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Detection of radio pulses from extensive air showers

A. Horneffer[a,b], W.D. Apel[c], F. Badea[c], L. Bähren[d], K. Bekk[c], A. Bercuci[e], M. Bertaina[f], P.L. Biermann[b], J. Blümer[c,g], H. Bozdog[c], I.M. Brancus[e], S. Buitink[a], M. Brüggemann[h], P. Buchholz[h], H. Butcher[d], A. Chiavassa[f], K. Daumiller[c], A.G. de Bruyn[d], C.M. de Vos[d], F. Di Pierro[f], P. Doll[c], R. Engel[c], H. Falcke[a,b,d], H. Gemmeke[i], P.L. Ghia[j], R. Glasstetter[k], C. Grupen[h], A. Haungs[c], D. Heck[c], J.R. Hörandel[g], T. Huege[b,c], K.-H. Kampert[k], G.W. Kant[d], U. Klein[l], Y. Kolotaev[h], Y. Koopman[d], O. Krömer[i], J. Kuijpers[a], S. Lafebre[a], G. Maier[c], H.J. Mathes[c], H.J. Mayer[c], J. Milke[c], B. Mitrica[e], C. Morello[j], G. Navarra[f], S. Nehls[c], A. Nigl[a], R. Obenland[c], J. Oehlschläger[c], S. Ostapchenko[c], S. Over[h], H.J. Pepping[d], M. Petcu[e], J. Petrovic[a], T. Pierog[c], S. Plewnia[c], H. Rebel[c], A. Risse[m], M. Roth[g], H. Schieler[c], G. Schoonderbeek[d] O. Sima[e], M. Stümpert[g], G. Toma[e], G.C. Trinchero[j], H. Ulrich[c], S. Valchierotti[f], J. van Buren[c], W. van Capellen[d], W. Walkowiak[h], A. Weindl[c], S. Wijnholds[d], J. Wochele[c], J. Zabierowski[m], J.A. Zensus[b] and D. Zimmermann[h]

(a) Department of Astrophysics, Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands
(b) Max-Planck-Institut für Radioastronomie, 53010 Bonn, Germany
(c) Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
(d) ASTRON, 7990 AA Dwingeloo, The Netherlands
(e) National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
(f) Dipartimento di Fisica Generale dell'Università, 10125 Torino, Italy
(g) Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany
(h) Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany
(i) Inst. Prozessdatenverarbeitung und Elektronik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
(j) Istituto di Fisica dello Spazio Interplanetario, INAF, 10133 Torino, Italy
(k) Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
(l) Radioastronomisches Institut der Universität Bonn, 53121 Bonn, Germany
(m) Soltan Institute for Nuclear Studies, 90950 Lodz, Poland
Presenter: Andreas Horneffer (A.Horneffer@astro.ru.nl), ger-horneffer-A-abs1-he13-oral

LOPES is a LOFAR Prototype Station aimed to measure radio pulses from air showers. LOFAR is a new digital radio interferometer, that is being built in The Netherlands. Working in the frequency range of 10-210 MHz LOFAR is well suited to measure the radio emission of air showers. LOPES is set up at the site of the KASCADE-Grande air shower array. It samples the radio signal in the band of 40-80 MHz with high bandwidth ADCs and stores the whole waveform information in digital form. This allows us to suppress the radio interference at this site with digital filtering and beam forming. Thus LOPES is able to continuously measure radio pulses from air showers. The data taken with the first phase of LOPES from January to September 2004 has been analysed in conjunction with air shower parameters from the KASCADE array. Clear correlations between the radio pulse height and the shower size and the angle to the geomagnetic field have been found. The data supports the theory that the emission is coherent synchrotron radiation in the geomagnetic field.

1. Introduction

A standard method to observe cosmic rays is to measure the secondary particles of an air shower with an array of particle detectors on the ground. Very useful information for the determination of primary particle energy and type can be obtained by observing the air shower as it evolves. So far this is only done by observing optical emission like fluorescence light. This requires clear, dark nights and limits the duty cycle to ca. 10%.

Measuring radio emission from air showers can be an alternative method for such observations, providing a much better efficiency. Radio emission from cosmic ray air showers were discovered for the first time by Jelly [5] at 44 MHz. The results were soon verified and in the late 1960's emission from 2 MHz up to 520 MHz were found. In the following years these activities ceased due to difficulty with radio interference, uncertainty about the interpretation of the results, and the success of other methods. The known radio properties of extensive air showers were summarised in a review by Allan [1]. The main result of this review can be summarised by an approximate formula for the received voltage per unit bandwidth:

$$\epsilon_\nu = 20 \left(\frac{\mathrm{E_p}}{10^{17}\mathrm{eV}}\right) \sin\alpha \cos\theta \exp\left(\frac{-\mathrm{R}}{\mathrm{R_0}(\nu,\theta)}\right) \left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right] \quad (1)$$

Here $\mathrm{E_p}$ is the primary particle energy, α is the angle to the geomagnetic field, θ is the zenith angle, R is the distance to the shower axis, $\mathrm{R_0}$ is around 110 m at 55 MHz, and ν is the observing frequency.

