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Recent results from cosmic-ray measurements with LOFAR

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ABSTRACT

LOFAR, the Low Frequency Array, is currently the world's largest distributed radio telescope observing at frequencies below 240 MHz. 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. We present measurements of the radio signal strength as well as high-precision measurements of wavefront curvature and polarization. These will enable us to disentangle the different emission mechanisms at play, such as geomagnetic radiation, charge excess, and Askaryan or Cherenkov effects, leading to a full understanding of the air-shower radio emission. Furthermore we give a first example on how the full complexity of the signal enables radio measurements to be used to study primary particle composition.

1. Introduction

High energy particles impinging on the Earth's atmosphere induce air-showers of secondary particles. A significant fraction of these secondary particles are charged and can generate radio emission [1]. When the wavelength of the emitted radiation is comparable to the shower disc thickness, as is true for MHz frequencies, this emission is coherent. The dominant geomagnetic component of this emission is caused by a time-varying lateral drift velocity of electrons and positrons due to the Lorentz force exerted by the Earth's magnetic field. This gives a short nanosecond timescale bipolar pulse that is linearly polarized in the $\vec{v} \times \vec{B}$ direction, where $\vec{v}$ is the direction of propagation of the shower and $\vec{B}$ the direction of the magnetic field [2–4]. Additionally, charge separation, a build up of negative charge at the shower front due to electrons traveling with the shower after being knocked out of atmospheric atoms leaving positively charged ions behind, generates a similar coherent pulse [5] but now linearly polarized in the radial direction away from the shower axis. Furthermore all radio emission travels through the atmosphere with non-unity refractive index giving rise to an Askaryan or Cherenkov effect which is expected to be particularly strong at higher frequencies [6]. All this leads to a very complex emission pattern observed at ground level [7]. However, the complexity of the emission also contains much information about the primary particle. The smoothness of the radio shower front allows for a more accurate determination of the direction of the incoming particle than is typically possible with particle detectors [8]. Furthermore, the power contained in the pulse is proportional to the square of the primary energy [8]. Most importantly however, the detailed emission pattern observed at ground level depends strongly on the atmospheric depth of shower maximum (X_{max}) [9] which in turn depends on the nature of the primary particle. Therefore, radio detection of cosmic-ray-induced air showers offers the possibility for composition studies of cosmic rays with a duty cycle of almost 100% only interrupted by thunderstorms [10].

2. LOFAR

LOFAR, the Low Frequency Array [11] is a next generation radio telescope located in the North or the Netherlands with extensions across Northern Europe. It has two basic antenna types covering

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the full frequency band from 10 to 240 MHz, excluding the commercial FM band at 90–110 MHz. The Low Band Antenna (LBA) consists of two simple inverted V-shaped dipoles measuring both polarizations of the radio signal at 10–90 MHz (but typically limited to 30–80 MHz). In contrast the High Band Antenna (HBA) measuring between 110 and 240 MHz clusters 16 dual-polarization antenna elements in a ‘tile’. The signals in a tile are combined by an analog beam-former thereby increasing the sensitivity in a predetermined direction chosen by the observer.

The antennas are grouped in stations and for astronomical observations the signals from all antennas in each station are beam-formed and sent over the network to the central processing facility in the city of Groningen to be correlated. Additionally the raw voltage signals from all antennas can be stored in ring buffers for up to 5 s to be read out upon request. The core of LOFAR contains 24 stations with 96 LBA's and 48 HBA's each on a total area of $\sim 4\ \mathrm{km}^2$. Due to signal path limitations only 48 preselected dual polarized antennas can be used at any given time. This high antenna density, combined with the ring-buffer storage of the raw signals, is ideal for cosmic-ray observations. Parallel observation capability built into LOFAR allows for almost continuous cosmic-ray observations.

2.1. LORA

LORA, the LOFAR Radboud air-shower Array [12] is a particle detector array extension of LOFAR. It is co-located with the central most seven stations on a 320 m diameter raised area called the superterp. It provides both the trigger to freeze the ring buffers as well as basic shower parameters such as shower energy, direction and core position for subsequent analysis. LORA consists of 20 detector units each containing two ($0.45\ \mathrm{m}^2$, NE 114) scintillators. Each scintillator is read out through a photomultiplier tube. A trigger in a single detector is generated, when a particle signal of more than 4σ over the noise is registered. Requiring 13 detectors to trigger in coincidence, before freezing the ring-buffers, gives an energy threshold of 2×10^{16} eV which is at the lower edge of detectability in the radio signal.

