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Abstract. Tunka-Rex is an experiment for the radio detection of cosmic-ray air showers in Siberia. It consists of 25 radio antennas, distributed over an area of 1 km^2. It is co-located with Tunka-133, an air-Cherenkov detector for cosmic-ray air showers. Triggered by Tunka-133, Tunka-Rex records the radio signal, emitted by air showers with energies above 10^{17} eV. Its goal is to probe the capabilities of a radio detector, especially for the determination of the energy and elemental composition of cosmic ray primaries. To compare the measurements of Tunka-Rex to other radio detectors or to models describing the radio emission, the radio signal in each station has to be reconstructed in terms of physical units. Therefore, all hardware components have to be calibrated. We show how the calibration is performed and compare it to simulations.

1. Introduction

Cosmic rays are a unique window in the close universe, possibly providing a look at the most violent processes in the universe in the high energy range. Because of the low flux of high-energy cosmic rays, huge devices are necessary to detect air showers in the Earth's atmosphere, with areas of up to thousands of km^2. Additionally, the different types of detectors suffer from systematics, e.g. due to the extrapolation of physics to high energies. Therefore, hybrid detectors are used, comprised by different systems, to allow for cross-checks and exploit the advantages of the different devices. Thus, there is a need for new types of detectors, which provide a new view on the measurement.

One possible candidate is the radio technique. The corresponding detector consists of several antennas, distributed in the detector field. Radio pulses were already measured and to some extent understood in the 1960s [1, 2]. Mainly due to the deflection of charged particles in the Earths atmosphere, the air shower produces a radio pulse of several 10 ns width. A second order

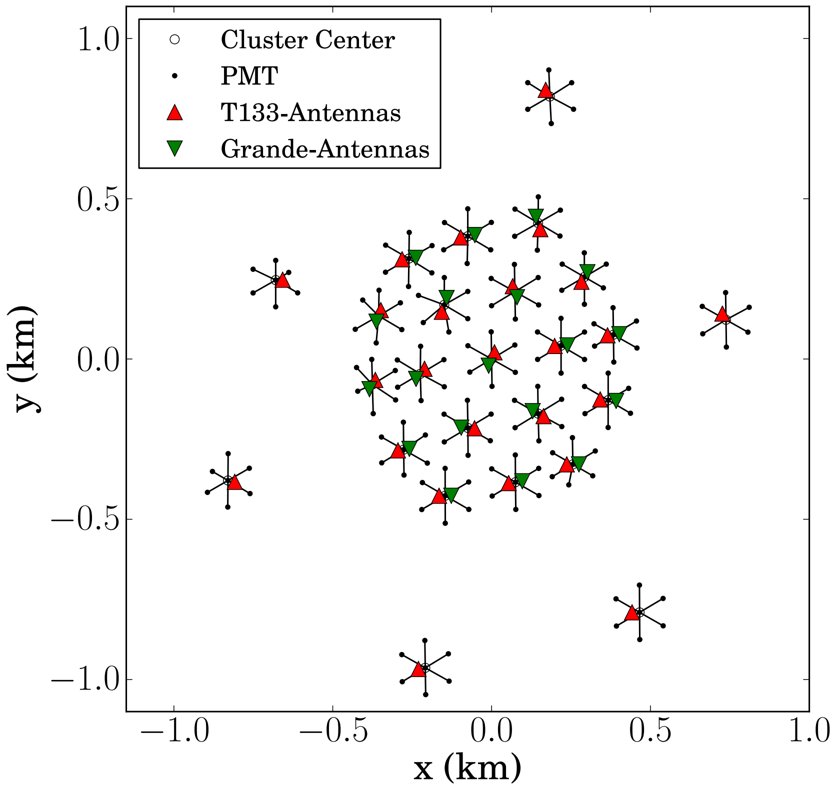

Figure 1. Map of the Tunka-Rex Layout. There is one antenna next to each cluster center of the Tunka-133 PMT stations.

contribution to the radio signal, arising from the Askaryan-effect [3], due to a time-varying net charge in the shower, was measured only recently [4]. Above around 10^{17} eV the power of the pulse exceeds the galactic background radiation several 100 m around the shower core, and thus can be detected. The main advantages of the radio detector are its almost full duty cycle and relatively low cost.
After the proof-of-principle in the 1960s, the radio technique vanished and returned only during the last decade due to improvements in electronics and digital signal processing. The feasibility of interferometry was shown and sensitivity to the energy and the depth of the shower maximum was proven [5]. Now, the capabilities of radio detectors have to be probed in more detail to prove its applicability in a contemporary detector for air showers.
With this goal the Tunka Radio Extension (Tunka-Rex) was deployed in 2012. It is a radio detector in Siberia, close to Lake Baikal and is collocated with Tunka-133, an air-Cherenkov detector for air showers above 10^{16} eV [6]. Tunka-133 triggers Tunka-Rex, therefore, Tunka-Rex can operate only during moonless nights in winter, when Tunka-133 is running. With a precision of 15% on energy and 28 g/cm^2 on X_{max} Tunka-133 also provides independent reconstruction information on the shower. Tunka-Rex and Tunka-133 can be cross-calibrated and the precision of Tunka-Rex can be determined by comparing its reconstruction results to the ones of Tunka-133 with its known precision.

