Measuring and parameterizing the two-dimensional pattern of radio emission in air showers with LOFAR

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Abstract. The detection of radio emission of air showers has rapidly advanced in the past years. New experiments have shed light on the details of the emission and air shower simulations provide rather accurate models of the measured emission. To exploit radio emission in large-scale experiments, a simple and analytic parametrization of the distribution of the radio signal at ground level is needed. Such a parametrization can allow for fast calculations of the expected signals and can be used to reconstruct the geometry of the measured air showers. Data taken with the Low-Frequency Array (LOFAR) show a complex two-dimensional pattern of pulse powers, which is sampled with hundreds of antennas per event. Earlier parametrizations of the lateral signal distribution have proven insufficient to describe these highly detailed data. We present a two-dimensional model with five free parameters derived from air shower simulations. All parameters show strong correlations with air shower properties, such as the energy of the shower, the arrival direction, and the height of the shower maximum. This parametrization represents the data taken with LOFAR very accurately. We present the application of this method to LOFAR data and discuss implications for the reconstruction of the shower geometry.

Keywords: Cosmic rays, Air showers, radio emission, LOFAR
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INTRODUCTION

After the convergence of the predictions of emission models, as well as the experimental confirmation of many predicted signatures [1], measuring the radio emission of air showers has the potential to advance to a standard technique to measure air shower properties. One step on the road towards a standard technique is the existence of a simple, practically useful function that can be employed to reconstruct the shower geometry. In order to find a function, similar to functions describing *the LDF* of the particles in an air shower (see figure 1), one can rely on a number of facts:

- The radio signal is not rotationally symmetric around the shower axis, due to the interplay of geomagnetic emission and charge excess, e.g. [2, 3, 4]
- The pattern has a favored direction along the $\vec{v} \times \vec{B}$-axis, e.g. [5]
- The fall-off of the signal is very steep and its slope changes as a function of $X_{\max}$, e.g. [6]
- The signal strength scales with the angle to the magnetic field and the energy of the primary particle e.g. [7]
- The changing index of refraction in the atmosphere introduces relativistic time-compression effects that can manifest themselves in a circular enhancement at the Cherenkov angle, e.g. [8]

One can now either combine this knowledge about the shape of the pattern into a model guided by first principles and physical quantities. Alternatively, one can parameterize the shape independent of the first principles, only based on shape consideration, in order to find robust and practical functions. Correlations with physical parameters can be established in second step. The latter approach is followed in [9]. This approach will be recapped shortly and the application to data from LOFAR [10] will be discussed.

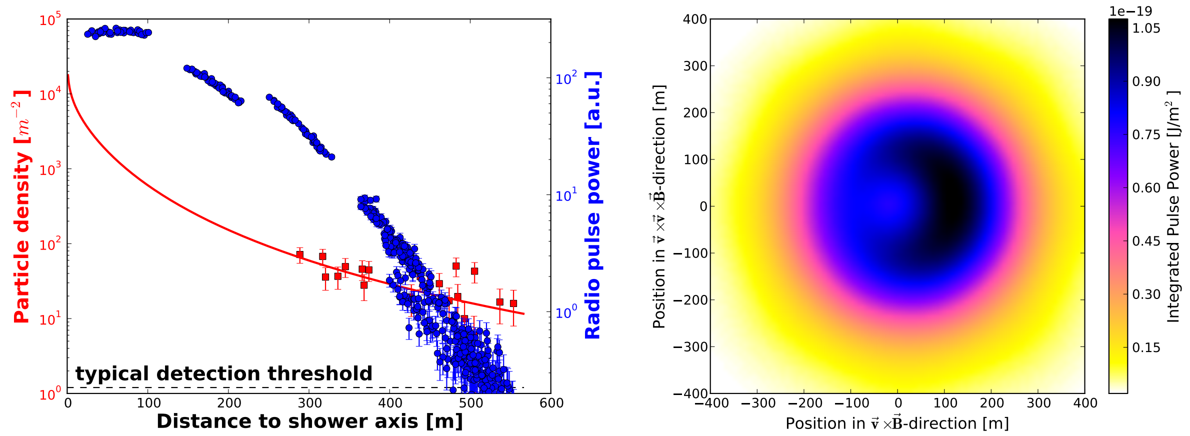

FIGURE 1. Left: Example of a measured particle and radio LDF. Shown are the radio and particle signals of an air shower measured at LOFAR as function of the distance to the shower axis. The particle densities reconstructed from the LORA scintillators [11] are shown in red squares (left axis) with an NKG-fit to the data as solid line. The corresponding radio signals are shown in blue circles (right axis). As the radio signals are given in arbitrary units they are scaled to a common detection threshold, which is indicated by the dashed line. Right: Interpolated intensity pattern of a CoREAS simulation. The air shower arrived with a zenith angle of 45° and an azimuth angle of 13°, where0° is east. The shower energy was set to 2×10^{18} eV. The antennas were positioned on a star-shaped pattern of 8 arms with distances of 15 m aligned with the $\vec{v} \times \vec{B}$-axis.

