Measuring air showers with the LOFAR radio telescope

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Abstract: LOFAR, the Low Frequency Array, is currently the largest distributed radio telescope. LOFAR has been measuring cosmic ray-induced air showers since June 2011 and has collected several hundreds of events with hundreds of antennas per individual event. We present the measurements in the frequency range of 30 to 80 MHz, as well as between 110 and 240 MHz in terms of rates, arrival direction and energy distribution. Furthermore, we will report on the measurements of the lateral distribution of the radio signals and their dependences on shower parameters, including the dependence of the signal strength on energy.

Keywords: cosmic rays, air showers, radio emission, experiments, LOFAR

1 Introduction

The radio emission of cosmic ray induced air showers has first been observed in the 1960s. It was discussed as a possible detection technique for large arrays but due to insufficient electronics and lacking broad-band receivers, it was abandoned, only to be rediscovered in the beginning of this century. Several path finding experiments [1],[2] have shown the feasibility of this technique and studies involving simulations have illustrated its power, e.g. [3],[4]. Yet, the full details of the emission mechanisms and their dependences on shower parameters, such as the energy and the mass of the primary particle, have to be experimentally verified. The detection of air showers with LOFAR will contribute to the fundamental understanding of this phenomenon, explore the competitiveness of this technique, and contribute to the knowledge about cosmic rays.

2 LOFAR

LOFAR, the Low Frequency Array [5], is currently the largest distributed radio telescope. In its center, LOFAR consist of more than 2300 individual antennas with a full-sky coverage on an area of 4 km^2, which makes it an excellent instrument to detect the radio emission of cosmic-ray induced air showers.

At LOFAR, measurements can either be conducted with a set of Low-band antennas (LBA) in the range from 30-80 MHz or with High-band antennas (HBA) in the range from 110-240 MHz. The set-up to detect air showers has been completed by an array of scintillators, which acts both as trigger and provides basic information about the characteristics of the air shower [6].

All data received from LOFAR are analysed in an automated pipeline, which eventually delivers reconstructed air shower parameters, such as the incoming direction, and calibrated signal strengths per antenna, as described in detail in [7] and [8]. These parameters, combined with the reconstructed information from the particle data, are used in the following sections.

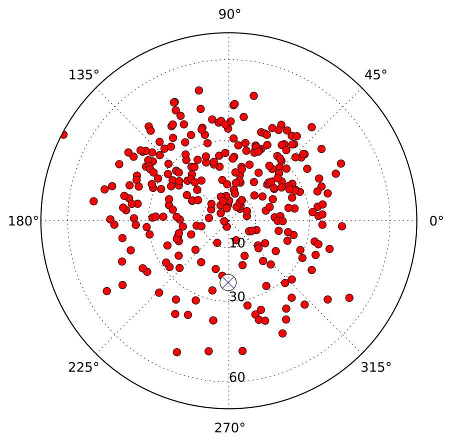

Fig. 1: All arrival directions of air showers detected in the LOFAR low-band antennas until March 2013. 0° is East and 90° North. The direction of the geomagnetic field is indicated with the blue cross.

3 Measurements from 30 to 80 MHz

The low-band frequency range has been explored by a number of experiments in the past decade. However, the high density of antennas in the core of LOFAR provides otherwise inaccessible information due to the unprecedented detail per event.

From June 2011 until March 2013 LOFAR has measured 375 events in the low-band frequency range. All events have been triggered by the array of particle detectors and have been recorded with different antenna configurations and trigger settings. The directions of the detected events are plotted in figure 1. A clear north-south asymmetry is visible. The probability of a detected event to come from the

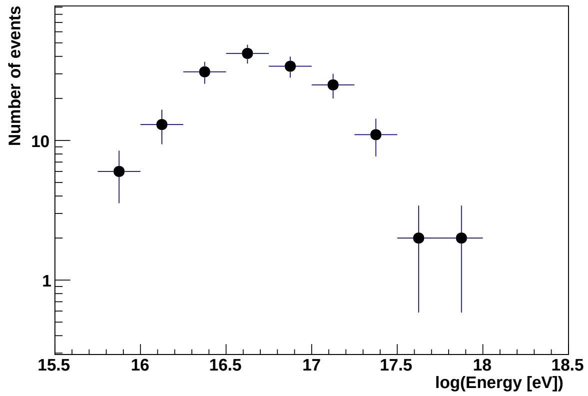

Fig. 2: Energies of all events triggered with the scintillator array, which have also been detected with a significant pulse in data in the low-band frequency range. The energy is the one reconstructed by the particle array, therefore quality cuts were applied.

northern part of the sky is $p = 0.69 \pm 0.02$. Events coming directly from the north are not necessarily favoured to be detected with LOFAR, despite having the most favourable angle with the geomagnetic field, as the LOFAR antennas are not aligned perpendicular and parallel to the magnetic field, but rotated by 45 degrees. Thus, higher pulses are needed to be detected in one polarization. However, this distribution still clearly confirms the interaction with the geomagnetic field to be the dominant mechanism. The energies of all recorded events are depicted in figure 2.

