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Search for extensive atmospheric showers with unusual spatial and temporal structure using the Tunka-Grande array data

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The spatial and temporal structure of extensive air showers is studied according to the data of the Tunka-Grande scintillation array.The results of the analysis of signals from the extensive air showers with an energy above 10 PeV are presented.

Keywords: Extensive air showers, Tunka-Grande array, multi-pulse signal.

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Introduction

Among the relevant areas of research carried out in the systems for detection of extensive air shower (EAS) components is studying the events distinguished by a complex spatiotemporal structure [1–4]. The interest is related to the search for EAS with several fronts tens and hundreds of nanoseconds apart from each other, as well as the search for particles that are delayed or advanced relative to the shower front [3]. The search for such events is conducted by examining the waveform of EAS recorded in the system detectors.

In 2023, a search was launched for EAS with a complex structure based on data from Tunka-Grande scintillation array. The Tunka-Grande system consists of 19 observation stations distributed over an area of $0.5\,km^2$. Each station includes a surface detector of EAS charged component with a total area of $\sim 8\,m^2$ and an underground muon detector with an overall area of $\sim 5\,m^2$. A detailed description of Tunka-Grande system is given in paper [5]. The following are the analytical data collected for ~ 360 h of the system operation.

1. Signals of EAS having complex structure according to data from Tunka-Grande

During ~ 360 h of operation, Tunka-Grande scintillation array has detected about 72 100 events where signals with an amplitude exceeding 0.5 of the amplitude from a single particle were observed in each half of three or more surface detectors. In most cases, the recorded pulses had a standard shape with a single peak, an even rise and fall of the front (Fig. 1). However, also pulses having a „multi-modal" configuration, with two-peak and multi-peak structure were observed (Fig. 1). Multi-pulse signals were also detected when, in addition to EAS pulse, separate delayed or advanced pulses were observed on the time sweep (Fig. 1). At that, major EAS pulses and delayed pulses had both, standard, and „multi-modal" configuration.

The following hypotheses have been put forward as the main hypotheses explaining the presence of multi-peak structures on time sweeps of signals recorded in Tunka-Grande detectors: 1) „multimodal" pulses reflect the spatiotemporal structure of EAS and are associated with an increase in the shower disc thickness as the distance from EAS axis becomes larger; 2) the advanced pulses in multi-pulse signals are caused by single atmospheric muons that hit the detectors somewhat earlier than EAS particles; 3) contributions to the delayed pulses in multi-pulse signals are provided by PMT after-pulses, single muons, and delayed EAS particles.

2. Signals distribution in terms of time and amplitude

For analysis, $\sim 26\,500$ time sweeps of signals in the surface detectors were selected, where, in addition to the main pulse with an amplitude of at least 0.5 of the level of one particle, there were additional pulses having similar amplitude condition. In the underground detectors ~ 3400 similar signals were detected.

The sweep length made it possible to observe the time distribution of the signal in the range $5\,\mu$s. The main EAS pulse in surface detectors was observed with a delay of $1.5\,\mu$s relative to the start of detection. Due to the time delays associated with muons approaching the underground detectors and transmission of signals over longer cables, the pulses from EAS muons recorded in the underground detectors were, on average, delayed by about 35 ns relative to the pulses of charged EAS particles in the surface detectors.

Figure 2 shows the amplitude and time distributions of pulses in multi-pulse signals recorded in surface detectors. The advanced pulses account for about 3% of the total number of additional pulses and are evenly distributed from the start of the time sweep detection to the main EAS pulse (Fig. 2, *a*). In most cases the delayed pulses are displaced relative to the main EAS pulses by ~ 300 ns (Fig. 2, *a*). The most probable amplitude of main EAS pulses and advanced pulses corresponds to the single-particle pulse amplitude (Fig. 2, *b*).

A similar pattern can be also observed in the underground detectors.

3. Discussion of the nature of „multi-modal" pulses and multi-pulse EAS signals

Fig. 3, *a* shows the integral distribution of $\sim 72\,100$ detected EAS depending on the number of responded stations in which „multimodal" pulses/multi-pulse signals (light gray diagram) or only multi-pulse signals (dark gray diagram) were observed in the surface detector.

Statistical data for individual stations showed that advanced pulses in the surface detectors are obsrved, in average, in $\sim 0.29\%$ of cases, and in the underground detectors in $\sim 0.05\%$ of cases. Retarded pulses are observed in the surface detectors in $\sim 9.89\%$ of cases, in the underground detectors — in $\sim 1.55\%$ of cases. Knowing the counting rate of single atmospheric muons, it is possible to calculate the probability of a single muon and a single muon hitting the detector within the time window $1.5\,\mu$s for the advanced pulses and 3.5 ns for the delayed ones. Calculations have shown that in the first case (advanced pulses), the ingress of a single muon and EAS particles into the surface detector should be observed in $\sim 0.3\%$ of events, in the underground detector — in $\sim 0.09\%$ of events. In the second case (delayed pulses) for the surface detector in $\sim 0.63\%$ of events, while in the underground detector — in $\sim 0.21\%$ of events. It can be concluded that the close approach of single muons and EAS particles into the detector makes it possible to explain the advanced pulses, but such events are not enough to provide the observed statistics on delayed pulses.

