Investigation of the Radio Wavefront of Air Showers with LOPES and REAS3

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Abstract: The wavefront shape of the radio emission by cosmic ray air showers is investigated with LOPES measurements and REAS3 simulations. The results indicate that the radio wavefront is approximately conical, and thus neither planar nor spherical as assumed in earlier analyses. According to the REAS3 simulations, the opening angle of the conical wavefront is correlated with the atmospheric depth of the shower maximum, $X_{\max}$. Thus, radio wavefront measurements provide a method for the estimation of the mass of the primary particle initiating the air shower. The radio wavefront can be reconstructed from pulse arrival time measurements in individual antennas, which has been done with LOPES. LOPES is a digital interferometric antenna array co-located with the KASCADE-Grande particle detector array for air shower measurements at KIT, Germany. Due to the precise time calibration of LOPES, the pulse arrival time measurements are only limited by noise. The radio wavefront of several hundred LOPES events has been reconstructed and compared to REAS3 simulations of the radio emission. The simulations are based on the KASCADE-Grande measurements of each individual air shower and are generally compatible with LOPES measurements. Although at LOPES the $X_{\max}$ precision is limited by noise, the method itself is very promising for future radio arrays in regions with low radio background.

Keywords: Radio Wavefront LOPES REAS

1 Introduction

The radio emission of cosmic ray air showers has meanwhile been detected by numerous experiments (see e.g., references [1] and [2]). Recent research focuses on how radio measurements can contribute to cosmic ray physics, e.g., by improving the measurement precision of air showers with hybrid detectors including digital antenna arrays. Therefore, it is necessary to understand the radio emission of air showers in sufficient detail, and to develop methods how to reconstruct the properties of the air shower from the radio signal – namely the arrival direction, the point of incidence with the ground (shower core), the energy, and the atmospheric depth of the shower maximum $X_{\max}$ which is linked to the mass of the primary particle. This paper will

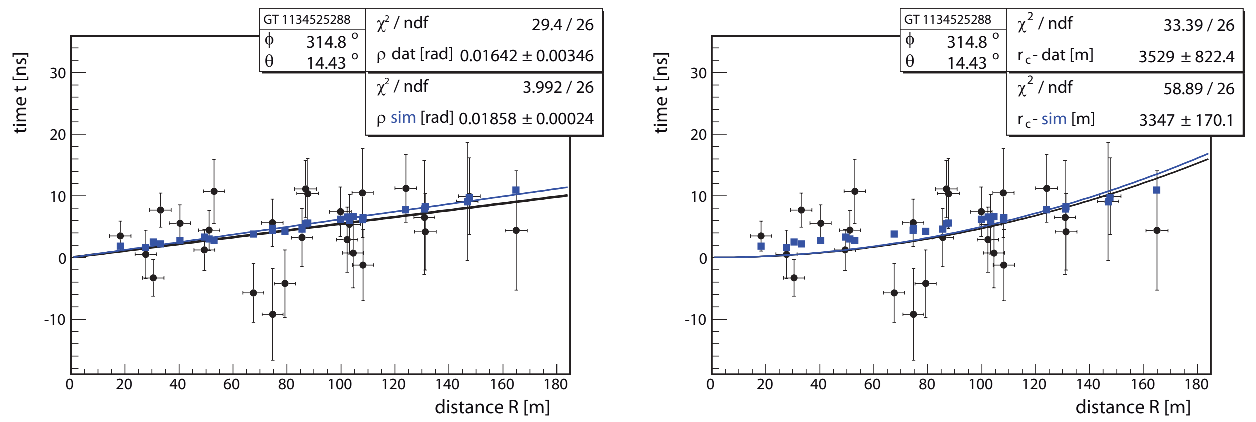

Figure 1: Example event for wavefront reconstruction (LOPES measurement: circles with error bars, REAS3 simulations: squares). Plotted are the pulse arrival times in the individual antennas corrected for the shower geometry ($\widehat{=}\tau_{\mathrm{proj}}$ in figure 2). A plane wavefront would correspond to a horizontal line at $0\,$ns. The same event is plotted twice, fitting a conical wavefront with a cone angle ρ (left) and a spherical wavefront with a curvature radius r_c (left).

follow this line of research by approaching the following two questions: Which is the shape of the radio wavefront and how can we use wavefront measurements for the reconstruction of the air shower properties?

To find answers to these questions, LOPES [3] measurements as well as REAS3 [5] simulations of the radio emission have been used. LOPES is a digital radio interferometer co-located with the KASCADE-Grande experiment [4] at the Karlsruhe Institute of Technology, Germany. LOPES consists of 30 calibrated dipole antennas which are triggered by KASCADE-Grande and digitally measure the radio emission between 40 and $80\,$MHz. More details on LOPES are available in reference [6]. Based on the KASCADE-Grande measurement, two REAS3 simulations have been performed for each LOPES event, for a proton respectively an iron nucleus as primary particle [7].

