33rd International Cosmic Ray Conference, Rio de Janeiro 2013
The Astroparticle Physics Conference

A Comparison of LOPES Lateral Distributions of the Air-shower Radio Signal with REAS 3.11 and CoREAS Simulations

F.G. Schröder[1], W.D. Apel[1], J.C. Arteaga-Velázquez[2], L. Bähren[3], K. Bekk[1], M. Bertaina[4], P.L. Biermann[5,1], J. Blümer[1,6], H. Bozdog[1], I.M. Brancus[7], E. Cantoni[4,8], A. Chiavassa[4], K. Daumiller[1], V. de Souza[9], F. Di Pierro[4], P. Doll[1], R. Engel[1], H. Falcke[3,10,5], B. Fuchs[6], D. Fuhrmann[11], H. Gemmeke[12], C. Grupen[13], A. Haungs[1], D. Heck[1], J.R. Hörandel[3], A. Horneffer[5], D. Huber[6], T. Huege[1], P.G. Isar[14], K-H. Kampert[11], D. Kang[6], O. Krömer[12], J. Kuijpers[3], K. Link[6], P. Łuczak[15], M. Ludwig[6], H.J. Mathes[1], M. Melissas[6], C. Morello[8], J. Oehlschläger[1], N. Palmieri[6], T. Pierog[1], J. Rautenberg[11], H. Rebel[1], M. Roth[1], C. Rühle[12], A. Saftoiu[7], H. Schieler[1], A. Schmidt[12], O. Sima[16], G. Toma[7], G.C. Trinchero[8], A. Weindl[1], J. Wochele[1], J. Zabierowski[15], J.A. Zensus[5]

[1] *Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), Germany*
[2] *Universidad Michoacana, Instituto de Física y Matemáticas, Morelia, Mexico*
[3] *Department of Astrophysics, Radboud University Nijmegen, The Netherlands*
[4] *Dipartimento di Fisica dell' Università Torino, Italy*
[5] *Max-Planck-Institut für Radioastronomie Bonn, Germany*
[6] *Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie (KIT), Germany*
[7] *National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[8] *Osservatorio Astrofisico di Torino, INAF Torino, Italy*
[9] *Universidade São Paulo, Instituto de Física de São Carlos, Brasil*
[10] *ASTRON, Dwingeloo, The Netherlands*
[11] *Fachbereich Physik, Universität Wuppertal, Germany*
[12] *Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe Institute of Technology (KIT), Germany*
[13] *Fachbereich Physik, Universität Siegen, Germany*
[14] *Institute of Space Science, Bucharest, Romania*
[15] *National Centre for Nuclear Research, Department of Cosmic Ray Physics, Łódź, Poland*
[16] *Department of Physics, University of Bucharest, Bucharest, Romania*

frank.schroeder@kit.edu

Abstract: We compare radio lateral distributions measured with LOPES to REAS 3.11 and CoREAS simulations of the radio emission. These simulation codes describe the measured radio signal significantly better than previous versions of REAS, which did not yet include the refractive index of air. The refractive index changes the coherence conditions of the radio emission. This causes flatter lateral distributions at LOPES distances (up to a few 100 m). In a few events the amplitude even falls towards the shower axis: a behavior which we observe both in simulations and measurements. Generally, REAS 3.11 and CoREAS can reproduce the measured slope of the lateral distributions within the uncertainties. With respect to the absolute amplitude of the radio signal, however, there is a difference between REAS 3.11 and CoREAS. The amplitude predicted by REAS 3.11 is approximately twice as large as the one predicted by CoREAS in frequency range (43 – 74 MHz) of LOPES, and REAS 3.11 is closer to the LOPES measurements. Overall, the comparison shows that the understanding of the radio emission has clearly advanced in the last years. It confirms that in addition to the dominant geomagnetic and the sub-dominant Askaryan effect (charge excess variation) the refractive index of the air plays an important role.

