Radio emission from air showers measured with LOFAR

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Abstract: The LOFAR cosmic ray experiment uniquely offers both the high antenna density and low radio frequency interference environment necessary to study the different processes within the air shower development that produce radio frequency emission. A detailed understanding of these processes allows radio emission measurements to be used to derive shower parameters such as Xmax. Here we will discuss the analysis and calibration methods used to reconstruct the full three-dimensional electric field vector at each of the ~ 2300 antennas spread over an $\sim 4\,\mathrm{km}^2$ area in the LOFAR core. We will present the first high-precision measurements of the shape of the wavefront of the radio emission, as well as polarization measurements of the radio emission at different locations on the ground. These are an indicator of the interplay of different emission mechanisms such as Geomagnetic radiation, charge excess and the Askaryan effect, or Cherenkov effects.

Keywords: cosmic rays, air showers, radio detection, experiments, polarization, LOFAR

1 Introduction

Radio emission from cosmic ray air showers, first detected by Jelley et. el. in 1965 [1], offers the prospect to study the longitudinal development of air shower during almost all weather conditions, thus offering a better duty cycle than can be obtained with fluorescence measurements. Air shower emission models based on both a microscopic approach [2], adding the emission contributions of all the individual charged particles, and a macroscopic approach [3], where the emission of the resulting time varying current is calculated, have recently converged to give similar predictions [4]. The expected radio signal is a short nanosecond bipolar pulse.

Although all emission is inherently produced by accelerated charged particles one can make a distinction between the physical processes responsible for the acceleration. The dominant Geomagnetic component in the emission is caused by the time varying lateral drift velocity of the electrons and positrons due to the Lorentz force exerted by the Earth's magnetic field. This gives a signal that is linearly polarized in the $\vec{v} \times \vec{B}$ direction where $\vec{B}$ is the direction of the magnetic field and $\vec{v}$ is the direction of propagation of the shower. In contrast, the emission generated by the time varying negative charge excess in the shower generates a signal that is linearly polarized in the radial direction with respect to the shower core. In addition all emission travels through the atmosphere which has a non-unity refractive index varying with depth. This gives rise to Cherenkov effects where signals emitted at different times arrive at the observer simultaneously for specific observing angles. The interplay of these emission mechanisms and the Cherenkov effects causes a complicated asymmetric radio footprint of the shower (see [2]). Verifying these models conclusively therefore requires dense sampling of the electric field at ground level, for which LOFAR is the optimal instrument.

2 LOFAR

The Low Frequency Array (LOFAR) [5] is a next generation radio telescope located in the North of the Netherlands with extensions across Northern Europe. It observes the sky at frequencies from 240 MHz down to the ionospheric cutoff at 10 MHz. Unlike traditional radio interferometer arrays, at LOFAR a novel phased array technique is used to combine the signals of relatively simple and cost efficient dipole antennas. Signals from groups of antennas, called *stations*, are combined in phase through analog and digital beamforming, each group giving both the pointing capability and collecting area of a dish in a traditional radio interferometer. In addition, each LOFAR station can continuously store the raw voltage signals from the last 1.3 s from all individual dipole antennas and read them out upon request [6]. For cosmic ray studies such 'triggers' are provided by a dedicated particle detector array [7]. In the core of the array more than 2300 antennas are installed within about 4 km², which allows cosmic ray induced air showers to be measured with unprecedented spatial resolution.

