A new parametrization for the radio emission of air showers applied to LOFAR data

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Abstract. The energy and mass composition of cosmic rays influence how the energy density of the radio emission of air showers is distributed on the ground. A precise description of the radio profiles can, therefore, be used to reconstruct the properties of the primary cosmic rays. Here, such a description is presented, using a separate treatment of the two radio-emission mechanisms, the *geomagnetic effect* and the *charge excess* effect. The model is parametrized as a function that depends only on the shower parameters, allowing for a precise reconstruction of the properties of the primary cosmic rays. This model is applied to cosmic-ray events measured with LOFAR and it is capable of reconstructing the properties of air showers correctly.

1 Introduction

The radio emission from air showers is the result of two main mechanisms of charge separation: the geomagnetic effect [1] and the charge excess effect [2]. The different polarization patterns of the mechanisms, interfere resulting in a bean-shaped pattern for the energy density of the radio emission on the ground. The shape of the distribution is mainly related to the geometrical distance to the emission region $D_{\max}$ and the signal strength is determined by the energy of the primary particle. $D_{\max}$ is dependent on the type of particle and the arrival direction. A good description of the radio profile on the ground is, therefore, an efficient way to study the radio signal from air showers. The current description for the radio profile used for LOFAR [3], is a model based on a double Gaussian distribution [4].

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The new model presented here is based on the separation of the two radio-emission mechanism components [5]. On a line perpendicular to the Earth magnetic field, the polarizations of the geomagnetic and charge excess components are perpendicular to each other and therefore can be separated. Simulations are used to study the contributions of the two components separately along this axis. The simulations used in this study are produced by the radio extension of the CORSIKA code, CoREAS [6]. A parametrization of a model for the radio signal based on the same concept is done in Ref. [5], where it is shown to be a precise method for reconstructing air shower simulations. In this work, this physics-based model is used to reconstruct cosmic-ray air showers measured with LOFAR.

The geomagnetic and the charge excess effect result in a circularly symmetric emission around the shower axis and, therefore, they are only dependent on r, the distance to the shower axis in the shower plane. To describe the geomagnetic contribution, the function

$$f_{\mathrm{geo}} = \begin{cases} \frac{1}{N_{R_-}} E_{\mathrm{geo}} \exp\left(-\left(\frac{r-R_{\mathrm{geo}}}{\sqrt{2}\sigma_{\mathrm{geo}}}\right)^2\right) & R_{\mathrm{geo}} < 0 \\ \frac{1}{N_{R_+}} E_{\mathrm{geo}} [\exp\left(-\left(\frac{r-R_{\mathrm{geo}}}{\sqrt{2}\sigma_{\mathrm{geo}}}\right)^2\right) + \exp\left(-\left(\frac{r+R_{\mathrm{geo}}}{\sqrt{2}\sigma_{\mathrm{geo}}}\right)^2\right)] & R_{\mathrm{geo}} \geq 0 \end{cases} \tag{1}$$

is used and for the charge excess contribution

$$f_{\mathrm{ce}} = \frac{1}{N_{\mathrm{ce}}} E_{\mathrm{ce}} r^k \exp - \frac{r^2(k+1)}{2\sigma_{\mathrm{ce}}^2}, \tag{2}$$

with $k \geq 0$ and $R_{\mathrm{ce}} = \sigma_{\mathrm{ce}} \frac{\sqrt{k}}{\sqrt{k+1}}$. Here $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$, x and y denote the positions in the shower plane and x_0 and y_0 denote the shower core position. E_{geo} and E_{ce} are the geomagnetic and charge excess energy, respectively and are correlated to the primary energy of the cosmic ray. R_{geo}, σ_{geo}, R_{ce} and σ_{ce} determine the shape of the distributions and therefore are correlated to D_{max}. Combining these two functions results in a model for the energy density of the radio emission with four parameters which are all properties of the air shower: the energy of the primary particle, the distance to the emission region, and the shower core position.

