The LOFAR Radio Telescope as a Cosmic Ray Detector

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Abstract: LOFAR, the Low Frequency Array, is currently the largest distributed radio telescope. LOFAR is measuring cosmic-ray induced air showers since June 2011 and has collected several hundreds of events with hundreds of antennas per individual event in the frequency ranges 30-80 MHz and 110-240 MHz. The set-up of LOFAR and its performance are described. We discuss the in-situ calibration of the antenna response and first data.

Keywords: air showers, radio emission, experiments, LOFAR

1 Introduction

High-energy cosmic rays impinging onto the atmosphere of the Earth induce extensive air showers. Many of the shower particles are electrons and positrons. Interaction with the Earth magnetic field yields to the emission of electromagnetic radiation with frequencies at tens of MHz. The radio emission provides information on the longitudinal development of air showers. It has the advantage of low attenuation in the atmopshere. Unlike e.g. fluorescence emission, which requires (optically clear) moonless nights, radio emission can be observed basically all the time — except during close by thunderstorms. This makes the radio detection of air showers a promising technique to investigate the composition of cosmic rays at energies exceeding 10^{16} eV.

The radio technique has been established with the LOFAR prototype station (LOPES) [1] (and in parallel with CODALEMA [2]), which subsequently led to the large-scale installations of radio detectors for cosmic rays at the Pierre Auger Observatory (AERA) [3] and LOFAR. Here, we focus on the latter. In the following, the set-up of LOFAR and its performance are described. An outlook on expected results is given.

2 Experimental set-up

LOFAR is a distributed radio telescope with a dense core in the North of the Netherlands [4]. The antennas of LOFAR are grouped into stations, comprising of a number of Low-Band Antennas (LBAs, $10-90$ MHz) and High-Band Antennas (HBAs, $110-250$ MHz). 24 stations are located in the dense core, covering an area of about 4 km^2 and are distributed in an irregular pattern that maximizes uv-coverage for standard interferometric observations. 16 additional remote stations in the Netherlands are distributed on a logarithmic periodic spiral. International stations are currently located in Germany, France, the United Kingdom, and Sweden, giving LOFAR a maximum baseline of 1158 km for interferometric observations. The Dutch stations consist of 96 LBAs plus 48 HBAs. International stations have 96 LBAs and 96 HBAs. At the center of the LOFAR core six stations are located in a roughly 320 m diameter raised area called the Superterp. While every LOFAR station is equipped with the necessary electronics to observe cosmic rays, the current data set is taken with the central 24 stations. The positions of the antennas of the seven most central LOFAR stations are shown in Fig. 1.

The LBAs are the main tool for cosmic-ray detection. An LBA consists of two orthogonal inverted V-shaped dipoles with a length of 1.38 m each. These are supported by a central PVC pole, which holds a low-noise amplifier and guides the signal cables, see also Fig. 1 (*right*). The dipoles are oriented in south-west to north-east and south-east to north-west directions. The low-noise amplifier has an intentional impedance mismatch with the antenna, this combined with the characteristic length of the dipoles, makes the system sensitive in a broad band from $10-90$ MHz. In principle, this allows observations from the ionospheric cutoff up to the start of the commercial FM radio band. For most observations the frequency range is limited by a combination of selectable hardware and software filters to $30-80$ MHz to suppress strong Radio Frequency Interference (RFI) in the outer bands. After amplification the signals from the individual dipoles are transmitted through coaxial cables to an electronics cabinet located at every station.

The HBAs have been optimized for a frequency band of $110-250$ MHz, for analyzes typically the frequency range $120-240$ MHz is used. The design clusters 16 antenna elements into a tile, the signals from these elements are amplified and combined in an analog beam former. This means that while the LBAs are sensitive to the whole sky the HBAs are essentially sensitive to a restricted part of the sky, chosen at the start of the observation, which results in a smaller effective area for cosmic-ray observations, as the measurement will only be optimal if the direction of the cosmic ray happens to coincide with the beam direction of the observation.

