Prospects for using geosynchrotron emission arrival times to determine air shower characteristics

S. Lafebre*, H. Falcke*‡, J. Hörandel*, T. Huege†, J. Kuijpers*

*Department of Astrophysics, IMAPP, Radboud University, P.O. Box 9010, 6500GL Nijmegen, The Netherlands
† Institut für Kernphysik, Forschungszentrum Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany
‡ Radio Observatory, Astron, Dwingeloo, P.O. Box 2, 7990AA Dwingeloo, The Netherlands
§Tyrell Inc., 123 Replicant Street, Los Angeles, California 90210–4321

***Abstract*. From CORSIKA and REAS2 simulations of geosynchrotron radio emission in extensive air showers at 10^{17} to 10^{20} eV, we present an empirical relation between the shape of the radiation front and the distance from the observer to the maximum of the air shower. By analyzing the relative arrival times of radio pulses at several radio antennas in an air shower array, this relation may be employed to estimate the depth of maximum of an extensive air shower if its impact position is known, allowing an estimate for the primary particle's species. Vice versa, the relation provides an estimate for the impact position of the shower's core if an external estimate of the depth of maximum is available.**

***Keywords*: Extensive air showers; Geosynchrotron radiation, Shower front curvature**

I. INTRODUCTION

Lately, there has been a surge of efforts toward the detection of extensive air showers by means of the electromagnetic pulse of geosynchrotron emission emitted by the shower particles [1, 2]. This observational technique allows one to look all the way up to the shower maximum, as there is hardly any attenuation of the signal. It has been shown previously [3] that the position of the maximum of inclined showers can be derived from the lateral slope of the electric field strength at ground level. Here, we use delays in the arrival time of the signal at different positions on the ground to estimate the value of the depth of maximum and the impact position of the shower core.

II. METHOD

Electron and positron distributions at different atmospheric depths were obtained from an air shower library [4] produced with CORSIKA simulations [5] and the COAST library [6]. Photon, proton, and iron-initiated air showers at energies of 10^{16} to $10^{20.5}$ eV, incident from zenith angles up to 60° were simulated.

A random sample of $\sim$ 700 simulations from this library was used to calculate the radio signal emitted by these airs showers. The REAS code version 2.58 [7, 8] was used to obtain geosynchrotron pulses associated with each air shower simulation. Antennas were placed on a radial grid at distances of 35 m to 1500 m with intervals of 80–300 m, with one antenna every 45°.

The magnetic field was taken to match values in northwestern Europe at a field strength of 49 μT and a declination of 68° in all simulations. The altitude of the detector array was fixed at 100 m above sea level or a vertical equivalent atmospheric depth of $X \simeq 1024$ g/cm^2.

III. PARAMETERIZATION

One has to compensate for projection effects for showers hitting the detector at an angle. Let θ_0 and ϕ_0 be the zenith and azimuth angle at which the primary particle enters the atmosphere. For a radio antenna a distance d on the ground away from the shower core in the direction δ with respect to the incidence angle ϕ_0, the perpendicular distance r to the shower core is

$$r = d\sqrt{1 - \cos^2\delta \sin^2\theta_0}. \quad (1)$$

The delay τ, converted to length units by multiplying with the speed of light in vacuum, is defined as the lag of the peak strength of the radio signal with respect to the arrival time at the shower impact location. It can be written as

$$\tau = t + d\cos\delta\sin\theta_0, \quad (2)$$

where $t(r, \delta)$ equals the delay caused by the non-planar shape of the shower front expressed in length units. We have included these geometrical compensations in the analysis throughout this paper.

If the particle front is a spherical shell, so will the expected shape of its emitted radio signal be. The delay t can then be written in terms of the distance to the center of the sphere R and the distance from the shower core r as

$$t = \sqrt{R^2 + r^2} - R \approx \frac{r^2}{2R}, \quad (3)$$

where the approximation holds for $r \ll R$. It was shown previously, however, that the assumption of a spherical shower particle front is unrealistic for large air showers [9]. Therefore, the shape of t as a function of r is expected to be different, too.

