A study of the radio frequency spectrum emitted by high energy air showers with LOFAR

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Introduction

The detection of radio signal emitted by extensive air showers allows to reconstruct the cascade geometry. Thus, important properties of primary particles (e.g. arrival direction, mass composition) can be inferred. A study of several geometrical parameters of the radio signal emitted by extensive air showers, and their correlation with the observed radio frequency spectrum is presented here.

In view of extending these measurements to all data detected by LOFAR [1] since 2011, a preliminary simulation study of the radio frequency spectrum has been conducted. Monte Carlo simulations of radio signals have been produced by using CoREAS, a plug-in of the CORSIKA particle simulation code. The final aim of this study is to improve the radio detection technique, thus contributing to affirm this technique as reliable method for the study of high energy cosmic rays.

LOFAR

- Radio antenna array consisted of 48 stations in Northern Europe
- Six central stations in the Northern Netherlands
- Low Band Antennas (LBAs) → 10 – 90 MHz
- High Band Antennas (HBAs) → 110 – 240 MHz

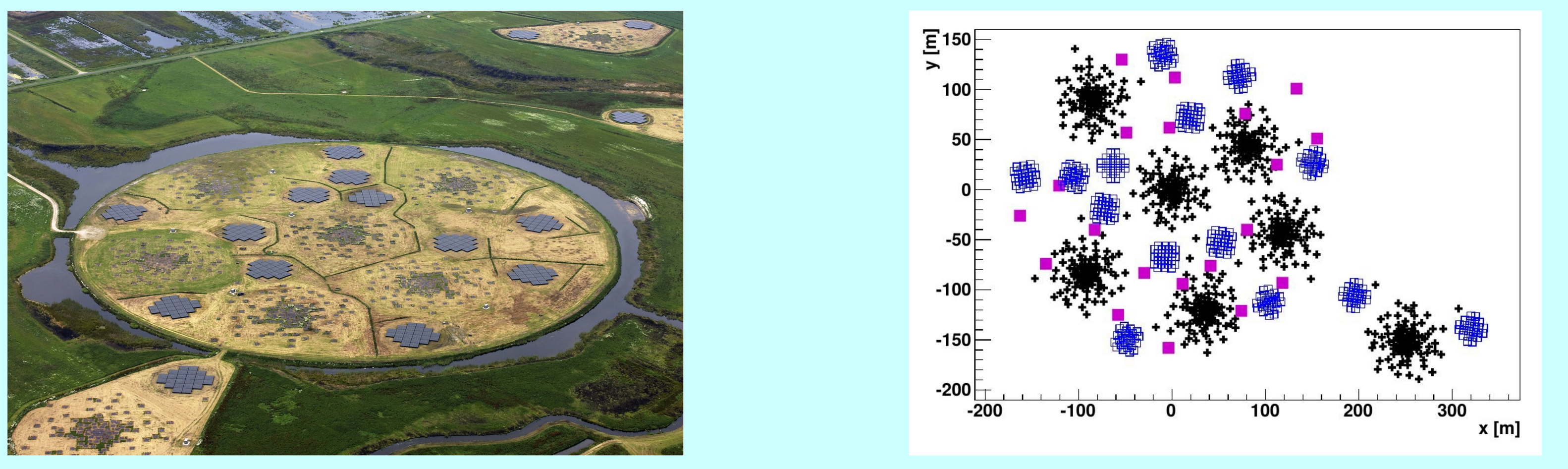

Figure 1. ***Left***: picture of LOFAR central stations. ***Right***: layout of LOFAR central stations. The location of LBA sets is depicted as black crosses; the position of the HBAs is shown as well (open blue squares). The magenta squares indicate instead the scintillator detectors.

Simulation study of the frequency spectrum

Main goal:

to measure cosmic ray energy and mass composition in the energy range **10^{16} – 10^{18} eV** through the analysis of radio signal in the frequency–domain

Procedure:

- preliminary study on simulated shower induced by **protons**
- simulations have been produced considering 160 antennas, distributed on 8 arms at an angle 45° between each other in the *shower plane* (i.e. plane perpendicular to both the shower axis and the geomagnetic field) (see figure 2–*left*)
- the signal has been converted to the frequency–domain by applying a Fast Fourier Transform; the frequency spectrum has been studied as function of distance to the shower axis in the frequency range 30 – 80 MHz (see figure 2–*right*) [2]
- frequency spectrum has been studied as function of distance to the shower axis, and as function of X_{max} through the 30th, 50th, and 70th percentile (see figures 3 and 4); the percentile indicates the frequency value, in the 30 – 80 MHz range, at which the integrated spectrum reaches the given percent of the total integral