For the present analysis only east-west aligned LOPES antennas are used, because they feature the best signal-to-noise ratio for most events. For comparison to the measurements, the east-west polarization component of the REAS3 simulations is used and filtered to the effective bandwidth ($43-74\,$MHz) of LOPES with a simple rectangular filter. This is a simplified approach, and a more sophisticated treatment of the simulations considering all detector properties is under development [8].

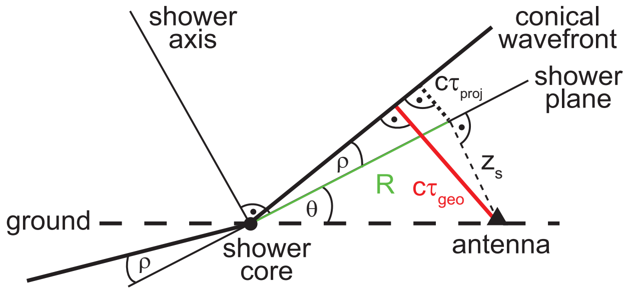

Figure 2: Sketch of conical wavefront with a cone angle ρ: the pulse arrival time in an individual antenna is delayed with respect to a plane wavefront since the geometrical delay τ_{geo} is enlarged. It depends on the lateral distance R of the antenna and the antenna height in shower coordinates z_s. Correcting for the shower geometry, one obtains the projected geometrical delay τ_{proj}. c is the speed of light, θ the zenith angle.

2 Shape of the Radio Wavefront

Reconstructing the shape of the radio wavefront requires a measurement of the shower geometry (shower core and arrival direction) as well as a measurement of the arrival time in each individual antenna. For LOPES events, the shower core is known from the KASCADE-Grande measurement with a high precision of typically $4-7\,$m, and the direction can be reconstructed from both the KASCADE-Grande and the LOPES measurement with a precision better than 1°. The arrival time of the radio wavefront is measured as the time when the instantaneous amplitude is maximum. This time is determined with a Hilbert envelope to the up-sampled trace of the measured electric field strength. The maximum precision is in principle $\sim 1\,$ns given by the time calibration of LOPES [9]. However, the high ambient radio noise level in Karlsruhe decreases the practically achieved precision. For low signal-to-noise ratios the total uncertainty can be up to $\sim 20\,$ns [10].

For the analysis of the wavefront, about 500 events have been selected with the interferometric LOPES standard pipeline. Depending on the specific analysis, at least 167 events survive all quality cuts applied to the radio reconstruction (see reference [12] for details on the selection and analysis method). For each of these events, a spherical and a conical wavefront has been fitted to the LOPES measurements and the corresponding REAS3 simulations (see figures 1 and 2).

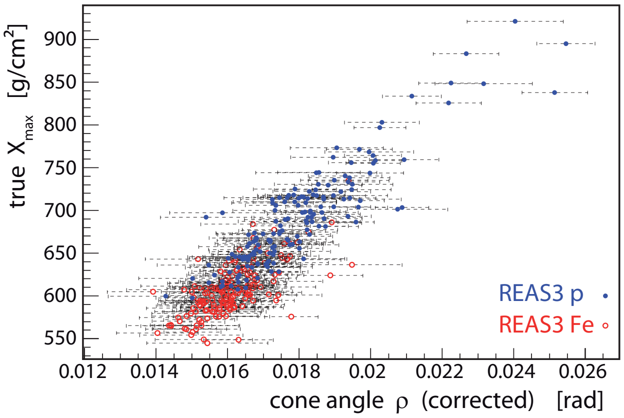

Figure 3: Correlation of the cone angle ρ of REAS3 proton and iron simulations with the true $X_{\max}$, after correcting ρ for its zenith angle dependence.

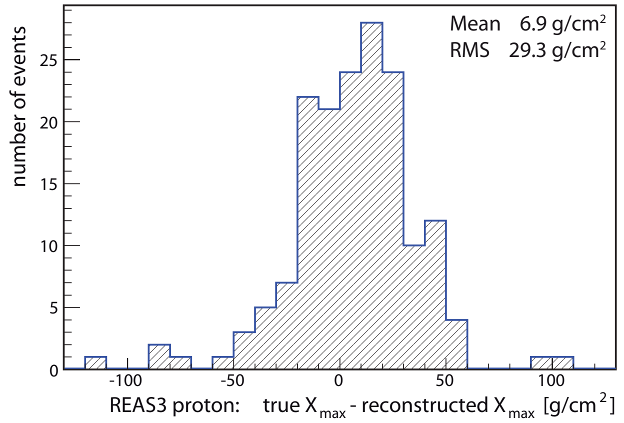

Figure 4: Deviation between the true and reconstructed $X_{\max}$ for the REAS3 proton simulations.