2. The detector
Tunka-Rex was deployed in 2012 and its first stage consists of 25 antennas, one connected to each PMT cluster of Tunka-133 (see Fig. 1). This results in an antenna spacing of 200 m in the

Figure 2. A Tunka-Rex antenna station with its two perpendicularly aligned SALLA antennas.

central detector, covering 1 km^2 and an antenna spacing of 500 m for the outer region, covering 3 km^2. Data of the antennas are recorded together with the Tunka-133 data for the 7 PMT of a cluster after a coincidental threshold trigger on cluster level. After data acquisition, events with multiple clusters are formed, if the single cluster triggers coincide within 7 µs.
In 2014 another 19 antennas were connected to the new scintillator detector upgrade of Tunka-133, which can operate also during day and significantly extend our measurement time.
The antenna stations consist of 2 channels, each equipped with a SALLA [7] antenna, perpendicular to each other and 45° rotated relative to the north-south and east-west axis, respectively. In Fig. 2 a station is shown. The SALLA is an economic, rugged antenna with little dependence on ground conditions, but also relatively low gain. The two channels, together with the incoming direction of the signal, enable the reconstruction of the polarization.

The SALLAs are directly connected to a low-noise amplifier (LNA) with 24 dB gain at their base. To avoid noise from other electronics, e.g., of the Tunka-133 trigger hardware, the antenna station is located at a distance of at least 20 m from the cluster centers with the electronics. A possible interfering signal is attenuated and interference from the trigger can be separated from the shower signal due to its delay. 30 m of RG213 cable connect the LNA to another filter-amplifier with about 32 dB amplification in the 30-80 MHz band and 60 dB attenuation outside. It is located in the electronics box in the cluster center and its temperature is regulated to about 18 °C during operation. On each trigger of the cluster a 5 µs trace around the trigger is recorded at a sampling rate of 200 MHz with 12 bit depth.

3. Calibration
For a comparison to model calculations and other experiments, one needs to reconstruct the electrical field strength from the measurements with the antennas. The transmission of the radio signal through a linear hardware chain can formally be described by the convolution of the signal with the response function of the system. Under usual circumstances, the convolution can be inverted if the response function is known. The response function can be factorized in its single components. To determine it, we measured the transmission parameters of the analog

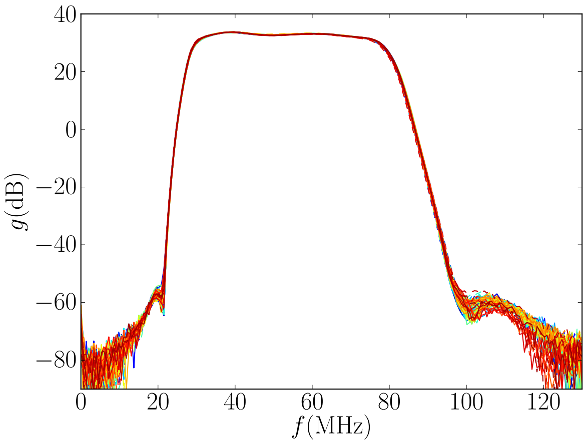

Figure 3. The gain of the filter amplifiers for all 25 filters in different colors.

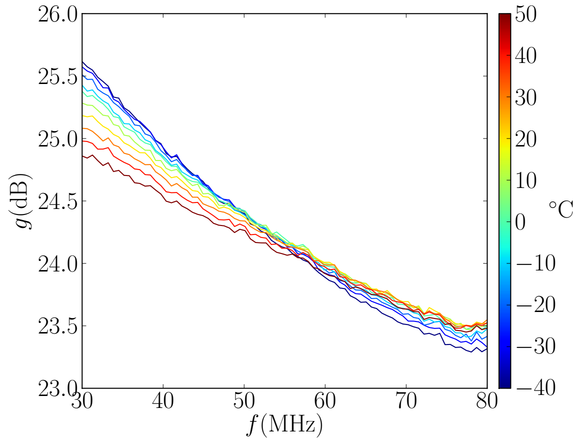

Figure 4. The gain of a LNA at different temperatures. During measurement, i.e., during winter nights we expect temperatures between -35 °C and 0 °C.

hardware chain and obtained the vector effective length (VEL) of our antenna from a simulation, combined with an amplitude calibration.

3.1. Electronics calibration

The electronics chain consists of the LNA, cables and the filter amplifier. They were calibrated using a network analyzer, which directly measures the forward transmission, i.e. the amplitude and phase shift for each frequency. This can be interpreted as the response function in the frequency domain. In Fig. 3, the amplitude gain of the filter amplifiers is shown.