The assumption that the delayed pulses are PMT after-pulses cannot explain the discovered dependence of the presence of delayed pulses in the station on its position relative to EAS axis. From Fig. 3, *b* we may see that „multi-modal" pulses and multi-pulse EAS signals most probably were observed in the stations located 200 m and more away from the shower axis. We therefore may conclude that EAS pulses of „multi-modal" shape and delayed pulses

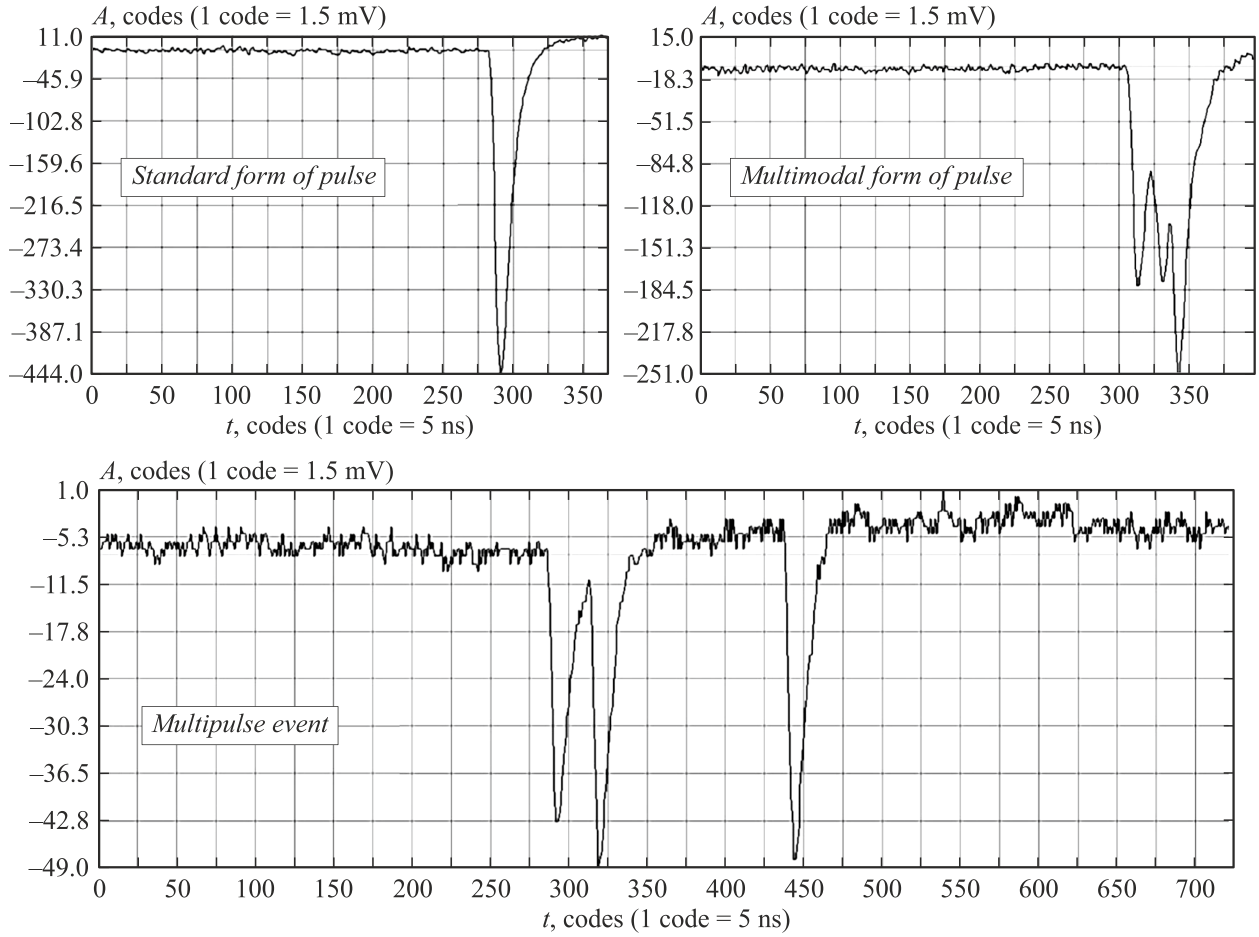

Figure 1. Shapes of signals according to experimental data (time code = 5 ns, amplitude code = 1.5 mV).