Originating from the geomagnetic mechanism, it has been reported that the signal strength of the radio pulse is proportional to the angle between the shower axis and the geomagnetic field, as well as the energy of the shower [1],[2]. However, all these observations depended on a model for the lateral distribution of the signal. This is due to the fact that most experiments measure single air showers with only a couple of antennas and therefore only sparsely sample every shower. Thus, in order to calculate an overall energy dependency with the necessary statistics an interpolation of the signal is needed. LOFAR is not bound by these restrictions as every shower is finely sampled at multiple points. It was suggested in studies with simulations that there should be a distance from the shower axis, in which the signal strength is the least sensitive to the height of the first interaction and therefore shows the best dependence on the energy of the shower [9]. LOFAR can directly probe these ideas by investigating correlations of energy and signal strength, such as shown in figure 3, for several bins of different distances and calculate the achieved energy resolution for every distance.

For this analysis, the average signal (peak amplitude) per antenna in a distance bin is calculated for every event. Usually, most of the LOFAR events have at least a data point in every bin with a width of 10 meters from 0 to 200 meters. The average signal is corrected for the angle, $\sin(\alpha)$, between shower axis $\vec{v}$ and geomagnetic field $\vec{B}$ according to the prediction of $\vec{v} \times \vec{B}$ for the geomagnetic emission. This corrected average signal can then be plotted against the energy of the shower separately for all distance bins. In order to avoid biases introduced by the energy scale, the signals are plotted against the natural variable

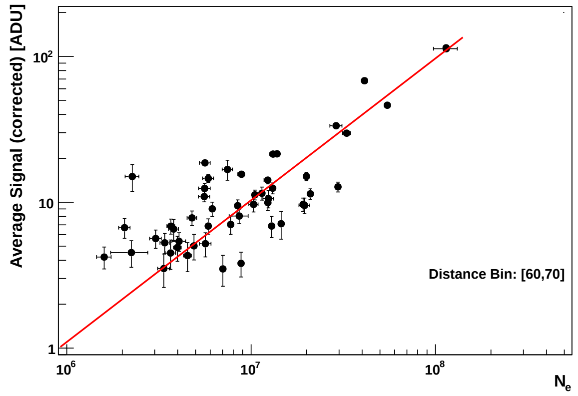

Fig. 3: Correlation of the air shower parameter N_e (number of charged particles) and the average radio signal (S) as detected in LOFAR in modified Analogue to Digital Converter Units (ADU). As average corrected signal, the average pulse amplitude at a distance of 60-70m from the shower axis is shown. This signal is corrected by the sine of the angle between this axis and the geomagnetic field at LOFAR. The distribution is here fitted with a function of two free parameters $S = A \cdot N_e^B$, but is overall similarly well described by $S = A + N_e \cdot B$.

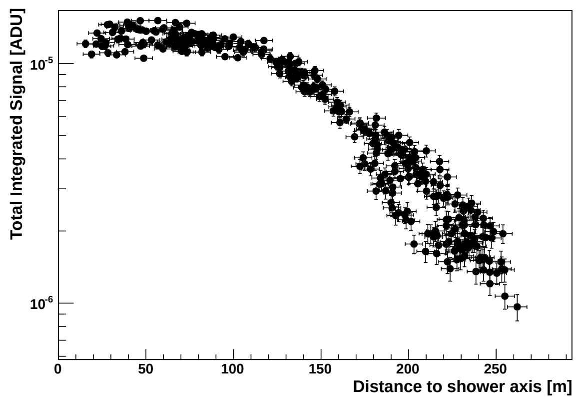

Fig. 4: Example signal strengths from a cosmic ray induced air shower as recorded with the LOFAR LBAs. The integrated signal per antenna is plotted against the distance to the shower axis as reconstructed from the particle data.