3 The cosmic ray analysis pipeline

Particle detector triggers are sent to the radio antenna array for all air shower detections with estimated energy of larger than $2 \cdot 10^{16}$ eV, which results in a trigger rate of approximately 0.8 triggers/hour. This corresponds to the threshold energy for radio emission to be visible above the sky-noise level at LOFAR for favorable shower geometries. Therefore most recorded datasets will have no detectable air shower radio emission necessitating an automated pipeline
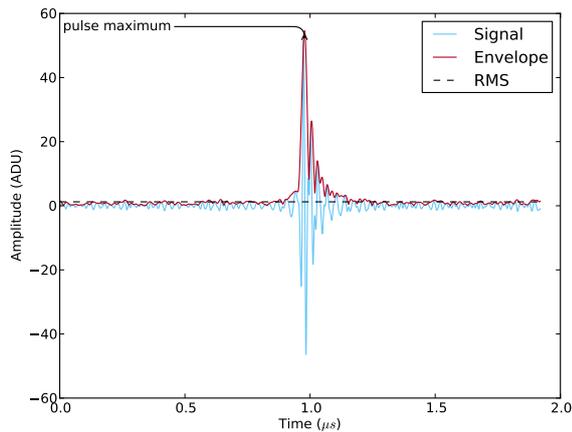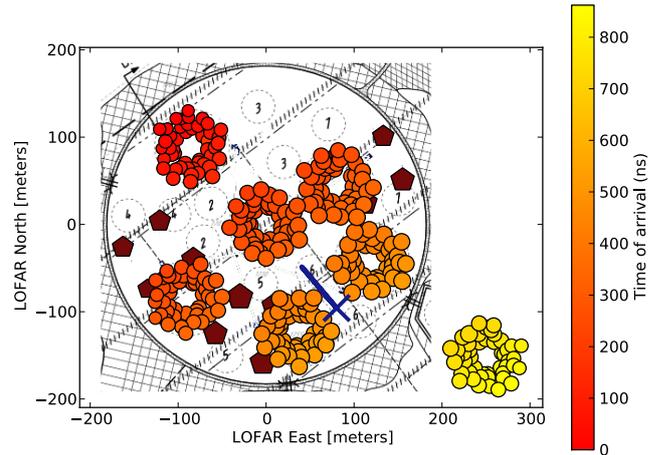
Fig. 1: An example cosmic ray pulse as detected with the low-band antennas ($10-90\,$MHz) for the event in figure 2. The solid light line shows the up sampled signal. Overlaid is the Hilbert envelope and the RMS noise in black dashes. Pending absolute calibration the signal strength is given in arbitrary units.

Fig. 2: Footprint of an air shower measured with LOFAR. The signal strength (peak amplitude of the radio signal) is encoded logarithmically in the size of the marker and the color shows the time of arrival. The pentagons represent the positions of the particle detectors, their size is proportional to the number of registered particles. The reconstructed shower axis as measured by the particle detector array is indicated by the cross for the core position and the line for the projected arrival direction.

[8] to identify interesting signals. Additionally, the pipeline automatically extracts physical parameters such as the shower arrival direction and the cosmic ray radio signal strength in all antennas. This pipeline is based on the task oriented PyCRTools framework consisting of fast low-level C++ routines glued together in Python for maximum flexibility. All extracted information is stored in an SQL database for subsequent data mining studies.

The LOFAR core is located in a designated radio quiet zone. However, some man made radio frequency interference is still present. This interference is first filtered out by removing all power at frequencies, which show stable relative phases between antennas over time. This is only expected for terrestrial transmitters [8]. Gain differences between the dipole antennas are calibrated out using the fact that the LOFAR low band antennas ($10-90\,$MHz) are sky-noise dominated. A first search for a cosmic ray radio signal is performed on the signal from all antennas of a station combined in phase for the arrival direction of the air shower as determined by the particle detector array. This gives an $\sqrt{N_{\mathrm{antennas}}}$ improved signal to noise for signals from the chosen direction, and therefore a lower probability of picking up noise pulses. Furthermore, when no cosmic ray signature is visible in this beamformed signal it will not be visible in individual antennas and the search can be aborted.

Due to its design as a radio telescope LOFAR antennas are rotated by $45°$ with respect to the North-South, East-West polarization frame. Thus, a pure North-West polarized signal expected for the dominant $v \times B$ emission component in a vertical shower will be mixed in both dipole antennas. To correct for this, and the frequency dependent antenna gain, the signals are unfolded using a simulated antenna model [6].

Subsequently, a pulse search is performed on the signals from each of the individual antennas within a narrow window around the beamformed pulse location to reduce false positives. An example pulse can be seen in figure 1. In order to avoid ambiguity due to limited sampling a pulse

maximum is found in the amplitude of the analytic signal or Hilbert envelope. In addition, the signal is first up-sampled by a factor 16 to ensure that the pulse maximum search is not the limiting factor for pulse timing resolution. This gives a pulse arrival time for each antenna. A plane wave fit to these arrival times gives the shower arrival direction. This fit is performed separately for each LOFAR station where, for the relatively small antenna spacing, a plane wave is a reasonable first order approximation to the wavefront shape. Graphically, the information obtained by the pipeline can be best expressed in the shower footprint (figure 2), where the signal strength and arrival time for each antenna are given as a two dimensional function of antenna position. Also depicted in this figure is the shower arrival direction as estimated by the particle detector array which nicely matches the radio data. This way of depicting the results illustrates best how densely a shower is sampled with the LOFAR radio antennas.