Recent theoretical studies, modelling the radio emission from air showers as coherent synchrotron radiation in the earth's magnetic field, have been able to reproduce the existing data to a good degree (see [4]).

2. LOFAR and LOPES

LOFAR is a new attempt to revitalise astrophysical research at 10-210 MHz with the means of modern information technology. LOPES is a "**LO**FAR **P**rototyp**e** **S**tation" tailored for the detection of air showers. The basic idea is to build an array of simple, quasi-omnidirectional dipole antennas in which the received waves are digitised and sent to a central computer. A new feature of this design is the possibility to store the entire data stream for a certain period of time. If one detects a transient phenomenon like an air shower one can then retrospectively form a beam in the desired direction. A related experiment, with a similar technology, uses part of the Nançay decametric array [6].

LOPES is set up at the site of KASCADE-Grande [7]. The data from a well tested air shower experiment not only allows us to calibrate the radio data with other air shower parameters. It also provides us with starting points for the air shower reconstruction. LOPES operates in the frequency range of 40 to 80 MHz and does direct sampling of the radio signal. Its short dipole antennas are currently set up to measure the east-west polarised component of the signal. After each trigger 0.82 ms worth of raw data are read out of the memory buffer and stored on hard disk.

3. Processing of Radio Data

The first step of the analysis is to Fourier transform the data into frequency space. Here, narrow-band interference shows as spikes in the spectrum and can be flagged. Then a beam is formed into the direction of the air shower, as given by KASCADE-Grande. For this the data for each antenna has to be shifted in time. Short time pulses that are not correlated with the air shower can then be identified by their different arrival times in the antennas. The left panel of Figure 1 shows the electric field of all antennas after filtering and time shifting for an example event. At $-1.8\,\mu$s a coherent pulse from the direction of the air shower can be seen (all the lines lie on top of each other). The region of $-1.75\,\mu$s to $-1.4\,\mu$s is filled by the noise from the particle detectors. When the data from all antennas is combined in the beamforming process, the coherent pulse is enhanced and the noise is reduced, as shown in the middle panel of Figure 1. (A more detailed description of LOPES and the LOPES data processing can be found in [3].)

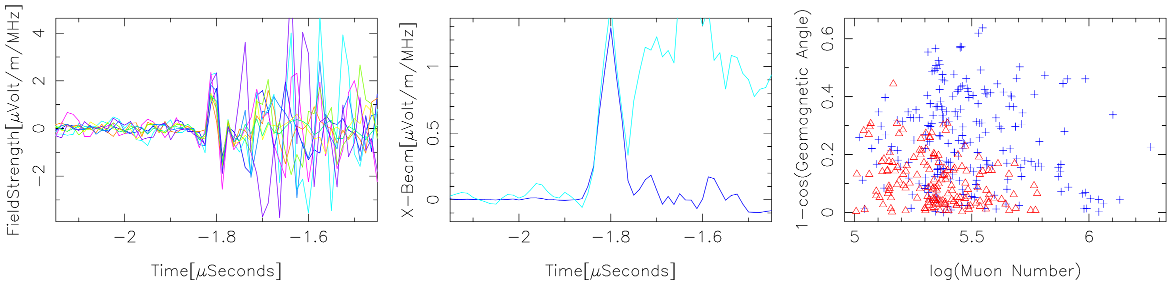

Figure 1. Left: The electric field of the LOPES antennas (in different colours) after filtering of narrow band interference and time shifting. The short pulse at $-1.8\,\mu$s is coherent (all the lines lie on top of each other), while the later pulses (noise from the particle detectors) are not. Middle: The same data after beamforming (dark blue) and as comparison the power averaged data (light blue). Right: Good events in which a coherent pulse from the air shower was detected (crosses), and bad events that were selected but in which no pulse from the air shower was detected (triangles). The fraction of good to bad events rises with muon number and angle to the geomagnetic field.