DEVELOPING A PARAMETRIZATION

Guided by the shape considerations discussed above, the following parameterization was chosen:

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right), \tag{1}$$

where A_-,$A_+ > 0$. This function of two Gaussians, which are shifted with respect to each other, is used to fit a large set of CoREAS [12] simulations. The results are used to explore correlations of fit parameters with each other and with shower characteristics.

Air shower simulations

For a large set of parameters simulations such as shown on the right in figure 1 have been generated for the LOFAR site. By placing the antennas on a regular star-shaped pattern centered around the shower axis, all azimuthal dependencies are covered and the general pattern can be reconstructed. It also removes the bias induced by the position of the shower axis, which one has to consider when dicing the axis on an equally spaced grid and the distance to the closest antenna varies. The simulations cover energies from 10^{17} until 10^{20} eV and zenith angles up to 60°. The individual shower parameters are randomly chosen within this set, however, most of the arrival directions correspond to actual measured air showers. For every air shower at least 25 different values for X_{max} are sampled.

Dependencies on air shower parameters and correlations

The test on the set of air shower simulations reveals correlations between fit parameters and of fit parameters with air shower characteristics. This allows one to reduce the number of parameters of equation 1 to:

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2+(y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c+x_-))^2+((y'-Y_c))^2]}{(C_1 \cdot e^{C_2 \cdot \sigma_+})^2}\right). \tag{2}$$

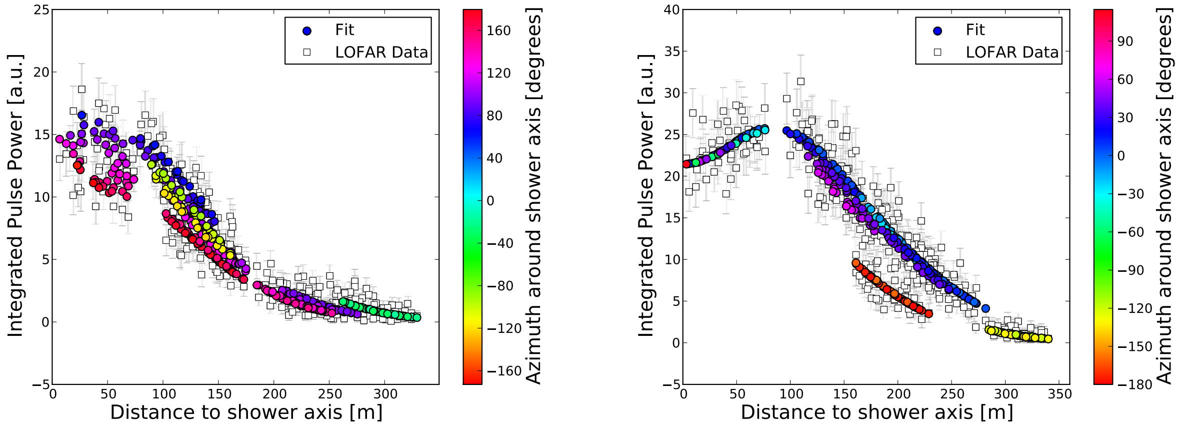

FIGURE 2. Examples of LOFAR data and the corresponding fit with equation 2. For both data (open squares) and fit (filled circles) the integrated pulse powers are shown as a function of distance to the shower axis. To illustrate the effect of the asymmetry of the pattern, the angle around the shower axis is indicated in color. Here, 0° corresponds to a station being east of the shower axis and 90° being north.

Here, X_c and Y_c are proxies for the position with the highest signal in the radio footprint. The parameters C_1,C_2 are constants, extracted from the simulations. The parameter C0 is not fully constant over the full range of zenith angles. It should therefore also be left free ($0.2 < C_0 < 0.8$) if enough data are available.

