Spatio-temporal structure of a shower disk in the ultra-high energy region observed by different components

Stanislav Knurenko, Zim Petrov, Yuri Yegorov
Yu. G. Shafer Institute for cosmophysical research and aeronomy SB RAS
E-mail: s.p.knurenko@ikfia.ysn.ru

Abstract. An analysis was performed on a set of EAS events containing recorded pulses in scintillation detectors of various area and located at different core distances. Events were categorised by the energy and zenith angle. A difference in pulse shapes was noted between young and old showers. In the data bank, several events were highlighted, with identical delayed pulses recorded in one or more scintillation detectors. Involving multi-component analysis of extensive air shower data we discuss possible connection of a second shower front (which the delayed pulses effectively represent) with yet unknown processes.

1. Introduction
For many years measurements of the pulse shape in Cherenkov and scintillation detectors have been carried out at the Yakutsk EAS array [1, 2]. Initial measurements of the pulse shape from 2-m² scintillation detector were performed in 1975, continued in 1988-1990 and renewed in 2005. Lately, a specially designed setup started operating. It consists of scintillation and Cherenkov detectors and is equipped with quick-response electronics. All these allows reconstruction of time-related characteristics of forward and back fronts of a shower disk and its curvature and thickness with a good precision. Measurements have shown that time-base of the signal in scintillation detector can be used in quantitative analysis of EAS data, including cosmic ray mass composition data.

2. Equipment used for registering the pulse shape from charged particles
For time-related measurements at the Yakutsk EAS array, scintillation detectors of different areas and thickness are used. One of the detectors \( s = 0.1 \text{ m}^2 \) has a 10 cm lead ceiling, similar detector has no roof and is covered with a thin black paper. These detectors are appointed for studying the influence of the cover material on detector response and the ratio between muons with \( E_{\text{thr.}} \geq 0.3 \text{ GeV} \) and electrons in a shower. For studying the spatio-temporal characteristics of Cherenkov radiation a camera-obscura was constructed [3].

For pulse shape recording we use a system based on an industrial computer of increased reliability. Registration is controlled by external “masters” generated by the main array when signals from three non-collinear scintillation detectors spaced by 500 m coincide (trigger-500). Masters are also generated by the small Cherenkov array when signals from three integral
3. Registration results

After $\sim 18000$ hours of duty cycle $\sim 1.2 \times 10^5$, showers were registered with energy above $10^{15}$ eV. In every event, the arrival time of the front of charged particles disk and Cherenkov light, build-up time and pulse half-width were measured and pulses from delayed particles were recorded on a time scale up to 15 mcs.

During the analysis several peculiarities were discovered in the shape of registered pulses in both “young” (vertical) showers and “old” (inclined) showers. The former have pulse half-width $200 - 250$ ns, the latter — $150 - 180$ ns. There are showers with large amount of delayed particles and in some events the time scale notably extends up to 10 mcs.

As it follows from fig. 1, in most EAS events delayed particles are distributed over the interval $\Delta t = 40 - 2000$ mcs, which coincides with particles picking time of the ADC at the Yakutsk array.

From the huge amount of data one can distinguish a small group of showers with a clearly visible double-peaked shape (see fig. 2). The delay time of the second group of particles lies within $60 - 350$ ns from the first one. The number of such events is all in all $\sim 1.5 - 2\%$ from the total number of registered EAS events. Electron-photon shower has larger pulse half-width and half-height compared to “muonic” one. Pulse structure consists of many saw-like peaks distributed in the interval from 0 to 1000 ns starting with the first particle arrived at the detector (see fig. 3). Such pulses to a greater degree reflect the string nature of particle production in

Figure 1. Delayed pulses distribution (relative to the “fastest” particle) over delay time $t$. Considered core distances are in the range of $80 - 1500$ m.

Figure 2. An example of anomalous pulse shape. Channel number 16 (detector without top cover). There are also double pulses in other detectors but with very small amplitude.

Figure 3. Pulse shape recorded at the core distance $R = 1298$ m. $E_0 = 1.7 \times 10^{19}$ eV, zenith and azimuth angles equal to $18^\circ$ and $78^\circ$ respectively.

