EAS detection by wide-angle cherenkov telescopes at the Yakutsk array

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Abstract. A proposed new method for measuring the Cherenkov light from extensive air showers (EAS) of cosmic rays (CR), which allows to determine not only the primary particle energy and angle of arrival, but also the parameters of the shower in the atmosphere - the maximum depth and "age". For measurements, it is proposed to use Cherenkov light produced by EAS in a ground network of wide-angle telescopes, which are separated from each other by a distance 100-300 m depending on the total number of telescopes operating in coincidence, acting autonomously, or includes a detector of the charged components, radio waves, etc. as part of the EAS. The energy measurement and CR angle of arrival, data on the depth of the maximum and the associated mass of the primary particle generating the EAS is particularly important in the study of galactic cosmic rays for E> 10^{14} eV, where currently there are no direct measurements of the maximum depth of the EAS.

1 Introduction

It has been realized that the angular and temporal structure of the Cherenkov light emitted by extensive air shower (EAS) can be used to infer the longitudinal development parameters of the shower [1–4]. The angular distribution of Cherenkov photons from EAS was calculated by V.I. Zatsepin [1] assuming it is determined mainly by that of electrons in the shower. Then Fomin and Khristiansen proposed [2] to use the pulse shape of the Cherenkov signal, namely the pulse width, to indicate the shower maximum position, x_m, in the atmosphere. Experimental measurements of the Cherenkov signal pulse shape were performed initially in Yakutsk and in Haverah Park [3, 4]. The results were used to not only estimate x_m but attempts were made to evaluate the cascade parameters of electrons at CR energies around 10^{17} eV [4, 5]. A variety of detectors are used then, for instance, in the Tunka experiment forming an array of Cherenkov detectors $_m$ currently $_m$ near Lake Baikal [6].

2 Pulse duration as a function of the distance to the shower core

The main feature of the signal is its duration rising with the shower core distance due to geometrical reasons. The first measurements of the parameter were made in Yakutsk [7] and Haverah Park [4]. The most recent results are provided by the Tunka array [8]. Our measurement of the full width at half-maximum of the signal confirms the previous results (see Fig.1). Event numbers are indicated above our data points. The relevant energy ranges are: Haverah Park (E) ~ 0.2 EeV; Yakutsk, 1975 E ∈ (0.001, 1) EeV; Tunka E ∈ (0.003, 0.03) EeV.

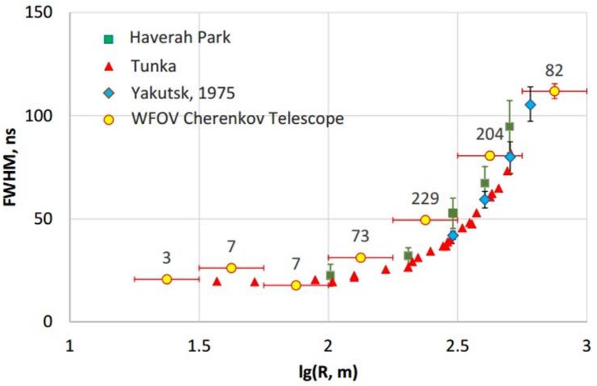

Figure 1. : Full width at half-maximum of the Cherenkov signal as a function of the shower core distance, R, measured by EAS arrays

We have analyzed the full width at half-maximum dependence on other shower parameters such as zenith and azimuth angles, and energy. No significant variation versus angles is found exceeding instrumental errors. On the other hand, an indication of the energy dependence of the pulse width is found in our data. Application of the FWHM(R) function is possible in the shower core location procedure in the array plane.

