Radio signal at 32 MHz with extensive air showers parameters

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Abstract. The paper presents correlations of radio signals measured at the Yakutsk array with air shower parameters: the shower energy \( E_0 \) and the depth of maximum \( x_{\text{max}} \). It is shown that from radio emission measurements of air showers one can obtain individual shower parameters and hence, the mass composition of cosmic rays. In addition, we also derived a generalized formula for calculating the primary energy of the air showers.

1. Introduction
The study of cosmic-ray properties by measuring the radio emission from charged particles in extensive air showers might be an alternative to traditional methods for large arrays [1, 2, 3, 4]. Such arrays consist of hundreds and thousands of scintillation detectors for the registration of charged particles, or of detectors, recording the optical emission from the relativistic particles in the EAS. Such arrays are very costly because of the large amount of detectors and the required complex technical equipment. On the other hand, the radio method is much cheaper and easier to operate with a nearly 100% duty cycle. It is sufficient to have an antenna and a simple radio receiver tuned to a given frequency. One of the main problems is to choose a noise free frequency range [5, 6, 7, 8]. The air shower registration is conducted at a frequency of 32 MHz, free from industrial noise. Yakutsk Radio Array operates since 2009. Data obtained during those several seasons includes showers with energy above \( 10^{19} \) eV.

2. Theoretical Background
The radio emission mechanisms are meanwhile well known and calculations [9] show that the radio emission of EAS depends on the development of the electromagnetic cascade in the atmosphere and the magnetic field near the level of observation. That means, the radio emission is directly associated with the physics of the air shower development: production of electrons and positrons in the atmosphere (longitudinal development of air showers) and the total number of charged particles (EAS energy).

The electric field induced on the antennas of the radio arrays, according to [10], can be represented as follows:

\[
\varepsilon_{\nu} = \frac{4\pi \nu^2 \mu_0}{G(\theta, \phi, \nu) c} \cdot \frac{1}{A_{\text{ele}(\nu) R_{\text{ADC}}}} \frac{V_{\text{ADC}}}{\Delta \nu}
\] (1)
Here $\nu$ is the observing frequency, $G(\theta, \phi, \nu)$ is the gain of the antenna, $A_{\text{ele}}(\nu)$ is the total gain of the electronics, $V_{ADC}$ is the voltage measured by the ADC, and $R_{ADC}$ is the input impedance of the ADC.

It was also shown that the amplitude $A_{\text{max}}$ of the radio pulse is proportional to the energy of the electromagnetic component of the EAS with $E_{\text{em}} = c \cdot A_{\text{max}} \ (\mu\text{V}^{-1} \text{ m GeV})$, where $c$ - is a shower geometry dependent parameter [9].

Combining our radio measurements and calculations of [9], we can determine the shower energy, regardless of the registration method, and then compare the two energy estimations, namely that by Cherenkov detectors data [11] and that by radio emission data.

In [9] calculations are performed, which show that the slope of the lateral distribution function (LDF) of the radio emission depends on the depth of the shower maximum $X_{\text{max}}$. This slope can be determined as the ratio of the measured amplitudes of the radio pulse at the flat and the steep part of the LDF. In our case the distances of 175 m and 725 m from the shower axis were used. Analytically, this relationship can be expressed by the formula [9]:

$$X_{\text{max}} = a \left[ \ln \left( \frac{A_{175m}}{A_{725m}} \right) \right]^c$$

Here $a$, $b$, $c$, are constants coefficients, $a = 856.1$, $b = 0.3149$, $c = 0.4340$. They are adapted to the latitude of the Yakutsk and coincide with calculation of [9] within experimental errors.

3. Short Description of Yakutsk Radio Array
First experiments at the Yakutsk array to register radio pulses from air showers have been performed in 1987-1989.

Radio signals from 6250 showers with energies above $10^{17}$ eV were registered, including some events with $E_0 \geq 10^{19}$ eV. In 2009, 6 antennas (half-wave dipole) for radio emission registration were installed at the Yakutsk array. The antennas are located at 300, 350 and 500 m distance from the array center. For an optimal frequency choice, the background frequency spectrum from 1 to 200 MHz was analyzed [6]. 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. Over this frequency range, the amplitude of galactic noises decreases much slower with the frequency than storm noises. At 32 MHz it is $1.0 - 2.0 \ \mu\text{V} \cdot \text{m}^{-1} \cdot \text{MHz}^{-1}$. 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. We installed an array tuned to a frequency of about 32 MHz with a bandwidth of 8 MHz. It consists of antennas, amplifiers and registration device with data storage [8]. We used a half-wave dipole installed at $\lambda/4$ above ground (Fig. 1). Crossed dipoles are oriented along East-West (on the magnetic latitude), and North-South (along the magnetic meridian). The bandwidth is $\pm 4$ MHz, sensitivity $\sim 10 \mu\text{V}$ ($2 \ \mu\text{V} \cdot \text{m}^{-1} \cdot \text{MHz}^{-1}$), the dynamic range is 50 dB.

Receiving channels are based on the principle of direct signal amplification and subsequent detection. Antenna amplifiers are placed into special containers and are located directly at the antenna. The main paths are based on the cascade amplifier circuit with mismatched contours.

The array currently consists two set of antennas, the distance between them is 500 m. The first set consists of 8, the second of 4 antennas. Each set is connected to an industrial computer. Directly under the antennas are electronic devices and matching amplifiers and grounded shielding grid. Testing and calibration of measurement including the antennas is done once in a measurement season (typically the period from September to May) using a broadband high-frequency generator and a control PC. Registration of radio emission is triggered by one of
two event triggers (masters) from the Yakutsk array. The location of the antenna sets is shown in Fig. 2.

