Radio Emission of Extensive Air Showers during Thunderstorms

M. Ender[†], W.D. Apel[*], J.C. Arteaga[†,xiv], T. Asch[‡], F. Badea[*], L. Bähren[§], K. Bekk[*], M. Bertaina[¶], P.L. Biermann[||], J. Blümer[*,†], H. Bozdog[*] I.M. Brancus[**], M. Brüggemann[††], P. Buchholz[††], S. Buitink[§], E. Cantoni[¶,‡‡], A. Chiavassa[¶], F. Cossavella[†], K. Daumiller[*], V. de Souza[†,xv], F. Di Pierro[¶], P. Doll[*], R. Engel[*], H. Falcke[§,x], M. Finger[*], D. Fuhrmann[xi], H. Gemmeke[‡], P.L. Ghia[‡‡], R. Glasstetter[xi], C. Grupen[††], A. Haungs[*], D. Heck[*], J.R. Hörandel[§], A. Horneffer[§], T. Huege[*], P.G. Isar[*], K.-H. Kampert[xi], D. Kang[†], D. Kickelbick[††], Y. Kolotaev[††], O. Krömer[‡], J. Kuijpers[§], S. Lafebre[§], P. Łuczak[xii], M. Ludwig[†], H.J. Mathes[*], H.J. Mayer[*], M. Melissas[†], B. Mitrica[**], C. Morello[‡‡], G. Navarra[¶], S. Nehls[*], A. Nigl[§], J. Oehlschläger[*], S. Over[††], N. Palmieri[†], M. Petcu[**], T. Pierog[*], J. Rautenberg[xi], H. Rebel[*], M. Roth[*], A. Saftoiu[**], H. Schieler[*], A. Schmidt[‡], F. Schröder[*], O. Sima[xiii], K. Singh[§,xvi], G. Toma[**], G.C. Trinchero[‡‡], H. Ulrich[*], W. Walkowiak[††], A. Weindl[*], J. Wochele[*], M. Wommer[*], J. Zabierowski[xii], J.A. Zensus[||]

[*]*Institut für Kernphysik, Forschungszentrum Karlsruhe, Germany*
[†]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[‡]*IPE, Forschungszentrum Karlsruhe, Germany*
[§]*Department of Astrophysics, Radboud University Nijmegen, The Netherlands*
[¶]*Dipartimento di Fisica Generale dell' Universita Torino, Italy*
[||]*Max-Planck-Institut für Radioastronomie Bonn, Germany*
[**]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[††]*Fachbereich Physik, Universität Siegen, Germany*
[‡‡]*Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy*
[x]*ASTRON, Dwingeloo, The Netherlands*
[xi]*Fachbereich Physik, Universität Wuppertal, Germany*
[xii]*Soltan Institute for Nuclear Studies, Lodz, Poland*
[xiii]*Department of Physics, University of Bucharest, Bucharest, Romania*
[xiv]*now at: Universidad Michoacana, Morelia, Mexico*
[xv]*now at: Universidade de São Paulo, Instituto de Fîsica de São Carlos, Brasil*
[xvi]*now at: KVI, University of Groningen, The Netherlands*

***Abstract*. The deflection of relativistic, charged particles in high energy air showers due to the geomagnetic field leads to a coherent emission of radio pulses. This process can be described by the geosynchrotron model. In particular during thunderstorms, there are additional strong electric fields in the atmosphere which can lead to further accelerations of the charged particles and thus can have influence on shape and strength of the radio pulse. To get a reliable energy reconstruction based on the measured radio signal it is mandatory to understand such effects. Furthermore, lightning strikes are a source of broadband radio emissions that are visible over very long distances. This could also cause difficulties in detecting the much lower signal of air showers.**

The influences of strong electric fields are currently explored with the LOPES experiment in Karlsruhe, Germany. LOPES measures in the frequency range between 40 and 80 MHz and is operated in coincidence with KASCADE-Grande. Additionally, meteorological data as well as the vertical electrical field near the ground are monitored.

