Possibilities of the Tunka-Grande and TAIGA-Muon scintillation arrays with the TAIGA-HiSCORE Cherenkov array joint operation in the research of cosmic and gamma rays

A Ivanova\textsuperscript{1,2}, N Budnev\textsuperscript{1}, A Chiavassa\textsuperscript{3}, A Dyachok\textsuperscript{1}, A Gafarov\textsuperscript{1}, A Garmash\textsuperscript{2,4}, V Grebenyuk\textsuperscript{5,6}, O Gress\textsuperscript{1}, T Gress\textsuperscript{1}, O Grishin\textsuperscript{1}, A Grinyuk\textsuperscript{1}, D Horns\textsuperscript{2}, N Kalmykov\textsuperscript{8}, V Kindin\textsuperscript{9}, S Kiryuhin\textsuperscript{1}, R Kokoulin\textsuperscript{9}, K Kompaniets\textsuperscript{2}, E Korosteleva\textsuperscript{8}, I Kotovschikov\textsuperscript{1}, V Kozhin\textsuperscript{8}, E Kravchenko\textsuperscript{2,4}, A Krykov\textsuperscript{5}, L Kuzmichev\textsuperscript{8}, A Lagutin\textsuperscript{10}, Y Lemeshev\textsuperscript{1}, B Lubsandorzhiev\textsuperscript{11}, N Lubsandorzhiev\textsuperscript{8}, R Mirgazov\textsuperscript{1}, R Mirzoyan\textsuperscript{1,12}, R Monkhoev\textsuperscript{1}, E Osipova\textsuperscript{8}, A Pakhorukov\textsuperscript{1}, A Pan\textsuperscript{3}, M Panasyuk\textsuperscript{6}, L Pankov\textsuperscript{1}, A Petrukhin\textsuperscript{1}, E Popova\textsuperscript{8}, A Porelli\textsuperscript{13}, E Postnikov\textsuperscript{8}, V Prosin\textsuperscript{8}, A Pushnin\textsuperscript{1}, R Raikin\textsuperscript{10}, G Rubtsov\textsuperscript{11}, E Rybov\textsuperscript{1}, Y Sagan\textsuperscript{12}, V Samoliga\textsuperscript{1}, A Silaev\textsuperscript{4}, A Silaev Jr\textsuperscript{8}, A Sidorenkov\textsuperscript{11}, A Skurikhin\textsuperscript{8}, C Slunecka\textsuperscript{5}, A Sokolov\textsuperscript{1,4}, Y Suvorkin\textsuperscript{1}, L Sveshnikova\textsuperscript{8}, V Tabolenco\textsuperscript{1}, A Tanaev\textsuperscript{1}, B Tarashansky\textsuperscript{1}, M Ternovoy\textsuperscript{1}, L Tkachev\textsuperscript{5,6}, M Tluczykont\textsuperscript{7}, R Togoo\textsuperscript{15}, N Ushakov\textsuperscript{11}, A Vaidyanathan\textsuperscript{1}, P Volchugov\textsuperscript{8}, D Voronin\textsuperscript{11}, R Wischnevski\textsuperscript{13}, A Zagorodnikov\textsuperscript{1}, D Zhurov\textsuperscript{1} and I Yashin\textsuperscript{9}

