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## Status of the Russian-Italian experiment NEVOD-EAS

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**Abstract.** The NEVOD-EAS air shower array is currently under construction in MEPhI, within the Russian-Italian NEVOD-DECOR partnership. The goal of the array is to provide an independent measurement of the size, of the core location and of the arrival direction of the extensive air showers (EAS) detected with the other facilities of the Experimental complex NEVOD. These measurements will provide a calibration of a novel perspective technique developed in the Experimental complex NEVOD for studying inclined muon bundles – the method of local muon density spectra. The array will also extend the opportunities of the Experimental complex NEVOD in carrying out multi-component studies of extensive air showers. The present status of the NEVOD-EAS air-shower array is described and the future perspectives are discussed.

### 1. Introduction

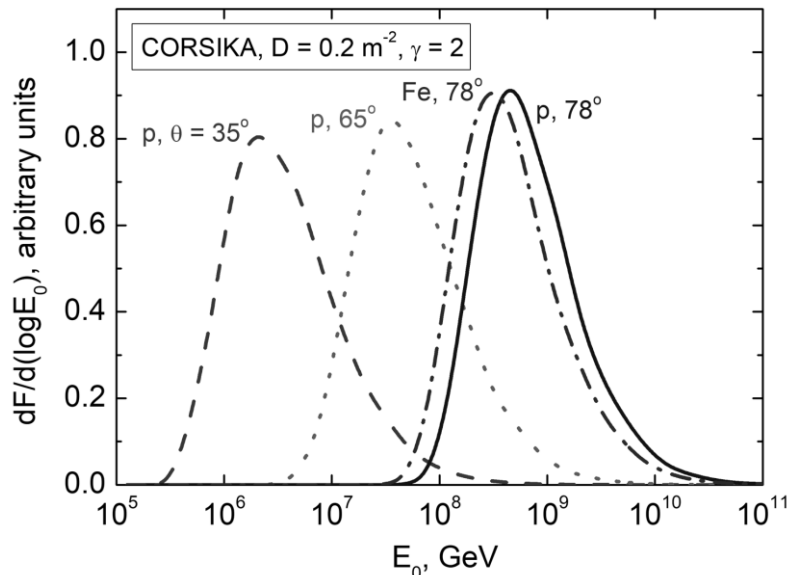
The central facility of the Experimental complex NEVOD (MEPhI, Moscow) is the 2000 m<sup>3</sup> Cherenkov water detector (CWD) NEVOD [1, 2]. The detection system of the CWD is a regular spatial lattice of 91 quasi-spherical optical modules (QSM) [3] located inside the water volume. The wide dynamic range of optical modules (from 1 to 10<sup>5</sup> ph.e.) and the dense lattice of QSMs allow CWD to operate in the calorimetric mode, measuring the energy deposit of muon bundles, EAS cores, and cascades generated by single muons in the water volume.

The coordinate-tracking detector DECOR [4] is deployed around the CWD and is designed to study cosmic rays on the Earth's surface at large zenith angles up to horizontal directions. DECOR consists of eight vertically arranged super-modules with a total area about 70 m<sup>2</sup>. Good spatial and angular characteristics of the DECOR detector (accuracies of the muon track reconstruction are better than 1 cm and about 0.7°, respectively) allow to reconstruct the arrival direction of muon bundles of inclined EAS with a high precision, as well as to determine the multiplicity and density of muons in the bundle.

The combination in the experimental complex of the CWD operating in the calorimetric mode and of the coordinate-tracking detector of a large area provides the opportunity to use the novel method of local muon density spectra (LMDS) for studying inclined EAS in the energy range of primary cosmic ray particles from 10<sup>15</sup> to 10<sup>19</sup> eV [5]. The possibilities of the LMDS method for estimating the energy



of primary particles are illustrated in figure 1 which shows the energy distributions of primary particles contributing to events with muon density  $D = 0.2 \text{ m}^{-2}$  at the observation point for different zenith angles [6]. Calculations for primary protons and iron nuclei were performed with the CORSIKA program using the QGSJET01 model; the value of the primary spectrum slope is taken equal to 2.0. For the ease of comparison, the calculated curves are normalized by the area.