2 The parametrization applied to CoREAS simulations

This analysis uses 230 CoREAS simulated showers, with cosmic-ray parameters corresponding to events measured by LOFAR. An atmospheric model is used based on the real-time weather conditions, since the distance to the emission region depends on the atmospheric properties [7]. Comparing the reconstructed values from the new model with the true values from the simulations, results in $\sigma_D = 26$ g/cm^2, $\sigma_E = 0.06$, $\sigma_{x0} = 7.58$ m and $\sigma_{y0} = 0.53$ m, which are the resolution for the distance to the emission region, the fractional energy resolution of the primary particle, and the resolution of the position of the shower core in the shower plane, respectively.

3 The parametrization applied to LOFAR data

The model is applied to air showers measured by the dense core of LOFAR antennas. The data set consists of 330 showers, all with at least four stations above threshold. An example of a reconstructed air shower is shown in Fig. 1. The colors in the figure correspond to different azimuth angles. A clear asymmetry in the energy density distribution is seen, as a result of the interference between the geomagnetic and charge excess contribution. For a more quantitative approach, the reconstructed shower properties are compared to values from a computational intensive method for high precision

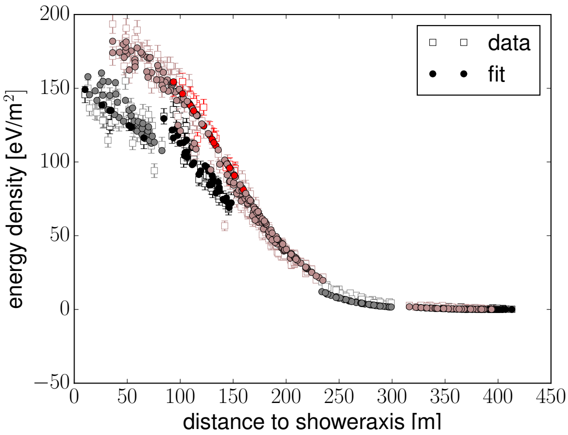

Figure 1. An example of a reconstructed air shower measured by LOFAR. The energy density is given as function of the distance to the shower axis. The colors indicate different azimuth angles. The red, pink, grey, and black points correspond to the northeast, southeast, southwest and northwest direction, respectively.

reconstruction of D_{max} based on CoREAS simulations [8]. This method uses starting values for the energy as reconstructed by the particle detectors or the parametrization function used in [4]. Using the new model, the energy of the primary particle, the distance to the shower maximum and the shower core position in x_0 and y_0 can be reconstructed with a precision of $\sigma_D = 42$ g/cm^2, $\sigma_E = 0.35$, σ_{x0}=8.8 m and σ_{y0}=9.5 m, respectively. Here σ is defined as the width of a fitted Gaussian to the distribution of the (relative) deviation between the reconstructed shower property by the new model and the values from the simulation method. The previous parametrization reconstructed D_{max} for events measured with LOFAR with a resolution of $\sigma_D \approx 51$ g/cm^2 [9]. In the previous parametrization a quality cut was made on the shower core reconstruction of 10 m, which is not done for the reconstruction with the new model. Therefore, the new model is capable of reconstructing measured air showers with higher precision than the currently used function.

4 Conclusion

Using CoREAS simulations to study the radio emission of the geomagnetic and the charge excess component separately, a model is derived to describe the energy density distribution of the radio emission from air showers on the ground. This model is only dependent on the shower properties: the energy of the primary particle, the distance to the emission region and the shower core position. The model allows for the reconstruction of the air shower properties of measured showers with LOFAR with a higher accuracy than the currently used model.

References

[1] F. D. Kahn, Royal Society of London Proceedings Series A **289**, pp. 206-213 (1966)
[2] G. A. Askaryan, Journal of the Physical Society of Japan Supplement **17**, p. C257 (1962)
[3] P. Schellart, Astronomy and Astrophysics **560**, 14 pp. (2013)
[4] A. Nelles, Astropart. Phys. **60**, pp. 13-24 (2014)
[5] C. Glaser, Astropart. Phys. (2018), arXiv:1806.03620
[6] T. Huege, Astropart. Phys. (2013), arXiv:1301.2132
[7] A. Corstanje, Astropart. Phys. **89**, 23-29 (2013)
[8] S. Buitink, Physical Review **90**, (2014)
[9] A. Corstanje, Private communication