Analysis of our simulations reveals that, to first order approximation, these delays can be described by the parameterization

$$t = R_1^{1-\alpha-1/\beta} r^\alpha (R + R_0)^{1/\beta}. \quad (4)$$

The distance $R + R_0$ represents the distance from the observer to a virtual source from which the air shower originates. This total distance is subdivided into R_0, representing the distance from the point of origin to the shower maximum, and R, which is the distance from the shower maximum to the observer. R can be converted unambiguously to a value of $X_{\max}$. The value of R_0 is fixed at 6 km. R_1 is a scale parameter, the exponent of which was chosen to match the dimension of t (distance).

The parameters in the above relation do not depend significantly on either primary energy or zenith angle other than through the respective influences on the depth of the shower maximum. This is expected, because the particle distributions responsible for the radiation do not exhibit any dependence on these parameters either [10, 9]. Though the values for R_0, α, and β depend on the orientation of the shower with respect to the magnetic field, the effect of this dependence is much smaller than that of the average statistical variation in showers. Therefore, we will therefore limit geometrical dependence to the angle δ only. A fit to the simulated pulse lags in the region 40 m $< d <$ 750 m yields the following overall best-fit parameters:

$$\begin{aligned} R_1 &= 3.87 + 1.56\cos(2\delta) + 0.56\cos\delta \quad \text{(in km)}, \\ \alpha &= 1.83 + 0.077\cos(2\delta) + 0.018\cos\delta, \\ \beta &= -0.76 + 0.062\cos(2\delta) + 0.028\cos\delta. \end{aligned} \quad (5)$$

The $\cos(2\delta)$ terms in these equations reflect the asymmetries in the east-west versus north-south direction. Note that $\alpha < 2$ for all δ, confirming the non-spherical shape of the wave front.

In a typical array of radio antennas, the delays τ can be determined accurately: using modern equipment, resolutions down to a few ns can be achieved. We can use the delay values to employ our parameterization in two ways: if the position of the shower core is known accurately by scintillator measurements, we can use it to estimate the distance to the shower maximum. If, on the other hand, an estimate for the depth of maximum is available, the position of the shower core can be reconstructed. We will discuss these approaches in detail in the following.

IV. Determining depth of shower maximum

By rearranging (4), we may write

$$R = R_1^{1-\beta+\alpha\beta} \left(\frac{t}{r^\alpha}\right)^\beta - R_0 \quad (6)$$

to reconstruct the distance to the shower maximum. Using this equation, the reconstructed distance to the shower maximum is plotted versus the simulated value in the left panel of Fig. 1. Each point in this plot represents the reconstructed value of R for one shower

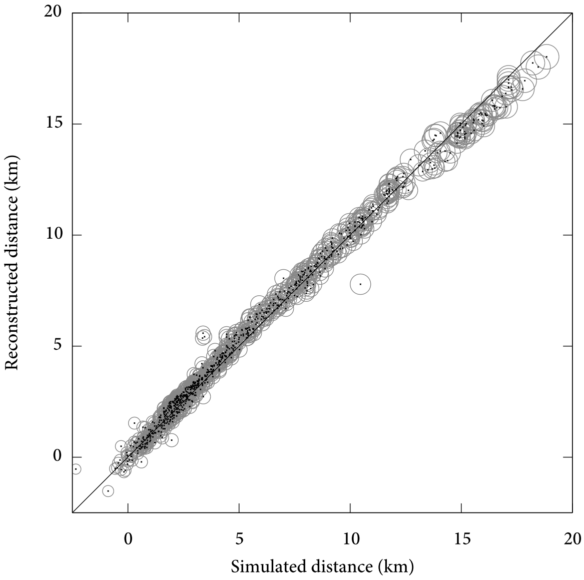

Fig. 1. Scatter plot for $\sim$ 700 showers of various species and energies $E > 10^{17}$ eV of simulated values for R versus the values as reconstructed by the method outlined in the text. Circles around each reconstruction represent error margins of 20 g/cm^2. No error sources were included.

event, obtained by taking a weighted average of the reconstructions from the delays in individual antennas. If the antennas are placed on a regular grid, a weight $\propto r^2$ seems justified to match each time delay to its expected relative error, since $\alpha \simeq 2$. Our simulated array is denser near the shower core, which was compensated for by a total weight for each antenna $\propto r^3$.

