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# The shape of the radio wavefront of extensive air showers as measured with LOFAR

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A B S T R A C T

Extensive air showers, induced by high energy cosmic rays impinging on the Earth's atmosphere, produce radio emission that is measured with the LOFAR radio telescope. As the emission comes from a finite distance of a few kilometers, the incident wavefront is non-planar. A spherical, conical or hyperbolic shape of the wavefront has been proposed, but measurements of individual air showers have been inconclusive so far. For a selected high-quality sample of 161 measured extensive air showers, we have reconstructed the wavefront by measuring pulse arrival times to sub-nanosecond precision in 200 to 350 individual antennas. For each measured air shower, we have fitted a conical, spherical, and hyperboloid shape to the arrival times. The fit quality and a likelihood analysis show that a hyperboloid is the best parameterization. Using a non-planar wavefront shape gives an improved angular resolution, when reconstructing the shower arrival direction. Furthermore, a dependence of the wavefront shape on the shower geometry can be seen. This suggests that it will be possible to use a wavefront shape analysis to get an additional handle on the atmospheric depth of the shower maximum, which is sensitive to the mass of the primary particle.



## 1. Introduction

A high-energy cosmic ray that enters the atmosphere of the Earth will interact with a nucleus of an atmospheric molecule. This interaction produces secondary particles, which in turn interact, thereby creating a cascade of particles: an *extensive air shower*. The origin of these cosmic rays and their mass composition are not fully known.

Due to the high incident energy of the cosmic ray, the bulk of the secondary particles propagate downward with a high gamma factor. As this air shower passes through the atmosphere and the Earth's magnetic field, it emits radiation, which can be measured by antennas on the ground in a broad range of radio frequencies (MHz–GHz) [1–3]. For a review of recent developments in the field see [4]. The measured radiation is the result of several emission processes [5], and is further influenced by the propagation of the radiation in the atmosphere with non-unity index of refraction [6]. Dominant in the frequency range considered in this study is the interaction in the geomagnetic field [7,8,3,9]. An overview of the current understanding of the detailed emission mechanisms can be found in [10].

The radio signal reaches the ground as a coherent broadband pulse, with a duration on the order of 10 to 100 ns (depending on the position in the air shower geometry). As the radio emission originates effectively from a few kilometers in altitude, the incident wavefront as measured on the ground is non-planar. Geometrical considerations suggest that the amount of curvature and the shape of the wavefront depend on the height of the emission region, suggesting a relation to the depth of shower maximum, $X_{\max}$. The depth of shower maximum is related to the primary particle type.

Assuming a point source would result in a spherical wavefront shape, which is used for analysis of LOPES data [11]. It is argued in [12] that the actual shape of the wavefront is not spherical, but rather conical, as the emission is not point-like but stretched along the shower axis. In a recent further refinement of this study, based on CoREAS simulations, evidence is found for a hyperbolic wavefront shape (spherical near the shower axis, and conical further out) [13]. Hints for this shape are also found in the air shower dataset collected by the LOPES experiment [14]. However, due to high ambient noise levels, the timing precision of these measurements did not allow for a distinction between spherical, hyperbolical and conical shapes on a shower-by-shower basis, and only statistically was a hyperbolic wavefront shape favored.

We use the LOFAR radio telescope [15] to measure radio emission from air showers, in order to measure wavefront shapes for individual showers. LOFAR consists of an array of two types of antennas: the low-band antennas (LBA) sensitive to frequencies in a bandwidth of 10–90 MHz, and the high-band antennas (HBA) operating in the 110–240 MHz range. While air showers have been measured in both frequency ranges [16,17], this study only uses data gathered with the 10–90 MHz low-band antennas. A combination of analog and digital filters limits the effective bandwidth to 30–80 MHz which has the least amount of radio frequency interference. For detecting cosmic rays we use the (most densely instrumented) inner region of LOFAR, the layout of which is depicted in Fig. 1. LOFAR is equipped with ring buffers (called Transient Buffer Boards) that can store the raw-voltage signals of each antenna for up to 5 s. These are used for cosmic-ray observations as described in [16].

Inside the inner core of LOFAR, which is a circular area of 320 m diameter, an array of 20 scintillator detectors (LORA) has been set up [18]. This air shower array is used to trigger a read-out of the Transient Buffer Boards at the moment an air shower is detected. The buffer boards provide a raw voltage time series for every

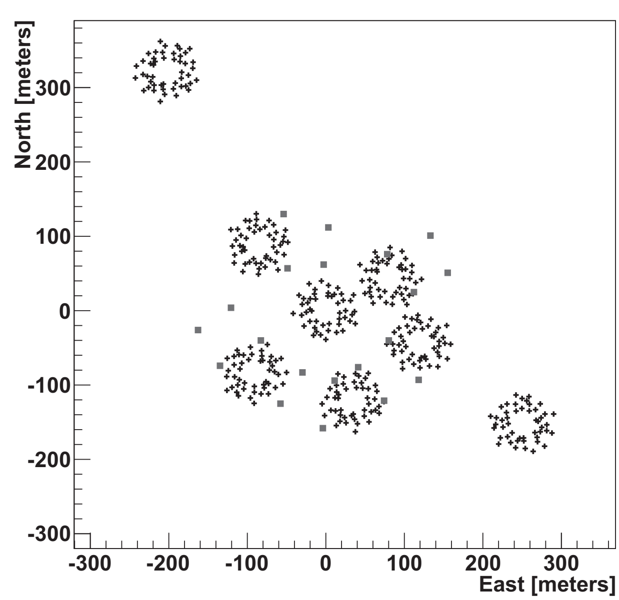


**Fig. 1.** Layout of the innermost 8 stations of LOFAR. For each station the outer ring of low band radio antennas (black plus symbols), used for the analysis in this paper, are depicted. Located with the innermost six stations are the particle detectors (gray squares) used to trigger on extensive air showers.