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Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex)

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A B S T R A C T

Tunka-Rex is a radio detector for cosmic-ray air showers in Siberia, triggered by Tunka-133, a co-located air-Cherenkov detector. The main goal of Tunka-Rex is the cross-calibration of the two detectors by measuring the air-Cherenkov light and the radio signal emitted by the same air showers. This way we can explore the precision of the radio-detection technique, especially for the reconstruction of the primary energy and the depth of the shower maximum. The latter is sensitive to the mass of the primary cosmic-ray particles. In this paper we describe the detector setup and explain how electronics and antennas have been calibrated. The analysis of data of the first season proves the detection of cosmic-ray air showers and therefore, the functionality of the detector. We confirm the expected dependence of the detection threshold on the geomagnetic angle and the correlation between the energy of the primary cosmic-ray particle and the radio amplitude. Furthermore, we compare reconstructed amplitudes of radio pulses with predictions from CoREAS simulations, finding agreement within the uncertainties.

1. Introduction

Despite much progress in cosmic ray physics during the last century, many questions, especially regarding the sources and mass composition of high-energy cosmic rays, remain unanswered. Established detection techniques have principal restrictions and current detectors already span over large areas and approach economical limits. To overcome these problems, new detection principles are explored. One promising candidate is the radio technique. Already in the 1960s [1,2] it was shown that the radio emission of air showers can be detected with antennas operating in the MHz frequency range. But due to technological restrictions at that time the interest in the technique faded quickly afterwards. Then, it experienced a renaissance during the last decade due to the fast advance and cheap availability of digital electronics and methods of signal processing [3–6].

With an advancing theoretical understanding of the radio emission, time-varying transverse currents, caused by geomagnetic deflection of charged particles in the atmosphere, were established as the dominant emission mechanism in air showers [7]. In addition, there is a contribution to the signal from the varying net charge, called Askaryan effect [8–11].

To evaluate the possible performance of a radio detector as a stand-alone device for measuring air showers or as part of a hybrid detector in future projects, its properties and especially the achievable precision have to be investigated in detail.

The Tunka Radio Extension (Tunka-Rex) is a radio detector for cosmic-ray air showers, which started data taking in October 2012. It is situated in Siberia, close to Lake Baikal, at the coordinates $51^\circ 48' 35'' \mathrm{N}, 103^\circ 4' 2'' \mathrm{E}$ at an altitude of 670 m, on the same site as Tunka-133 [12], an air-Cherenkov detector for air showers above 10^{16} eV. Furthermore, the TAIGA experiment for gamma astronomy [13] is currently built at the site. It consists of multiple detectors, from

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which Tunka-Grande [13] has the highest relevance for Tunka-Rex. Tunka-Grande is a particle detector array based on former KASCADE-Grande [14] scintillators. Since Tunka-Rex plugs into the digitizers and data acquisition of Tunka-133 and Tunka-Grande, it is a relatively economic device compared to other digital antenna arrays.

In its first two seasons of operation, until 2014, Tunka-Rex was solely triggered by Tunka-133. Thus, all events of the air-Cherenkov detector have the radio signal recorded as well. While this strips Tunka-Rex of one of the main advantages of a radio detector, i. e., its full duty cycle (the air-Cherenkov detector operates only during moonless nights with good weather), it provides an independent measurement of the shower parameters. From end of 2014 on, a part of Tunka-Rex (see. Fig. 1, circle markers) is triggered by Tunka-Grande.

The main goal of Tunka-Rex is to cross-calibrate air-Cherenkov and radio measurements to determine the achievable precision of the radio detector for the reconstruction of shower parameters, i. e., shower axis, energy and atmospheric depth of the shower maximum, which is a statistical measure of the elemental primary composition. Tunka-133 provides these measurements with a precision of 15% for the energy and 28 g/cm^2 for the shower maximum [12].

In this paper we describe Tunka-Rex, its calibration and show first results on its performance.