**Figure 1.** The distribution of primary particle energies contributing to the events with a fixed muon density [6].

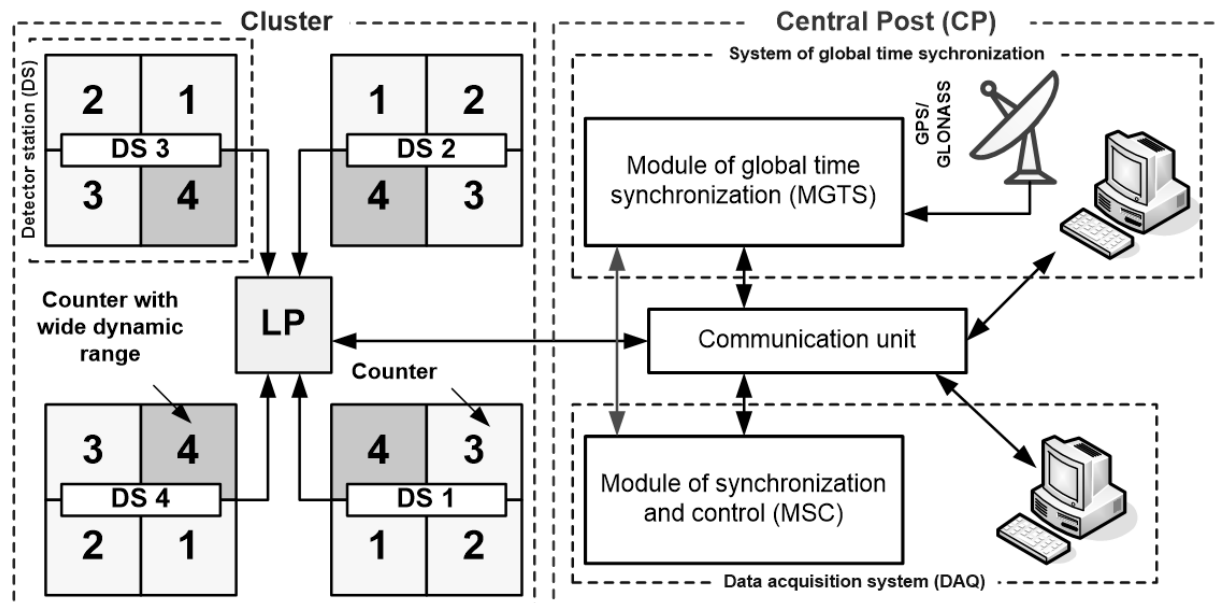
As we can see in figure 1, for the same muon density, different zenith angles of muon bundle arrival correspond to the effective primary particle energies differing by the orders of magnitude. However, the typical width of the primary energy distributions (for a fixed muon density) is characterized by a standard deviation  $\sigma_{\lg E} \sim 0.4$ . Such uncertainties of primary particle energy estimations are caused by contribution of extensive air showers of different energies registered at different distances from the core to the events with a fixed local muon density.

The NEVOD-EAS air-shower array which is under construction in the Experimental complex NEVOD will allow to:

- improve the accuracy of estimates of the energy spectrum of primary cosmic ray particles obtained with the LMDS method completing the data on the muon bundle characteristics with the information on the EAS core position;
- correlate the data on EAS muon component obtained with the LMDS method to the measurements of electron-photon component using the classical technique;
- increase the area of the EAS electron-photon component measurement in multi-component studies of cosmic rays.

## 2. NEVOD-EAS shower array

The NEVOD-EAS array is dedicated to the detection of the electron-photon component of extensive air showers in the energy range from  $10^{15}$  to  $10^{17}$  eV. The detectors are deployed on the roofs of the University buildings and on the ground (the altitude difference reaches 20 m) that is the main difference of the array from the classical installations for EAS investigations in which detectors are usually located on a plane surface. The difference of altitudes of the NEVOD-EAS detectors determines the cluster organization of the array. Each cluster of the array consists of 4 scintillation detector stations (DS) located in the horizontal plane at the vertices of the rectangle with characteristic side lengths of about 15 m and combined by a Local Post (LP) of primary data processing. The structure of the registering system of the NEVOD-EAS air-shower array is shown in figure 2.