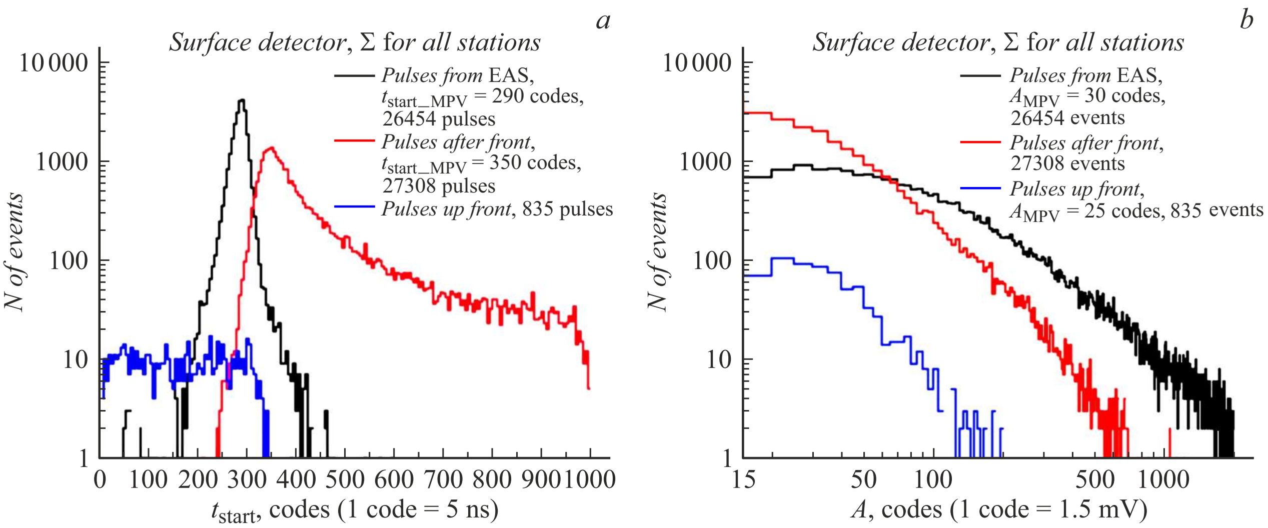

Figure 2. Distribution of pulses in the surface detectors: *a* — depending on the time of the pulse start, *b* — by amplitude. Single-particle pulse amplitude $A_1 = 30$ codes, the graphs illustrate distribution of pulses with an amplitude not less than $A_{\text{threshold}} = 0.5A_1$.

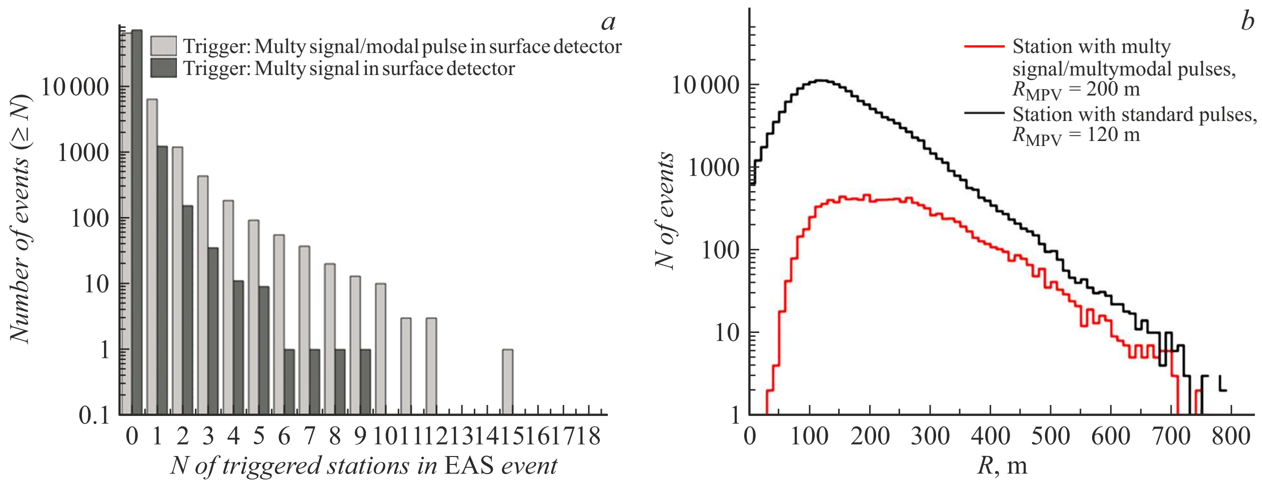

Figure 3. *a* — distribution of EAS events depending on the number of responded stations with multi-pulse signals and „multi-modal" pulses on the surface; *b* — distribution of responded stations depending on the distance to EAS axis.

are associated with the spatiotemporal EAS structure and indicate the growth of the shower disc thickness with the growth of distance from EAS axis.

Conclusion

The shape of „multimodal" pulses reflects the features of particle propagation at large distances from the shower axis. The delay time of particles relative to the front edge of EAS increases as the distance from the shower axis becomes higher. If the detector is located at a distance of 200 m and more from EAS axis, then, the delayed particles that enter it give additional peaks in the detected signal.

The advanced pulses detected on the time sweeps are caused by single atmospheric muons entering the detector along with EAS particles. This is proved by consistent results of computations and experiment. There's no any unambiguous explanation of the nature of delayed pulses. We believe that, apart from the PMT after-pulses and single muons, sufficient contribution is provided by the delayed EAS particles. The issue of the nature of delayed pulses is still unclear and requires further investigation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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