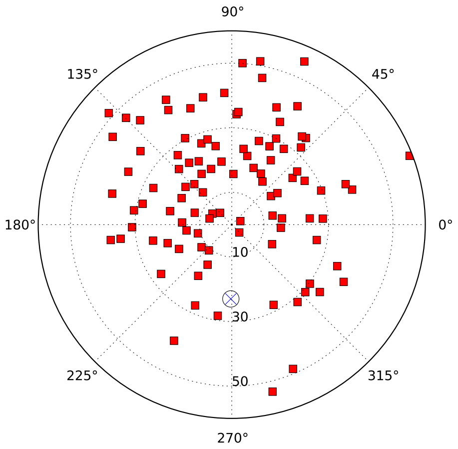

Fig. 5: All arrival directions of events detected in the LOFAR high-band antennas until March 2013. 0° is East and 90° North. The direction of the geomagnetic field is indicated with the blue cross.

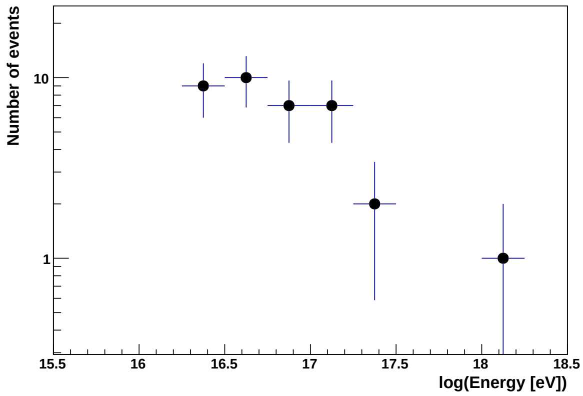

Fig. 6: Energies of all events (after cuts) triggered with the scintillator array, which have also been detected with a significant pulse in data in the high-band frequency range. The energy is the one reconstructed by the particle array, therefore quality cuts were applied.

of a scintillator array N_e, the number of charged particles. With this method the optimal distance can be extrapolated without an a priori correction for the distance to the shower axis, just by comparing the achieved energy resolution for every distance bin. The optimal distance for such a measurement will be reported in a forthcoming publication.

Despite being able to determine the energy of the cosmic ray without a suitable model for the lateral distribution, the understanding of the lateral distribution is essential for those events that were not measured at the preferred distance. The lateral distribution of the signals seems to be rather complex and it will not do the data justice to describe them with an only distance-dependent, thereby rotational-symmetrical model, as shown in the example events in figure 4. There, the ring like structure in which the LOFAR antennas are arranged can be seen in the one-dimensional projection at around 200 meters. If the signal distribution was rotationally symmetric, antennas with the same distance to the shower axis would not differ systematically in signal strength with respect to the azimuthal angle.

As presented in [10], the shape of the lateral distribution also heavily depends on the height of the shower maximum, X_{max}, resulting in the need for an even more dimensional parametrization. As shown in [8] the different polarizations of the signal also contain essential information.

4 Measurements from 110 to 240 MHz

The frequency band covered with the LOFAR HBAs is mostly unexplored for radio emissions of cosmic rays. While in the 1960s singular frequencies in this band have been explored with mixed success [11],[12], more recent experiments have focussed on even higher frequencies in the microwave range [13],[14]. Some observations have been reported in all frequency ranges. Still, there have been hints that the amount of emission decreases (at least for vertical showers) with higher frequencies, and due to Cherenkov effects, concentrates only at a ring around the shower core. This has also been predicted by various simulations, e.g. [15] or [3].

In the time from June 2011 until May 2013 LOFAR has been taking data for cosmic ray observations also with the HBAs. However, the time of observations dedicated to this was shorter than the one for the LBAs. Furthermore, all data taken with the HBAs is pre-beamformed in the direction of observation for small subsets of antennas. This means that the signals of 16 antennas are combined into a tile by correcting for the delay that the direction of a source of choice would introduce. For astronomical observations, this source corresponds to the object that is targeted during the observation. For cosmic ray observations, this in turn means that if a cosmic ray happens to come from the same direction as was chosen for the observation, an enhanced signal will be recorded. The signal will be enhanced with respect to the noise by a factor $\sqrt{N}$, where N is the number of antennas. All other events will have a decreased signal depending on the angular distance between the incoming direction and the direction of the observation. Pulses should still be visible (see figure 7) but their shape will be distorted and will possibly no longer be detectable in case of small signals. This pre-beamforming essentially reduces the sensitivity of HBA observations in contrast to LBA observations.