Keywords: LOPES, ultra-high energy cosmic rays, extensive air showers, radio detection, lateral distribution

1 Introduction

A sufficient understanding of the radio emission by air showers is crucial for the use of antenna arrays as cosmic-ray detectors. Although the principles of the radio emission are known for more than 40 years [1], the theoretical understanding at this time was on the level of qualitative features and the order of magnitude of the radio signals. Only recently theoretical models and simulations have improved such that they can make more precise predictions of the radio signal at ground. To test our current level of understanding, we compared two recent simulation codes, REAS 3.11 [2] and CoREAS [3], to LOPES [4] measurements of the radio-lateral distribution. Since neither REAS 3.11 nor CoREAS have free parameters to tune the absolute scale of the radio signal, the comparison is meaningful on a quantitative level.

Both codes include the geomagnetic deflection of particles [5] and the variation of the net charge during the shower development [6] as sources for the radio emission. Moreover, the refractive index of the atmosphere is included which affects these emission processes and the propagation of the radio waves. In particular, the refractive index changes the coherence conditions for the emission and leads to a Cherenkov-like beaming [7, 8]. However, the normal Cherenkov radiation due to the excitation of air molecules is neglected in the tested models. By comparing the simulations to the LOPES measurement, we hence tested whether this model might be a sufficient description of reality.