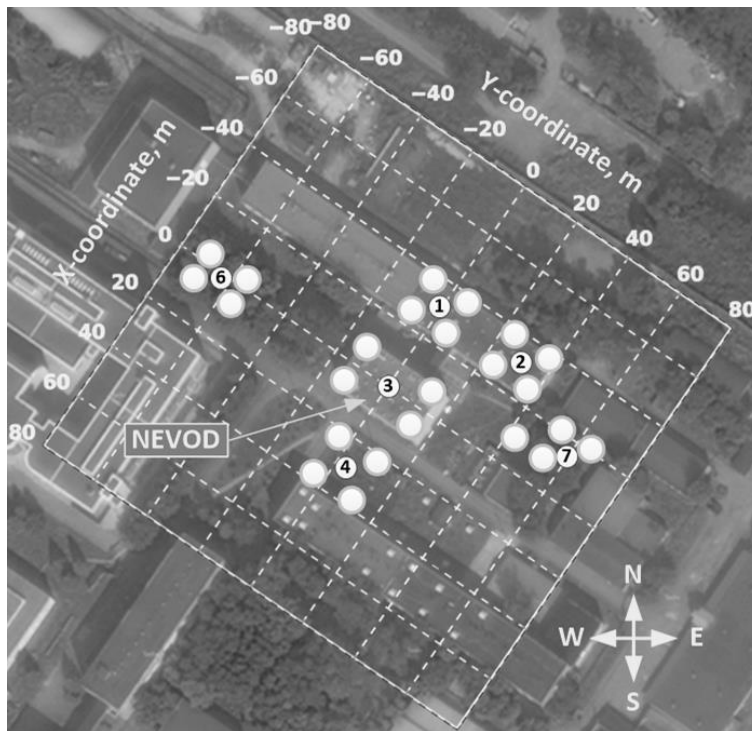
**Figure 2.** Structure of the NEVOD-EAS registering system.

Detector station includes four scintillation counters sampling the electron-photon component of extensive air shower. These counters were previously used in the EAS-Top [7] and KASCADE-Grande [8] experiments. Scintillation counter consists of NE102A scintillator with the dimensions of  $800 \times 800 \times 40 \text{ mm}^3$  and one or two Philips XP3462 PMTs installed inside the pyramidal stainless steel housing. The detailed description of results of studies of the PMT and scintillator characteristics, as well as the techniques of the NEVOD-EAS counter assembly and adjustment are presented in [9, 10]. Three of the four DS counters are equipped with one ("standard") photomultiplier Philips XP3462 which is used for the time and density measurements during EAS registration. The gain of the standard PMTs is chosen in order to generate, at the transit of a single vertical muon, signals of the same amplitude ( $\sim 13 \text{ pC}$ ). The fourth DS counter is equipped with two (a "standard" and an "additional") photomultipliers. The additional PMT extends the linearity range up to high particle densities ( $\sim 10000 \text{ particles/m}^2$ ) and has a typical response to the passage of near-vertical muon of about  $0.15 \text{ pC}$ . For the protection against the environmental influences, the DS counters are enclosed inside the special external housings. The sensitive area of the detector station is about  $2.5 \text{ m}^2$ .

Each cluster operates as a standalone EAS array, collecting and digitizing analog signals from DS with a sampling frequency of  $0.2 \text{ GHz}$ . The trigger condition in each cluster is the coincidence of up to 4 DS in a time window with a duration from  $10 \text{ ns}$  to  $2 \text{ }\mu\text{s}$ , events have a time stamp with  $10\text{-ns}$  accuracy. Thus each NEVOD-EAS cluster is an independent array sampling both the number and the transit time of EAS particles in each detector station. Information on registered EAS events (timestamp and 8 waveforms from flash-ADCs) is sent by the cluster to the Central Post (CP) of the array via fiber-optic communication lines.