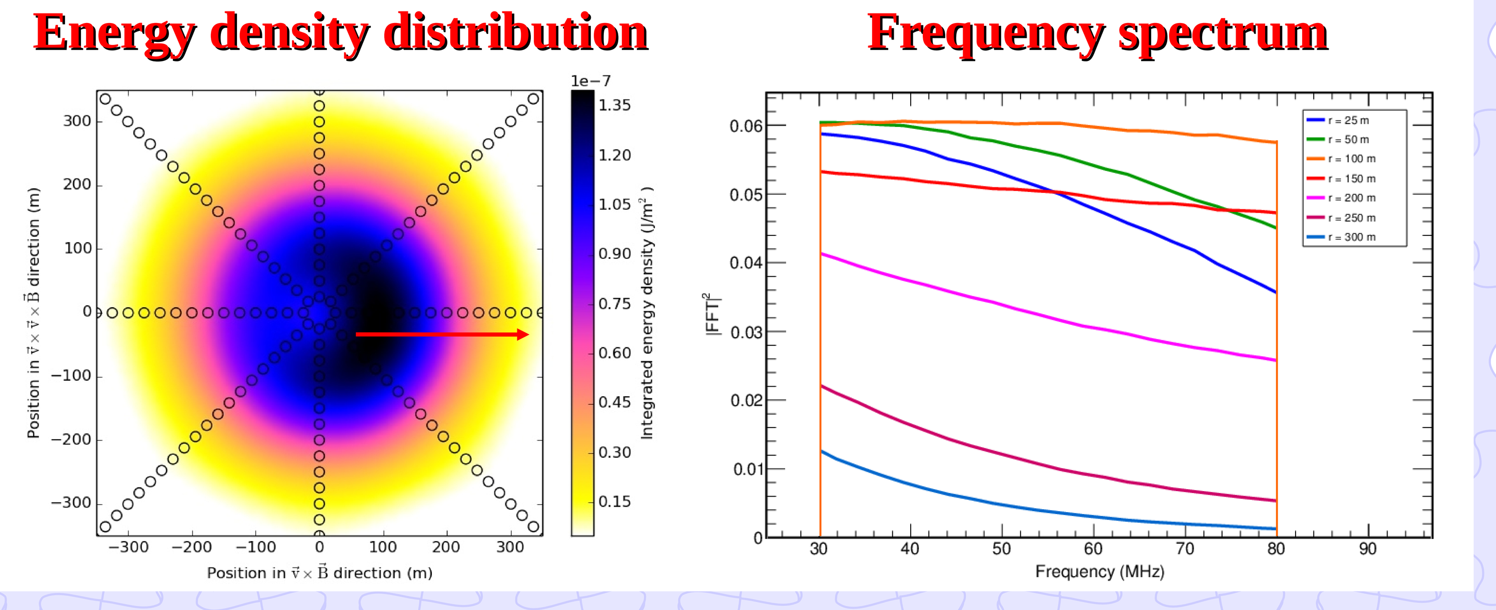

Figure 2. ***Left***: integrated energy density for one simulated shower. The shower has energy E = 2.04 · 10^{18} eV, and an arrival direction with zenith angle 46.73°. The antenna layout is projected on the shower plane, where the centre corresponds to the position of the shower axis. The asymmetric distribution of the radio signal around the shower axis is clearly visible [3, 4]. ***Right***: distribution of the FFT as function of frequency for seven antennas positioned along the arm underlined by the red arrow.