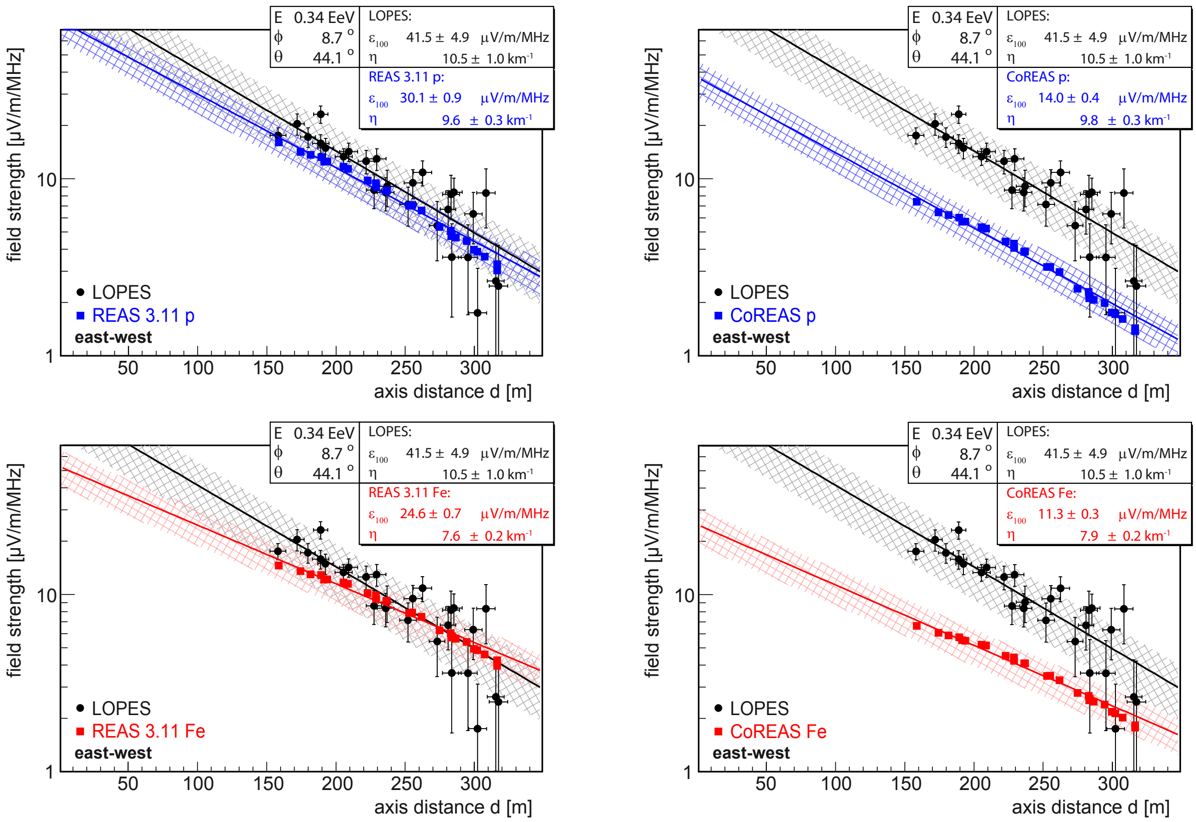

Figure 2: Example event for a LOPES lateral distribution compared to REAS 3.11 simulations (left), and CoREAS simulations (right), for protons (top) and iron nuclei (bottom) as primary particles: amplitudes at the individual antennas and the fit of the exponential LDF. The band around the measurements is the 35 % scale uncertainty for the LOPES amplitude, and the band around the simulations is the 20 % systematic scale uncertainty due to the energy uncertainty of KASCADE-Grande. For reference, also the energy E, the zenith angle θ and the azimuth angle ϕ are given.

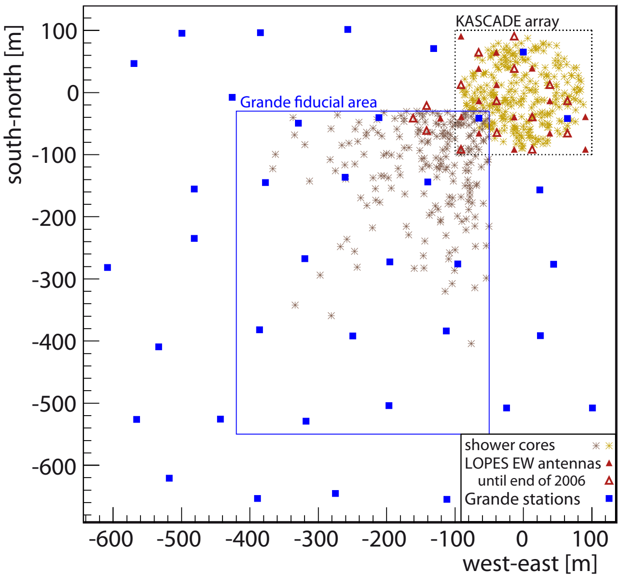

Figure 1: Map of the LOPES array co-located with the KASCADE-Grande experiment, and shower cores of the selected LOPES events.

2 Measurements

Basis for the comparison are 503 events with energies above 10^{17} eV, which have been measured with the east-west aligned LOPES antennas in the effective frequency band of 43 – 74 MHz. The energy and shower geometry of these events is provided by the co-located KASCADE-Grande experiment [9], which also provided the trigger for LOPES. The selected events had to fulfill several quality cuts for both the KASCADE-Grande and the LOPES measurements. E.g., the shower cores have to lie inside of the fiducial area of the KASCADE or the Grande particle detector arrays (Fig. 1), and the radio signal measured by LOPES has to be clearly distinguishable from the background.

To each LOPES event we fitted the following exponential lateral-distribution function (LDF), where $\varepsilon(d)$ is the amplitude of the radio signal at a distance d to the air shower axis:

$$\varepsilon(d) = \varepsilon_{100} \cdot \exp\left(-\eta \cdot (d - 100\,\mathrm{m})\right) \qquad (1)$$

There are two fit parameters: ε_{100}, the amplitude at 100 m, which is sensitive to the primary energy [10, 11], and a slope parameter η, which is sensitive to the longitudinal shower development [12]. Since ε_{100} depends only slightly on the shower development, we tested whether ε_{100} can be reproduced by the simulations on an event-by-event basis. For the lateral slope, we tested only whether the simulations can reproduce η on average, because a comparison for individual events is hampered by shower-to-shower fluctuations. Although the exponential LDF is for several rea-

