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An approach for identification of ultrahigh energy extensive air showers with scintillation detectors at TAIGA experiment

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Abstract: The TAIGA astroparticle observatory is under development at Tunka valley close to the Baikal Lake. This simulation study is concentrated on the ultrahigh energy extensive air showers (EAS) induced by gamma-quanta or proton in the range from 1 PeV to 10 PeV and zenith angle ranging 0°–45°. For this work, a set of air showers was created by CORSIKA software package. The list of useful secondary particles at the ground level is produced using the COAST library package. The interaction of secondary particles with the soil and detectors was simulated with GEANT4 package. The method based on neural network has been developed for the separation of EAS induced by gamma-quanta or proton. The air showers having energy ranging 1–10 PeV show more than 90% of identification efficiency of protons while keeping identification efficiency of gamma around 50% or more.

Keywords: Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc); Particle identification methods; Performance of High Energy Physics Detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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Contents

1 TAIGA-experiment

The scintillation detection array of the TAIGA experiment has been extended last year by three new stations. Nowadays, the TAIGA experiment consists of 2 imaging air Cherenkov telescopes, 85 wide-angle optical detectors, and 428 scintillation detectors [1]. The existing scintillation array, Tunka-Grande, has been collecting data since 2016. This new type of scintillation detectors was developed specially for TAIGA experiment at Novosibirsk State University and Budker Institute of Nuclear Physics [2]. The detectors have detection area of 0.94 m^2 and 48 detectors are installed as three different stations. Each station contains 16 counters (8 surface counters and 8 underground counters). The simulation study of optimal station positioning and separation of gamma-quanta and proton induced EAS in the energy region 0.1–1.0 PeV was done earlier [3]. This simulation study is conducted to find an identification method giving the optimal station position for separation of gamma-quanta showers from proton background showers in the energy region from 1 to 10 PeV.

2 Simulation

For this study a dedicated code has been developed using CORSIKA [3] and GEANT4 software packages [5, 6]. The COAST library [7], FLUKA library packages [8], and several standard C++ programs were used as supporting tools.

2.1 EAS simulation

A set of EAS from gamma-quanta or proton were created by using CORSIKA-76400. The showers were simulated with QGST4-II (hadronic interaction) and FLUKA-2011 (low energy interaction) options. This simulation did not consider Cherenkov photons. Standard energy cuts were used for electromagnetic particles (0.501 MeV) and hadrons (100 MeV). The shower core was randomized to 450 m radial circumference. So the shower cores were distributed by area covering all scintillation detector installations. Two sets of EAS were used for this study, with fixed energies and angles, and known range of randomly distributed energies and angles. The created showers are listed in table 1. From this simulation the secondary particles at the ground level were selected taking into

Table 1. The list of simulated EAS using CORSIKA.

Zenith angle	Energy (PeV)	Number of events	Particles
	1.0	120000	
0°, 15°, 30°, 45°	3.0	36000	gamma and proton
	10.0	10000	
	1.0–1.5	120000	
0°–15°, 15°–30°, 30°–45°	2.25–3.5	36000	gamma and proton
	7.0–10.0	10000	

account the station positions (area of interest). The COAST library package was used to select these particles. This selection is different for Tunka-Grande and Taiga-Muon stations because of different layout geometry. The areas of interest are $28.6\,\mathrm{m}^2$ and $31.36\,\mathrm{m}^2$ for Tunka-Grande and Taiga-Muon respectively. The passage of selected secondary particles is simulated using GEANT4 model similar to real experiment. The electromagnetic particles with energy less than 10 MeV are neglected while selecting the secondary particles. The areas of interest of Tunka-Grande and Taiga-Muon are shown in figure 1.