The response of the full electronics chain can be retrieved by frequency wise multiplication of the single responses.

While the filter amplifiers are heated in the cluster centers, the LNAs are located outside, prone to temperature fluctuations. Therefore, we also measured the temperature dependence of the responses, by repeating the response measurement at different temperatures in a temperature chamber. In Fig. 4, the amplitude gain of the LNA at different temperatures is shown. The variation for the expected temperatures between -35 °C and 0 °C are about 0.3 dB.

3.2. Antenna calibration

The response function of the antenna is called VEL. Several other radio experiments have performed antenna calibrations to determine the VEL [7, 8, 9]. It is measured by observing a reference source with known emitted power or amplitude. One popular choice are sources in space, or for non-directional antennas, galactic noise. Alternatively, one can use a man-made reference source. Since the electronics noise for Tunka-Rex was estimated to be in the order of magnitude of the received galactic noise, and due to availability, we decided to rely on the latter option.

The VEL depends on the incoming direction of the signal and is very cumbersome to measure. Therefore, we decided to use an antenna simulation to obtain the directivity of the antenna. However, the amplitude is determined with an antenna calibration from a certain direction to have the right scale. A similar approach, using the very same calibration source, is applied by the LOPES collaboration [8], and lately at the LOFAR experiment [9]. For the simulation of the antenna the NEC2 simulation code [10] was used.

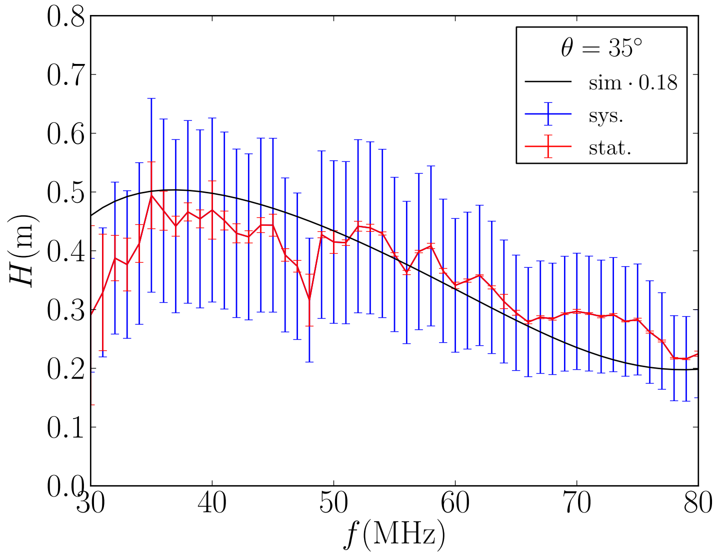

Figure 5. The vector effective length of the SALLA, obtained from the calibration of a Tunka-Rex antenna station and from simulation data. The latter is scaled down for easier comparison.

The absolute amplitude calibration was performed with the commercial calibrated source TESEQ VSQ 1000. It is a biconical antenna with known amplitude at 10 m distance in the main direction. We arranged the source with a crane at 10 m height above the antenna. The exact distance was measured with about 10 cm precision by a differential GPS. Then, we aligned it with strings from ground and recorded traces. By comparing the recorded trace with the calibration data, we obtained a total response function, from which we then removed the electronics chain to get the effective antenna height.
In Fig. 5, the resulting vector effective length of the antenna is shown and compared to the simulation. Although the frequency dependence roughly fits, the absolute scale seems to be overestimated by the simulation. Thus, in our reconstruction, we use the simulated antenna pattern and scale it by a constant factor. This result is currently cross-checked to see if it is a technical detail, or if it has physical implications, since the SALLA design was partially motivated by simulations.

The calibration was performed at 5 different zenith angles relative to the antenna, 0°, 20°, 35°,50°, and 68°. The correction factors for the simulated antenna model are for all measured zenith angles roughly the same, with no significant systematic shift. The mean standard deviation for the different zenith angles over the relevant frequency range is about 15%. We chose to normalize the simulated antenna model to the measurement at 35°, since most of our high quality events are close to this angle.

4. Summary and Outlook
The radio signal of cosmic-ray air showers can be reconstructed with measurements from Tunka-Rex by deconvolution of the signal with the hardware response. The required hardware response contains the transmission function of the hardware and the vector effective length of the antenna. The transmission parameters of the analog hardware are measured with a network analyzer. For the vector effective length of the antenna we use an antenna simulation and normalize the amplitude according to an absolutely calibrated source.
We found a significant deviation in the absolute scale of the predicted amplitudes of the simula-

tion and the one found with the calibration. However, the directivity is still well aproximated. With the calibrated detector it will be possible to directly compare the calibration curve of Tunka-Rex [11] to other calibrated radio experiments, operating in the same frequency band, and to test model predictions for the absolute amplitudes of the radio signal emitted by an air shower.

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