1 Irkutsk State University, Karl Marx str. 1, Irkutsk, 664003 Russia
2 Novosibirsk State University, Pirogova str. 2, Novosibirsk, 630090 Russia
3 Dipartimento di Fisica Generale Universiteta di Torino and INFN, Via P. Giuria 1, Turin, 10125 Italy
4 Budker Institute of Nuclear Physics SBRAS, Ac. Lavrentiev Avenue 11, Novosibirsk, 630090 Russia
5 JINR, Joliot-Curie str. 6, Dubna, 141980 Russia
6 Dubna State University, Universitetskaya str. 19, Dubna, 141982 Russia
7 Institut für Experimental physik, University of Hamburg, Luruper Chaussee 149, Hamburg, D-22761 Germany
8 Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninsky gory 1 (2), GSP-1, Moscow, 119991 Russia
9 NRNU MEPhI (Moscow Engineering Physics Institute), Kashirskoe hwy 31, Moscow, 115409 Russia
10 Altai State University, pr. Lenina 61, Barnaul, 665049 Russia
11 Institute for Nuclear Research of the RAS, prospekt 60-letiya Oktaybrya 7a, Moscow, 117312 Russia
12 Max-Planck-Institute for Physics, Fohringer Ring 6, Munich, D-8085 Germany
13 DESY — Zeuthen, Platanenallee 6, Zeuthen, D-15738 Germany
14 IZMIRAN, Kaluzhskoe hwy 4, Troitsk, Moscow, 4108840 Russia
15 Institute of Physics and Technology Mongolian Academy of Sciences, Enkhtaivan av. 54B, Ulaanbaatar, 210651 Mongolia
Abstract. The Tunka-Grande scintillation array is part of the TAIGA Gamma Observatory. It is intended for investigation of energy spectrum and mass composition of primary cosmic rays in the energy range $10\text{ PeV} - 10\text{ EeV}$ and the search for diffuse cosmic gamma rays. The TAIGA-HiSCORE Cherenkov array aims at observing gamma-rays with the energy from 1 TeV. TAIGA-Muon low-threshold scintillation detector array is a network of surface and underground detectors for registration charge particles of EAS. Currently, 3 clusters have been deployed. The first cluster is running in test mode. It is planned that in the future the total area of the TAIGA-Muon will be about 2000 sq. m. and it will search astrophysical gamma-rays in the energy range from 100 TeV together with the Tunka-Grande scintillation array and the Cherenkov experiments of the TAIGA Gamma Observatory. To evaluate the possibility of joint operation Tunka-Grande, TAIGA-Muon and TAIGA-HiSCORE, a simulation was performed using the CORSIKA and Geant4 software packages. The status of model-based studies is presented and assessed the prospects for joint operation of the arrays.

1. Introduction
Nowadays, high-energy gamma radiation is of great interest to researchers. However, the flux of astrophysical gamma-rays is very small compared to the total flux of cosmic rays. Scientists face with the difficult task of separating events generated by gamma quanta from background events produced by high-energy charged particles. A hybrid approach to event reconstruction is a promise method of search astrophysical gamma rays. The approach is based on using information about different EAS components to reconstruct a single event. It is only possible in experiments using different types of detectors.

Currently, astrophysical observations in the Tunka valley are made using a hybrid experimental complex. It consists of the Tunka-133 and TAIGA-HiSCORE Cherenkov arrays [1,2], the Tunka-Grande scintillation array [3], and the TAIGA-IACT Cherenkov imaging telescopes [4]. The TAIGA-Muon scintillation array is being deployed [5].

One of the goals of the hybrid experimental complex is to search astrophysical gamma quanta with energy above 100 TeV. To solve non-trivial task of discrimination gamma rays from the hadron background two methods are chosen: a study of EAS image form using IACTs and a study of EAS muon component using scintillation detectors.

The first method is based on experimental data from the TAIGA-HiSCORE Cherenkov array and TAIGA-IACT imaging telescopes [6]. The second, alternative, method, to which this article is devoted, is based on the analysis of data from Cherenkov and scintillation arrays [7]. Its advantage is relative simplicity and low cost. The main feature of second method is that the reconstruction of energy, position, and direction of the EAS will be performed with the data of the TAIGA-HiSCORE timing array. To discriminate gamma rays from the hadron background, the scintillation arrays are used. However, to confirm the possibility of using this method and evaluate its efficiency, model studies (computer simulation) are needed.

2. Status of the TAIGA-HiSCORE Cherenkov array and scintillation arrays

2.1. The TAIGA-HiSCORE
The TAIGA-HiSCORE [2,8] – an array of wide-angle air Cherenkov stations distributed over an area of 0.6 km$^2$ (see figure 1). The first cluster of TAIGA-HiSCORE consists of 32, second – 27, and third – 30 observation stations. Each of the existing TAIGA-HiSCORE stations consists of four 8-inch PMTs with a total light collection area of 0.5 m$^2$ and a 0.6 sr field of view. All stations are tilted in the direction to the South at an angle of 25° in order to increase the period of observation of the Crab Nebula.

