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Status and first results of Tunka-Rex, an experiment for the radio detection of air showers

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Abstract

Tunka-Rex is a new radio detector for extensive air showers from cosmic rays, built in 2012 as an extension to Tunka-133. The latter is a non-imaging air-Cherenkov detector, located near Lake Baikal, Siberia. With its 25 radio antennas, Tunka-Rex extends over an area of 1 km^2 with a spacing of 200 m and therefore is expected to be sensitive to an primary energy range of approximately 10^{17}-10^{18} eV. Using Trigger and DAQ from Tunka-133, this setup allows for a hybrid analysis with the air-Cherenkov and radio technique combined. The main goals of Tunka-Rex are to investigate the achievable precision in the reconstruction of energy and composition of the primary cosmic rays by cross-calibrating to the well understood air-Cherenkov detector. While the focus in the first season was to understand the detector and calibrate the detector, an early analysis already proves the detection of air-shower events with dependencies on energy and arrival direction as expected from a geomagnetic emission mechanism. Furthermore, in near future tests will be conducted for a joint operation of Tunka-Rex with Tunka-HiSCORE, a prototype gamma ray observatory at the same site, and the upcoming scintillator extension of Tunka-133.

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1. Introduction

The measurement of high energy cosmic rays remains to be a challenging research field and therefore many riddles, especially about the origin of cosmic rays, remain unsolved. One of the problems is the low flux at high energies above 10^{15} eV, making it impossible to measure these cosmic rays directly in balloon or satellite borne experiments. Sparsely spread ground arrays of particle detectors or optical devices, observing vast volumes of the earths atmosphere extend the measurable energy range up to at least 10^{20} eV. Extending over up to many km^2 on ground, they use the earths atmosphere as a calorimeter to measure air showers, induced by the high energy particles. But these arrays bring their own problems: the convoluted process of shower development makes it very challenging to reconstruct certain parameters of the primary

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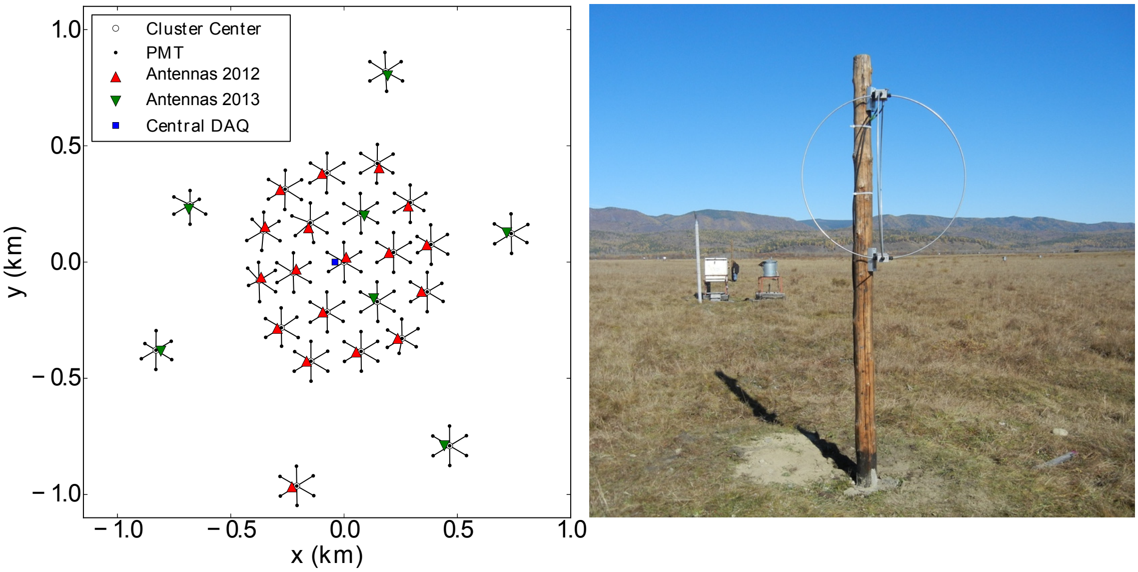

Fig. 1. **Left**: Map of the Tunka-133 and Tunka-Rex detector layout with installation date of the antennas. **Right**: A Tunka-Rex antenna station in front of the central PMT and the DAQ of one of the 25 Tunka-133 clusters. and the cluster center.

particles, especially their mass, from the shower observables. At the highest energies also statistics are limited, especially for the optical devices, which often come with higher sensitivity to the primary mass, but also with restrictions in their duty cycle.