2. The detector setup

2.1. Layout

Tunka-133 is organized in 25 clusters, each consisting of 7 open, large-size PMTs, arranged in a hexagonal pattern and connected to an ADC board in its center [15]. It operates only during moonless nights with good weather from October to April, resulting in a duty cycle of about 5%. During summer it is shut down for maintenance.

The layout of Tunka-Rex is depicted in Fig. 1. It consists currently of two separately operating detectors, with a total of 44 antenna stations: there are 25 antenna stations triggered by Tunka-133, one per cluster of Tunka-133. The central, dense array of this part covers 1 km^2 with 19 antenna stations, resulting in a spacing of about 200 m. With the outer clusters a total area of about 3 km^2 is reached, but the distance between the antennas increases in the outer region to 500 m.

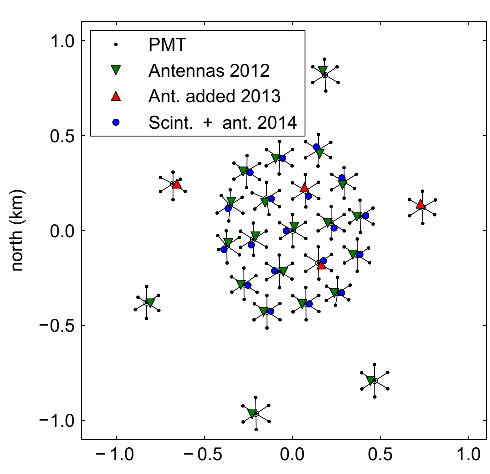

Fig. 1. Layout of Tunka-133 and Tunka-Rex after deployment campaigns in October 2012 and October 2013. In 2014, also the scintillator extension Tunka-Grande was installed with one additional antenna station at each scintillator station.

Additionally, there are 19 antenna stations of the same type, triggered by and connected to the detector stations of Tunka-Grande, featuring both surface and underground scintillators. These antenna stations are located close to the 19 cluster centers of the inner, dense array. They have the same design and very similar hardware as the first antenna stations. This detector, including the antenna array, is capable of operation around-the-clock and may greatly extend the uptime of Tunka-Rex. Furthermore, the antenna array may be used to cross-calibrate Tunka-133 and Tunka-Grande. This extension is still under commissioning and will not be evaluated further in this paper.

2.2. Trigger

Until the commissioning of Tunka-Grande, Tunka-Rex was solely triggered by Tunka-133. The trigger of Tunka-133 works on a single cluster basis [15]. If at least 3 PMTs pass a threshold trigger within 0.5 μs, data from the whole cluster is saved, including data of the Tunka-Rex antennas. Data from single cluster triggers are then combined to events in an offline coincidence search if they occur within a time window of 7 μs. The radio signal is usually only detectable in events with multiple clusters above the detection threshold since the threshold for the air-Cherenkov detector is generally lower. We apply further cuts during the reconstruction to exclude radio stations with accidental noise (see Section 4).

2.3. Hardware of the antenna station

The full hardware chain of a Tunka-Rex antenna station consists of two active antennas, connected via 30 m cable to the input of a filter amplifier, which is connected to the digitization boards.

The antenna type is a SALLA (Short Aperiodic Loaded Loop Antenna) [16] with 120 cm diameter (see Fig. 2), an economic and rugged type of loop antenna. The lower box, which connects the antenna arcs, houses a load, making the antenna less sensitive to radiation from below and thereby reducing its dependence on ground conditions. As shown in Fig. 3 this is confirmed by an antenna simulation. The trade-off for this lower systematic uncertainty is a generally lower gain compared to alternatives [17]. However, the impact of the lower gain is manageable, since for any gain the galactic noise inevitably remains a significant contribution to the background, limiting the possible benefit of a higher gain. Even for the SALLA, the galactic noise is responsible for about half the background. For a typical alternative antenna with 10 dB higher gain than the SALLA, e. g., the energy threshold for air showers would decrease only by about 30%. Additionally, the loss in sensitivity is compensated by the comparably high geomagnetic field of

Fig. 2. A Tunka-Rex antenna station in front of the cluster center, housing filter digitization and data acquisition electronics.