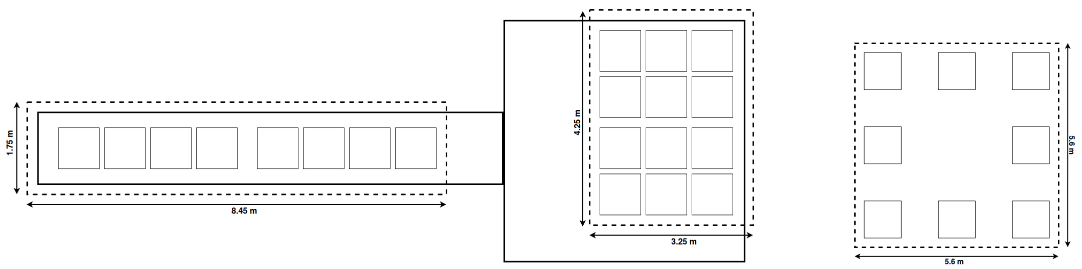

Figure 1. The area of interast (dashed line) of surface and underground counters of Tunka-Grande (left). The area of interest of Taiga-Muon (right).

2.2 Simulation of secondary particle

In GEANT4, 19 Tunka-Grande and 3 Taiga-Muon stations are modelled. The position of stations in Geant4 model is close to the observation site. The standard chemical composition is used to describe the materials utilized in the model. The geological test result has been used to describe the chemical composition of the soil absorber. There is 1.5 m height of soil dumped on the top of underground tunnel in Tunka-Grande setup. This height is considered to fix the position of plane from where the secondary particles are generated in GEANT4 model. After the simulation of secondary particle interaction with counters, the total energy deposition in the scintillator plate of each counter by each primary event is taken out for data analysis.

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Table 2. The list of event efficiency of gamma and proton EAS in percentage.

Zenith angle	Energy (PeV)	Station selection	Gamma (%)	Proton (%)
0°	1.0	At-least 1	99.0	97.9
		At-least 2	74.7	72.4
		At-least 3	38.4	38.3
0°	3.0	At-least 1	100	100
		At-least 2	99.4	98.9
		At-least 3	93.1	91.5
0°–15°	1.0–1.5	At-least 1	99.5	98.9
		At-least 2	81.4	80.1
		At-least 3	47.7	48.8
0°–15°	2.25–3.5	At-least 1	100	100
		At-least 2	98.9	98.2
		At-least 3	90.5	88.9

3 Data analysis

The total energy deposition by each primary event is normalised to the detection area of counters. The minimal energy cut of 0.2 MeV is imposed, considering that, the stations could work with an external trigger. Then the normalised mean amplitudes in underground and surface counters for each events are calculated.

3.1 Position of Taiga-Muon stations

The event efficiency is defined by the rate of coincidence of secondary particles registration in stations. It was calculated to optimize the position of new stations. For this purpose three different combinations of station position have been tested. The position of shower core is randomized to 450 m radius from the geometrical center. Only vertical showers with energy 1 PeV have been utilised to analyse the event efficiency. First of all, it was checked by Tunka-Grande stations and then the same shower events are repeated with addition of the new three stations.

If we claim the coincidence of any three stations or more, there is a gain of 3% in the event efficiency because of the new three Taiga-Muon stations (from ∼ 92% to ∼ 95%). For higher energy events this gain becomes negligible because the event efficiency reaches 100% even with 19 Tunka-Grande stations. This event efficiency does not depend on station position. Thus one position has been used to deploy the new stations taking into account convenience of location. The event efficiency for all 22 stations calculated by selecting different combination of stations is shown in table 2.

3.2 Identification method of EAS induced by gamma-quanta and proton

It is known that the lateral distributions of particle density in gamma-quanta and proton EAS are different at the ground level. Also, the density of muons is different. To use both these characteristics together for the EAS identification we suggest using a neural network classifier. For this purpose TensorFlow library, and Keras library are used in Python program [9, 10]. The amplitude signals from surface and underground detectors of each station are used as input parameters for classifier.

