A detailed comparison of MGMR and REAS3 simulations

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Abstract: We compare the results of two very different and completely independent approaches for modelling radio emission from extensive air showers. On the one hand, there is MGMR, a macroscopic model based on the bulk motion of charged particles in the air shower with the transverse currents as leading contribution. On the other hand, there is REAS3, a Monte Carlo code based on the endpoint formalism calculating and superposing the radiation from individual particles of the air shower. In a first comparison between both models it was already shown that the results obtained with REAS3 and MGMR agree within a factor of 2-3. This agreement was a breakthrough in the modelling of radio emission from air showers since previous comparisons made contradicting conclusions on the pulse shapes and differed by factors of 10 or more in the pulse height. However, it is essential to understand the remaining differences in detail. In this contribution, we present studies on the influence of differences in the implementations, such as the underlying air shower and atmosphere models.

Keywords: radio emission, extensive air showers, modelling and simulation

1 Introduction

Over the past decade, considerable effort has been made to model the radio emission from extensive air showers. However, until recently, different models made largely contradicting predictions. Most models predicted unipolar radio pulses, while others predicted bipolar radio signals; also, the predicted amplitudes varied by orders of magnitude. A prominent example of a model with unipolar pulses was REAS2 [1], a microscopic Monte Carlo code based on CORSIKA [2] simulations of air showers. In contrast, the MGMR model [3], a fast macroscopic model based on air shower parameterizations which has also been interfaced with Monte Carlo codes [4], predicted bipolar radio pulses.

Soon it became clear from basic physical arguments that the pulses of the air shower radio emission had to be bipolar [5]. It turned out that the models predicting unipolar pulses treated the calculation of the radio emission inconsistently — they did not take into account a radio emission contribution associated with the time-variation of the number of charged particles during the air shower [6].

Using the endpoint formalism [7], the missing radiation contributions have been incorporated in REAS3 [8], changing the pulse shape from unipolar to bipolar. In a first detailed comparison of MGMR and REAS3 [6], we demonstrated that with these changes the two models achieved an agreement within a factor of 2–3, as depicted in figure 1. This general agreement in pulse shapes and amplitudes between two independent and completely different models was a breakthrough in the modelling of radio emission from extensive air showers.

However, the remaining amplitude differences, prominent in particular close to the shower axis, had to be investigated. A likely explanation for the deviations were the differences in the underlying air shower models used in the two approaches. In this article we investigate the influence of such modelling details and demonstrate that indeed they can account for the majority of the observed differences.

2 Setup of the comparison

To make sure that the results obtained with both models are directly comparable, a set of prototype showers was defined for the simulations. All of these air showers have a fixed geometry with a specific energy for the primary particle. The observer positions were chosen the same for both models and were all set to 1400 m above sea level, which corresponds to the altitude of the Pierre Auger Observatory. The values for the magnetic field were set to the configuration at the site of the Pierre Auger Observatory.

For each prototype shower, a set of CORSIKA showers was simulated. To minimize the influence of shower-to-shower fluctuations, one typical shower, i.e. one which has a shower maximum $X_{\max}$ close to the mean $X_{\max}$, was then selected from this set. The hadronic interaction mod-

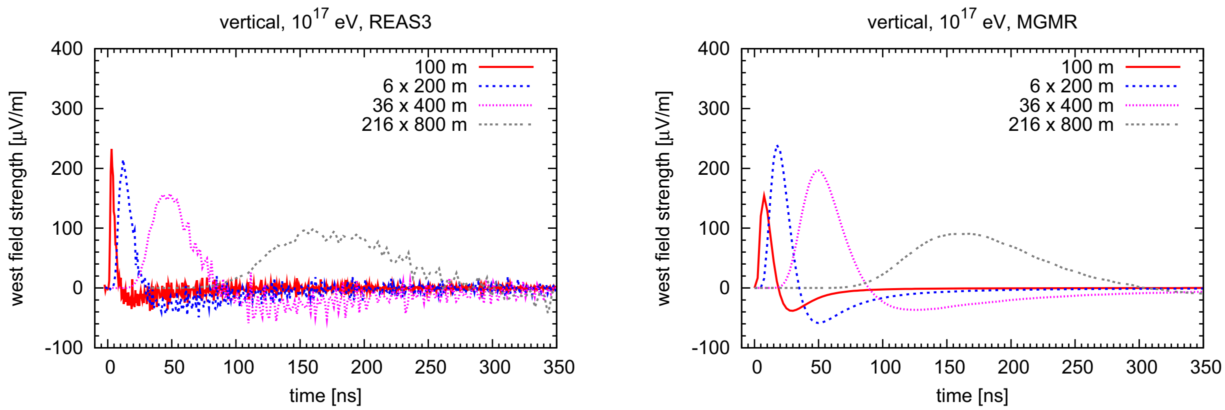

Figure 1: Comparison of the western polarization unlimited bandwidth radio pulses for vertical showers with a primary energy of 10^{17} eV for REAS3 (left) and MGMR (right) as published in [6].