The algorithm correctly reconstructs the distance to the shower maximum as simulated, with a standard deviation of 216 m. Note that both simulated and reconstructed events extend to negative distances: showers in this region have a maximum that lies below the observation level of the radio antennas. By design of he algorithm, correct reconstruction of these events is possible only if the downward distance is smaller than R_0.

We have thus far considered ideal circumstances, assuming exact knowledge of the impact angle and position of the shower axis as well as the delay of the radio pulses. A more realistic picture is obtained by introducing error sources in the reconstruction. For a dense array of radio antennas such as LOPES [2] or LOFAR [11], the accuracy in the arrival direction is of the order of 1.0° [12], and a feasible time resolution for determining the maximum pulse height is about 10 ns. We adopt a typical value from the analysis of the KASCADE experiment data of 1 m [13, 14] for the shower core impact location. It is assumed that reconstruction with a dense radio array such as LOFAR will be on a par with this number. All of the above errors are assumed to follow Gaussian distributions. Additionally, we ensure that the signal is sufficiently strong by demanding a certain field strength.

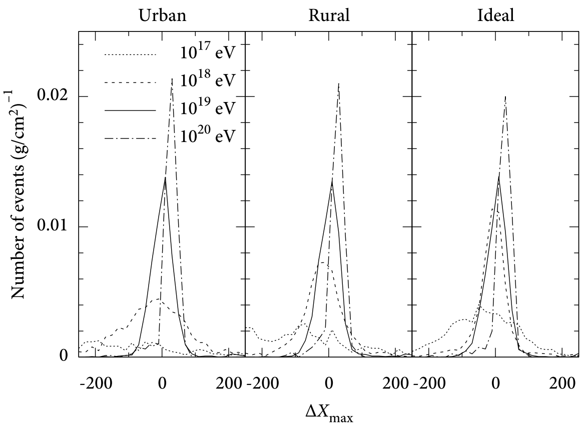

Fig. 2. Distribution of residuals for the reconstruction of the depth of maximum for various primary energies. Plots are shown for urban, rural, and ideal noise level scenarios.

Applying these errors, the correlation is reduced significantly, which is mainly the result of the uncertainty in the arrival direction of the shower. For very inclined showers in particular this can change the expected delay times dramatically. When the accuracy of the shower impact location is reduced, this mostly affects showers for which the maximum lies at a large distance from the observer. When the error is increased to 5 m, for example, hardly any predictions can be made for distances > 10 km.

The distribution of residuals $\Delta X_{\rm max}$ (i.e. the reconstructed minus the simulated value of the depth of maximum) is shown in Fig. 2 for primary energies between 10^{17} and 10^{20} eV. A homogeneous detector sensitivity up to zenith angles $\theta < 60^{\rm o}$ is assumed. Three background noise scenarios are shown: one for an ideal noise level (requiring a field strength $|\mathbf{E}| > 65\ \mu$V/m for determination of t), one for a rural environment ($|\mathbf{E}| > 180\ \mu$V/m), and one corresponding to an urban area ($|\mathbf{E}| > 450\ \mu$V/m) [3].