***Keywords*: LOPES, thunderstorm, lightning**

I. INTRODUCTION

Radio detection of air showers is an upcoming new technique to measure the properties of very high energy cosmic rays. Compared to fluorescence or air Čerenkov measurements a much higher duty cycle is achieved. Only during strong and nearby thunderstorms, the measurements are distinctively different compared to fair weather conditions. To determine whether a measurement is reliable or not, it is very important to understand the processes happening in the atmosphere during a thunderstorm and how they affect the radio emission in air showers.

The radio emission of extensive air showers in the energy range from $5 \cdot 10^{16}$ to 10^{18} eV is studied with the LOPES experiment [4][6]. It has been built as a LOFAR prototype station and is located at the site of the KASCADE-Grande experiment in Karlsruhe, Germany [1][7]. LOPES consists of thirty inverted v-shaped dipole antennas, half of them oriented to measure the east-west and half of them the north-south polarization. The frequency is limited to a range between 40 and 80 MHz.

For the purpose of studying the effects of thunderstorms on the radio emission of air showers, an electric

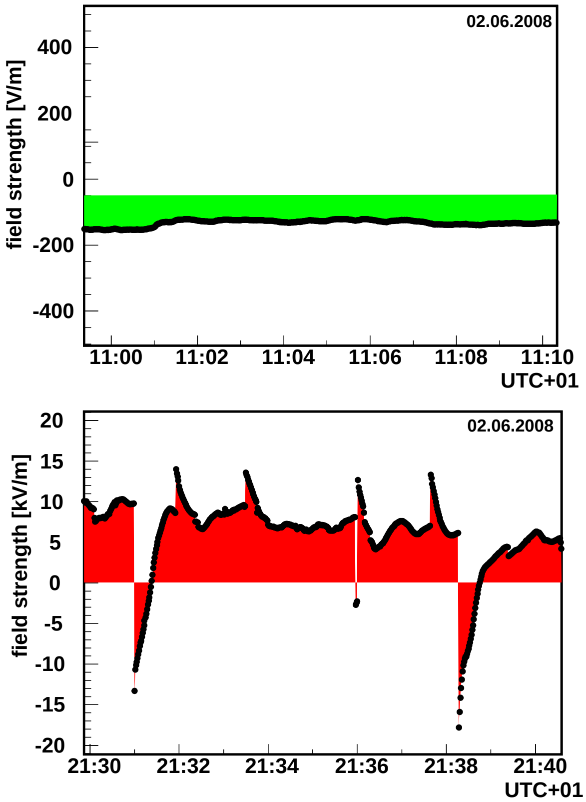

Fig. 1: Vertical component of the static electric field near the surface during fair weather conditions (upper figure) and during a thunderstorm (lower figure). Please note the different scales of the field strength. The lightning discharges are clearly visible as discontinuities. Each plot shows ten minutes of the atmospheric electric field.

field mill has been set up at the LOPES array. It measures the vertical component of the static electric field near the ground once a second. With this information a reliable automatic detection of thunderstorms is possible [8].

II. Monitoring the atmospheric electric field

During fair weather conditions, the static electric field near the surface varies only slowly between -100 and $-200\ \mathrm{Vm}^{-1}$. When rain clouds move overhead, the amplitudes become bigger but the changes are still smooth. During thunderstorms this is completely different. The field strength can reach values up to $\pm 20\ \mathrm{kVm}^{-1}$ on ground level. Additionally, discharges are visible as discontinuities that can even invert the polarity of the field. Together, these are reliable indicators to automatically detect thunderstorms [9].

Whenever a thunderstorm is detected (figure 1), LOPES is switched to a special data acquisition mode that records an eight times larger data block. Instead of the usual 0.82 ms, about 6.55 ms of data are taken, while the pre-trigger time of 0.41 ms remains the same. This strongly increases the probability to find in addition to the shower signal a signal from lightnings inside the recorded trace.

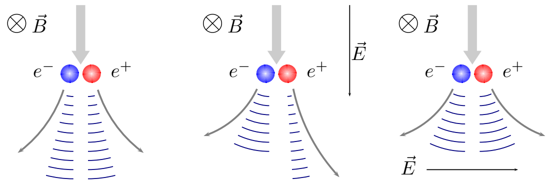

Fig. 2: Additional electric fields lead to different trajectories and therefore different radio emission of the charged particles.