The pipeline is described in more detail in [8]. Here, we will focus on two example studies that are currently underway using LOFAR cosmic ray radio data to develop a detailed understanding of air shower radio emission processes. Both studies utilize the data-set as described in [9].

4 Wavefront curvature

As the radio emission from the air shower comes from (effectively) a finite height in the atmosphere, the radio wavefront incident at the antenna array will have a nonzero curvature, rather than being planar. One can use the arrival times of the pulses at each antenna, as measured from their Hilbert envelope maxima, to trace the shape of the wavefront.

The largest contribution to the arrival times comes from the geometric delay that arises from the incoming direction
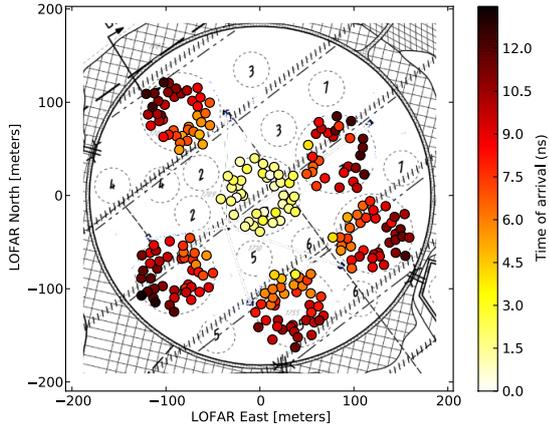
Fig. 3: Wavefront curvature obtained by subtracting the times for the best-fitting plane wave from the measured arrival times as a function of antenna positions.

of the emission. Treating the curvature as a perturbation to a planar wavefront, we can subtract the time delays for a best-fitting plane wave, and study the remainder as the curvature signal. This is a simplistic way of detecting and studying the wavefront shape, as no a priori knowledge of the shower axis (incoming direction and core position) is needed. In further analysis, the shower core position is also taken into account.

The shape of the wavefront could be (approximately) spherical, or conical, depending on the region of maximal emission. If the emission comes effectively from a small volume, the wavefront will be mostly spherical, as from a point source; if the emission is better modeled as a moving source, a conical shape would be more reasonable. In [10] it is argued, supported by REAS3 simulations and combined LOPES data, that the shape should be more conical. The high density of antennas of LOFAR, and an improved timing resolution should allow to distinguish between these shapes.

To get an idea of the timing resolution required, we can approximate the arrival times for a point source to second order, giving an order of magnitude of the timing signal we could expect. Taking altitude h, elevation angle α, coming in on an antenna array with diameter d, we get at the edge of the array:

$$c\Delta t = \frac{d}{2}\cos\alpha + \frac{d^2}{8h}\sin^3\alpha \simeq 250\,\text{ns} + 6\,\text{ns}, \qquad (1)$$

being the arrival time along the direction of the incoming vector. Example numbers are taken at the edge of the LOFAR inner core region, with $d = 300\,\text{m}$, a point source at $h = 4\,\text{km}$ and an elevation of 60 degrees. At the edge of the core along the direction of propagation, the signal will lag behind the plane wave approximation by about 6 ns with respect to the array center. Therefore, to study curvature we have to measure arrival times at an accuracy in the order of 1 ns. Thus, the sampling rate at LOFAR of 200 MHz, which corresponds to a period of 5 ns, is not sufficient, when used alone. It is clear that up-sampling, in combination with techniques such as the Hilbert envelope, whose results do not depend on the original sampling, are needed to resolve the curvature.