Central Post includes two hardware and software related systems: data acquisition and global time synchronization. These systems receive, analyze and store information from clusters, control clusters and ensure synchronization of their local clocks with an accuracy of  $10 \text{ ns}$ . Detailed description of the LP and CP electronics is presented in [11].

In 2014-2016, the first stage of the NEVOD-EAS array including 6 clusters deployed over the area of  $10^4 \text{ m}^2$  was installed (figure 3). Clusters Nos. 1-3 are located at the roofs of the laboratory buildings of the Experimental complex NEVOD. Clusters Nos. 4, 6 and 7 are on the ground surface. The distance between the neighboring clusters is about  $30 \text{ m}$ .



**Figure 3.** The layout of the NEVOD-EAS air shower array clusters.

### 3. First experimental results

#### 3.1. Experimental series at the array

Currently 6-cluster configuration of the NEVOD-EAS array is in a continuous operation. The data taking is organized in experimental series. Experimental series are sequences of runs with a duration of 24 hours. Each run is divided in six 4-hour intervals during which the array operates in 2 different modes: exposition (3 hours 50 minutes) and monitoring (10 minutes).

In the exposition mode all array clusters detect extensive air showers independently from each other. The intra-cluster triggering condition is at least 2-fold coincidence of detector stations within the time gate with a duration which is determined by the maximal distance between the cluster DS. Registration threshold for each detector station of the cluster is about 0.75 MIP.

During monitoring, the charge spectra of detector stations are measured in a self-triggering mode (minimal multiplicity of triggered DS of each cluster is 1, registration threshold is about 0.5 MIP). Using these spectra the responses of DS to the passage of single muons are calibrated.

According to the data obtained during the one-day run a set of parameters is determined for each cluster of the array. Counting rates of cluster and its detector stations, as well as mean and r.m.s. values of the ADC base lines are used to control the stability of the cluster. Triggering delays of detector stations, responses of stations to passage of single particle, calibration coefficients for DS additional PMTs are accounted in the reconstruction of EAS events. For each event registered by the cluster, the EAS arrival direction and number of particles detected by detector stations are measured.

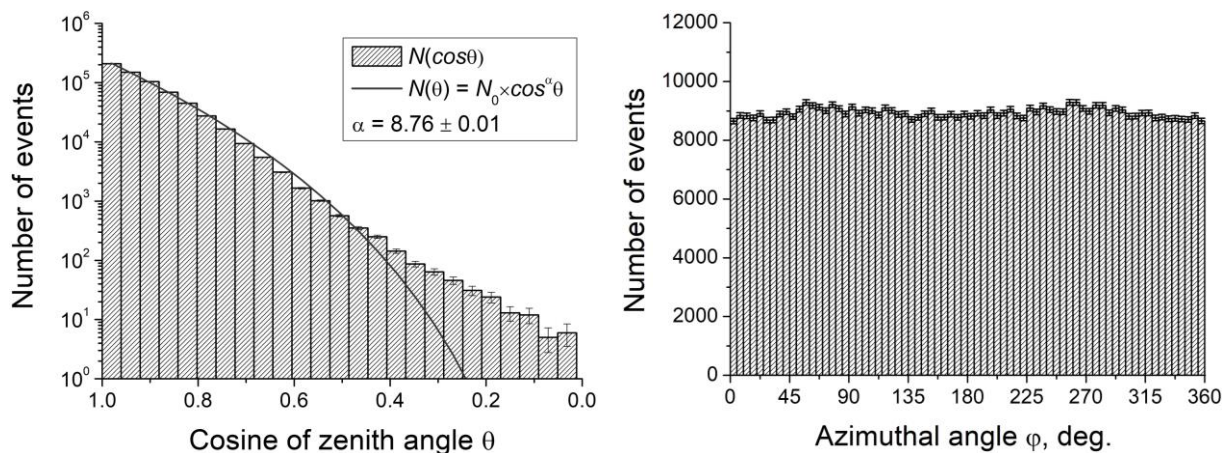
Then using the timestamps of events in separate clusters, the offline search for coincidences of clusters within the time gate with the duration of 350-400 ns (determined by the maximal distance between detector stations of the array) is performed, and the database of detected EAS is formed.