In the electronics cabinet the signals are again amplified, filtered, and digitized by a 12 bit A/D converter with a sam-

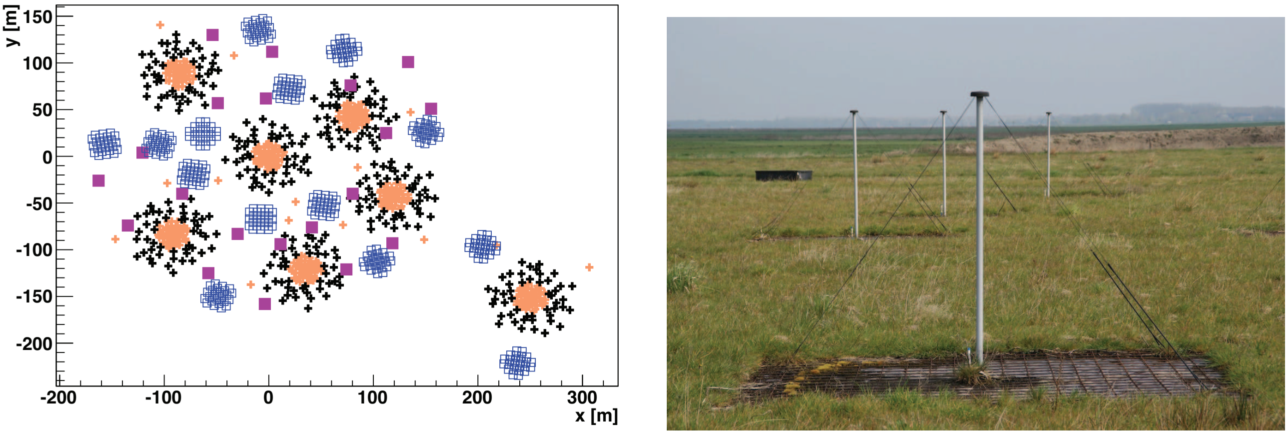

Figure 1: *Left*: Layout of the center of the LOFAR radio telescope. The crosses indecate the low-band antennas and the open squares represent the positions of the high-band antennas. The LORA particle detectors are located at the positions marked by squares. *Right*: Low-band antennas in the central core of LOFAR, in the background a scintillatior detector (black box).

pling frequency of 200 MHz. Due to signal path limitations in the Dutch stations only 48 dual-polarized or 96 single-polarized antennas can be processed at a given time. For the dual-polarized option the antennas are grouped into an inner and outer set, which has to be chosen before an observation. For astronomical observations the data are then beam-formed and sent to the central processing facility. In addition, there is the possibility to store a snapshot of the original data. Every station is equipped with ring-buffers, the Transient Buffer Boards (TBBs). These continuously store the last 1.3 s of raw data (an extension to 5 s is being deployed). When triggered, the contents of the TBBs are frozen and read out via a Wide Area Network and stored on disk for further analysis. The trigger can be generated in an FPGA at the local receiver unit or can be received from an external source. Currently, the main trigger for cosmic rays is generated by an array of particle detectors that has been built in the center of LOFAR. Later, a self-trigger is planned to be implemented, using the current data set as a training set to deduce trigger criteria, so that the FPGA trigger can be run independently at every LOFAR station. Essential for measuring cosmic rays with LOFAR as a radio telescope is that the whole process, of triggering and storing radio-pulse data, can take place without interfering with the ongoing observations.

Scintillator array LORA, the LOFAR Radboud Air Shower Array, is an array of particle detectors in the core of LOFAR [5]. The array provides basic information about air showers, such as the direction and the position of impact, as well as the energy of the incoming cosmic ray. It also provides the time of arrival, which is used to trigger LOFAR. LORA consists of 20 detector units distributed on the Superterp, as shown in Fig. 1. Each detector contains two scintillators (0.45m^2, NE 114), which are individually read-out through a photomultiplier tube. The detectors are inside weatherproof shelters and have been tested to not create any interference at radio frequencies.

A trigger in a single detector is generated, when a particle signal of more than 4σ above the noise is registered. Requiring 13 detectors to trigger in coincidence yields an energy threshold of about $2 \cdot 10^{16}$ eV with an average trigger rate of 0.8 events/hour. This trigger rate has been selected as the optimal setting for observations.

