Radio Detection Techniques for Cosmic Rays

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Radio signals emitted from cosmic showers in air or in solid matter may give a new access to the detection of cosmic rays or neutrinos at energies above 10^{17} eV. The LOPES experiment in Karlsruhe demonstrated for the first time that the radio flashes emitted from cosmic showers in the atmosphere can be understood in terms of the geosynchrotron effect and has a coherent appearance. The results show that it should be possible to determine the origin, energy, and composition of ultra high energy cosmic rays with combined radio and particle detectors. The environment of Auger-South will now be used to test this new technique up to the highest energies and their application as cost effective instrument for detection of air showers. Similar holds for the interaction of cosmic rays and neutrinos with solid but radio transparent matter. The applied techniques and experiments are described.

1 Introduction

The origin of cosmic rays at ultrahigh energies (UHECRs) above 10^{18} eV remains a mystery. They are likely to be of extragalactic origin, but particles with energies higher than 10^{20} eV should be slowed down within 50 Mpc through interactions with the cosmic microwave background. Also the composition of UHECRs is unclear, whether they consist of protons, heavy nuclei, neutrinos or γ-rays. The rare occurrences of cosmic rays above 10^{18} eV afford large detectors with high duty cycles combining multiple detection techniques. More and better experiments and new detection methods are necessary to find a consistent answer to these questions. Radio emission from UHECRs is such a new detection method with several advantages over other detection techniques for cosmic rays.

When UHECRs interact with particles in the atmosphere or the soil of the earth or the moon, they produce a shower of elementary particles propagating with almost the speed of light. The first prediction that these showers could produce radio emission was made by Askaryan [1] based on a charge-excess mechanism, which is very strong for showers developing in solid media. This effect leads to relative short shower paths in these dense media. In a couple of experimental activities between 1962 and 1975, coincidences between radio pulses and air shower events were indeed reported [2,4], and the papers cited herein. Due to the limitations of the electronics in these days, the measurements were cumbersome and did not lead to useful relations between radio emission and air shower parameters. As a consequence the methods were not pursued for a long time and the historic results came into question.

However, recently the mechanism for the radio emission of extensive air showers in the atmosphere and radio signal production in solids by neutrinos was revisited and for the first time experimentally proved. Due to these discoveries an inflationary rising number of new experiments were started to use these effects for the detection of cosmic showers above 10^{18} eV.

After a short description of the underlying techniques the paper will focus on the detection of radio flashes from UHECRs in air with low-cost digital radio receivers. The LOPES experiment in Karlsruhe demonstrated for the first time beyond doubt that there is radio emission during the shower development and that the radiation can be understood in terms of the geosynchrotron effect. Using these results it should be possible to determine the origin, energy, and composition of UHECRs with combined radio and particle detectors, and may be also used for neutrino-induced showers. Now we take the advantage of the environment of Auger-South to test this new technique up to the highest energies and their application as cost effective instrument for detection of UHECRs.

2 What is the physics behind radio emission of cosmic rays?

There are two effects known which may produce radio emission by cosmic ray showers:

1. The coherent radio Cerenkov emission or Askaryan-Effect [1] for neutrinos or UHECR induced showers in ice, salt, lunar regolith, and sand. The basis for this effect is an electron charge excess in the electron-gamma part of neutrino or CR induced showers. The coherence of electric fields added in phase give an enhancement of 10^{11} in the power of the observed radio signal for 10^{19} eV showers. D. Saltzberg et al. gave the proof of the effect at SLAC [5] by observing the microwave radio emission between 200 MHz and 5 GHz of a 3 GeV photon beam with 5 ps long bunches dumped in a box filled with 3.5 tons of sand, see Fig. 1. The strength, polarisation and angular distribution of the emitted radio signal were consistent with theory. There is no theoretical prediction in air above 10^{17} eV [15]. A growing number of experiments plan to or already use this effect in the soil of earth or moon especially for neutrinos and UHECRs: RICE/ANITA [18], AMANDA/IceCube [17], LOFAR [10], and nuMoon [16]. All these experiments may have sufficient detection probability at energies above 10^{21} eV.