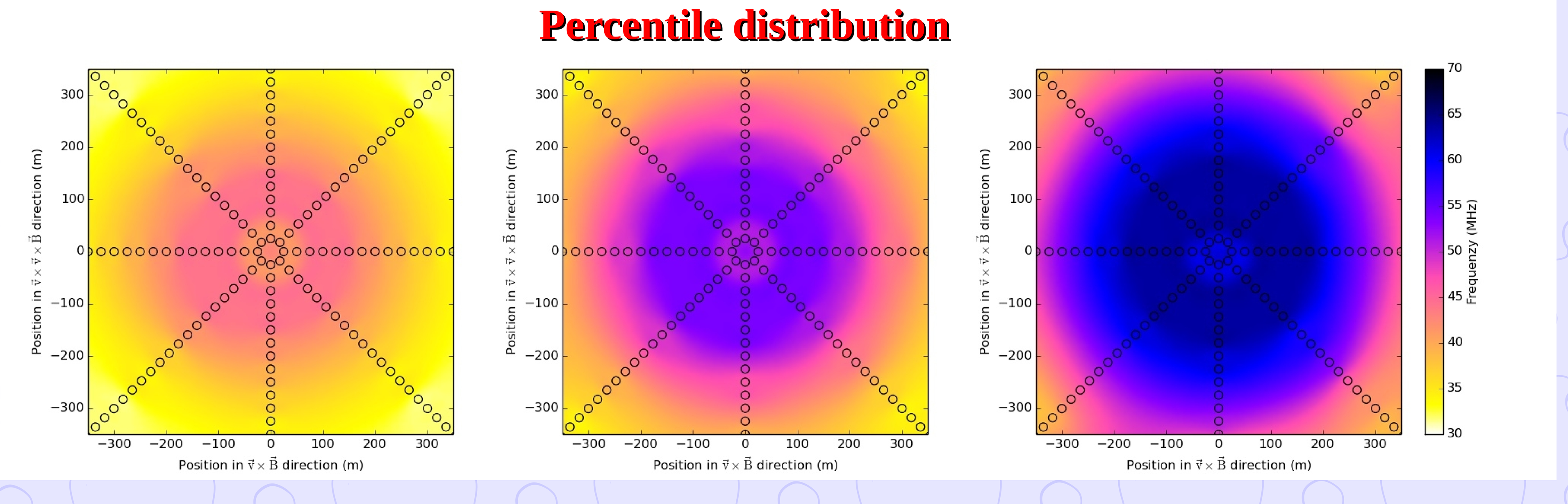

Figure 3. Frequency distribution for all the 160 antennas and for the same simulated event shown in figure 2. The frequency distribution corresponds to the 30th percentile (***left***), 50th percentile (***centre***), and 70th percentile (***right***). Frequency values on the full shower plane have been evaluated through a polar coordinate interpolation.

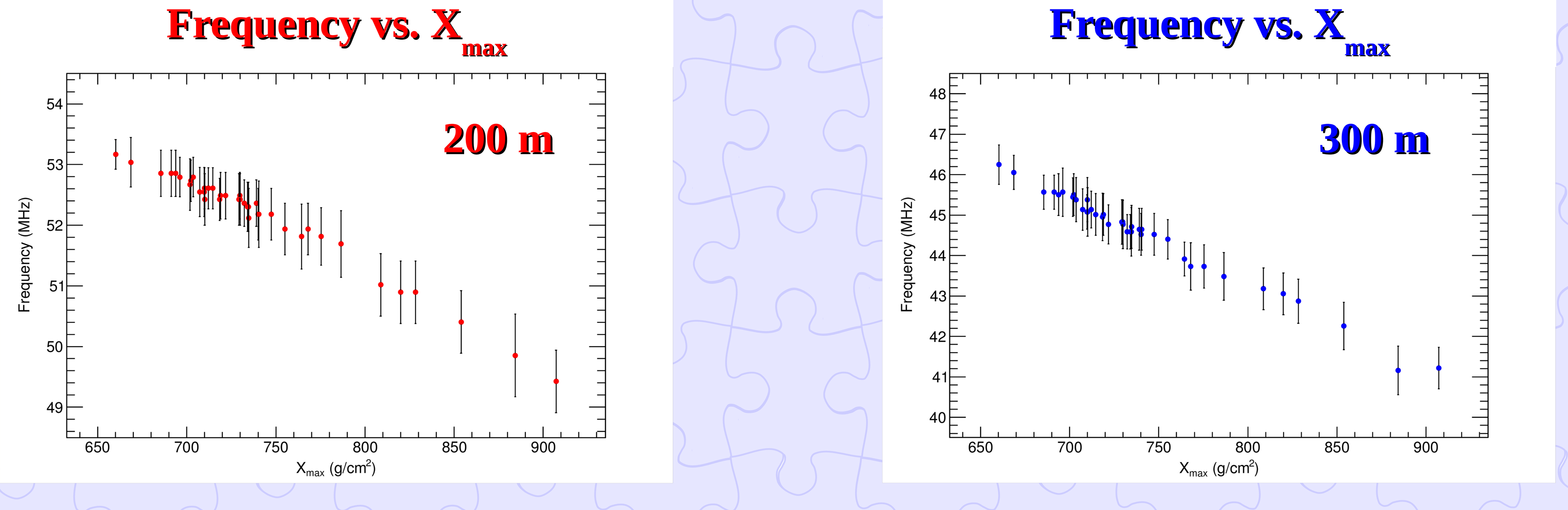

Figure 4. Correlation between X_{max} and the 50th percentile of the frequency spectrum for an observer located on the shower plane at a distance of 200 m (***left***) and 300 m (***right***) from the shower axis. Forty simulated showers have been generated with the same initial conditions as for the event shown in figure 2.

Conclusions and outlook

- Simulation study of radio signals emitted by protons in the frequency–domain
- dependence of the frequency spectrum as function of distance to the shower axis, and as function of X_{max} has been found
- the method presented here will be applied to all data detected by LOFAR since 2011

References

[1] M.P. van Haarlem et al., *Astronomy & Astrophysics*, **556**, A2, 53, 2013; [2] K.D. de Vries, O. Scholten, and K. Werner, *Astroparticle Physics*, **45**: 23–27, 2013; [3] O. Scholten, K. Werner, and F. Rusydi, *Astroparticle Physics*, **29**: 94–103, 2008; [4] K. Werner and O. Scholten, *Astroparticle Physics*, **29**: 393–411, 2008

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