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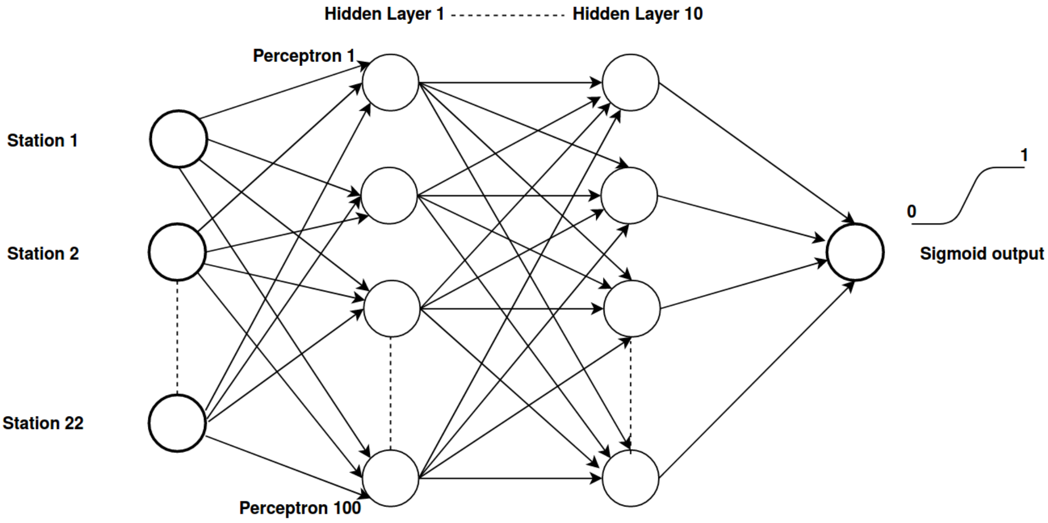

Figure 2. The schematic representation of neural network working principle.

There are 44 input parameters from 22 stations. The neural network comprizes a set of nodes (perceptrons) arranged in 10 layers (figure 2). Each layer consist of 100 perceptrons. At every node rectified linear unit (ReLU) is assigned as the activation function and at the output, the sigmoid function is the classificator. The result of the classification will be the parameters of the output activation function (sigmoid function). There are two sections for neural network analysis, data training, and testing.

The training is performed through different phases. The set of variables (signal amplitudes in the station) are assigned with an indicator variable (0-gamma and 1-proton). The training of the network is done by minimization of cross-entropy loss function [11]. The objective function which is used for cross entropy minimization is:

$$H_p(q) = \frac{-1}{N} \sum_{i=1}^{N} y_i \log(p(y_i)) + (1 - y_i) \log(1 - p(y_i)), \tag{3.1}$$

where: y_i — event indicator value (0 or 1), $p(y_i)$ — classificator value (ranges from 0 to 1).

During training parameters of each rectified linear unit are tuned up in such a way that resulting value of the sigmoid function will be close to 1 for proton EAS (indicator 1) and close to for gamma-quanta EAS (indicator 0). From the whole set of randomly distributed data of two different types of EAS, 80% of data is selected for training. The result of the training is tested using remaining 20% of independent data. For the event selection using our neural network a prerequisite threshold value on classifier result is assigned. If classifier value is larger than threshold the event is selected as type 1 (proton EAS), if less it is type 0 (gamma-quanta EAS).

To understand the stability of results in case of incorrect energy and angle measurement, a set of EAS are tested with combination of individual energy and angle (first set in table 1). One set of resulting amplitude distribution of EAS with discrete energy and angle (for example, gamma and proton with 1 PeV and 0°) was trained with the network. Then another discrete set (for example, gamma and proton with 3 PeV and 0°) has tested. This process has repeated for combination of

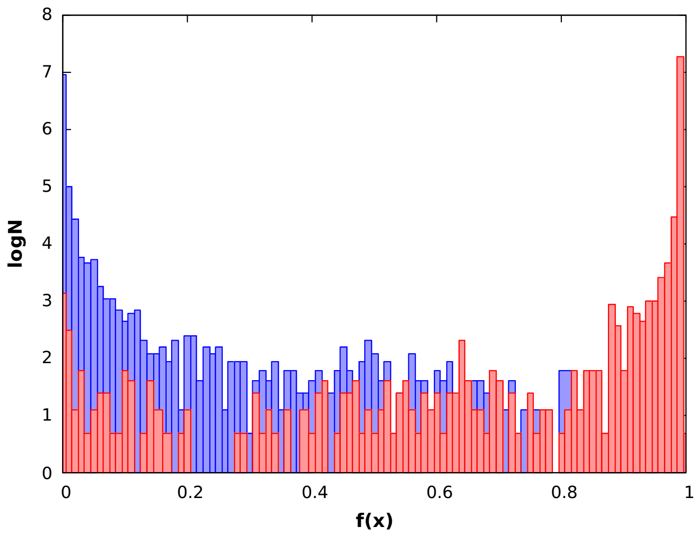

Figure 3. The classificator value distribution for gamma (blue) and proton (red) EAS (7.0–10.0 PeV energy and 0–15 degree).

