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Radio emission of air showers with extremely high energy measured by the Yakutsk Radio Array

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A B S T R A C T

The Yakutsk Array is designed to study cosmic rays at energy $10^{15}-10^{20}$ eV. It consists several independent arrays that register charged particles, muons with energy $E \geq 1$ GeV, Cherenkov light and radio emission. The paper presents a technical description of the Yakutsk Radio Array and some preliminary results obtained from measurements of radio emission at 30–35 MHz frequency induced by air shower particles with energy $\varepsilon \geq 1 \cdot 10^{17}$ eV. The data obtained at the Yakutsk array in 1986–1989 (first set of measurements) and 2009–2014 (new set of measurements). Based on the obtained results we determined: Lateral distribution function (LDF) of air showers radio emission with energy $\geq 10^{17}$ eV. Radio emission amplitude empirical connection with air shower energy. Determination of depth of maximum by ratio of amplitude at different distances from the shower axis. For the first time, at the Yakutsk array radio emission from the air shower with energy $>10^{19}$ eV was registered including the shower with the highest energy ever registered at the Yakutsk array with energy $\sim 2 \cdot 10^{20}$ eV.

1. Introduction

The method of registration of radio emission of ultrahigh energy particles is based on the motion of charged particles in the geomagnetic field [1,2] and Askaryan effect [3]. Apparently, both generation mechanisms are effective in passing air shower particles through the atmosphere. Their contribution to the generation of radio emission depends on the conditions of the shower development in the atmosphere: height of the shower maximum, zenith angle of the incoming shower and energy. Full research of radio emission mechanisms is only available on the arrays with a hybrid registration system of extensive air showers (EAS) particles: electrons, muons, Cherenkov light, ionization and radio emission.

Influence from both mechanisms affects the symmetry of the lateral distribution of air showers radio emission as shown from the experiments. This is especially noticeable at small distances from the shower axis, where the radio emission intensity decreases significantly.

In the following years after this discovery, there have been many experimental studies of radio emission from air showers [4,5], including the Yakutsk array [6]. Short reviews of the air shower radio emission work can be found in [7–10]. In paper [7] pointed out the possibility of registration of extensive air showers (EAS) with energies above 10^{19} eV, employing radio equipment placed on the surface of the Earth and registering the radio emission by satellites on the Earth orbit. Surface arrays require a huge area of 3–5 thousand square kilometers for the registration of showers with such energies. In addition, it requires relatively quiet in terms of radio interference place in the urbanized society that is difficult to find. At the same time, satellite based arrays would allow a large solid angle which covers bigger areas and detects a larger number of air showers with highest energies. Thus, the problem of statistics of such showers would have been solved, and the spectrum of cosmic rays would be studied at energies up to 10^{21} eV. But before one put this idea into practice, we need to ensure the effectiveness of this method of registration of showers with ultra-high energies. For these purposes would most be suited the currently existing large ground arrays where exist a corresponding infrastructure which can be used for registration of radio emission. Experiments on radio radiation from the EAS were actively carried out in 60–70 years of the last century. For example, the array of the Moscow State University in the 70s registered air shower radio emission at energies $10^{16}-10^{17}$ eV [11,12]. Later, in 1986–1989, at the Yakutsk array were carried out measurements of radio emission in the energy range above 10^{17} eV [6,13,14].

In recent years, interest in the air shower radio emission, as an independent method to study the physics of the EAS has grown significantly, and for registration of radio emission were built arrays of significant size [15,16]. This method makes it possible not only to evaluate the energy but also to reconstruct the longitudinal shower development, namely, the depth of maximum X_{max} [17,18]. This is especially important for huge arrays where the uncertainty

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in the estimation of shower energy with different methods of detecting air showers reaches about (20 – 40)%. For example, Auger and Telescope Array difference is 20 % and the cause of differences still remains unknown [19]. Thus, the radio emission, in conjunction with other methods could be employed for inter-calibration of huge arrays [20–22].

This paper presents radio emission of EAS with ultra-high energies data obtained by Yakutsk array in 1986–1989 and 2009–2014 years.

The paper structured as follows. In the Section 2 the Yakutsk array is described: frequency choice for registration, equipment, software for registration and analysis. Methodological issues like background noises at the Yakutsk array region is discussed in Section 3. In section 4 the results of registration of air showers with energy E = 10^{17} – 10^{18} eV and E ≥ 10^{19} eV are presented, also energy estimation, determination of depth of maximum development and mass composition of CR. Conclusion is discussed in Section 5.

2. Yakutsk radio array

2.1. First stage

In the mid 80-es of the last century, the Radio Array with registration bandwidth 30–40 MHz was designed as an extension of main Yakutsk particle array [6]. The setup consisted of two parts: analog and digital. The analog part comprises the reception, amplification of the radio signal, matching circuits of the output signals by the level and frequency with the parameters of the digital recorder. The digital part of the array converts input analog signals into digital code and writes information of the radio noise state and the signal from the shower to a buffer RAM. Then the information about the noise field and a radio pulse from EAS were copied to the computer hard disc drive (HDD). Air shower radio emission is registered by 20 receiving antennas, which are installed on 10 pillars as shown in Fig. 1.