3. Measurements

From June 2011 until March 2013 LOFAR has measured 375 cosmic-ray events at 30–80 MHz. Additionally since November 2013, 102 events have been measured at 110–240 MHz where no observations have been performed since the 1960s [13]. Observations are still ongoing and the dataset is growing.

All cosmic-ray observations are processed with a fully automated pipeline which is described in detail in Ref. [14]. This pipeline both identifies radio signals from cosmic-ray induced air showers and extracts basic physical parameters such as air-shower direction and signal strength in all antennas.

Graphically the information obtained by the pipeline can be best represented in the shower footprint (Fig. 1), where the signal

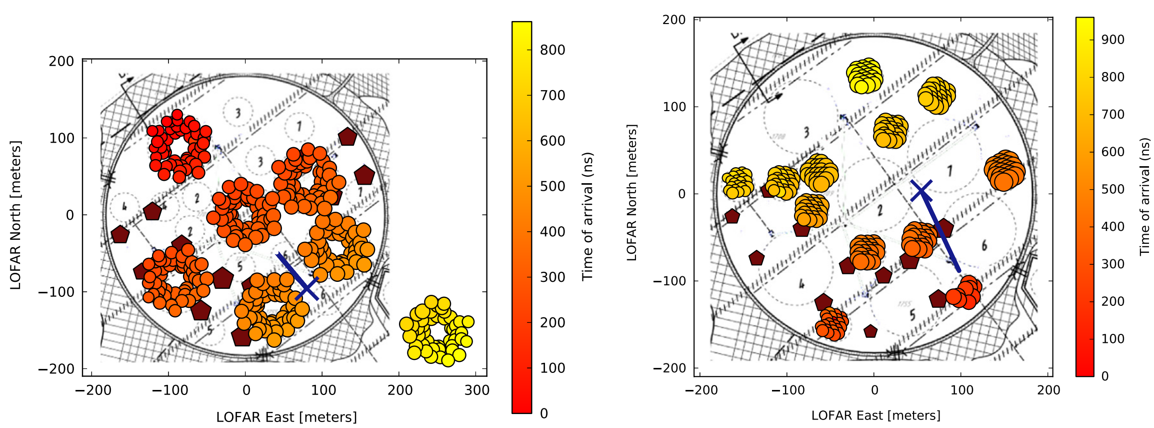

Fig. 1. Footprint of an air shower measured with LOFAR low-band antennas (30–80 MHz, left) and a second air shower measured with the LOFAR high-band antennas (110–240 MHz, right). The signal strength (peak amplitude of the radio signal) is encoded logarithmically in the size of the marker and the color 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. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

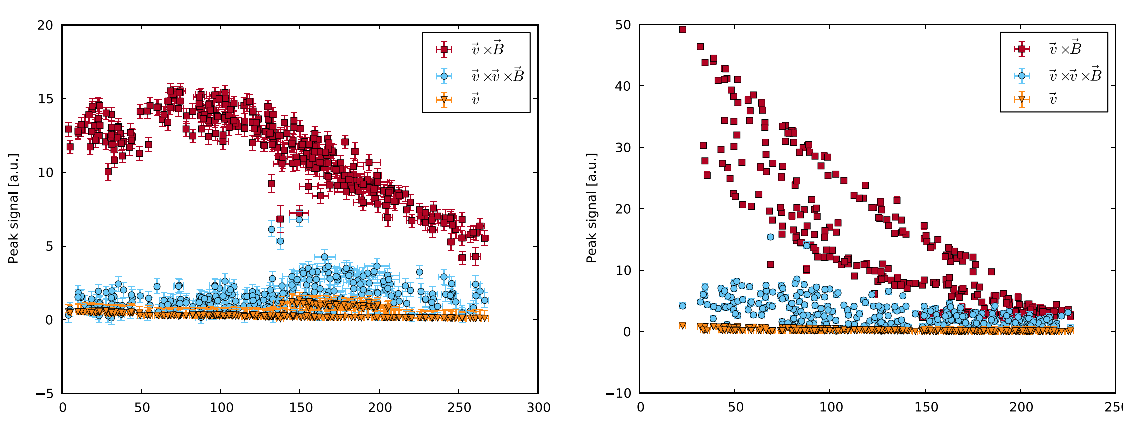

Fig. 2. Distribution of radio signals with respect to the distance from the shower axis. The two example events show different signatures in the depicted signal polarizations.