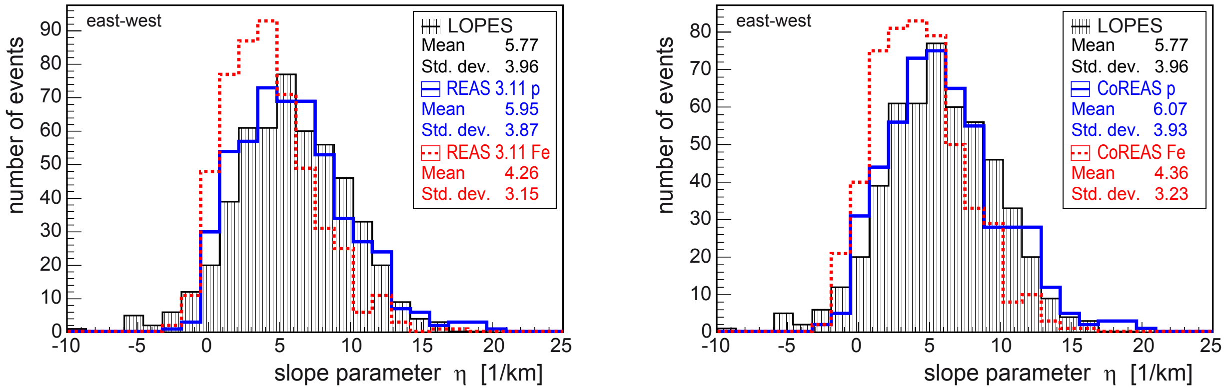

Figure 3: Comparison of the slope parameter η between LOPES measurements and REAS 3.11 (left) and CoREAS (right) for protons and iron nuclei as primary particles.

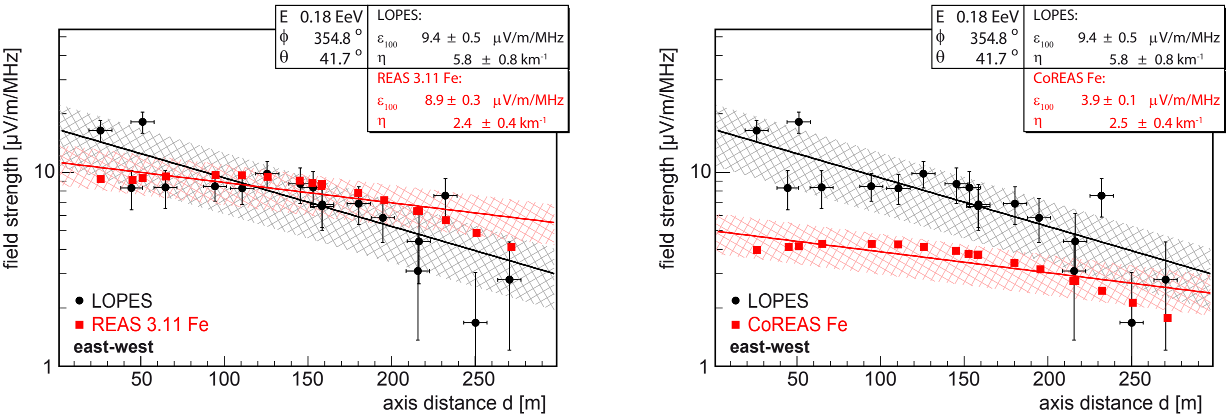

Figure 4: Example for lateral distribution which flattens towards the shower axis.