Table 3. The selection efficiency at threshold 0.2.

Energy (PeV)	Zenith angle	Gamma (%)	Proton (%)
1.0–1.5	0°–15°	47.4	88.7
	15°–30°	44.3	87.2
	30°–45°	31.7	89.9
2.25–3.5	0°–15°	66.1	89.9
	15°–30°	63.9	85.6
	30°–45°	65.8	83.1
7.0–10.0	0°–15°	78.8	95.6
	15°–30°	78.5	92.3
	30°–45°	80.1	89.0

angles (for example, gamma and proton EAS with 3 PeV and 0°has used for training then tested with 3 PeV and 15°). The selection efficiency does not show significant difference. So that, the EAS with certain range of energy and angle has been used for further study (second set in table 1). The distribution of sigmoid function (classificator) values is shown in figure 3. For all set of EAS, the resulting sigmoid function values have been reviewed with threshold conditions. The selection efficiency of both gamma and proton shower were analyzed for all threshold conditions (figure 4). The selection efficiency for events of different type at 0.2 threshold is presented in table 3.

4 Conclusion

- The Monte Carlo simulation for Taiga experiment was developed.
- The position of new stations was studied with three different arrangements. It was found that event efficiency does not depend on the station position.

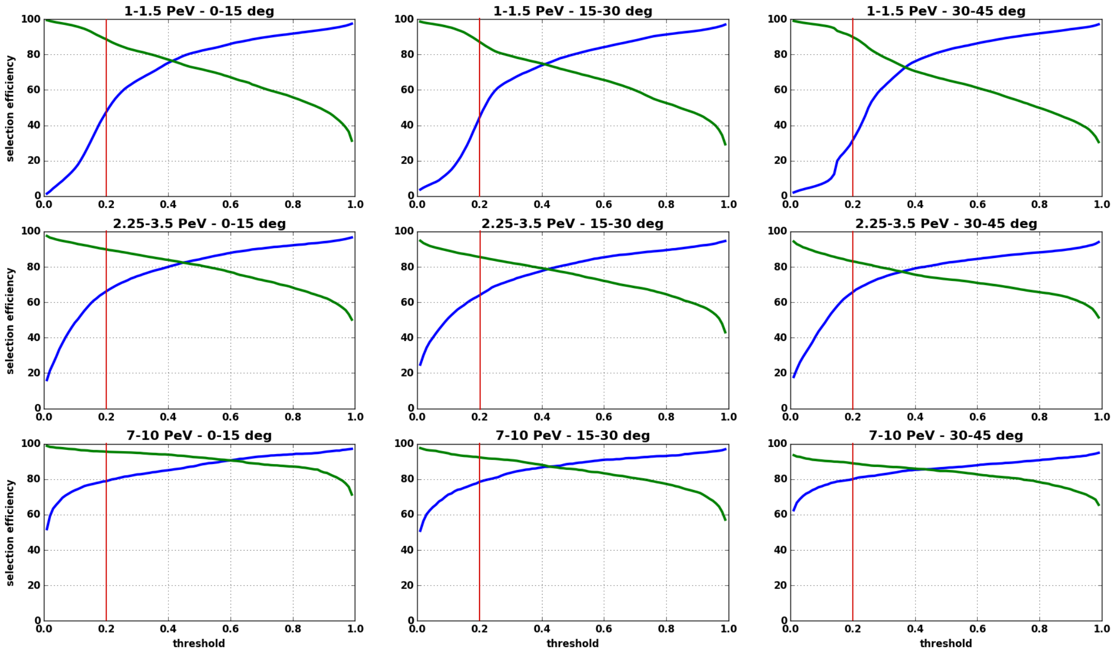

Figure 4. The selection efficiency of gamma and proton EAS at various threshold conditions.

- An identification method based on neural network was suggested.
- The air showers having energy ranging 1.0–10.0 PeV show more than 90% of identification efficiency of proton while keeping identification efficiency of gamma around 50%.

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