Cherenkov detectors located in apexes of equilateral triangle with side 50, 100 and 250 m coincide.
showers. Such a pulse shape usually is peculiar to vertical showers with low maximum in the atmosphere.

"Muonic" showers have round pulse peak and notably 30% lesser half-width compared to pulse from the electron-photon shower component (see fig. 4), particles are distributed in a lesser time interval from 0 to 550 ns. Such a pulse shape can be observed in inclined showers and in showers with low maximum of development.

![Figure 4. Pulse shape recorded at the core distance $R = 1000$ m. $E_0 = 2.4 \times 10^{19}$ eV, zenith and azimuth angles equal to 56° and 200° respectively.](image)

It was assumed that both single detectors and their combinations are to be considered in the analysis. This is due to the fact, that detectors have different relative apertures on core distances and different threshold for registering relativistic particles — 10, 5 and 2 MeV. Also, the relation of signals from two geometrically identical detectors (with and without additional shielding, $E_{\text{thr.}} \geq 0.3$ GeV for muons) was taken into account. Preliminary analysis of the experimental data has shown that scintillation detectors with different areas have different registering efficiency. In showers with $E_0 = 10^{17} - 10^{18}$ eV counters with $s = 0.1, 0.25$ m$^2$ effectively operate at the core distance $R \leq 500$ m and counters with $s = 2$ m$^2$ do so at $R \leq 1500$ m. Thus, smaller counters can participate in generation of trigger-500 and larger ones — in generation of trigger-1000. It was noted, that pulse characteristics strongly depend on the detector type. From the analysis of showers with different energies one may conclude, that the signal in showers with energy $\sim 10^{17}$ eV is represented by the single-peaked pulse, not unlike the pulse from an inclined shower, and this fact speaks well for faster development compared to showers with energy $\sim 10^{19}$ eV with maximum of development at the depth 750 - 850 g/cm$^2$.

Analysis of the signal amplitude has also shown that in some cases the amplitude in shielded detectors is much higher, than in unshielded ones (see fig. 6). Preliminary analysis of such showers hints of a low-energy hadrons in a stream, interacting with shielding material and generating a micro-shower resulting in increased signal amplitude. From the comparison with QGSJet simulation for single muons [4] it follows that in case of $n \geq 5$ relativistic particles, there is an excess of registered particles over simulated, which also requires explanation. One of the versions — Cherenkov emission in glass of a PMT photocathode.

The time-related shower characteristics are shown on fig. 5. They were obtained from the measurement of the arrival times of charged particles and Cherenkov photons. A wide distance range was covered, showers with energy above $10^{17}$ eV were selected. Measurements have shown, that up to distances $\sim 300$ m, shower front is semi-flat and slightly exceeds the precision of zenith angle measurement at the Yakutsk array (100 ns). At $R \geq 300$ m from the core, delay increases significantly and at 1000 - 1500 m amounts to 400 - 800 ns. Thus, this delay should be accounted when measuring EAS arrival angles.

Using the value of particle arrival delay at the detector $\langle \tau \rangle$, one can obtain curvature radius of the shower front. These times characterize areas of shower development in the atmosphere.
from which at a given core distance the main portion of particles arrives. Radius of curvature is determined by formula:

$$R_{\text{curv}} = \frac{R^2 - (ct)^2}{2c\tau},$$

where $R$ — core distance, $\tau$ — particle delay, $c$ — speed of light. For experimental data of the Yakutsk array at mean core distance 790 m and $\langle \tau \rangle = 248$ ns, $R_{\text{curv}} = 4180$ m. Along with the core distance the curvature radius increases, meaning that particles arrive from larger heights.

4. Conclusion
Registration of the time-related shower characteristics (particle arrival time at the detector, pulse shape in scintillation detectors) allowed us to make the following conclusions: a) “Young” and “old” showers have drastically different pulse shape; b) Pulses delayed by $\geq 2$ mcs are observed in showers but not in all; Anomalous pulse shapes are presented; c) Curvature of the forward front of showers with energy $> 10^{17}$ eV at the core distance 500 – 800 m equals 3.9 – 4.9 km; d) Analysis of the response from scintillation detectors with different energy thresholds have shown that pulses delayed by larger periods are generated by low-energy particles (electrons) which were possibly born in the process of neutron moderation in the frozen ground [5].

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