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Comparing LOPES measurements of air-shower radio emission with REAS 3.11 and CoREAS simulations

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ABSTRACT

Cosmic ray air showers emit radio pulses at MHz frequencies, which can be measured with radio antenna arrays – like LOPES at the Karlsruhe Institute of Technology in Germany. To improve the understanding of the radio emission, we test theoretical descriptions with measured data. The observables used for these tests are the absolute amplitude of the radio signal, and the shape of the radio lateral distribution. We compare lateral distributions of more than 500 LOPES events with two recent and public Monte Carlo simulation codes, REAS 3.11 and CoREAS (v 1.0). The absolute radio amplitudes predicted by REAS 3.11 are in good agreement with the LOPES measurements. The amplitudes predicted by CoREAS are lower by a factor of two, and marginally compatible with the LOPES measurements within the systematic scale uncertainties. In contrast to any previous versions of REAS, REAS 3.11 and CoREAS now reproduce the shape of the measured lateral distributions correctly. This reflects a remarkable progress compared to the situation a few years ago, and it seems that the main processes for the radio emission of air showers are now understood: The emission is mainly due to the geomagnetic deflection of the electrons and positrons in the shower. Less important but not negligible is the Askaryan effect (net charge variation). Moreover, we confirm that the refractive index of the air plays an important role, since it changes the coherence conditions for the emission: Only the new simulations including the refractive index can reproduce rising lateral distributions which we observe in a few LOPES events. Finally, we show that the lateral distribution is sensitive to the energy and the mass of the primary cosmic ray particles.

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1. Introduction

Hundred years after the discovery of cosmic rays [1] the origin of the highest energy particles is still unclear and requires further measurements. The interesting energy range above 10^{17} eV where the transition from galactic to extragalactic cosmic rays is presumed [2] cannot be accessed by direct measurements since the flux of cosmic rays above $\sim 10^{14}$ eV is too low. Instead, cosmic rays are measured indirectly by detecting air showers of secondary particles. Established techniques for air shower measurements are the detection of the secondary particles at ground, and the measurement of atmospheric Cherenkov and fluorescence light emitted by air showers. The aim of all measurements is to reconstruct the properties of the primary cosmic ray particles from the air-shower observables, i.e. their arrival direction, energy and mass. In particular, the latter two techniques give more precise measurements of the energy since they provide a calorimetric measurement of the air showers. However, they have the disadvantage that they can be used only during dark, moonless nights [3].

An alternative instrument for air shower detection is given by digital radio antenna arrays, which also can provide a measurement of the shower energy [4,5] and feature a duty-cycle of almost 100% like particle detector arrays [6,7]. Current efforts like LOPES [8–10], CODALEMA [11,12], at ANITA [13], the Pierre Auger Observatory [14], or at Tunka [15] still focus on engineering work, i.e. to prove the applicability of the radio technique to large scale observatories, and to show that a precision similar to the one of the fluorescence and air-Cherenkov techniques can be achieved.

To make the radio technique competitive, it is crucial to understand the radio emission mechanism in sufficient detail. From previous work (e.g., Ref. [6]) we know that the radio emission of air showers originates mainly from the geomagnetic deflection of electrons and positrons [16,17], but also other effects play a role, in particular the Askaryan effect [18], i.e. the variation of the net charge excess over the shower development. Recent models and simulation codes also take into account the refractive index of the air, which affects the coherence conditions for all radio emission mechanisms [19–21], as was already discussed more than 40 years ago in Ref. [22]. Cherenkov emission due to constant, not-accelerated charges moving with superluminal velocity in a refractive medium, however, is generally not included in recent simulation codes because its contribution is considered negligible [23]. The best way to test our understanding of the overall emission is to compare experimentally measured quantities, like the lateral distribution of the radio signal, with simulations based on certain models.