III. Influence of strong electric fields on the radio emission of EAS

The main component of the radio emission from an extensive air shower can be described by the geosynchrotron model. The geomagnetic field causes a Lorentz force which leads to a coherent emission of synchrotron radiation.

The electric fields inside thunderstorm clouds, especially within the convective region, can reach peak values up to $100\ \mathrm{kVm}^{-1}$. This leads to additional forces on the electrons and positrons that are added to the forces caused by the geomagnetic field. Depending on the direction of the electric field, this can lead to an amplification or a weakening of the radio emission [3] as illustrated in figure 2.

Figure 3 shows two air shower events initiated by primary cosmic rays of very similar energy and direction but with different radio signals. This is an example where such an amplification during a thunderstorm has occurred. The upper event was recorded during normal weather conditions and shows no signal from the air shower which would be expected at $-1.8\ \mu$s, as would be expected for the relative low estimated primary energy of $5.4 \cdot 10^{16}$ eV. The incoherent signal of some antennas after $-1.75\ \mu$s is noise caused by the particle detectors of KASCADE. The direction of this event has been reconstructed from KASCADE data to $\phi = 110.4\,°$ and $\theta = 31.5\,°$, where ϕ is the azimuth of the shower direction and θ the zenith angle.

The lower figure shows an event with a very similar geometry of $\phi = 110.4\,°$ and $\theta = 32.1\,°$ and even a slightly lower estimated energy of $4.3 \cdot 10^{16}$ eV. Also the average distance of the antennas to the shower core is similar. Nevertheless, the event shows a strong and coherent radio pulse at -1.8 μs, which is not expected at that energy. This can be explained by amplification of the radiosignal in a thundercloud.

Unfortunately, due to low event statistics during thunderstorm conditions only for a few events such a twin can be found. During 2007 and 2008, about 3400 events have been recorded during thunderstorms, which also passed the quality checks for a reliable reconstruction. That corresponds to approximately two days of data taking in thunderstorm mode.

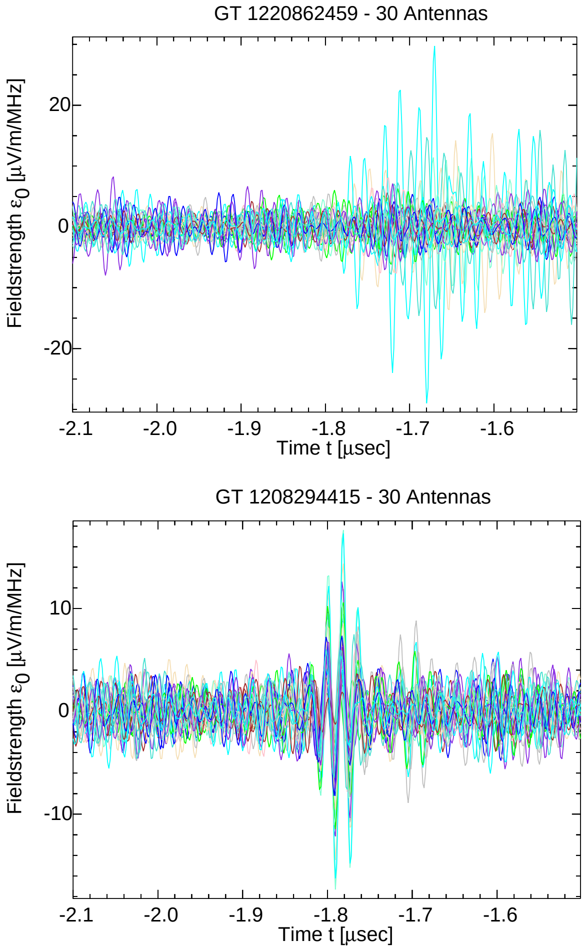

Fig. 3: The upper figure shows an event with no coherent signal from the air shower. In the lower figure which shows an event with similar geometry and even slightly lower estimated energy, there is a clearly visible coherent pulse at -1.8 μs.