Parameter (name)	**Value**	**Comment**
drift velocity v_d	$0.025 \cdot c$	c = speed of light
pancake thickness L	3.9 m	assumed as constant
fraction of charge excess	0.23	assumed as constant
velocity of the pancake	$v = c$	

Table 1: Overview of the parameters set in MGMR-v1.6 used for the comparison with REAS3 presented here.

els used for the CORSIKA simulations fed to REAS3 were QGSJetII.03 [9] and UrQmd1.3.1 [10]. The longitudinal air shower profiles of the CORSIKA showers were used as input to MGMR.

While the air shower is completely determined by the CORSIKA simulations in case of REAS3, a number of parameterizations are used within MGMR (see section 3). These parameterizations require the setting of some free parameters. For this comparison, the parameters were chosen the same as published in [11] and are listed in table 1.

3 The underlying air shower models

To understand the differences remaining between REAS3 and MGMR and evaluate the influence of the underlying air shower model, we modified REAS3 to mimic the parameterized air shower model used in MGMR.

In MGMR, the arrival time distribution, i.e. the longitudinal displacement of the particles inside the shower pancake, is described with a $\Gamma-$probability distribution function following the relation:

$$f(h) = h \cdot e^{-2h/L} \cdot \frac{4}{L^2}, \qquad (1)$$

where h denotes the distance from the shower front and L denotes the pancake thickness, here set to 3.9 m. To assess the influence of this choice of longitudinal distribution, we replaced the longitudinal displacement of the particles in REAS3 with this $\Gamma-$probability distribution function.

Another difference between the models is the treatment of the lateral particle distribution. In MGMR, the lateral spread of the electrons and positrons is neglected. However, to take into account the effect of the systematic shift between the electron and positron distributions, a radiation contribution from a static dipole with a total length of 15 m is added to the overall radio signal. To reproduce this behaviour in REAS3, we switched off the lateral distribution of particles, but shifted the electrons by 7.5 m in the eastern direction of the shower axis and the positrons by 7.5 m in the western direction .

In figure 2, the changes resulting from these two modifications to REAS3 are shown for two different observer positions, one at 100 m north from the shower core (top) and the second at 800 m north from the shower core (bottom) of a vertical air shower with primary energy of 10^{17} eV. Obviously, the changes to the air shower model adapted in REAS3 influence the radio pulses close to the shower axis much more strongly than they affect those at large lateral distances. With the adopted simplifications, the REAS3 pulses become much more similar to the predictions made by MGMR. For the more distant observer, all three simulations are nearly identical, i.e. the details of the air shower model are not important at large lateral observer distances. The reason is that at large lateral distances, geometrical time delays associated with the propagation of the emission from the sources to the observers dominate over the intrinsic timescales determined by the spatial distribution of particles in the shower pancake.

The largest differences between MGMR and REAS3 were previously observed for inclined air showers (cf. [6]). This has geometrical reasons, since for inclined showers a given ground distance can correspond to a significantly smaller axis distance. To evaluate the changes for inclined showers, the influence of the air shower model was also studied for an air shower with zenith angle of $50°$ coming from south-

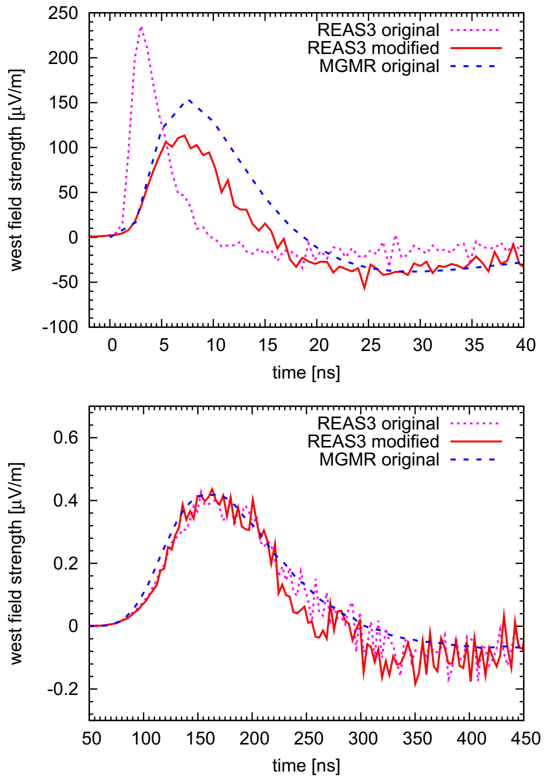

Figure 2: A comparison between the radio pulses predicted by MGMR and a modified version of REAS3 where the longitudinal displacement of the particles in the shower pancake follows the distribution used in MGMR and the lateral distribution is replaced by a systematic offset of electrons and positrons. The pulses for a 10^{17} eV vertical air shower are shown for observers 100 m (top) and 800 m (bottom) north of the shower core.

