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The convergence of EAS radio emission models and a detailed comparison of REAS3 and MGMR simulations

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ABSTRACT

Over the previous decade, many approaches for the modelling of radio emission from cosmic ray air showers have been developed. However, there remained significant deviations between the models, reaching from important qualitative differences such as *unipolar* versus *bipolar* pulses to large variations in the predicted absolute amplitudes of up to factors of 20. Only recently, it has been realized that in the many models predicting *unipolar* pulses, a radio emission contribution due to the time-variation of the number of charged particles or, equivalently, the acceleration of the particles at the beginning and the end of their trajectories, had not been taken into account. We discuss here the nature of the underlying problem and demonstrate that by including the missing contribution in REAS3, the discrepancies are reconciled. Furthermore, we show a direct comparison of REAS3 and MGMR simulations for a set of prototype showers. The results of these two completely independent and very different modelling approaches show a good level of agreement except for regions of parameter space where differences in the underlying air shower model become important. This is the first time that two radio emission models show such close concordance, illustrating that the modelling of radio emission from extensive air showers has indeed made a true breakthrough.

1. Introduction

Due to renewed interest in radio detection of cosmic ray air showers, the need for reliable and detailed models of the radio emission process has increased continuously over recent years. Although the emission process had already been investigated extensively in the early days of air shower radio detection, it became clear that renewed modelling efforts were necessary. Consequently, modelling of the radio emission of EAS was restarted by a number of different groups as early as 2001. (A review on the evolution of the modern radio emission approaches can be found in Ref. [1].)

When more and more models appeared on the market, it became obvious that there were contradictions between them. In particular, two classes of models could be identified. On the one hand there were models predicting *unipolar* radio pulses, the frequency spectra of which levelled off at a constant value towards very low frequencies. Most strikingly, this was the case for most of the models working in the time-domain. On the other hand, there were models predicting *bipolar* pulses, the frequency spectra of which fall to zero for very low frequencies. All frequency-domain approaches had this characteristic feature.

These issues were first discussed in detail during a workshop dedicated to radio emission theory at Forschungszentrum Karlsruhe [2]. In an article by Gousset et al. [3], a direct comparison was made between a description predicting *bipolar* pulses and a formulation producing *unipolar* pulses (see Fig. 1). The resolution of the contradiction, however, was not yet found.

From the fact that the source of the radio emission exists only over a finite time in a finite region of space, however, one can argue that the zero-frequency component of the emission (which corresponds to an infinite time-scale), can contain no power [4]. Therefore, the models with *unipolar* pulses, which have frequency spectra leveling off at a constant value at frequency zero, had to be suffering from some problem. The resolution of this problem has been found only recently.

In this article, we shortly review the models producing *unipolar* and *bipolar* pulses before explaining what causes the discrepancy and how the affected time-domain models can be corrected. Finally, we compare two very different and completely independent models with correct implementations, namely the REAS3 [5,6] and MGMR [7,8] models. We demonstrate that for the first time, two models show a good agreement in the predicted radio emission features. This marks a major milestone in the modelling of radio emission from extensive air showers.

2. Modern modelling approaches

In this section, we provide an (incomplete) overview of modern modelling approaches for radio emission from extensive air showers and demonstrate how they can be grouped into models

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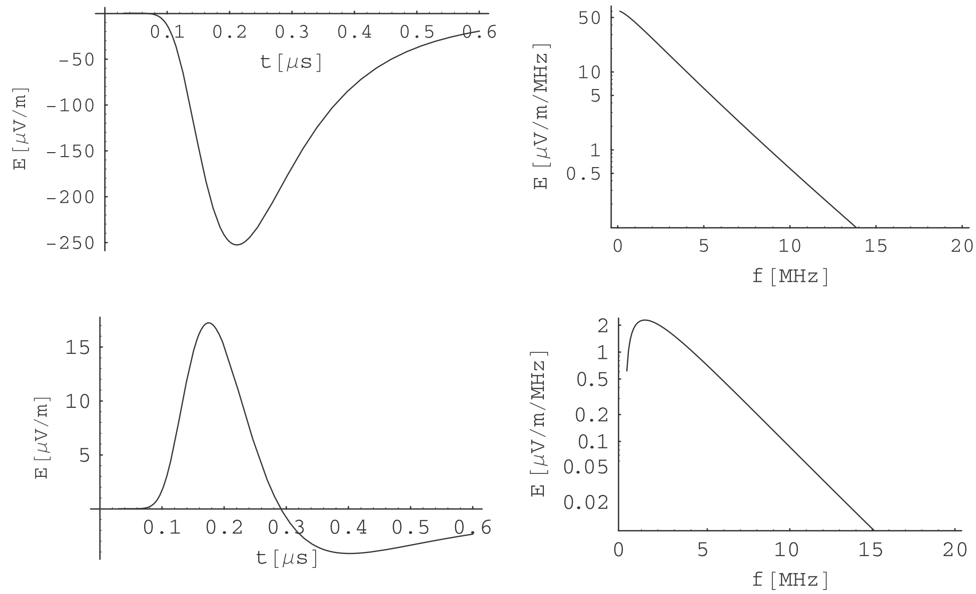

Fig. 1. Time pulses (left) and frequency spectra (right) calculated with the large impact parameter analytical radio emission model of Gousset et al. [3] for the acceleration component (top, *unipolar*) and the current component (bottom, *bipolar*).