From this figure, we observe that the reconstruction accuracy for $X_{\rm max}$ decreases rapidly at low energies. This is because low-energy showers do not occur very deep in the atmosphere on average, raising the distance to the shower maximum, especially in slanted showers. This results in a radiation front with less curvature, necessitating delay measurements further away from the impact location to obtain the same level of reconstruction accuracy. The produced field strength, however, is proportional to the primary energy, decreasing the patch size that is sufficiently illuminated. The combined effect is that it is hard to make correct estimations for the depth of maximum of low energy showers, unless an array at high altitude is employed.

Additionally, the behaviour of the reconstruction accuracy curve at 10^{18} eV in the three scenarios highlights the importance of low background interference levels: the root mean square deviation σ from the mean decreases from $\sigma = 113$ g/cm^2 (urban) to 102 g/cm^2 (rural) to 62 g/cm^2 (ideal) at this energy. It is also observed that σ does not vary much for energies of 10^{19} and 10^{20} eV at $\sigma \simeq 40$ g/cm^2 and $\sigma \simeq 30$ g/cm^2, respectively. For comparison, the value for Pierre Auger fluorescence detectors is $\sigma \simeq 25$ g/cm^2 for protons, though perfect geometry reconstruction is assumed in that number [15].

If the maximum available distance to the shower core is very small, as would be the case for an array such as LOPES, the fraction of good reconstructions is reduced dramatically. This makes sense, as the shower front shape can no longer be probed accurately. In particular, if the radius of the array shrinks to less than ~ 500 m, the amount of useful reconstructions is negligible.

V. Determining shower core position

If an estimate for $X_{\rm max}$ (and thus for R) is available, we can employ (4) in an alternative way to estimate values for the distance r of the observer to the shower axis, by writing

$$r = R_1^{1+1/\alpha\beta-1/\alpha} \frac{t^{1/\alpha}}{(R+R_0)^{1/\alpha\beta}}. \qquad (7)$$

In an actual experimental setting, the dependencies of α, β, and R_1 on δ need to be taken into account, for example through an iterative fitting procedure for r and δ. We will only reconstruct the distance to each antenna here, and we will assume the general direction of the core impact position to be known. This decision is motivated by the fact that the effect on the value of r caused by variations in δ is generally small.

In the theoretical limit, the position of the impact location is accurate to within 5 m distance. When similar error sources as in the previous section are introduced, this distance is increased to 15 m or so. In both theoretical and smudged case, there is a substantial difference in reconstruction accuracy between the direction perpendicular to the arrival direction and parallel to it. This results directly from the uncertainty imposed on θ_0: even a small deviation of the zenith angle will make a noticeable difference in the obtained value for t from (2).

Analogous to the situation in the previous section, the average error increases drastically when the radius of the array is smaller than 500 m. The error does not increase significantly, however, when the minimum distance is set to 300 m. This is slightly counterintuitive, but it is again related to the accurate probing of the shower front shape. Of course, the requirement remains that the arrival delay at the impact location is known to 10 ns or so.

VI. Discussion

In this paper, we have worked with the relative delays of geosynchrotron emission from extensive air showers from the raw, unfiltered pulse shape. In real experiments, however, the antennas used are bandwidth-limited, which will be reflected in the shape of the measured pulse. The effect on the arrival time of the pulse is negligible for close antennas ($r < 300$ m), but for remote antennas it will become important, as the pulse is much broader in these regions. In particular, we expect this to become troublesome for antennas which clip frequencies below ~ 40 MHz.

Another effect that has not been investigated is that of the observer's altitude: in our simulations, this height was fixed at 100 m above sea level. We do not anticipate a significant change of the parameterization or its parameters, however, because the description is valid independent of zenith angle. Changing this angle is comparable to varying the observer's altitude.

Though a deviation from a planar wave is indeed observed in LOPES measurements [2], at only 200 m this array is too small to benefit from the theoretical knowledge of the shape of the radio pulse front. There are currently two other experiments under construction, however, that could make use of the technique outlined in this work. One of these is the initiative in which radio antennas inside the Pierre Auger observatory [16] will be erected [17]. Such an array could use the method in Sect. V to increase the accuracy of the estimated core impact position, since its reconstruction error for the surface detectors is in excess of 100 m. A precise estimate for $X_{\max}$ would have to be provided by fluorescence detectors. The planned spacing of radio antennas is > 500 m, which would allow an accuracy in the reconstruction of around 30 m if the core lies within the radio array.