Since November 2011 102 cosmic ray events have been measured in the HBA frequency range. A detection is reported when a significant pulse (3σ) is detected in more than 5 tiles in a station and if the direction fitted from the arrival times of these pulses points in the direction that is also measured with the particle detectors (to an accuracy of 15 degrees). The last cut is more loose than the one for LBA events, as the HBA station configuration gives only a small lever-arm for direction reconstruction and the pre-beamforming can have a negative effect on the timing accuracy. The arrival directions of all confirmed events are shown in figure 5. Again, a clear north-south asymmetry is visible. However, as the directions of beams are not equally distributed in azimuth a possible bias cannot be excluded. The measured energies of all high quality events are shown in figure 6. There are less low energy events than in LBA. This might be a combination of sensitivity loss due to pre-beamforming, other instrumental effects or a reduced signal strength in this band. A full efficiency discussion, also including a consideration of the location of the impact

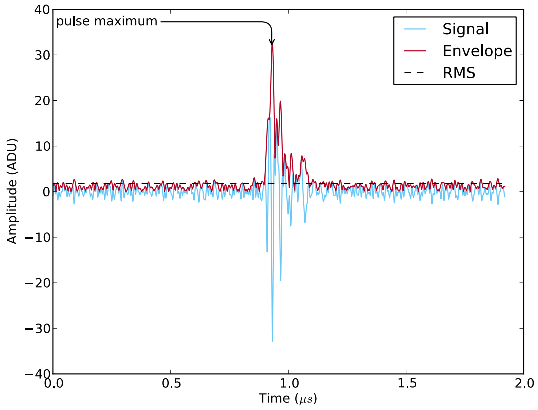

Fig. 7: A cosmic-ray induced pulse from the example event of figures 8 and 9 as reconstructed by the automated pipeline.

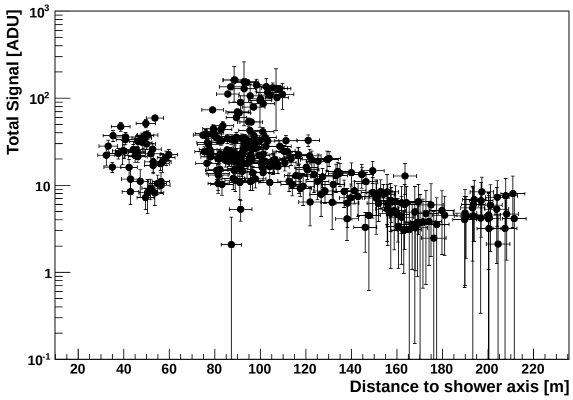

Fig. 8: Signal distribution of an example event as detected in the LOFAR high-band antennas. The total signal strength (peak amplitude) is shown as a function of distance to the shower axis. The uncertainty of the signal in the HBA is generally higher than the one in the LBAs due to instrumental effects.

point with respect to the positions of the stations, would go further than possible in the scope of these proceedings.

General statements about the lateral distribution of the signals of the events measured in HBA, as well as signals of a possible enhanced Cherenkov ring at these frequencies will be reported on in a forthcoming publication. An example event is shown in figures 8 and 9, for which all stations in the core of LOFAR have detected a pulse in the HBA band. The direction of observation was separated from the incoming direction by 81°. This one event already contains more measured points at these frequencies than ever recorded before.

5 Conclusions

With their great detail the measurements with LOFAR will help to understand the nature of the radio emissions and conclusively confirm models of the emissions. With the high-band antennas a frequency range is explored that is not covered by any other modern experiment. The dataset from the low-band antennas is now large enough to start the

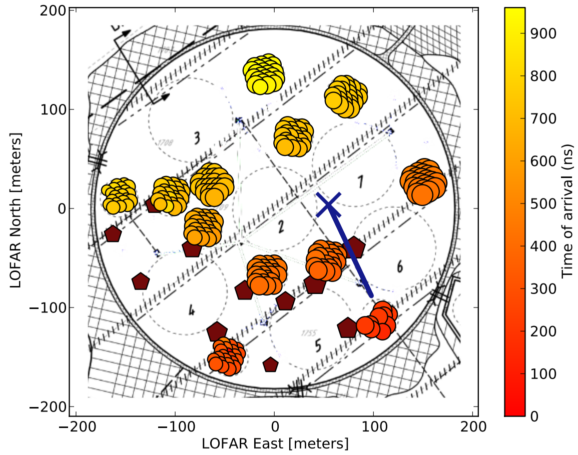

Fig. 9: Example event as detected in HBA. Shown is the most inner core of LOFAR. Every circle depicts an HBA tile and the dark red pentagrams correspond to the particle detector array. The size of the circles and pentagrams corresponds to signal strength and the colour of the circles indicates the time of arrival. Also shown is the reconstructed shower axis. Large empty circles are the location of the LBAs.

analysis of physical shower parameters and to measure the properties of cosmic rays at energies exceeding 10^{16} eV.

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