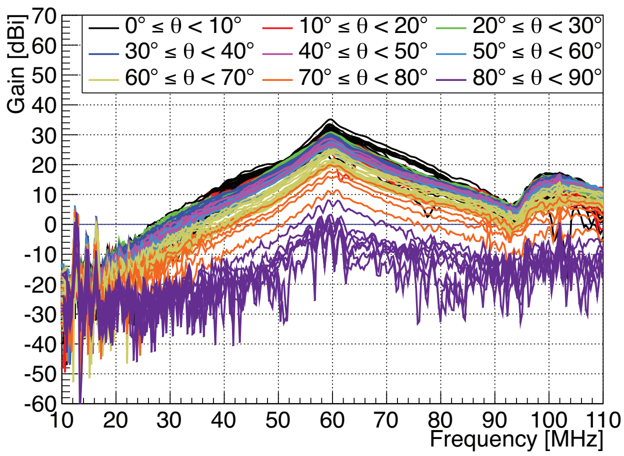

Figure 2: Measured antenna gain as a function of frequency.

3 In-situ calibration of the antennas

The antenna response as a function of frequency as well as zenith and azimuth angle — the antenna gain — is an important property, playing a crucial role for the interpretation of the measured radio signals. The antenna gain of the low-band antennas has been measured in-situ with a reference antenna, placed at a distance of 30 – 50 m from a LOFAR antenna. A biconical reference antenna is used with a frequency range from 30 to 1000 MHz. This low-weight (300 g) antenna is carried by an optocopter to specific points (in azimuth and zenith) above a LOFAR antenna. A vector network analyzer sends signals via a cable to the reference antenna. The LOFAR antenna in question is connected to the input of the vector network analyzer. Thus, the full (frequency dependent) gain pattern of the antenna is recorded. We measured an antenna in the center of a LOFAR station (LBA inner) and another antenna at the edge of a station (LBA outer).

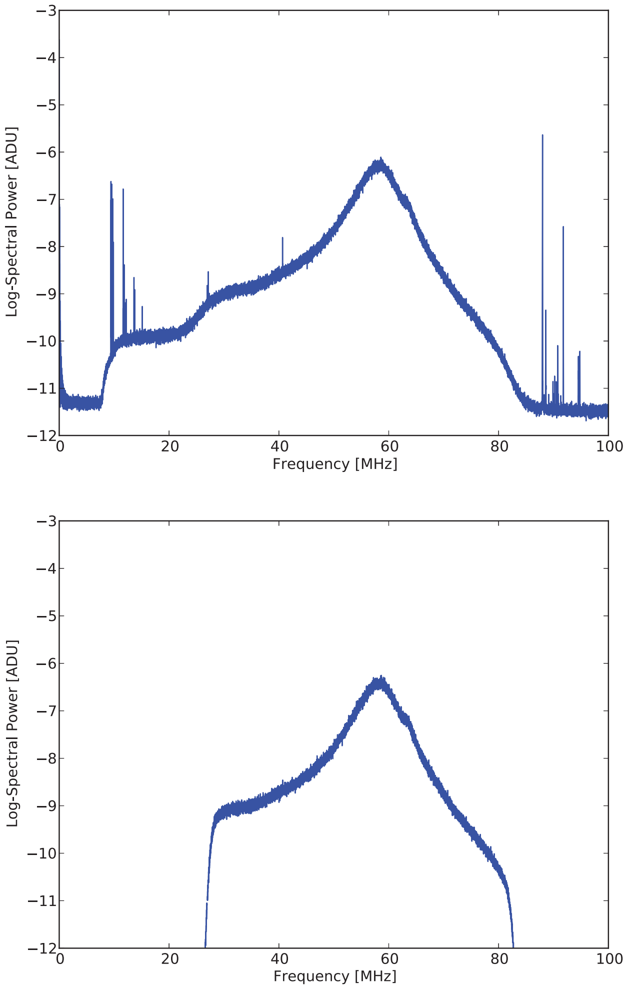

Figure 3: The average spectrum of a typical LBA event (*top*) and cleaned from RFI and clipped to 30 80 MHz (*bottom*).