Due to the fact that the trigger threshold for LOPES is lower than the detection threshold of about $5 \cdot 10^{16}$ eV and the steep spectrum, only a small fraction of all triggered events shows a radio pulse. The fraction of events with a ratio of peak value of the formed cross-correlation beam to the rms value of the beamformed data larger than a certain value is here defined as detection efficiency.

Only a fraction of $(0.96 \pm 0.12) \cdot 10^{-2}$ of the events recorded during fair weather conditions has a detected coherent signal. During thunderstorms the situation changes. Then a fraction of $(2.39 \pm 0.27) \cdot 10^{-2}$ has a detected coherent signal. That corresponds to 81 air shower events with a cross-correlation beam above threshold, recorded during thunderstorm conditions.

This shows that a significant fraction of the events during thunderstorms is affected by the atmospheric conditions. The influence of atmospheric electric fields with smaller peak amplitudes as they can occur in rain clouds has still to be studied more carefully. At the moment it does not seem as if there is a big effect [3]. The only case might be rain clouds with extraordinary strong field. But they are even less frequent than thunderstorms. Thus, the number of events within such periods is quite low.

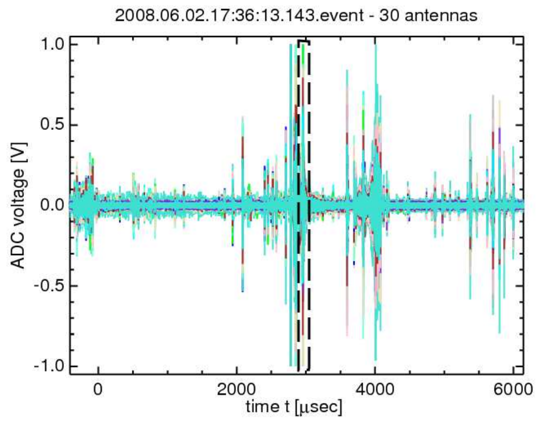

Fig. 4: Example of a thunderstorm event with strong additional signals caused by lightning. An EAS signal would be visible at time zero with an amplitude less than 0.1 V. The dashed frame marks the region which is used for the skymap shown in figure 5.

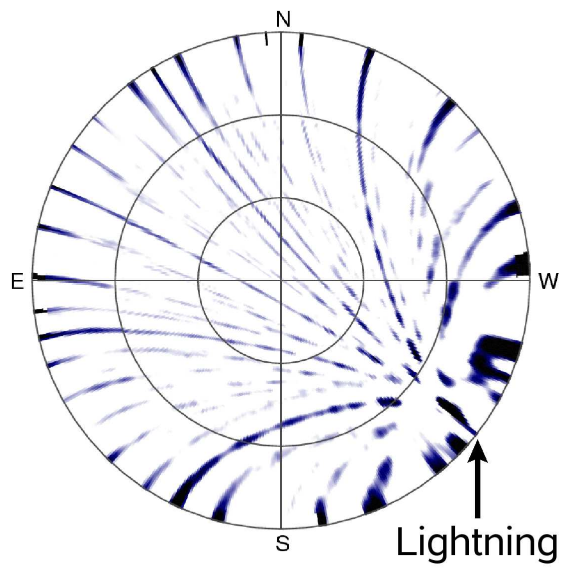

Fig. 5: The figure shows a skymap of the cross-correlation beam of the event shown in figure 4. It shows the whole sky with zenith in the center and horizon at the edge. The strong lightning signal in south-west is the discharge region and the grating lobes of the antenna array cause the signals covering the whole sky.