The method was pioneered by John Linsley [9] using the charged particle signal width vs R. While in the Yakutsk array group the particle and Cherenkov photon density distribution functions are used to locate the shower core, the FWHM(R) function can be used additionally (or instead) to refine the core coordinates in the array plane. As an illustration, the signal width is shown as a function of energy Fig. 2. A systematic variation of the width is

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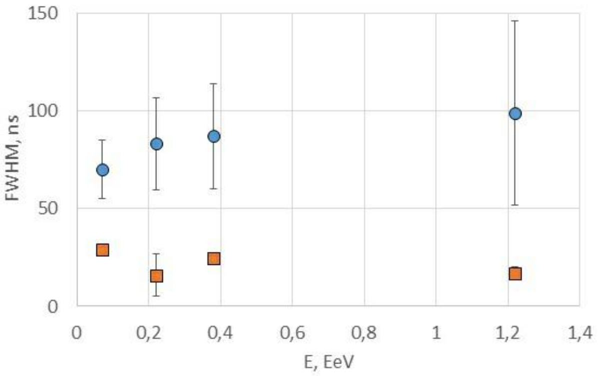

Figure 2. Energy dependence of Full width at half-maximum of the Cherenkov signal

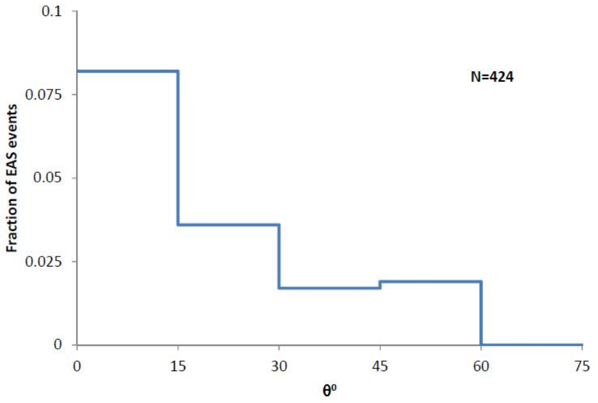

Figure 3. Zenith angle distribution of the shower fraction detected with telescope

visible, although the tendencies are contradictory in the shower core distance intervals. More data are needed, especially at distances to the shower core less than one hundred meters, to reveal a reliable energy dependence. Application of the FWHM(R) function is possible in the shower core location procedure in the array plane at least additionally to the Cherenkov photon density distribution.

3 Cherenkov telescope working in coincidence with surface detectors

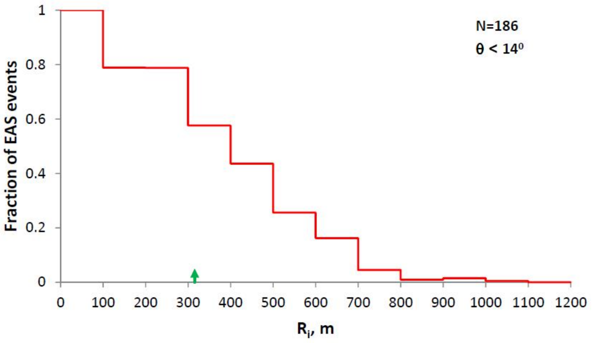

Figure 4. Axis distance distribution of the shower fraction detected with telescope

During the field testing of the telescope we had 604 hours of clear moonless nights that yielded 11124 EAS events detected by the scintillator subset of the array, from which 424 events resulted in a nonzero simultaneous signal in the telescope. From the numbers above (and the array area of $8.2km^2$) we determined the effective radius of the telescope acceptance $R_{eff} = 315m$. This radius can be used in planning the grid of telescopes. The fraction of EAS events detected with a nonzero telescope signal is 3.8%. The dependence of the signal on the zenith angle and the shower axis distance is illustrated in Fig. 3; the primary energies were in the region $E_0 > 10^{16}$eV. While the telescope FOV is 308 sq. degrees $\theta \in (0^0; 14^0)$), EAS events were detected with zenith angles up to $\theta = 60^0$. This observation can be explained by the broad angular distribution of the electrons emitted in the shower and the photon scattering in the atmosphere. Another contribution is the angular uncertainty of the shower reconstruction procedure, which is considerably increased at the lower threshold energy of the array. To avoid this uncertainty, we selected showers within $\theta < 14^0$ to define a distribution of the shower axes (Fig.4). The effective radius of the telescope detecting area, R_{eff}, is indicated by the arrow on the R_i axis as well.