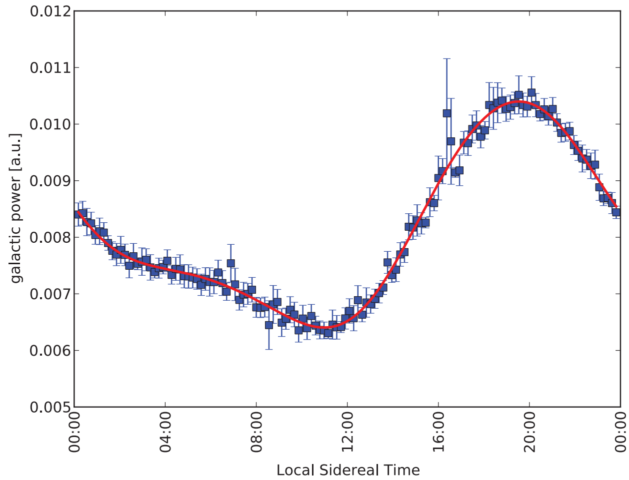

Figure 4: The integrated spectral power, normalized to the bandwidth, after RFI cleaning as a function of local siderial time for the north-east south-west polarization direction.

The measured antenna gain as a function of frequency for an outer antenna is depicted in Fig. 2. The response is shown for diferent zenith angles. One clearly recognizes the resonance frequency of the dipole at about 59 MHz. The antenna exhibits maximum gain values for vertically incident showers. The antennas in the center of each station are located very close to each other (at distances below a wavelength). Thus, one expects cross talk between different antennas. Such a behavior has been confirmed by the in-situ calibration. The antenna pattern is slightly deformed for frequencies around the resonance frequency. The antenna response has also been calculated, using a state-of-the-art simulation tool. Comparisons of the measured and the simulated antenna gain patterns are ongoing.

The time calibration of the six stations in the superterp has been tested. For this purpose, a reference pulse generator has been carried by an octocopter above the superterp. Very sharp pulses have been transmitted and their arrival time at each LOFAR antenna has been recorded. One expects that the signals arrive simultaneously on a shell with radius $c \cdot t$ around the reference antenna, c being the speed of light. The measured pulses typically deviate less than 0.5 ns from such a behavior. This confirms on the 1% level an earlier calibration of the cable lengths, based on interferometric methods.

4 Performance

RFI cleaning Narrow-band RFI in the time series signal can be revealed in an average power spectrum [6]. An example is shown in Fig. 3 (*top*), where the spectral power is plotted as a function of frequency. Most of the strong RFI is visible outside the $30-80$ MHz range. The average power spectrum is created by averaging the square of the absolute value of the Fourier transform over many blocks of data. Here 216 samples are used, giving a resolution of ~ 3 kHz, enough to resolve most RFI lines.

The Fourier transformation of a real-valued signal gives a complex-valued signal. By looking only at the amplitude spectrum, the additional phase information is ignored. If an RFI transmitter is seen by all antennas, the phase difference between each pair of antennas will be a constant value as a function of time with a small non-constant random noise contribution. Note that the exact value of the constant, which only depends on the geometric delay between antennas, is not relevant, only its non time-varying nature. When no transmitter is present, the relative phase is expected to be both random and time varying, as the signal then consists of the added signals from many incoherent sources on the sky with additional random noise. Therefore, RFI can be identified using the phase information by looking at the stability of phase differences between antennas over time.

Applying this method, RFI peaks are identified and removed from the data. Finally, we focus on our frequency range of interest between 30 and 80 MHz. The cleaned and clipped spectrum is shown at the bottom of Fig. 3.

Radio background The LOFAR LBA measurements are dominated by sky noise, which in turn is dominated by the Galaxy moving through the antenna beam pattern [6]. Therefore, the noise as seen by each antenna is a function of the Local Sidereal Time (LST) and can be used to correct for differences in gain between antennas. Instead of correcting all antennas at all times to a fixed value, which would be over or underestimating the noise at certain times, the received power can be normal- ized to a LST-dependent reference value. In Fig. 4 the integrated spectral power, af-