The first of the two possible triggers is the main Yakutsk array trigger, which registers in an area of 12 km$^2$ showers with energy more than $10^{17}$ eV. The Small Cherenkov array registers in an area of 1 km$^2$ showers with energy $10^{15} \cdot 5 \cdot 10^{17}$ eV. The data collection system is based on an industrial computer and is able to recording signal from multiple antennas simultaneously. We use a fast 8-bit ADC, which records the prehistory (before the trigger arrival) for 25 µs and history (after the arrival of the trigger) for 15 µs (Fig. 3).

Fig. 3 shows the ADC values of the radio signals from 4 antennas, the X axis spans 40 µs. Vertical line marks the arrival time of the trigger signal.
4. Results

The Radio Array [8] benefits from the co-location with a particle detector experiment, which provides values for the fundamental parameters defining an air shower: primary energy, depth of shower maximum, shower core and arrival direction [12, 13]. The goal of this work is to find a correlation: a) between signal amplitude and air shower energy (the energy is estimated from the Cherenkov light flux [11, 14]); b) between LDF and longitudinal development (depth of shower maximum as determined by the Cherenkov data [15, 16]). If such a correlation is experimentally confirmed, then using theory and calculations [9] it is possible to determine energy and depth of the maximum by radio emission data and to use these parameters to study high energy cosmic rays. In this section we present the recent results obtained at Yakutsk.

As seen in Fig. 4, the average slope of the LDF varies with the distance. At small distances (50-200 m) the slope is flat, at larger distance (~300 m) it becomes steeper [17]. For example in the showers with energy \( \sim10^{17} \), slope at a distance 100 meters is \( \sim0.71\pm0.1 \), at the distance of 100-700 m \( \sim0.97\pm0.1 \).

As it is shown in Fig. 4 the average slope of the LDF varies with distance. At large distances from the shower axis, the radio signal attenuates slowly.

Using equations (1) and (2) and the measured EAS radio signals we tried to find correlations between a) the amplitude of the radio signal and the shower energy \( E_{\text{em}} \) (derived from the
Cherenkov light signal) and b) between the ratio of the radio signals at 175 m and 725 m and the depth of the shower maximum $X_{\text{max}}$ [15, 16].

For this analysis, we selected 421 events for which simultaneously have been measured charged particles, muons and Cherenkov light. In Fig. 5 the correlation between radio signal amplitude and shower energy is shown. Data can be fitted by formula (3).

$$\varepsilon_{EW} = (1.3 \pm 0.3) \left( \frac{E_0}{10^{17}} \right)^{(0.99 \pm 0.04)}$$ (3)

Here $\varepsilon_{EW}$ denotes the estimated radio amplitude and $E_0$ the energy of the primary particle.

The generalized formula (4) allows to determine the energy of individual shower coming with zenith angle $\theta$, the amplitude of the radio signal registered at a distance of 350 m from the shower axis:

$$\varepsilon = (15 \pm 1)(1 - \cos \theta)^{1.16 \pm 0.05} \cdot \exp \left( - \frac{R}{350 \pm 25.41} \right) \cdot \left( \frac{E_p}{10^{17}} \right)^{0.99 \pm 0.04}$$ (4)

where, $\theta$ - zenith angle, $R$ - the distance to the antenna, $E_p$ - energy of the primary particle.

As seen from calculations [9], the slope of the LDF is correlated with the longitudinal development of the EAS. Using the amplitude of the radio signal at different distances from the shower axis, with formula (2) we can determine $X_{\text{max}}$ of the shower. We can estimate $X_{\text{max}}$ using the average LDF data (Fig. 4) with correcting for the influence of noise as it proposed in [18]. The estimation of $X_{\text{max}}$ from radio data is compared in Table 1 with the $X_{\text{max}}$ obtained from Cherenkov data [16].

| $E_0$, eV | $A_{175m}$ | $A_{725m}$ | $A_{175m}/A_{725m}$ | $X_{\text{rad}}^{\text{max}}$ g/cm$^2$ | $X_{\text{Cher}}^{\text{max}}$ g/cm$^2$ |
|-----------|------------|------------|---------------------|------------------------------------|------------------------------------|
| $1.7 \cdot 10^{17}$ | 2.71 | 0.54 | 5.02 | 610$\pm$25 | 644$\pm$18 |
| $4.3 \cdot 10^{17}$ | 8.52 | 1.67 | 5.11 | 621$\pm$25 | 675$\pm$15 |
| $1.3 \cdot 10^{18}$ | 29.71 | 4.95 | 6.01 | 704$\pm$25 | 710$\pm$15 |

One sees that the values agree within experimental uncertainty. This confirms the possibility of using radio emission for the study of the longitudinal development of air showers. In future we plan to estimate the mass of the primary cosmic rays with larger statistics like in [19].

The calculations in [19] show that the $X_{\text{max}}$ distribution at fixed energy represents the contribution of different groups of nuclei and can be used to analyze the mass composition of cosmic rays.

Figure 5. Dependence of the amplitude of the radio emission pulse from the shower energy.
5. Conclusion
The radio data of the Yakutsk array show that: a) the measured amplitude of the radio signal correlates with the shower energy; b) the depth of the shower maximum can be determined from radio measurements if a reliable adjustment of the noise contribution in the radio signal [18] can be performed.

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