The lateral distribution of the radio signal is the variation of the radio amplitude ϵ with the distance to air shower axis d. It has already been studied with LOPES [24,25] and other experiments (e.g., CODALEMA [12]), and already it was compared to simulations [26], however, only for single events or with a limited statistics. These limited studies had been sufficient to show that earlier models, not yet including the refractive index of the air, could not fully reproduce the measurements. Now, we present the results of a systematic, per-event comparison of radio lateral distributions measured with LOPES to two recent, publicly available Monte Carlo simulation codes: REAS 3.11 [27] and CoREAS (v 1.0) [28], respectively. Since LOPES features an absolute amplitude calibration [29], and neither REAS nor CoREAS have free parameters to tune the absolute scale, the presented comparison is not only qualitatively, but also quantitatively meaningful.

There are other simulation codes available, e.g., ZHAireS [21], EVA [30], MGMR [31], SELFAS [32] and the model described in Ref. [33]. Although they use different approaches and techniques, they basically simulate the same physics for the radio emission of air showers, i.e., the geomagnetic and the Askaryan effect, and some codes also include the refractive index of the air. Since we have chosen on purpose two simulation codes with a fixed, non-tunable absolute scale, other codes can be indirectly compared to LOPES when comparing them with REAS 3.11 or CoREAS, respectively. Such model-to-model comparisons have already been performed, e.g., in Refs. [34,35]. In future, the next-generations experiments LOFAR [36] and AERA [37] can be used to test simulations in much more detail or, respectively, at much larger axis distances.

2. Measurements

For the reconstruction of the lateral distribution we use LOPES measurements of the years 2005–2009. During this period, LOPES consisted of 30 absolute calibrated, inverted v-shaped dipole antennas. Until the end of 2006, all antennas were east–west aligned, since for most shower geometries the radio signal is preferentially east–west polarized due to the geomagnetic radio emission. Afterwards, half of the antennas were aligned in the north–south direction. In this paper we focus on the lateral distribution measured with the east–west aligned antennas, since the statistics are larger and the signal-to-noise ratio is generally higher. At the end of the paper, we also present first results for lateral distributions measured with the north–south aligned antennas.

The LOPES antennas are located within the KASCADE-Grande experiment [38] at the Karlsruhe Institute of Technology, Germany, and form an array with a lateral extension of about 200 m. Whenever KASCADE-Grande detects a high-energy shower ($10^{16} - 10^{18}$ eV), it triggers LOPES which then digitally measures the radio emission. The effective bandwidth of LOPES is $43 - 74$ MHz, the trace length about 0.8 ms, and the sampling rate 80 MHz. This means that the LOPES setup fulfills the Nyquist sampling theorem, i.e. the full information of the electrical field strength in the measurement bandwidth is contained in the data. Thus, the electrical field strength between the sampled data points is retrieved by up-sampling.

2.1. Analysis procedure

The KASCADE-Grande reconstruction provides the shower direction and the shower core (= intersection of the air shower axis with the ground), as well as the primary energy, and the measured numbers of muons and electromagnetic particles. A subset of these parameters (arrival direction, core position, energy, muon number) is used as input for the REAS 3.11 and CoREAS simulations, and another subset (shower direction, core position) as input for the LOPES analysis, whereby the shower direction is optimized during the LOPES analysis using the radio measurements.[1]

An essential part of the LOPES analysis is cross-correlation beamforming. First, the electrical field strength traces of each antenna are shifted in time corresponding to the arrival direction of the air shower (Fig. 1 (a)), and, second, a cross-correlation between the different traces is calculated (CC beam, Fig. 1 (b)) as well as a power beam measuring the total power from the air shower arrival direction. Details of this procedure can be found in Refs. [39,40]. The present analysis of the lateral distribution uses the cross-correlation and power beam only for two purposes: a selection of events with a clear radio signal, and a determination of the exact time of the radio pulse, which is an important input to determine the radio amplitude in antennas with low signal-to-noise ratio.

The radio signal in each individual antenna is determined with a Hilbert envelope of the up-sampled trace (Fig. 1 (c)), where the

[1] The LOPES analysis software is available as open-source at 'http://usg.lofar.org'.