The accuracy of EAS parameters reconstruction according to TAIGA-HiSCORE data is given in the article [8]. Currently, the 4th TAIGA-HiSCORE cluster consisting of 32 stations is being developed.
2.2. The Tunka-Grande
The Tunka-Grande scintillation array [3] (see figure 2, left part) contains 19 scintillation stations located on the area of the Cherenkov Tunka-133 array in a circle with a radius of ~ 400 m. The total area of the Tunka-Grande is about 0.5 sq.km. Each observation station includes a surface part with a total area of 8 square meters, and an underground part with a total area of 5 square meters. Surface part consist of 12 scintillation counters that previously worked as part of the KASCADE-Grande array, underground part consists of 8 such counters. Each scintillation counter is a light-collecting duralumin case in the form of a truncated pyramid. Inside the case is an NE102A plastic scintillator in the form of a flat plate 800 \times 800 \times 40 \text{ mm} in size, and a Philips XP-3462 photomultiplier tube (PMT). Surface part is installed in special containers. The underground part is located under a 1.5 m layer of soil in the immediate vicinity of the surface part. The scintillation array was fully operational at the end of 2015.

2.3. The TAIGA-Muon
The TAIGA-Muon low-threshold scintillation array (see figure 2, right part) is a network of surface and underground detectors to registrate the electromagnetic and muon components of the EAS (Figure 2). It is assumed that in the future the total area of the array will be about 2000 sq. m. and it will search for
cosmic gamma-rays in the energy range from 100 TeV together with the TAIGA-HiSCORE Cherenkov array.

Currently, there are 3 TAIGA-Muon clusters deployed. Each cluster consists of 8 underground and 8 surface scintillation detectors. Surface and underground detectors are located in pairs, surface detectors are strictly above the underground ones at a depth of 1.6 m, along the perimeter of a square with a side of 5 m. The selected thickness of the soil above the muon detectors is sufficient for the existing composition of the soil to absorb the main stream of EAS charged particles and gamma quanta. The area of each detector is 1 sq m. The complex inside structure of counters is described in [9].

3. Simulation

Software based on the Monte Carlo method is a necessary tool for simulation EASs, experiments, and analyze of experimental data. In this work, the CORSIKA [10, 11] (based on the QGSJET-II-04 high-energy hadron interaction model [12]) and Geant4 [13] software was used. Simulations were conducted for Tunka valley conditions and parameters of TAIGA-HiSCORE, Tunka-Grande, and TAIGA-Muon arrays.

3.1. The EAS simulation

A database of artificial EASs was created to simulate the joint operation of Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays. The database contains showers generated by a primary protons, gamma quanta and iron nuclei with energies in the range from 100 TeV to 1 PEV (lg(E) = 14, 14.25, 14.5, 14.75, 15), with different angles of incidence (θ = 0, 15, 30, 45, 60°). The minimum value of the simulated energy is selected taking into account the threshold energy of the TAIGA-HiSCORE Cherenkov array (E_{th} = 100 TeV). For each single shower, information about all secondary EAS particles registered at the observation level (for the Tunka valley h = 675 m above sea level) as well as information about Cherenkov radiation is stored.

3.2. The TAIGA-HiSCORE simulation

Simulation of TAIGA-HiSCORE operation was carried out at the stage of simulating artificial EASs. We used special extension for CORSIKA that enables Cherenkov light production – IACT/ATMO package [14]. TAIGA-HiSCORE optical stations were simulated as spherical detectors with diameter of 1 m and located at distances about 106 m as in the real experiment. According to the real parameters of the TAIGA-HiSCORE optical station, conditions were imposed on each sphere for the viewing angle and light collection area. In the simulation, we took into account the geometric features of the station (the area of the light – Collecting surface of the station is 0.5 m²), its slope (all optical stations are inclined to the South by 25°), and its limited viewing angle-30°.

The densities of Cherenkov photons for each station of the array were obtained for each simulated EAS. In the future, it is planned to simulate the TAIGA-HiSCORE response using the experimentally measured angular distribution of quantum sensitivity and the direction efficiency of optical stations.