The tasks of the first experimental series are:

- analysis of EAS angular distributions and counting rate;
- array response at registration of EAS of different energies to verify the calibration procedures;
- determination of conditions to search joint events in NEVOD-EAS and other detectors;
- estimation of the NEVOD-EAS angular resolution.

### 3.2. EAS arrival direction reconstruction

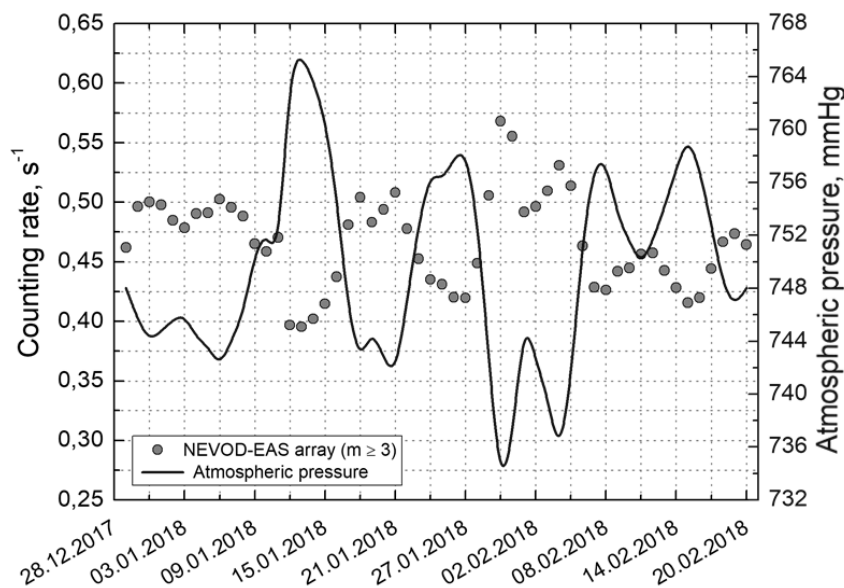
To study the angular distributions of detected air-showers, the events satisfying the following conditions are selected: at least 3-fold coincidence of the NEVOD-EAS clusters; the EAS arrival direction should be reconstructed by at least 1 of triggered clusters. Figure 4 shows the distributions of selected events in cosine of zenith angles  $\theta$  (left) and in azimuthal angles  $\varphi$  (right) of arrival direction of extensive air showers. The line shows the result of approximation of the experimental distribution of events in the cosine of the EAS arrival direction zenith angle by the function  $N(\theta) = N_0 \cdot \cos^\alpha \theta$ . The exponent  $\alpha$  of the cosine of zenith angle obtained from the distribution approximation is  $\approx 8.8$  and agrees with the expected (at MEPhI observation level) value of about  $8.5 \div 9$  for showers generated by hadrons. In the range of zenith angles from  $62^\circ$  to  $88^\circ$  (value of  $\cos\theta$  from 0.47 to 0.03), the excess of the number of events in comparison with the expected distribution which may be associated with showers produced by high-energy muons is observed. Distribution in azimuthal angles is nearly uniform.



**Figure 4.** Distributions of detected EAS in the cosine of zenith angles (left) and azimuthal angles (right) of arrival direction.

### 3.3. Counting rate of extensive air showers

Using the NEVOD-EAS data we measure the daily average of the events counting rate, the results are shown in figure 5, where the behavior of the atmospheric pressure is also reported.