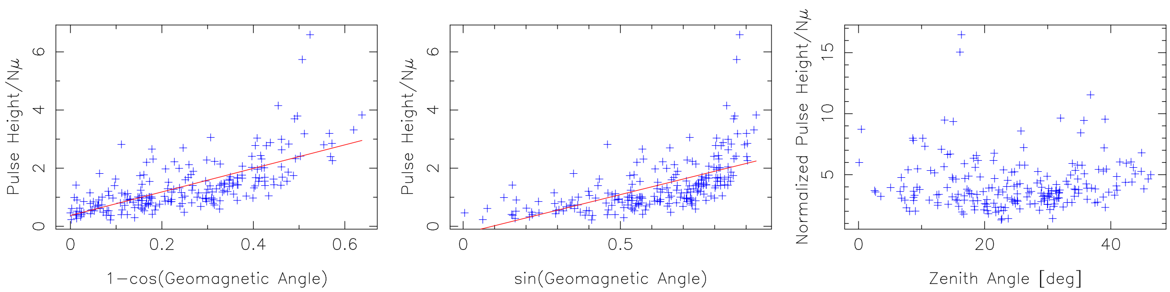

Figure 2. Left: Height of the radio pulse, divided by the muon number, against the cosine of the geomagnetic angle. Middle: Pulse height against the sine of the geomagnetic angle. Both relations (sine and cosine) can be approximated by a linear dependence, although the cosine gives a better fit. Right: Radio pulse height scaled with the results of the fit in the left panel. After taking out the effect of the geomagnetic angle, no further dependence on the zenith angle can be seen.

4. Results

From January to September 2004 LOPES collected ca. 630 thousand events. For this analysis we selected the largest events in which: a) the KASCADE array processor did not fail, b) the distance of the shower core to the array centre was less that 91 m, and c) the electron number was greater than 5×10^6 **or** the truncated muon number was greater than 2×10^5. This selected 412 events, in 228 of which events we found a coherent pulse from the air shower and which are therefore called "good" events. In the remaining "bad" events the pulse from the air shower is too small so that it is hidden in the noise.

The height of the radio pulses correlates with several air shower parameters: It rises with shower size (i.e. with the electron number or the muon number), it rises with increasing angle to the geomagnetic field and it falls with increasing distance of the shower axis to the antennas. This explains the rise of the fraction of good to bad events with muon number and geomagnetic angle, seen in the right panel of Figure 1.

As the dependence on the shower size is most pronounced, in a first step we normalised the pulse height by dividing by the truncated muon number. The left and middle panel of Figure 2 show the dependence of the thus normalised pulse height on the cosine and sine of the geomagnetic angle. Both relations show an approximately linear dependence, although the cosine gives a somewhat better fit. This difference in the quality of the fit is

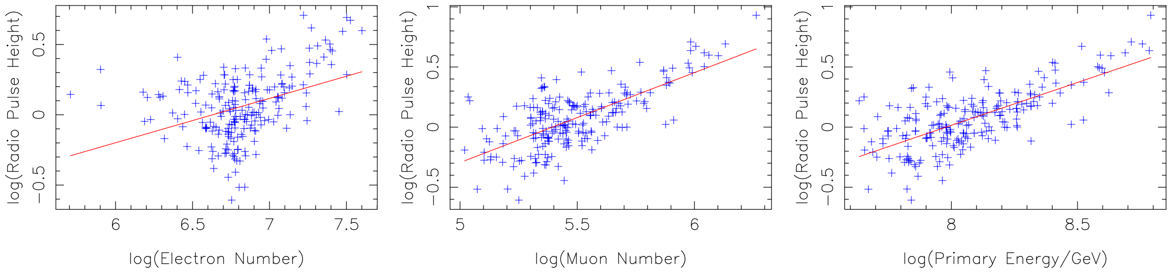

Figure 3. Normalised radio pulse height after scaling by the fit to the geomagnetic angle and distance to the shower axis. Plotted against the electron number (left), muon number (middle) and primary particle energy (right).

present in all (sub)selections of the data. In the right panel of Figure 2 we additionally normalised the pulse height with the values of the fit in the left panel, by multiplying with the fraction of the fit results at 90° to those at the angle of the air shower. After taking out the effect of the angle to the geomagnetic field, no further dependence on the zenith angle can be seen. The same is true for the azimuthal angle.

In Figure 3 the pulse height was scaled with the results of the fit to the geomagnetic angle and the results of a fit to the distance of the antennas to the shower axis. The difference between the left and the middle panel shows that the radio pulse height is better correlated with the muon number than with the electron number. This is expected as at the KASCADE Grande experiment the muon number is a better tracer of the total number of particles during the shower evolution than the electron number. Combining electron and muon number to a value for the primary particle energy does not improve the correlation compared to the muon number alone. The slope of the linear fit to the log(pulse height) vs. log(primary energy) plot is close to one. That means that the field strength indeed rises linearly with primary energy and thus the received power rises quadratically.

5. Conclusions

LOPES is able to reliably measure radio emission from air showers, and already took enough data for a first science analysis. Compared to the Allan-formula two discrepancies have been found: One is the better correlation of the pulse height with the cosine of the geomagnetic angle, compared to the sine. The other is that no dependence on the zenith angle has been found after the effect of the geomagnetic angle has been removed.

This analysis confirms the results given in [2]. With a wider selection including lower energy events and larger distances to the shower axis the detection efficiency drops as expected and more scatter is introduced. But it gives the same basic trends, i.e. 100% detection efficiency for large events, strong dependence on the geomagnetic angle and nearly linear raise of the pulse height with energy.

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