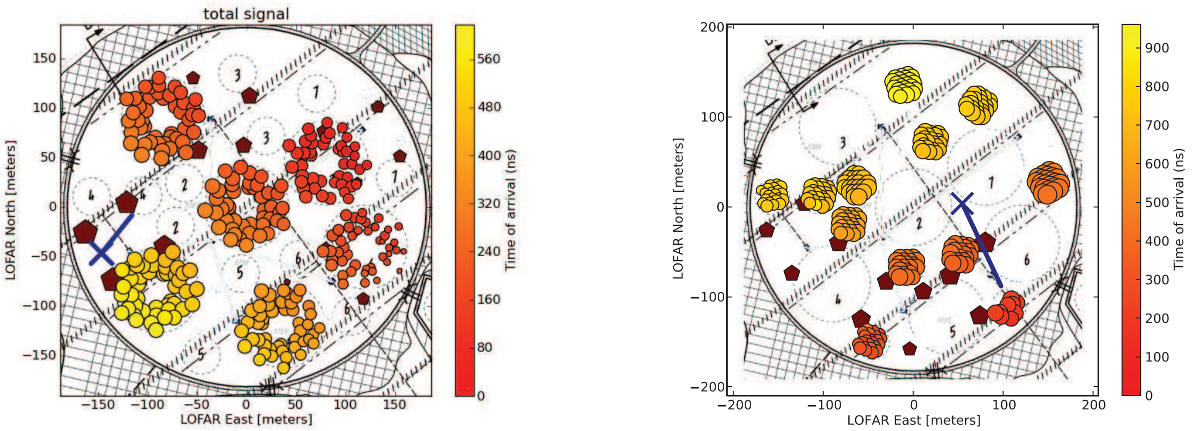

Figure 5: Footprints of two air showers meaured by LOFAR with the low-band antennas (30 – 80 MHz, *left*) and the high-band antennas (110 – 240 MHz, *right*). Circles represent the radio antennas, pentagons the scintillator detectors. The symbol size is proportional to the measured signal strength. The color denotes the arrival time.

ter RFI cleaning, is given as a function of the local siderial time. A siderial modulation of the background can be clearly seen, indicating the sensitivity of the system, being limited by the Galactic background only.

Accuracy of the scintillator array The performance of the scintillator array has been measured with air showers, dividing the array into two sub arrays [5]. The air shower propertieds have been reconstructed independently in the two arrays. Comparison of the reconstructed values for the same showers yields the resolution for the different quantities. The position of the shower axis is obtained through a fit of a NKG function to the measured particle densities with uncertainties of about 5 m. The arrival direction of a shower is obtained through a plane fit to the measured arrival times of the particles in each scintillation detector with an uncertainty of about 0.8°. The number of charged particles in a shower is obtained through a fit of a NKG function to the measured lateral particle densities with an uncertainty of about 27%. To calculate the energy of the primary particle, the reconstructed number of charged particles is normalized to a reference zenith angle of incidence (21°), using measured attenuation coefficients and a linear relation is applied $\lg E = a + b \lg N_{ch}(21^\circ)$, with the constants $a = 1.23$ and $b = 0.95$ [7, 8].

5 First data

LOFAR is recording routinely air showers since June 2011. The first data, up to February 2013 contain 3187 recorded triggers, of which 1438 pass the strict quality cut for a good data reconstruction of the particle measurement, e.g. the core is contained within the array. Of all triggers, 367 events contain reconstructed radio signals of cosmic rays with a threshold energy of 10^{16} eV.

As an example, the footprints of two showers as measured by the low-band and the high-band antennas as well as the scintillator array are depicted in Fig. 5.

6 Summary and Outlook

Since June 2011 LOFAR is routinely recording data from cosmic-ray induced air showers. Radio emission from the showers between 10 and 250 MHz is measured with the radio telescope and particles arriving at ground are detected with a scintillator array (LORA) in the core of LOFAR.

At present, we are working on various aspects of the data analysis. They are described in accompanying publications. The set-up and performance of LORA [5] and first results, measuring the properties of cosmic rays with energies exceeding 10^{16} eV using LORA [7]. An overview on the activities is given [9], the radio analysis is described [10, 6], and the depth of the shower maximum X_{max} is extracted from the radio measurements of air showers [11]. The mass composition of cosmic rays will be discussed in a forthcoming publication.

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