4 Method to Estimate the Distance to the Shower Maximum via Cherenkov Light Measurements

Common methods in use to find the height in the atmosphere, h_m, where the number of EAS particles reaches a maximum, which rely on Cherenkov light detectors, are based on the measurement of the lateral distribution of the photon density and pulse duration[10–12]. We propose another approach to height maximum evaluation resulting from our measurements of the Cherenkov light induced by EAS. Knowing the time delay of the Cherenkov signal maximum in the detector relative to the shower axis crossing the array plane at a distance R, one is able to calculate the distance, h_θ, to the height in atmosphere, h_m, where the emission of Cherenkov photons reaches a maximum. Other shower parameters needed are the coordinates of the shower axis and the EAS arrival angles. In our case, these parameters can be provided by the set of synchronized surface detectors of the Yakutsk array. The time difference is determined by triangles consisting of R, h_m, h_θ. More information about this method can be found in reference [13].

$$c\Delta t = \sqrt{h_\theta^2 + R^2 - 2Rh_\theta \sin\theta\cos\phi} - h_\theta,$$

where ϕ, θ are shower arrival angles; c=0.3 m/ns. A solution is given by

$$h_\theta = \frac{0.5(R^2 - (c\Delta t)^2)}{c\Delta t + R\sin\theta\cos\phi},$$

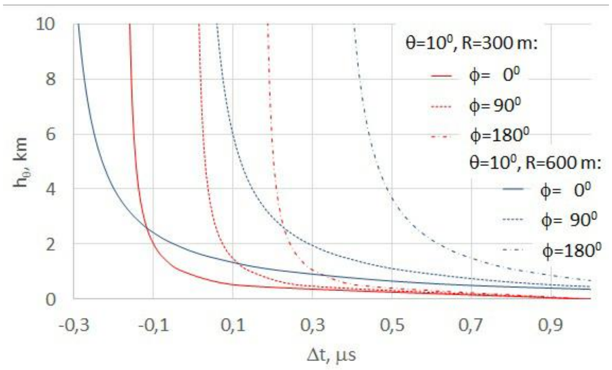

Figure 5. The height of Cherenkov light emission maximum as a function of time difference

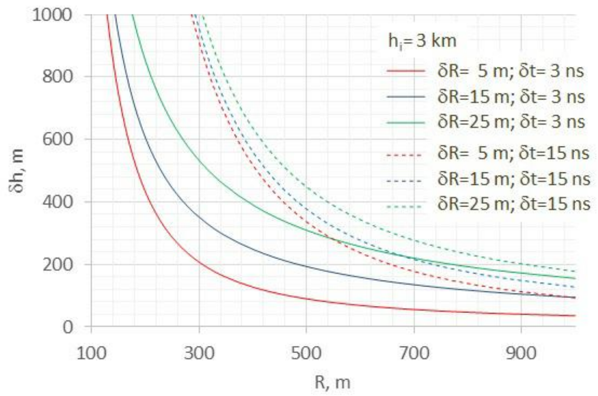

Figure 6. Estimation of the height reconstruction accuracy as a function of the shower core distance.

The solution of the equation is shown in Fig. 5. Rather large values of the derivative dh_θ by dΔt near the time difference threshold restrict the maximum location possibilities within narrow limits due to moderate timing accuracy. On the other hand, relatively small heights can be resolved with reasonable timing resolution.

We illustrate in Fig.6 the maximum height location accuracy achievable with the different shower core and time measurement errors. The present accuracy for the Yakutsk array detectors is not sufficient to measure the distance to the shower maximum with reliable results. But the Yakutsk array modernization program now in progress includes the best part of the improvements needed. Specifically, a target synchronization accuracy of detectors will equal 5 ns due to Gigabit Ethernet via optical fibers. New scintillation counters and Cherenkov light detectors will provide the core location accuracy of showers within 15–20m. Accordingly, the modernized array will be able to measure xCher m with an accuracy of 3–4 % , if the time resolution of the Cherenkov light detectors will be better than 5 ns.

5 Conclusions

A wide fov Cherenkov telescope prototype obtained experimental data from 19.10.2012 to 29.03.2017, on 220 clear moonless nights with about 1670 hours of observation, during the observation of the master load 30,000 times, of which the Cherenkov telescope gave a signal to the coincidence of about 1450 times. This allowed to build the width at half-maximum as a function of the distance from the shower core (R); these calculations will help determine the shower core in the array plane, and further modernization of the array will enable the height of the shower maximum to be calculated by the time delay.

Acknowledgments

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