The distance between antenna pillars was 50, 100, 200, 300 and 500 m, covering an area of roughly 0.35 km^2. One pillar consists two independent half-wave dipoles with orientation E-W and N-S. Antennas installed at $\lambda/4$ above ground, thus ensuring a maximum of the radiation pattern of the emission coming from the top.

Fig. 1 shows the location of antennas. At the lower part of the antenna pillar special container is located. In order to enhance the radio signals, unified broadband receivers with direct amplification at the bandwidth of 30–35 MHz were applied. Suppression of the gain at frequency 29 MHz ≥ 40 dB, at frequencies less than 28 MHz and more than 36 ≥ 60 dB.

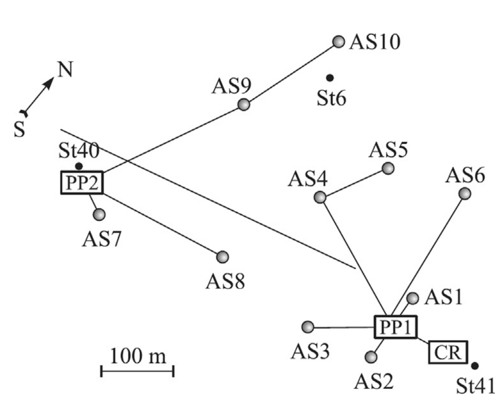

Fig. 1. The arrangement of the radio antennas, in 1986–1989. AS – antenna station; PP – peripheral (intermediate) collection point for air shower data; CR – central registration point; ST station with scintillation detectors of Yakutsk array.

Constructively, the receivers are designed as two blocks. The first block is located under the antenna, the block consists a low noise amplifier with a gain of Ku ≅ 40 dB and output matching with the cable. In the second block, the final amplifier with gain Ku ≅ 40 dB was placed. To match with a bandwidth of the ADC at the output of the amplifier amplitude detectors are used. To improve detection of linearity powerful FET (Field Effect Transistor) type KP901 and KP902 were used.

All recording equipment: power amplifiers, detectors and ADC were placed in the two warm cabins, because of the extremely low winter temperatures (−40 °C). Also, the cabins contain calibration generators and high-frequency switches.

Calibration. During the calibration process, the input of the antenna amplifier is disconnected from the antenna and is connected to the output of the calibration generator via coaxial cable. Calibration is performed automatically without operator intervention at specified intervals of time. For this purpose, the remote-controlled generators G4-151 and RF switches on the relay of REV-15, which is controlled by a central computer, were used. To improve the accuracy of timing synchronization of additional ADC of crystal oscillators has been introduced.

ADC. In the first stage of the experiment, ADC F-4226 with the following parameters were used: sampling frequency – 20 MHz, conversion time – 50 ns, accuracy −8 bits (256 amplitude points), RAM-1024 word capacity (51 ms). Continuous operation of the converter allows one to store information in the memory of the radio pulses before receiving the ADC trigger signal input from the scintillation detectors of the Yakutsk array. The 9th bit of data word is a sign of the data are in the RAM to run.

Additional synchronization with EAS provided by a separate channel of signal detection for time synchronization at a frequency of 207 MHz with an accuracy of 100 ns, using the same type of ADC.

2.2. Current state of radio array

2.2.1. Selection of optimal frequency for air showers radio emission registration

In 2009, for an optimal frequency choice, the background frequency spectrum from 1 to 100 MHz was analyzed [23], according to work [24]. We used digital spectrum analyzer ASA-2332. At frequencies, up to 20 MHz due to the presence of large natural radio noise (primarily storm origin), it is not possible to distinguish air showers pulses with sufficient efficiency. Therefore, it is reasonable to select frequencies above 20 MHz, since ionosphere noises amplitude decreases dramatically in the transition to high frequencies and is about (0.5–1) μV m^{-1} MHz^{-1} at the frequency ~20 MHz. Over this frequency range, the amplitude of galactic noises decreases much slower with the frequency than storm noises. At 32 MHz it is 1.0–2.0 μV m^{-1} MHz^{-1}. Thermal noise of the antenna is much smaller than the galactic noise at frequencies up to 100 MHz and has almost no influence on our measurements. Therefore, the most favorable frequency range for the measurements at the Yakutsk array is 30–40 MHz, where expected the best signal-to-noise ratio because at higher frequencies the spectrum is limited by strong interfering man-made signals, e.g. broadcast television.

Also, we measured background noise at the output of the analog receiver (Fig. 2) of the Yakutsk radio array. The Fig. 2 indicates the window with a frequency of 28–42 MHz with no significant interference.

2.2.2. Hardware and Measurement Technique

In early 2009, at the Yakutsk array, the radio array was reconstructed [25]. It consists 12 crossed at 90° receiving antennas (6 pillars with 2 antennas each) oriented in directions W – E (West – East), N – S (North – South), the peripheral recording device (PRD) and data storage on a personal computer. PRD was located directly