New detector types are explored to overcome these problems either on their own or in combination with established types as part of a hybrid detector. One promising candidate is the radio detection technique: an array of radio antennas is used to measure the radio emission of the air shower. The radio emission is predominately caused by geomagnetic deflection of charged shower particles and the consequent time-varying transverse currents [1]. A second order contribution comes from the Askaryan effect, due to the time-varying net charge of the shower [2]. The proof of principle for the radio technique was already achieved in the 1970s [3], but practically it became interesting again in the last decade, when cheaply available digital electronics and computers made it applicable. The next question is, if and by how much a cosmic ray observatory benefits from a radio detector, to pave the way for sophisticated use in future projects.

With this in mind, Tunka-Rex was build in 2012. It is a radio detector for cosmic ray air shower close to Lake Baikal in Siberia, Russia. It was built on the site as Tunka-133, a an air-Cherenkov detector for cosmic rays. With each Tunka-133 trigger, the radio data from Tunka-Rex is also stored, so reconstruction methods for the radio signal can later be compared to the well-established methods of the air-Cherenkov detector. The main goal of Tunka-Rex is to cross-calibrate Tunka-Rex and Tunka-133 and to measure the achievable precision of Tunka-Rex for the reconstruction of shower parameters. The most important ones being energy and shower maximum, which is a statistical estimator for the mass composition of primary cosmic rays.

2. The detector setup

Tunka-133 consists of 25 clusters with 7 PMTs each in a hexagonal grid. In the center of each cluster is the cluster center housing the electronics. Tunka-Rex consist of 25 antenna stations, one connected to each cluster center. This results in an array with a spacing of 200 m, spread over about 1 km^2 (see Fig. 1 left).

The trigger of Tunka-133 is based on coincidences within individual clusters. If at least 3 PMTs pass a threshold trigger in coincidence, the data of the whole cluster is saved, including the radio data. These