**Figure 5.** Counting rate of the array and atmospheric pressure in the period from 29.12.2017 to 20.02.2018.

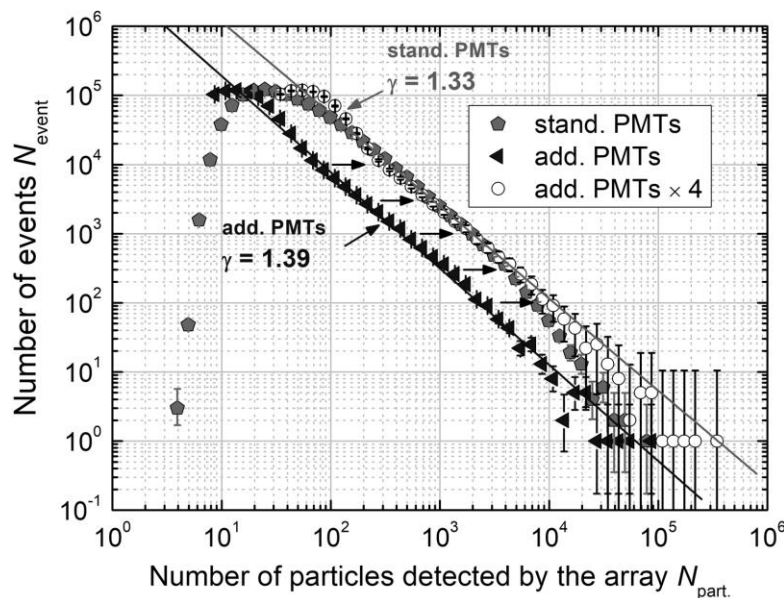
The NEVOD-EAS average counting rate of extensive air showers is about  $0.47 \text{ s}^{-1}$ . A clear anti-correlation between the counting rate of the array with the atmospheric pressure is observed. The barometric coefficient for extensive air showers is  $\sim -1.08 \text{ \%/mmHg}$  (or  $-0.81 \text{ \%/mbar}$ ) and is in accordance with the value of  $-0.77 \pm 0.07 \text{ \%/mbar}$  [12] obtained for the threshold energy of about  $3 \times 10^{14} \text{ eV}$  at the sea level.

### 3.4. Response to EAS of various energies

To check the charge calibration procedure of detector stations we use the spectrum of the number of particles measured by the array. Figure 6 shows the distributions obtained with:

- data of standard DS photomultipliers (pentagonal dots);
- data of additional PMTs (triangular dots) installed in 1 of 4 DS counters;
- responses of additional PMTs (circle dots) extrapolated to the DS area assuming that at high particle densities all DS counters detects the same number of particles.

The number of detected particles for each DS and its additional PMT was determined accounting the calibration parameters of clusters calculated for every run of the experimental series.



**Figure 6.** Distributions of events detected with the NEVOD-EAS array in the measured size of extensive air showers.

In the distribution obtained using the data of standard PMTs, the influence of the intra-cluster triggering conditions can be observed in the range from 3 to 150 particles. In the range from 150 to 5000 particles, the standard PMTs and the corresponding ADC channels of the clusters operates in the linear mode, and the distribution has a constant slope ( $\gamma \sim 1.33$ ). With increasing the EAS size the slope of distribution changes due to the saturation of standard PMTs.

In the distribution obtained according to the responses of additional PMTs, the threshold effect is observed up to about 50 particles. In this case threshold effect is determined both by the intra-cluster triggering conditions and by an ambiguous allocation of additional PMT signals against the background of the cluster ADC baselines at low particle densities. At higher particle numbers ( $N_{\text{part.}} > 50$ ) the distribution has a constant slope ( $\gamma \sim 1.39$ ).

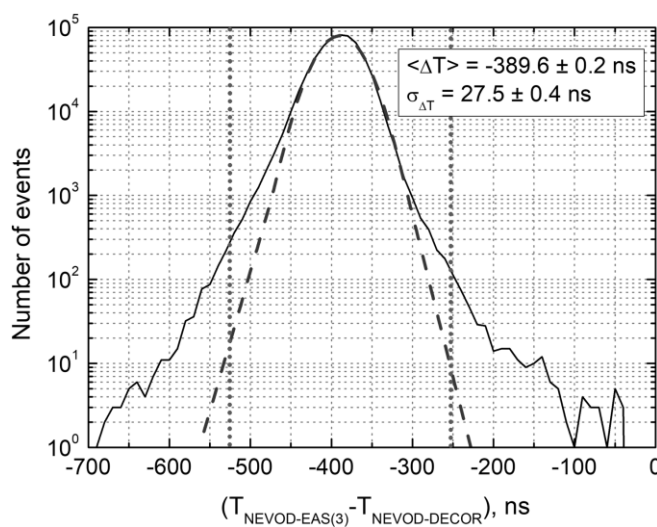
In the range from 150 to 5000 particles, the distribution obtained according to the responses of additional PMTs extrapolated to the DS area is in good accordance with the distribution for standard photomultipliers which indicates the correctness of operation of the procedures for calibration of the response of the array detecting elements.