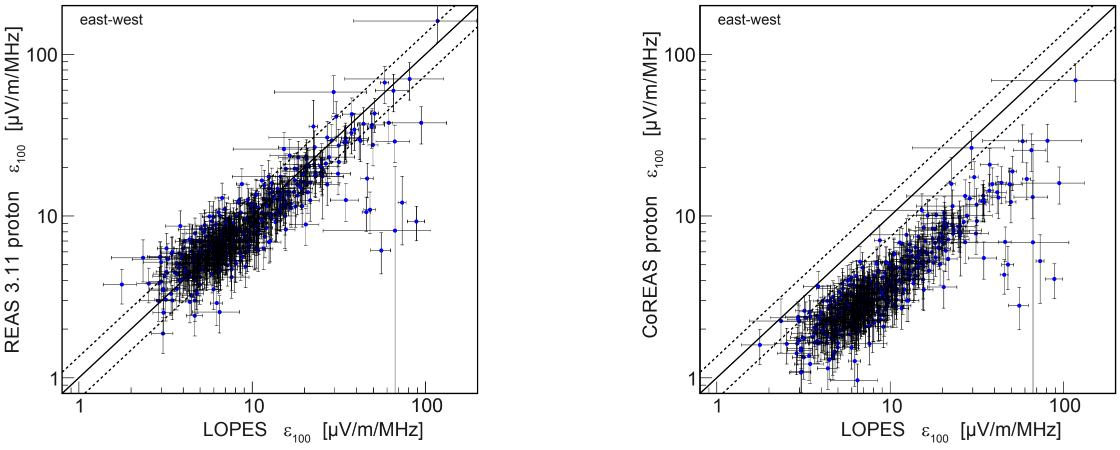

Figure 5: Per event comparison of the amplitude parameter ε_{100} between LOPES measurements and REAS 3.11 (left) and CoREAS (right) for protons as primary particles. The dashed lines indicate the scale uncertainty of ±35 % due to the absolute amplitude calibration of LOPES. For iron nuclei as primary particles, a similar level of agreement is achieved, since ε_{100} is almost independent of the primary mass.

sons a simplification of the true lateral distribution, it is still sufficient to test whether the simulations are compatible to the measurements, because the same LDF is used for both simulations and measurements.

3 Simulations

For each of the 503 LOPES events we made two CORSIKA [13] simulations with QGSJET II [14] using the energy and geometry of the primary particle reconstructed by KASCADE-Grande. Since the type of the initial particles is unknown, we simulated once a proton and once an iron nucleus as primary particle, which we consider to be the extreme cases. With CoREAS, the radio signal is calculated directly during the CORSIKA simulation, while REAS 3.11 calculates the radio emission based on histograms of the particles simulated by CORSIKA. Generally, both codes predict approximately the same shape for the lateral distributions in the distance and frequency range of LOPES, but their amplitudes differ by a factor of approximately two (see Fig. 2 for an example of a simulated event).

4 Results

We observe that both REAS 3.11 and CoREAS can reproduce the shape of the measured lateral distributions - at least within the uncertainties and with respect to the tested features. In particular, the slope parameter η is on average compatible with the LOPES measurements for both simulation codes, provided that the true composition lies anywhere between a pure iron and a pure proton composition (Fig. 3). Already in Ref. [15], we observed a flattening towards the shower axis for some events, which is now reproduced by simulations. In some cases the lateral distribution first rises and than decreases (Fig. 4), which for a few events leads to rising LDFs, i.e., negative values for η. Also this feature is reproduced by both simulation codes, and likely caused by the refractive index of the air, as predicted more than 40 years ago by Allan [7].

For the amplitude we find a difference between REAS 3.11 and CoREAS: the amplitude parameter ε_{100} of the REAS 3.11 simulations is about twice as large as for CoREAS (Fig. 5). The REAS 3.11 simulations agree with the LOPES measurements within a 35 % scale uncertainty of our absolute amplitude calibration [16]. In addition, we have another scale uncertainty of 20 % due to the energy scale of KASCADE-Grande which is used as input for the simulations. If by chance these two scale uncertainties add fully up in the same direction, then also the amplitude predicted by CoREAS could be compatible with the LOPES measurements. The spread of the points in Fig. 5 does not indicate any incompatibility, but is compatible with what we expect due to the individual error bars, with the exception of the few outliers which remain under investigation.