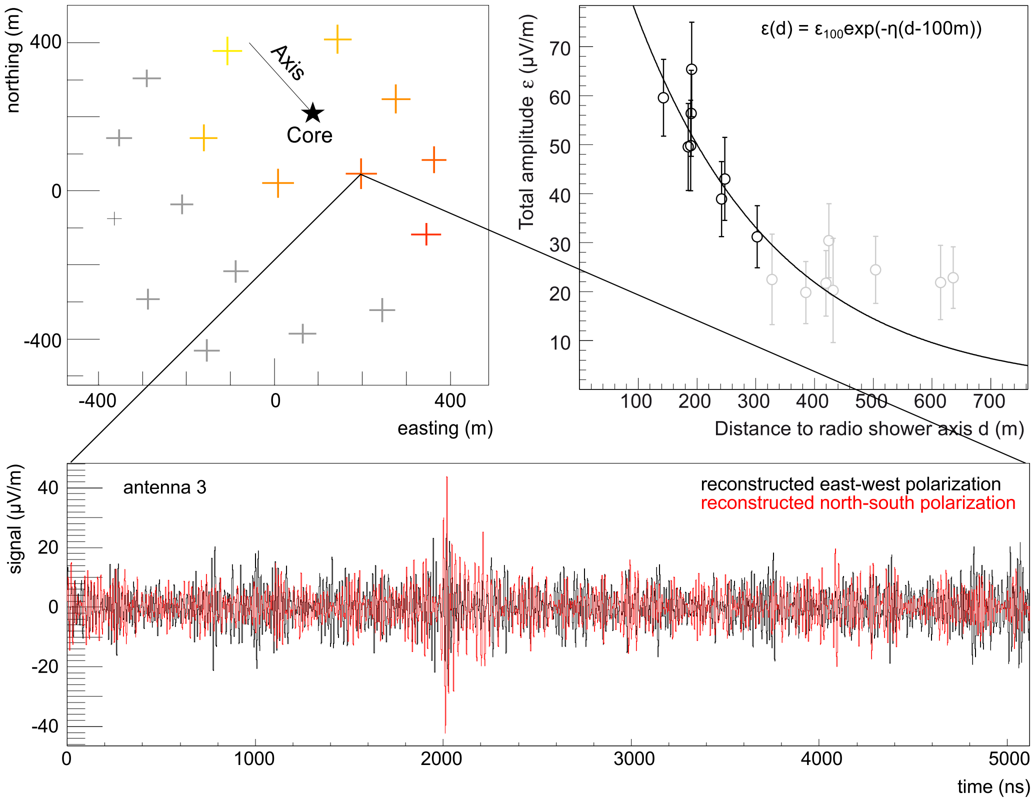

Fig. 2. **Left**: Footprint of the radio signal of a measured shower. The color code indicates the arrival time of the radio pulses. **Right**: Lateral distribution of radio amplitudes for the same event with a fit exponential function. **Bottom**: Trace of the indicated antenna. The radio pulse is at about 2000 ns.

single cluster triggers are afterwards, offline combined to events, if they occurred coincidently and fit a common direction reconstruction, based on the arrival times of the signal pulses.

A Tunka-Rex antenna station is shown in Fig.1 right. It has 2 channels whose antennas are aligned perpendicularly to each other and rotated 45° relative to the north-south/east-west axis. Thereby, we maximize the rate of events with signal in both channels for the predominantly east-west polarized radio emission. The used antenna is the SALLA [4]. It is a broadband antenna with low directivity, therefore covering a big portion of the sky. It has relative low gain, but also low dependence on ground conditions, which is essential for low calibration uncertainties.

A low noise amplifier at the antenna foot point enhances the signal by 24 dB and transmits it via coaxial cable to the electronics in the cluster center. There a filter cuts the signal to the design band, 30-80 MHz, and amplifies it by another 32 dB before digitization. The digitizer samples at 200 MHz with 12 bit depth and finally a 5 μs trace around the trigger is stored.

In Fig. 2 bottom, an event trace with a pulse from an air shower at about 2000 ns is shown. In Fig. 3, the average spectrum of a station over one night is shown. Due to the filter, it is steeply cut to 30-80 MHz. There is a narrow peak 20 MHz, from the heater electronics in the cluster center and peaks at 25, 50 and 75 MHz from other cluster electronics, also seen in the PMTs and directly induced into the ADCs, as well as several other narrow, unidentified sources. These narrow peaks are not much of a problem, since air shower pulses give broad signals in frequency space and the narrow noise peaks are easily filtered digitally.

To reconstruct the incoming radio signal in terms of electric field strength we use the measured hardware response of filter and amplifier together with a simulated antenna response pattern. For details see [5]. Measurements for an antenna calibration were performed in summer 2013 and are currently evaluated.