Due to the high ambient noise level, the uncertainties of the individual LOPES events are too large to determine the exact shape of the wavefront. However, on a statistical basis, considering all events of the selection, LOPES measurements clearly disfavor a plane wavefront which was expected from earlier results [11]. As shown in reference [12], the measurements slightly favor a conical versus a spherical wavefront, which is reasonable, since a spherical wavefront corresponds to a static point source. Air showers can better be approximated by a moving radio source which is expected to produce an approximately conical wavefront – like a ship moving on a lake produces an approximately conical bow wave.

Consistent with that expectation, the REAS3 simulations can be fitted significantly better by a conical wavefront than by a spherical wavefront. Furthermore the average cone angle of the simulations (0.0147 ± 0.0024 rad for proton primaries and 0.0132 ± 0.0020 rad for iron primaries) is consistent with the average cone angle of the LOPES measurements (0.0144 ± 0.0055 rad). Thus, we conclude that the radio wavefront is approximately conical, at least within the typical lateral distance of LOPES events ($\lesssim 200\,$m).

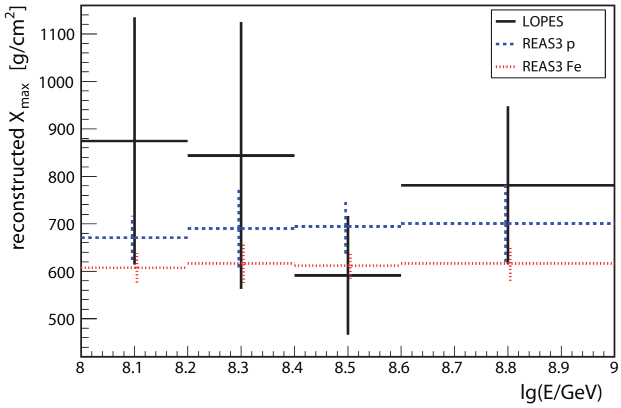

Figure 5: Reconstructed $X_{\max}$ (mean and standard deviation) for the LOPES measurements and the REAS3 proton and iron simulations using the calibration constant c_ρ determined with the simulations.

3 Reconstruction of $X_{\max}$

Since the radio emission of an air shower reflects its longitudinal development, a radio measurement in general ought to be sensitive to $X_{\max}$. Already from principle considerations it can be derived that one of the $X_{\max}$ sensitive radio parameters is the shape of the wavefront (another one is the slope of the lateral distribution [13]). The general $X_{\max}$ sensitivity of the radio wavefront has already been discussed in reference [14], though only for simulations and assuming a curved wavefront. The argument still remains true for a conical wavefront: Showers initiated by light nuclei (e.g., protons) on average have a larger $X_{\max}$ than showers initiated by heavy nuclei (e.g., iron nuclei). Thus, iron showers are expected to have a flatter wavefront (i.e., a smaller cone angle ρ) than proton showers.

For the REAS3 simulations, the cone angle ρ depends indeed on $X_{\max}$, but also on the zenith angle θ, since the distance from the shower maximum to the ground depends on θ. The θ dependence can be almost completely removed dividing ρ by $\cos^{3/2}\theta$. However, the reason for the exponent of $3/2$ is still unclear. After this correction, ρ depends approximately linearly on $X_{\max}$ (see figure 3). This linear correlation can be exploited to reconstruct $X_{\max}$ by measuring the cone angle ρ of the wavefront:

$$X_{\max} = c_\rho \cdot \rho \cos^{-3/2}\theta \quad (1)$$

where c_ρ is a simple constant including the properties of the air shower radio emission in the atmosphere. For the REAS3 simulations made for the LOPES events, $c_\rho \approx 38,000\,$g/cm^2/rad best reproduces the true $X_{\max}$ of the proton and iron simulations. For this choice of c_ρ, the deviation between the mean reconstructed and true $X_{\max}$ is $6.9\,$g/cm^2 for the proton simulations and $-5.8\,$g/cm^2 for the iron simulations. The precision of the $X_{\max}$ reconstruction is estimated by the standard deviation to $29.3\,$g/cm^2 for the proton simulations (see figure 4) and $26.8\,$g/cm^2 for the iron simulations.

For the LOPES measurements, the precision of the $X_{\max}$ reconstruction is significantly worse, since they are limited by noise (while the REAS3 simulations do not contain noise). The precision of the LOPES measurements is estimated by the standard deviation of the reconstructed $X_{\max}$ values to about $200\,\text{g/cm}^2$ (see figure 5).