In figure 3, the wavefront curvature (times for best-fitting plane wave subtracted) is shown for one of the cosmic ray
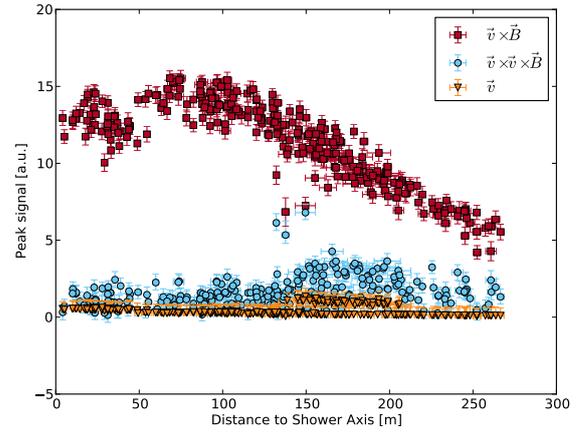
(a)
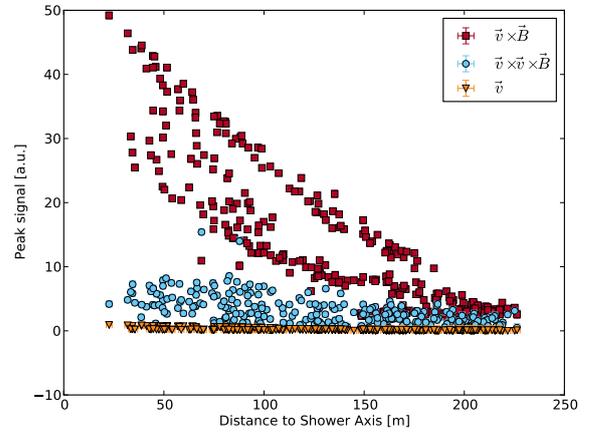
(b)

Fig. 4: Distribution of radio signals with respect to the distance from the shower axis. The two example events show different signatures in the depicted signal polarizations.

events in the current data-set. It was selected to have a good detection of the pulse (i.e. high signal-to-noise ratio) in the majority of antennas in all six radio stations in the inner core. With a general timing accuracy of about 1.5 ns as seen from adjacent antennas, the signal clearly stands out from the noise. As expected, going towards the edge of the array, the pulse times lag behind the signals in the central antennas.

With this information we will study the wavefront shape in more detail. Using the shower core position inferred from the LORA particle detector array distinguishing between spherical and conical shapes will be possible.

A comparison with simulations should allow for an estimation of shower parameters such as Xmax, using the shape of the wavefront. Such a comparison is independent from similar studies using the lateral power distribution.

5 Polarization

Before one can use radio emission to study cosmic rays a thorough understanding of the emission mechanisms is needed. A method to disentangle different mechanisms can be through analysis of the polarization of the detected

signal instead of the total power received by each antenna. For a cosmic ray induced air shower with arrival direction $-\vec{v}$ the natural coordinate frame for polarization studies is $\vec{v} \times \vec{B}$ where one expects the strongest contribution from the emission generated by interacting with the magnetic field $\vec{B}$ and the perpendicular directions $\vec{v} \times \vec{v} \times \vec{B}$ and $\vec{v}$. Therefore, for polarization analysis, the signal is first projected onto this coordinate frame before again performing the pulse search and extracting the pulse parameters.

In figures 4a and 4b the strength of the radio signal, here defined as the peak amplitude, is plotted as a function of projected distance from the shower axis for two different showers.

Although the shape of this lateral distribution function looks wildly different for different events [11], as a result of the complicated non-symmetric nature of the emission [2], the expected dominance of the Geomagnetic component is clearly visible. In a future study, we will measure the relative contributions of the different components through their distinctive signatures, for example by studying the polarization angle as a function of azimuthal angle in the projected shower frame. The combination of the many data points in every event will allow for an event-by-event comparison of the contributions without the necessity to stack several events. This will ensure that also small contributions to the signal can be identified.

6   Conclusions

In order to use radio emission from air showers to study cosmic rays one first needs to thoroughly understand the emission processes that generate it. This information is for example encoded in the polarization signature of the emission and is measured in great detail by LOFAR. Furthermore, the measurement of the wavefront curvature through extremely accurate pulse arrival timing offers the possibility of an independent radio measurement of the shower maximum, X_{max}. With LOFAR, now routinely measuring cosmic-ray induced air showers, several ways of measuring the longitudinal development of the air showers (see also [11]) open new opportinuties for cosmic-ray studies.

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