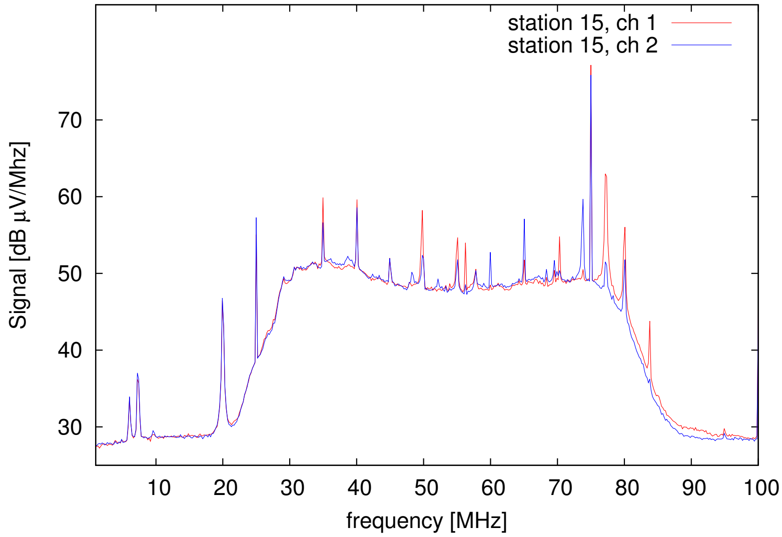

Fig. 3. Mean background spectrum of a Tunka-Rex station over on typical night. A filter attenuates the signal outside the design band of 30-80 MHz. Several narrow band noise sources lie within this band, of which currently only some are identified. However, they can easily be suppressed digitally during data analysis.

3. First results after one season of operation

Tunka-Rex started in October 2012 with 18 antennas and runs since, whenever Tunka-133 is on to provide trigger. Tunka-133 operates during moonless nights from October to April. The summer months are used for maintenance. In the first season, we accumulated a total of 392 hours of operation. In a first rudimentary analysis, we looked for radio signal in a 400 ns window around the arrival time expected from the shower geometry. We estimated the background from the first 500 ns of the trace and required a signal-to-noise ratio (amplitude^2/background^2) of at least 6. Furthermore, at least 3 antennas are needed for an independent determination of the arrival direction. This direction has then to deviate from the reconstruction of Tunka-133 by less than 5°, implying that a successfully reconstructed Cherenkov event has to coincide with the radio event. The last cut excludes radio events with an accidental noise peak in the expected signal window and affects about 30% of the radio events in this very simple reconstruction. We expect this number to shrink in future, more sophisticated analyses. For this reconstruction a modified version of the Offline software framework was used, developed by the Pierre Auger Collaboration [6] [7].
With these requirements, we found 49 vertical events with zenith angles $\theta \leq 50°$, for which Tunka-133 can provide a reconstruction of the energy and the shower maximum. In Fig. 2, an example event is shown, with its footprint, the LDF and an example trace. An energy estimator can be obtained from the radio technique by fitting the lateral distribution of amplitudes (LDF) with an exponential function, interpolating the amplitude at 100 m distance from the shower axis and normalizing it to $\sin\alpha$, with the geomagnetic angle α [8]. In Fig. 4 this estimator is shown as a function of the reconstructed energy from Tunka-133. It shows in this rudimentary event selection already a clear correlation to the energy.
Furthermore, another 82 inclined events with $\theta > 50°$ were found, where Tunka-133 can only provide a reconstruction of the shower geometry. Still, the inclined events are of special interest, since most detector types have trouble to reconstruct very inclined events or loose efficiency. The radio technique on the other hand may be especially effective for those, since the radio emission is boosted by the high geomagnetic angle and suffers only little attenuation due to the higher atmospheric depth of inclined showers.
In Fig. 5 the distribution of all events on the sky is shown. The Earths magnetic field is also indicated. As other radio experiments [9] [10] [11], we observe a north-south asymmetry due the the detection threshold in combination with the asymmetric distribution of geomagnetic angles (relative to the incoming shower

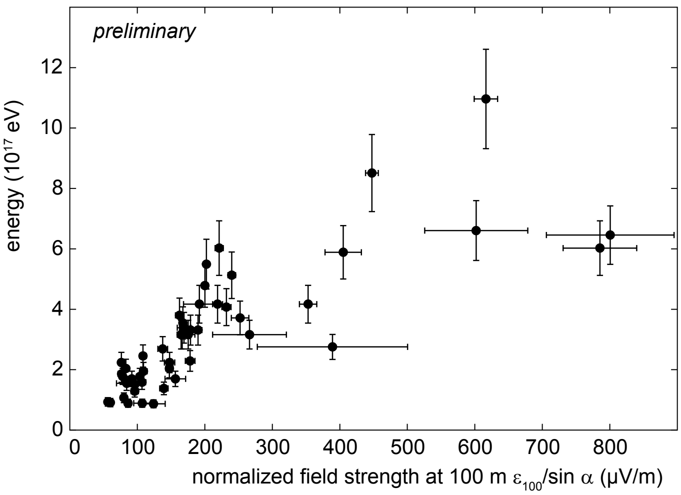

Fig. 4. Correlation of the field strength at 100 m, normalized to sine of the geomagnetic angle, with the energy of the air shower (reconstructed by Tunka-133).

axis) on the sky.