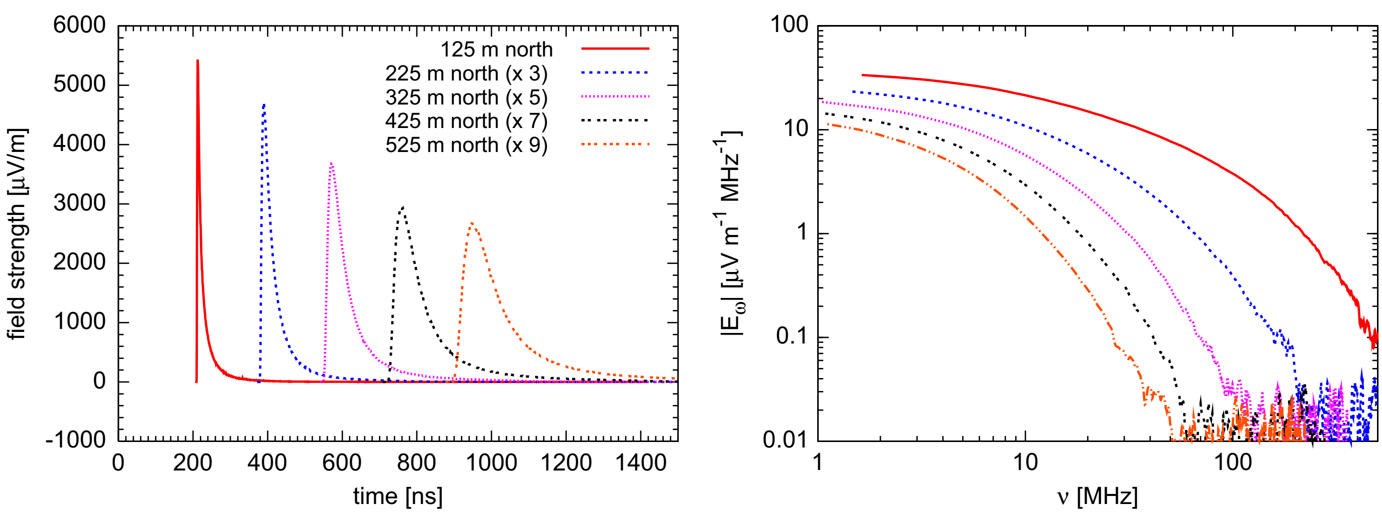

Fig. 2. *Unipolar* radio pulses (left) of a 10^{18} eV air shower with 30° zenith angle simulated with REAS2 [14] and the corresponding frequency spectra (right).

predicting *unipolar* pulses and models predicting *bipolar* pulses. For models we could not mention here, we kindly refer the reader to the review by Huege [1].

2.1. Models with unipolar pulses

In 2003, Falcke and Gorham [9] motivated that the radio emission from extensive air showers could be described as "geosynchrotron radiation" arising from the acceleration of air shower electrons and positrons in the Earth's magnetic field. This approach was afterwards followed by a number of authors with implementations in both the frequency-domain (see Section 2.2) and time-domain. In principle, calculations in both the frequency-domain and time-domain can be considered equivalent. As the radio signal, however, is very localized in time, a time-domain calculation has a number of technical advantages. Also, the treatment of retardation effects is simpler in the time-domain than in the frequency domain.

The first time-domain implementation of the geosynchrotron approach, for the emission from the air shower maximum only, was made by Suprun et al. [10]. In contrast to the frequency-domain calculation carried out in parallel by Huege and Falcke [11], the frequency spectra predicted by the Suprun et al. calculation levelled off at very low frequencies and the pulses were *unipolar* (see Figs. 4 and 5 in Ref. [10]).

In the following years, much effort was spent on developing a detailed time-domain implementation of the geosynchrotron model by Huege and Falcke and later Huege , Ulrich and Engel in a series of publications [12–14]. The first implementation (REAS1, [12]) was based on a parameterized air shower model. Later, a transition was made to realistic air shower characteristics derived on a per-shower basis from CORSIKA [15] simulations (REAS2, [14]). A common feature of all of these time-domain calculations was the prediction of *unipolar* pulses with frequency spectra leveling off at very low frequencies, as seen in Fig. 2 for the case of REAS2.

The geosynchrotron approach was also implemented in the AIRES air shower radio emission code [16] by DuVernois et al. [17]. This implementation exhibited the same characteristic *unipolar* pulses and frequency spectra leveling off at very low frequencies.