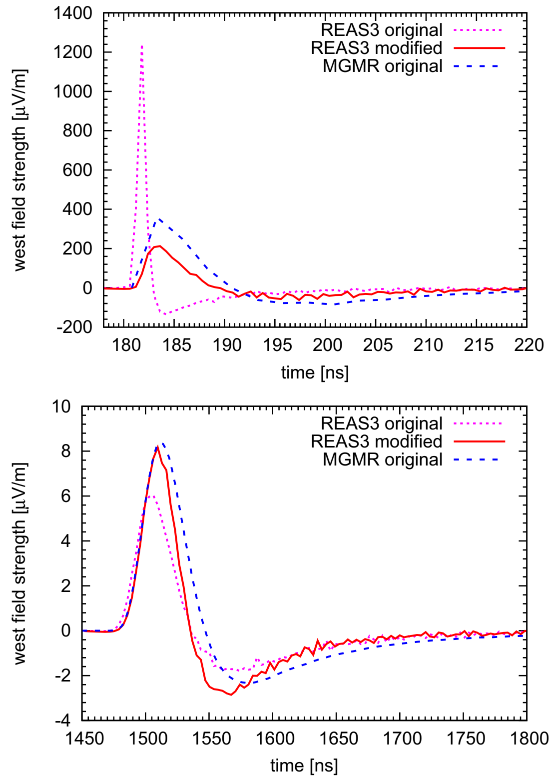

Figure 3: A comparison between the radio pulses predicted by MGMR and a modified version of REAS3 where the longitudinal displacement of the particles in the shower pancake follows the distribution used in MGMR and the lateral distribution is replaced by a systematic offset of electrons and positrons. The pulses for a 10^{17} eV air shower with a zenith angle of $50°$ are shown for observers 100 m (top) and 800 m (bottom) north of the shower core.

east and a primary energy of 10^{17} eV. In figure 3, the results of this comparison are shown.

Also in this case, the version of REAS3 adapted to the parameterizations used in MGMR predicts signals much closer to the MGMR result than before. For the observer at 100 m distance (top), the original REAS3 predicted pulses with amplitudes a factor of ~ 3 larger than those calculated by MGMR and the arrival times differed as well. The predictions by the modified version of REAS3 differ less than a factor of 2 from the predictions obtained by MGMR. Again, at large lateral distances, the details of the air shower model have a smaller influence, but even here the agreement becomes noticably better for the modified REAS3 version.

In summary, these results confirm our expectation that the differences observed earlier between REAS3 and MGMR can be largely attributed to differences in the underlying air shower model.

4 Additional model differences

As demonstrated, differences in the longitudinal and lateral distributions of the air shower particles can account for a majority of the deviations observed in the comparison between MGMR and REAS3. In the end, however, analyses of experimental data require an understanding of the radio emission on a level of 10% or better. A number of additional differences between the models should thus be investigated in the future.

One relevant difference is the treatment of the atmosphere. The choice of a specific atmospheric model has influence on the radio emission because it changes geometric scales associated with the air shower development (e.g., the geometrical distance of the shower maximum from the observers). For the CORSIKA and REAS3 simulations of the present prototype showers, the US standard atmosphere was used. The atmosphere model implemented in MGMR, however, follows the following exponential function for the whole air shower development:

$$X\,[h] = \frac{1000.0}{\cos\theta}\,\frac{\mathrm{g}}{\mathrm{cm}^2}\cdot\exp\left[\frac{\log(0.68)}{4000.0}\,\frac{h}{\mathrm{m}}\right], \qquad (2)$$

where θ is the zenith angle and h is the height above sea level from where the signal is emitted.

Another aspect to be studied in the comparison between the two models is the choice and parameterisation of the charge excess fraction used in MGMR. As specified in table 1, it was set to a constant value for the MGMR simulations shown here. However, the fractional charge excess certainly varies over the course of the air shower evolution.

Similarly, the drift velocity adopted in the MGMR simulations was set to a constant value, although, again, it is bound to undergo variation over the course of the air shower evolution.

5 Conclusions

With the general agreement of two very different and completely independent models observed in a previous comparison, a breakthrough had been achieved in the understanding of radio emission from extensive air showers. However, the initial comparison showed remaining deviations of a factor of 2–3, which were assumed to be related to differences in the air shower models used in MGMR and REAS3.

To assess the influence of these differences in the underlying air shower models, we adapted the REAS3 code to mimic the parameterizations used in MGMR. The results show that this simplified version of REAS3 predicts radio signals which are in much better agreement with MGMR than observed before. As expected, these changes mainly occur for observers close to the shower axis, and matter more for inclined than for vertical air showers. At large lateral distances, the details of the air shower model play no important role, again as expected before.

To achieve an understanding of the radio emission on a 10%-level, as desired for analyses of experimental data, further comparisons will have to be made. In particular, the influence of the chosen atmosphere and of the charge excess fraction and drift velocity adopted in MGMR should be investigated in more detail.

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