5 Conclusion

REAS 3.11 and CoREAS can describe lateral distributions measured by LOPES much better than any previously tested versions of REAS not yet including the refractive index of air. This indicates that in addition to the geomagnetic emission by the air shower and the Askaryan effect, the refractive index plays an important role, since it changes the coherence conditions. Only the new simulations including the refractive index can describe correctly that in some cases the lateral distribution first rises and then drops with increasing axis distance, as indicated also by measurements of other experiments [17, 18].

While there is little difference in the shape of the lateral distributions predicted by REAS 3.11 and CoREAS in the distance and frequency range of LOPES, there is a yet unexplained difference in the amplitude scale. Although there is a clear offset between the amplitude predicted by CoREAS and the LOPES measurements, we cannot definitely exclude that they are compatible within the experimental scale uncertainties. Still, the difference is meaningful, since neither REAS 3.11 nor CoREAS have free parameters to tune the absolute scale. In future, we can continue our investigations by comparing LOPES measurements also to other simulation codes and results of other radio arrays.

Summarizing, we found no contradiction between the tested simulations and the LOPES measurements, though there is a certain tension in the absolute amplitude. To definitely solve the question of the amplitude scale, measurements by other experiments are needed, which have a higher accuracy in both the calibration of the radio amplitude as well as in the energy scale used as input for the simulations. Nevertheless, the present comparison with LOPES measurements shows a remarkable progress in the understanding of the radio emission by air showers, since for the first time a tested simulation code is compatible with LOPES lateral distributions within the measurement uncertainties.

Acknowledgment:LOPES and KASCADE-Grande have been supported by the German Federal Ministry of Education and Research. KASCADE-Grande is partly supported by the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education and by the Romanian Authority for Scientific Research UEFISCDI (PNII-IDEI grant 271/2011). This research has been supported by grant number VH-NG-413 of the Helmholtz Association. The present study is supported by the Helmholtz Alliance for Astroparticle Physics - HAP funded by the Initiative and Networking Fund of the Helmholtz Association, Germany.

References

[1] H. R. Allan, Prog. in Elem. Part. and Cosmic Ray Phys. **10** (1971) 171.
[2] M. Ludwig, T. Huege, Astropart. Phys. **34** (2011) 438.
[3] T. Huege, *et al.* , Proc. 5th ARENA, Erlangen, Germany, AIP Conf. Proc. **1535** (2013) 128.
[4] H. Falcke, *et al.* (LOPES Collaboration), Nature **435** (2005) 313.
[5] F. D. Kahn, I. Lerche, Proc. Roy. Soc. A **289** (1966) 206.
[6] G. A. Askaryan, Soviet Phys. JETP **14** (1962) 441.
[7] H. R. Allan, Proc. 12th ICRC Tasmania, Australia, **3** (1971) 1108.
[8] K. Werner, K. D. de Vries, O. Scholten, Astropart. Phys. **37** (2012) 5.
[9] W. D. Apel, *et al.* (KASCADE-Grande Collaboration), Nucl. Instr. Meth. A **620** (2010) 202.
[10] F. G. Schröder, *et al.* (LOPES Collaboration), Proc. 5th ARENA, Erlangen, Germany, AIP Conf. Proc. **1535** (2013) 78.
[11] N. Palmieri, *et al.* (LOPES Collaboration), paper 0439, these proceedings.
[12] W. D. Apel, *et al.* (LOPES Collaboration), Phys. Rev. D **85** (2012) 071101(R).
[13] D. Heck, *et al.* , FZKA Report **6019** (1998) Forschungszentrum Karlsruhe.
[14] S. Ostapchenko, Nucl. Phys. B Proc. Suppl. **151** (2006) 147.
[15] W. D. Apel, *et al.* (LOPES Collaboration), Astropart. Phys. **32** (2010) 294.
[16] S. Nehls, *et al.* , Nucl. Instr. Meth. A **589** (2008) 350.
[17] W. E. Hazen, *et al.* , Phys. Rev. Lett. **22** (1969) 35.
[18] A. Nelles, *et al.* (LOFAR), Proc. 5th ARENA, Erlangen, Germany, AIP Conf. Proc. **1535** (2013) 105.