3.3. The simulation of scintillation arrays

Geant4 [13, 15] was chosen as a software for simulation of Tunka-Grande and TAIGA-Muon operation. This software has great practical potential. It allows you to create a difficult spatial geometry of arrays, take into account the chemical composition of components, and simulate the interaction of matter with various types of elementary particles [16].

The computer model of the Tunka-Grande array corresponds to reality as much as possible. The difficult spatial geometry of scintillation counters (and observation stations) is described. The chemical composition and the materials of counters are described.

Each of the 19 observation stations is described according to its actual size and orientation in space.

The computer model of the TAIGA-Muon array is simplified. Currently, the software simulates the operation of the first TAIGA-Muon cluster. The spatial position of the 16 counters and the chemical
composition of the soil correspond to the real ones. But the counters themselves are set scintillator in the form of a flat plate 100 × 100 × 1 sm in size without considering their difficult inside structure.

4. Analysis of the prospects for joint operation of the Cherenkov and scintillation arrays
Simultaneously with the simulation, a search and analysis of joint events were carried out using independent experimental data from the Tunka-Grande and TAIGA-HiSCORE arrays for 2018-2019. We selected events for analysis in which at least three Cherenkov and three scintillation observation stations were triggered.

The window size of ± 10 µs for searching the joint events was chosen based on the array size. Data analysis showed that time difference between arrays was up to 4 µs for different days.

The time window was varied for verification within ± 100 µs. The number of detected joint events was changed by units.

It was found that during the independent operation of the TAIGA-HiSCORE and Tunka-Grande array, 80-85 joint events per hour are detected using condition 3 or more triggered stations.

An example of the distribution of detected joint events over the zenith and azimuth angles is shown in figure 3, left part.

The event-averaged value of the plane angle between the shower arrival direction reconstructed using Tunka-Grande data and the EAS arrival direction reconstructed using TAIGA-HiSCORE data is about $\psi_{\text{Grande-HiSCORE}} \approx 2.17$ degrees (see figure 4, right part). The average difference between the EAS core position reconstructed from the Tunka-Grande data and the core position reconstructed from the TAIGA-HiSCORE data is 25 m.

Most of the joint events selected by using condition 3 or more triggered stations are in the energy range of 1-100 PeV.

Also, there are joint events, in which at least three TAIGA-HiSCORE stations and only two scintillation stations are triggered. The energy, from which such events are detected, starts from 0.7 PeV. In the case of using the hybrid approach, the data on the position of the shower axis, arrival direction, and energy of the primary particle will be reconstructed from the TAIGA-HiSCORE data. Therefore, we can use such events for analysis.

![Figure 3](image-url)

Figure 3. Left part: Distribution of the joint events Tunka-Grande and TAIGA-HiSCORE. Right part: Distribution of events by plane-angle between the EAS direction reconstructed from the Tunka-Grande data and the direction reconstructed from the TAIGA-HiSCORE data.
5. Conclusion
The software to simulate the operation of Tunka-Grande, TAIGA-Muon, and TAIGA-HiSCORE arrays was developed. It is intended for the approbation of the method for gamma quanta events separation that based on the analysis of EAS muon and electromagnetic components. Using the software, we can study the prospects for joint work of the TAIGA-HiSCORE array and scintillation arrays. Analysis of Tunka-Grande and TAIGA-HiSCORE experimental data showed the presence of joint events. Most of the joint events in which at least three scintillation and three Cherenkov stations triggered are in the energy range of 1-100 PeV. The method of primary particle type separation using EAS muon component data analysis has great potential if the trigger for the Tunka-Grande will be set to "less than 3 stations" and the TAIGA-HiSCORE experimental data will be used to reconstruct the angular direction, the core position of EAS, and energy of the primary particle.

Acknowledgments
This work is supported by Russian Foundation for Basic Research (grants 19-32-60003, № 19-52-44002) the Russian Science Foundation (grant 19-72-20067 (Section 2), the Russian Federation Ministry of Science and High Education (agreement № 075-15-2019-1631, projects FZZE-2020-0017, FZZE-2020-0024). We are grateful to the Irkutsk Supercomputer Center of SB RAS for providing computational resources of the HPC-cluster «Akademik V.M. Matrosov» [17] that made it possible to carry out our tasks.

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