Another possible experiment is the LOFAR telescope [11], comprising a dense array of approximately 2 km in diameter, with groups of 48 radio antennas every few hundred meters. Its size and spacing make this setup ideally suited to determine $X_{\max}$ using the method outlined in Sect. IV.

VII. CONCLUSION

We have derived an empirical relation between the relative delay of the radio pulse emitted by the air shower front and the atmospheric depth of the shower maximum through simulations. By analysis of the radio pulse arrival delays in radio antennas in an array of low-frequency radio antennas, this relation can be used to estimate the depth-of-maximum if the impact position is known or vice versa.

We have confirmed that both methods work with no information other than radio signal delays used in the reconstruction. When the algorithm is tested under realistic conditions, however, the accuracy of the method is reduced. In the case of determining the shower maximum, reconstruction down to a useful confidence level is possible only for shower maxima up to ~ 7 km away, and only if the shower core impact position is known down to a few meters. When the parameterization is used to derive this position, the critical quantity is the accuracy in the zenith angle of the shower, which needs to be significantly less than a degree to reconstruct the shower impact location to an accuracy of 10 m at high inclinations up to 60°.

VIII. ACKNOWLEDGEMENTS

This work is part of the research programme of the 'Stichting voor Fundamenteel Onderzoek der Materie (FOM)', which is financially supported by the 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)'. T. Huege was supported by grant number VH-NG-413 of the Helmholtz Association.

REFERENCES

[1] Huege, T. & Falcke, H. 2003, Astronomy & Astrophysics, 412, 19

[2] Falcke, H. et al. 2005, Nature, 435, 313

[3] Huege, T., Ulrich, R., & Engel, R. 2008, Astropart. Phys., 30, 96

[4] Lafebre, S., Huege, T., Falcke, H., & Kuijpers, J. 2007, in Proc. 30th Int. Cosmic Ray Conf.

[5] Heck, D., Knapp, J., et al. 1998, CORSIKA: A Monte Carlo code to simulate extensive air showers, Tech. Rep. 6019, Forschungszentrum Karlsruhe

[6] Ulrich, R. 2007, http://www-ik.fzk.de/~rulrich/coast/

[7] Huege, T. & Falcke, H. 2005, Astronomy & Astrophysics, 430, 779

[8] Huege, T., Ulrich, R., & Engel, R. 2007, Astropart. Phys., 27, 392

[9] Lafebre, S., Engel, R., Falcke, H., et al. 2009, Astroparticle Physics, 31, 243

[10] Nerling, F., Blümer, J., Engel, R., & Risse, M. 2006, Astropart. Phys., 24, 421

[11] Falcke, H. D., van Haarlem, M. P., de Bruyn, A. G., et al. 2007, Highlights of Astronomy, 14, 386

[12] Nigl, A., Apel, W. D., Arteaga, J. C., et al. 2008, A&A, 487, 781

[13] Antoni, T., Apel, W. D., Badea, A. F., et al. 2004, ApJ, 608, 865

[14] Glasstetter, R., Antoni, T., Apel, W. D., et al. 2005, in Proc. 29th Int. Cosmic Ray Conf., Vol. 6, 293

[15] Ewers, A., Geenen, H., Kampert, K.-H., et al. 2005, in Proc. 29th Int. Cosmic Ray Conf., Vol. 7, 115

[16] Abraham, J., Aglietta, M., Aguirre, I. C., et al. 2004, Nuclear Instruments and Methods in Physics Research A, 523, 50

[17] Van den Berg, A. M. & et al. 2007, in Proc. 30th Int. Cosmic Ray Conf.