From the function, the parameter A_+ shows the best correlation with the energy of the primary particle. The correlation is linear in amplitude and quadratic in power, as predicted from coherence. The resolution gets better, if one corrects for the influences of $\sin(\alpha)$, where α is the angle between shower axis and magnetic field. The parameter σ_+ correlates well with the distance to the shower maximum, as the width of the footprint changes with the distances that the shower travels. Furthermore, the parameters X_c and Y_c are related to the position of the shower axis, but are found to show some systematic deviations. These parameters are used on data to test whether the predicted correlations can be retrieved.

TESTING THE PARAMETERIZATION ON LOFAR DATA

All data measured with LOFAR until May 2014 have been fitted with the predicted function. Two examples are shown in figure 2. What at first sight might have been interpreted as misreconstructed shower axis, can clearly be explained by the azimuthal asymmetry of the air shower footprint.

The agreement between model and data is remarkable, leaving a vast majority with a $\chi^2/ndof$ of better than 2. There is the tendency that the parameterization is less good for vertical events ($\theta < 20°$). The rise of the Gaussian seems too small to fully represent the measured signals. However, even those events show an acceptable $\chi^2/ndof$ of better than 2, which makes the parameterization a suitable tool.

As discussed above, the parameters X_c and Y_c are proxies for the position with the highest signal in the footprint. They are related to the position of the shower axis, however, not the same. In order to explore whether the axis is properly reconstructed using this method, the parameters are compared to the shower axis position that is reconstructed from the particle data. To retain a large set, there are no quality cuts applied to the particle data. Therefore, the resolution of the shower axis is dominated by the uncertainties of the particle reconstruction. Figure3 shows the difference between the particle reconstruction and the reconstruction of the radio signal. Clearly, there is a systematic difference between X_c and the X from the particle data. This can be attributed to the asymmetry of the pattern, which finds the highest signal always in positive direction of $\vec{v} \times \vec{B}$ with respect to the actual shower axis. If X_c is corrected with the prediction from simulations for the shift (a function of azimuth angle), the systematic offset vanishes and the shower axis can be reconstructed from radio data alone. Also for other air shower parameters, the predicted dependencies are confirmed in data.

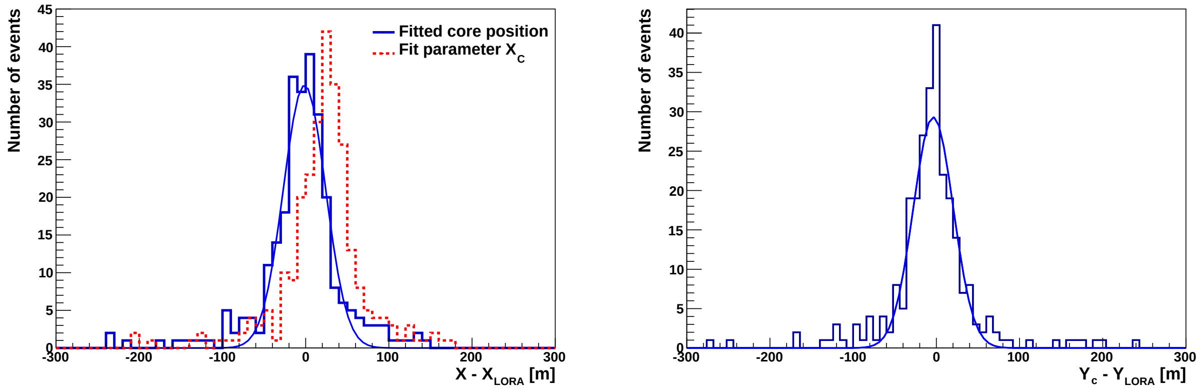

FIGURE 3. Position of the shower axis for a number of events measured with LOFAR and as reconstructed with equation 2. The positions are shown with respect to the shower axis reconstructed from the particle measurements from LORA. Left: Position in $\vec{v} \times \vec{B}$-direction. The fit parameter X_c (dotted line) deviates systematically from the LORA parameter. The distribution shows a mean of (24.6 ± 1.7) m. After correcting for the offset (solid line) the mean is (-1.4 ± 1.7) m. The distribution shows a width of $\sigma = 25.1$ m. Right: Position in $\vec{v} \times (\vec{v} \times \vec{B})$-direction. The distribution shows a mean of (-3.6 ± 1.6) m with a width of $\sigma = 24.0$ m.

CONCLUSION

The presented parameterization for the signal distribution of the radio emission is suitable to describe all LOFAR data. The parameterization can be used to reconstruct all relevant air shower parameters. The predictive quality will be used in a faster simulation strategy to extract energy and X_{max} for every measured shower.

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