The low number of events below 30° indicates, that our antenna distribution seems to be to sparse with the simple selection criteria for these very vertical events. This is due to the steep slope of the lateral distribution of the radio signal. Future, more sophisticated analyses will probably increase the efficiency in general and enable us to select events more independently of Tunka-133.

4. Conclusion and Outlook

Tunka-Rex started in October 2012 and successfully detected radio events above 10^{17} eV in its first season. It is triggered by the air-Cherenkov detector Tunka-133 and thus provides automatically for hybrid events with measurements from the air-Cherenkov and radio detector. We observe a correlation of the radio amplitude at 100 m with the energy and furthermore an asymmetry in the measured event distribution that fits the assumed geomagnetic emission mechanism. Both are confirmed features of radio events and prove the functionality of Tunka-Rex.

For the coming seasons we plan to improve our reconstruction methods, e.g. by increasing the purity of stations with signal by looking for geometrical compactness of these stations, narrowing the signal window or optimizing our SNR cut. Furthermore we want to apply more accurate LDF functions, which may include possible azimuthal asymmetries in the lateral distribution. Finally, we will also start the analysis of the precision of the shower maximum reconstruction. We plan to have a semi-blind analysis, optimizing at least one reconstruction method for the shower maximum on the first seasons data and then test it on the second season after unblinding. Possible methods for the reconstruction of X_{max}, which are suggested by recent studies exploit correlations with the slope of the LDF [12], the cone angle[13] or the spectral slope[14].

Several extensions to the Tunka facility are already planned. In summer 2014, a scintillator array will be deployed on the Tunka site comprised by former KASCADE-Grande [15] scintillators. We plan to connect antennas to the scintillator DAQ and have them triggered by the scintillator detector. Thereby we extend Tunka-Rex by another 19 antennas and increase its exposure possibly by a factor of 10, since the scintillators can operate around-the-clock and not only during moonless nights. Additionally we also plan to connect antennas to HiSCORE [16] stations, another experiment on the site dedicated to the detection of air showers from high energy gamma rays. Thus, we will not only possibly increase our statistics significantly, but also study the radio technique in joint application with different detector types.

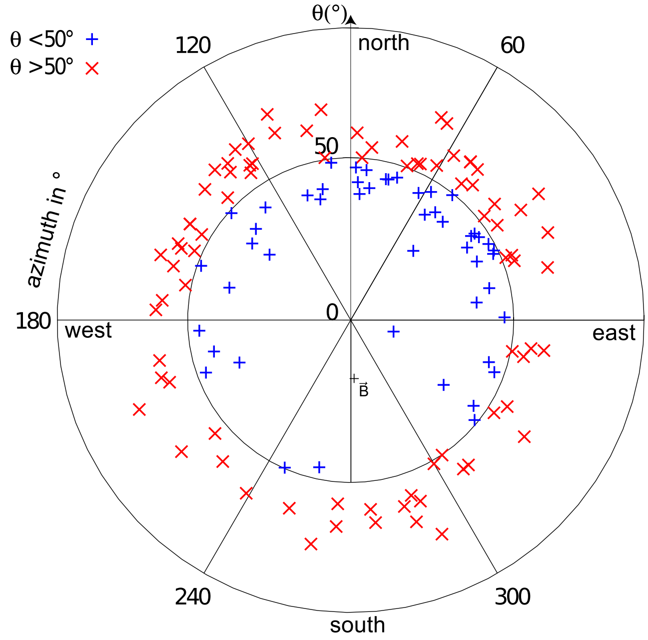

Fig. 5. The event distribution of the preliminary analysis of the first seasons data. There is a north-south asymmetry due to the geomagnetic emission mechanism, as seen by other radio detectors.

Acknowledgments

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