The obtained slopes of distributions of detected EAS in the measured size are in accordance with the known slope of the EAS size spectrum for the given observation level [13].

### 3.5. Selection of joint events in NEVOD-EAS and NEVOD-DECOR

To determine the conditions for searching joint events in NEVOD-EAS and NEVOD-DECOR, the following events are considered: for NEVOD-EAS – the events with at least 3-fold coincidence of clusters; for NEVOD-DECOR – all events falling into the time gate from -770 to 0 ns from the trigger of the 3<sup>rd</sup> NEVOD-EAS cluster.

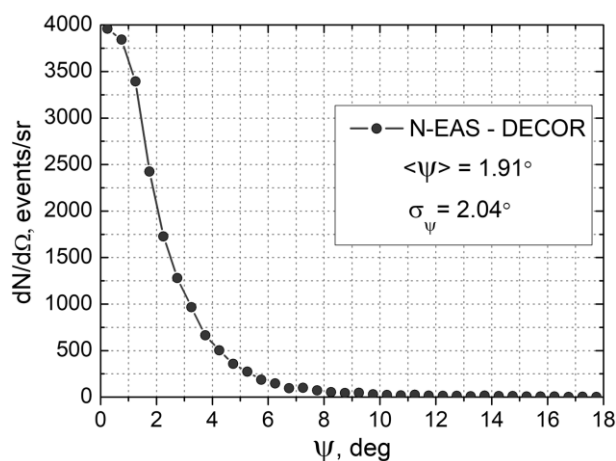
Distribution of time difference between triggers in the 3<sup>rd</sup> NEVOD-EAS cluster and NEVOD-DECOR complex is shown in figure 7. According to the distribution, on average cluster No. 3 is triggered 390 ns earlier than the NEVOD-DECOR complex. The optimal duration of the time gate for searching joint events is about 275 ns. The borders of the time gate are shown as dotted lines in figure 7. Accounting the average time between events in the NEVOD-EAS (2 s) and NEVOD-DECOR (50 ms), the probability of incorrect definition of an event as a joint one is less than  $5.5 \times 10^{-3}$ .



**Figure 7.** Distribution of time difference between triggers in the 3<sup>rd</sup> NEVOD-EAS cluster and NEVOD-DECOR complex.

### 3.6. NEVOD-EAS angular resolution

To estimate the NEVOD-EAS angular resolution, using the data of joint events the direction of extensive air showers reconstructed by the array was compared to the muon bundle direction obtained with the DECOR detector. Among all joint events, only events with at least 3 parallel muon tracks observed in the DECOR detector were selected for the analysis. The obtained distribution of the number of events per unit of solid angle in intervals of angular deviation of direction in NEVOD-EAS from the direction in NEVOD-DECOR is shown in figure 8. According to figure 8, angular resolution of the array estimated as the FWHM of these distribution is about 2°. In 90 % of events, EAS direction reconstructed by the array deviates from muon bundle direction by less than 3.75°.



**Figure 8.** Distribution of the number of events per unit of solid angle in intervals of angular deviation of direction in NEVOD-EAS from the direction in NEVOD-DECOR.

#### 4. Conclusion

In 2017, the first experimental series were started at the first stage of the new NEVOD-EAS shower array including 6 independent clusters of scintillation detector stations. The obtained results have demonstrated that the EAS counting rate, reconstructed arrival direction and spectrum of measured size are in good accordance with the expected dependences and distributions which means that all calibration procedures work correctly. The NEVOD-EAS angular resolution obtained via the analysis of joint EAS events in air-shower array and NEVOD-DECOR complex is about  $2^\circ$ . The registering system based on independent clusters, as well as the developed cluster approach to the NEVOD-EAS experimental data analysis will be used for the extension of the array over the area of  $\sim 0.2 \times 10^6 \text{ m}^2$ .

#### Acknowledgments

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