IV. Background signals caused by lightnings

The strong currents during lightning strikes cause strong broadband radio signals that are detectable over very large distances. Depending on the distance and the kind of the discharge, the time structure of the

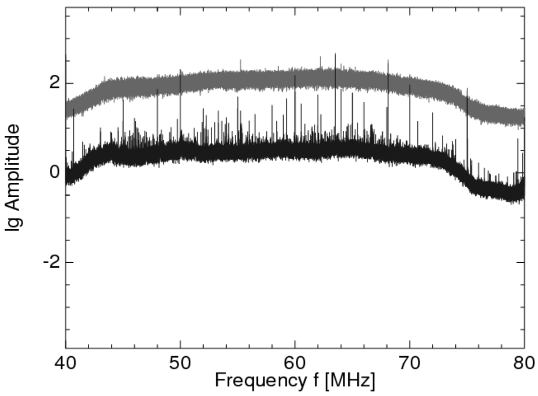

Fig. 6: The figure shows a comparison between the usual background spectrum (black) and the spectrum with a lightning signal inside (grey). The power inside the LOPES frequency range is approximately a hundred times higher than in the usual case. The sine waves emitted by a beacon, that are needed for phase calibration, at 63.5 and 68.1 MHz are almost covered by the lightning signal.

signal varies. Very short and strong pulses from located discharges inside the clouds in altitudes between 5 and 20 km, as described as narrow bipolar pulses by A. V. Gurevich [5]. For large scale applications of the radio detection technique it is aspired to trigger on the radio pulse directly. This self-trigger technique has been developed with LOPES-STAR [2]. The trigger decision is based on various conditions including the shape of the observed pulse. It might be important to know the properties of the short pulses originating from thunderstorms to avoid wrong trigger decisions.

Discharges between clouds or from cloud to ground are the origin of longer lasting signals (figure 4). The lightning signal in all antennas can be used for a beamforming to localize the origin of the lightning (figure 5). Due to the grating lobes of the antenna array, the lightning signal which originates near the horizon causes additional signals all over the sky. With a higher number of time-frames the evolution of the discharge can be watched.

Furthermore there is a beacon, mounted at the roof of a nearby building that is emitting two sine waves at 63.5 and 68.1 MHz as a reference for the timing. The lightning signal can be stronger these sine waves, as shown in figure 6, that are used for the phase calibration. The phase calibration gives a precise relative timing between the recorded traces, which is necessary for beamforming. Therefore a good signal to noise ratio is necessary at these frequencies. Thus the background produced by lightnings can make it impossible to analyse a specific air shower event.

The very sensitive electronics that are necessary in order to measure the low radio signal from air showers is often saturated by lightning signals. In these cases the events cannot be used for the standard analysis.

V. Conclusion

The reconstructed energy of an air shower based on radio measurements is influenced by electric fields during thunderstorms only, and not at normal weather conditions. This leads to a larger fraction of events with a detected coherent signal. To obtain reliable air shower information from the measured radio signal it is mandatory to monitor the electric field of the atmosphere and thus record the signatures of thunderstorms.

Another possibility to prove whether an event has been influenced by additional electric fields or not, is the polarization of the recorded signal. An aberration of the measured polarization from the theoretically expected polarization is a considerable hint to a changed emission process. For this analysis the yet obtained statistics are still too low. There are hardly any events taken in thunderstorm mode that show a visible pulse in both polarization channels.

The exact origin of the radio signal observed during thunderstorms is not yet known for all of the different shapes. Nevertheless it is evident that they form a strong noise background that sometimes causes a failure of the analysis software.

References

[1] T. Antoni et al. - KASCADE Collaboration, NIM A **513**, 429 (2003).
[2] T. Asch, FZKA report **7459**, Forschungszentrum Karlsruhe (2009)
[3] S. Buitink et al. - LOPES Collaboration, A&A, 467, 385, 2007
[4] H. Falcke et al. - LOPES Collaboration, Nature **435**, 313 (2005).
[5] A. V. Gurevich, K. P. Zybin, Physics Letters A 329 (2004) 341-347, 2004
[6] A. Haungs et al. - LOPES Collaboration, NIM A, in press (2009), arXiv:0811.1919.
[7] G. Navarra et al. - KASCADE-Grande Collaboration, NIM A **518**, 207 (2004).
[8] S. Nehls, FZKA report **7440**, Forschungszentrum Karlsruhe (2008).
[9] V. Rakov, M. Uman, ISBN 0-521-03541-4, CAMBRIDGE Univ. Press, 2005