4 Discussion and Outlook

The present analysis demonstrates the principle feasibility that $X_{\max}$ can be reconstructed by measuring the radio wavefront. The fact that the $X_{\max}$ values reconstructed with LOPES measurements have the expected order of magnitude is an additional hint that the proposed method works not only for simulations but also in practice. However, there are large systematic uncertainties regarding the absolute scale of the constant c_ρ. There are two main possible biases currently under investigation, the first one concerning the method how to measure the cone angle, the second one concerning the REAS3 simulations.

First, the LOPES standard analysis pipeline still implies a spherical wavefront for the interferometric beamforming analysis which precedes the wavefront reconstruction with the pulse arrival time measurements. Alternatively ρ can be determined directly by assuming a conical wavefront for the interferometric beamforming. However, this procedure results in ρ values almost twice as large as the ones determined with the preceding standard pipeline involving the spherical wavefront. Currently, a new tool is developed allowing beamforming for the REAS3 simulations [8], which will help to understand this quantitative difference.

Second, the REAS3 simulations used for this analysis did neglect the refractive index n of the air. Since the refractive index causes a delay of the radio pulse, it will probably enlarge the cone angle ρ of the simulations. Currently, there are efforts to include the effect of the refractive index into REAS [7], which will allow to quantize the effect. The maximum effect has been roughly estimated by assuming that the refractive index at ground ($n \approx 1.0003$) would be constant throughout the whole atmosphere: In this case, ρ could be significantly enlarged by up to a factor of 2.

Fixing the absolute scale of c_ρ cannot only be done by improving the analysis and the simulations, but also by cross-calibration with air shower experiments featuring fluorescence or Cherenkov detectors. Such a cross-calibration with the $X_{\max}$ reconstructed by a fluorescence light measurement can be done by the Auger Engineering Radio Array [15], and a cross-calibration with the Cherenkov emission of air showers will be possible with a future radio extension of the Tunka experiment [16].

5 Conclusion

The evaluation of LOPES measurements and REAS3 simulations shows that the radio wavefront of air showers is approximately conical and not spherical or planar as assumed in previous analyses. The REAS3 simulations experience an almost linear correlation between the cone angle ρ of the wavefront and the atmospheric depth of the shower maximum $X_{\max}$. Although the proportionality constant c_ρ has presently a large uncertainty and might be biased by the analysis method, the presented results offer great prospects for the measurement of air showers: First, a detailed knowledge on the wavefront will improve the angular resolution of digital radio arrays, and second, a measurement of the wavefront allows a reconstruction of the shower core (= apex of the cone) as well as of $X_{\max}$ which is sensitive to the primary mass.

LOPES has successfully shown that a radio measurement of $X_{\max}$ is in principle possible, but its precision is limited by the high ambient noise level, though. Next generation experiments in regions with lower radio background (e.g., Argentina, Antarctica or Siberia) can test the $X_{\max}$ precision achievable by radio measurements. This way radio measurements of air showers might become an interesting alternative to fluorescence and Cherenkov measurements, since radio measurements are not limited to dark moonless nights and thus allow a duty cycle close to $100\,\%$.

References

[1] H.R. Allan, Prog. in Elem. Part. and Cosmic Ray Phys. **10** (1971) 171.

[2] M. Melissas for the Pierre Auger Collaboration, ASTRA **7** (2011) 207. accepted by ASTRA.

[3] H. Falcke et al. (LOPES Collaboration), Nature **435** (2005) 313.

[4] W.-D. Apel et al. (KASCADE-Grande Collaboration), NIM A **620** (2010) 202.

[5] M. Ludwig, T. Huege, Astropp. **34** (2010) 438.

[6] T. Huege et al. (LOPES Collaboration), NIM A (in press), DOI:*10.1016/j.nima.2010.11.081*.

[7] M. Ludwig, T. Huege, these proceedings **#0149**.

[8] K. Link et al. (LOPES Collaboration), these proceedings **#0404**.

[9] F.G. Schröder et al., NIM A **615** (2010) 277.

[10] F.G. Schröder et al. (LOPES Collaboration), NIM A (in press), DOI:*10.1016/j.nima.2010.11.009*.

[11] A. Nigl et al. (LOPES Collaboration), A&A **487** (2008) 781

[12] F.G. Schröder, PhD Thesis, KIT (2011) *http://www.astro.ru.nl/lopes/publications/phd_theses*.

[13] N. Palmieri et al. (LOPES Collaboration), these proceedings **#0309**.

[14] S. Lafebre et al., Astropp. **34** (2010) 12.

[15] J. Kelly for the Pierre Auger Collaboration, these proceedings **#0556**.

[16] S.F. Berezhnev et. al (Tunka Collaboration et al.), these proceedings **#0495**.