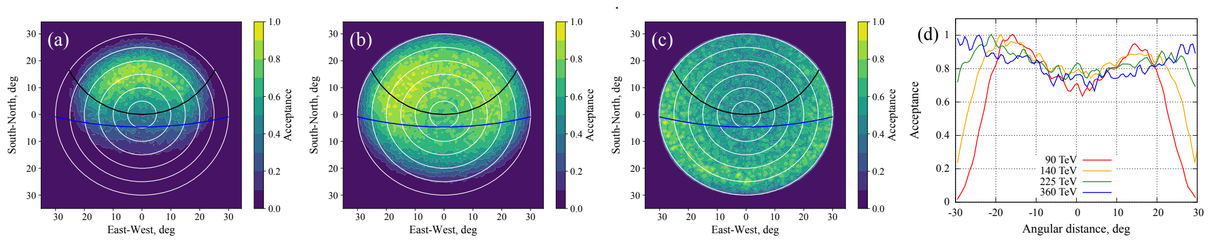
So, for $\rho_{bg}=10^4$/deg^2 and $\delta=0.3$ degrees we obtain $N_s=532$. The figures below show the simulation results for such a case. It should be taken into account that in case of a lack of background events near the source position we need to have $N_s>5\sigma$. For example, if the signal significance of background events is -3σ in the source area, it is necessary to have $N_s=8\sigma$.



Simulation of a source and background events and detection of the source by the proposed method:
a) Distribution of the source events (550) with δ = 0.3 degrees
b) Distribution of background events + the source events
c) Significance of a signal without the source events
d) The level of the reconstructed signal from the source, the initial value Ns is reached at the point of the source location
e) Significance of the signal with the source events

Angular acceptance of the TAIGA-HiSCORE

In [3], the distribution of recorded events in the field of view (FoV) of the installation was determined. It is associated with the design features of the detectors: PMT orientation and Winston cone properties. The resulting distribution is summed up from the dependence on the zenith angle of arrival of the primary particle and the angular distance from the center of the field of view (radial distribution).
Figures below show distribution of the detected events for different energy ranges with no zenith angle correction: a) 50 -100 TeV, b) 100 - 300 TeV, c) 300 - 1000 TeV.
The distribution becomes more uniform with increasing energy due to more transparent atmosphere for high energy events. In order to obtain radial distribution we selected events in a range of zenith angles 25°±0.5° (black line on fig. a-c). Radial distribution also becomes more uniform with energy increase above 200 TeV (fig. d). There is an asimmetry below 200 TeV because of some detectors with 3 PMTs instead of 4.

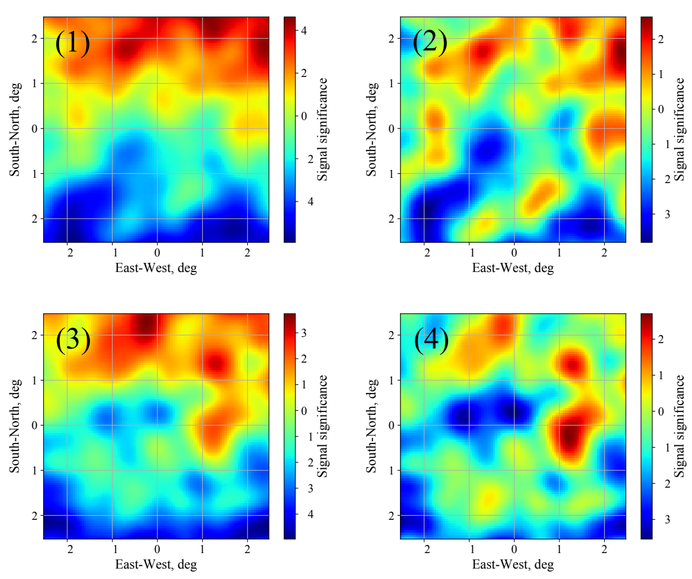


Data analysis

The proposed signal estimation method was applied on the experimental data of the TAIGA-HiSCORE installation for 3 years of observations (2017-2020).
The events were selected in the area around the Crab Nebula with radius of 5° around the Crab Nebula in several energy ranges. For each energy range, correction weights for events were determined in accordance with their distributions - zenith angle and radial - in the field of view of the facility. The figures on the right show the results:

100 -125 TeV, about 90,000 events
1) without correction, 2) with correction
125 - 160 TeV, about 100,000 events
3) without correction, 4) with correction

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 (-3σ, + 3σ).



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 CR

- 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 obtained from their distributions of events in the zenith angle and radial distribution in the field of view of the installation

- the obtained results demonstrate the alignment of distributions towards the normal distribution in the range close to (-3σ, + 3σ)

- at the moment, this method has not been able to detect the signal from the Crab Nebula due to the insufficient number of registered events

References:

1) N. Budnev et al., *TAIGA: A Complex of Hybrid Systems of Cooperating Detectors for Gamma Astronomy and Cosmic Ray Physics in the Tunka valley*. Bull.Russ.Acad.Sci.Phys. **83** (2019) no.8, 951-954

2) O. Gress et al., *The wide-aperture gamma-ray telescope TAIGA-HiSCORE in the TunkaValley: Design, composition and commissioning.* Nucl. Inst. Meth. in Phys. Res. A **845** (2017) 367–372

3) V. Samoliga and A. Pakhorukov. *Correction for angular acceptance of the TAIGA-HiSCORE.* IOP Publishing **15** (2020) no.7, C07010-C07010

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