2. J.V. Jelley [2] and H.R. Allan [4] proposed the radio emission for air showers to be a geomagnetic mechanism. In a more precise derivation by Falcke and Gorham [6] secondary electrons and positrons produced in the particle cascade rush with velocities close to the speed of light through the magnetic field of the earth and are deflected, see Fig. 2. Like in synchrotron radiation, this produces dipole radiation that is beamed relativistically into

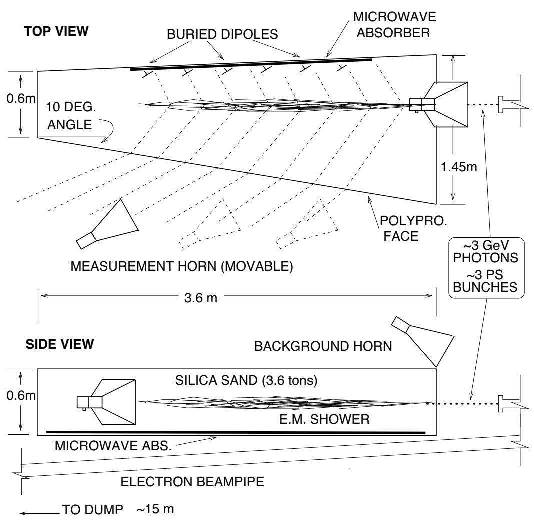

Figure 1: Top and side view of the sand beam-dump for the first detection of radio Cerenkov emission of 3 GeV photons

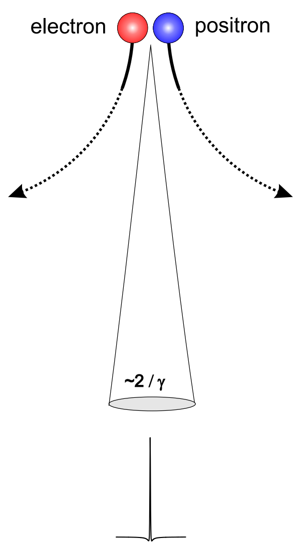

Figure 2: The magnetic field of the earth forces electrons and positrons on a counter circular movement creating radio emission with an opening angle $2/\gamma$

an opening angle of the order $2/\gamma$. The shower front emitting the radiation looks like a curved pancake with a thickness in the range of a meter and less depending on the energy of the shower. Hence the emission is expected to be coherent to a large extent for frequencies below 100 MHz and greatly amplifies the signal. Assuming UHECRs radio signals are detectable in the frequency range of 30 - 80 MHz we are in a window with only a low level of human caused noise. Below 8 km depth in the atmosphere the radio signal is unaffected by attenuation and we get at ground the bolometric sum of the electromagnetic signal over the shower evolution. Furthermore radio signals have a high duty cycle (24 hours/day), and promise calorimetric measurements with high directional accuracy, and antennas are cheap detectors, and easy to deploy.

3 Simulation of Radio Emission from Air Showers

The calculation of radio emission from cosmic ray showers in the atmosphere started 2003 with an analytical expression by Falcke and Gorham [6] and are now described in a new Monte Carlo simulation by Huege [8]. The code uses time domain radio emission in conjunction with a realistic air shower model based on per shower multi-dimensional CORSIKA generated histograms. The first test of the simulation was how far we get really a coherent result. Fig. 3 shows for vertical showers the summed field strength as function of the energy of the protons initiating the simulated shower [9]. The scaling is nearly linear at small distances from the shower direction and shows the coherent nature of the geosynchrotron emission. With larger distance from the shower core the energy dependance flattens due ton effect by $X_{\max}$ [9].

Fig. 4 shows the simulated lateral profiles for radio signals of 10 MHz and a primary energy of 10^{17} eV as function of the distance from the centre of the shower [9]. We get a flattening with increasing zenith angle with an approximate exponential scaling. Also at this relative low energies we may get considerable radio signals at large distances if we tolerate large azimuth angles as large as 45°.

The more realistic CORSIKA based particle distributions affect the predicted radio emission

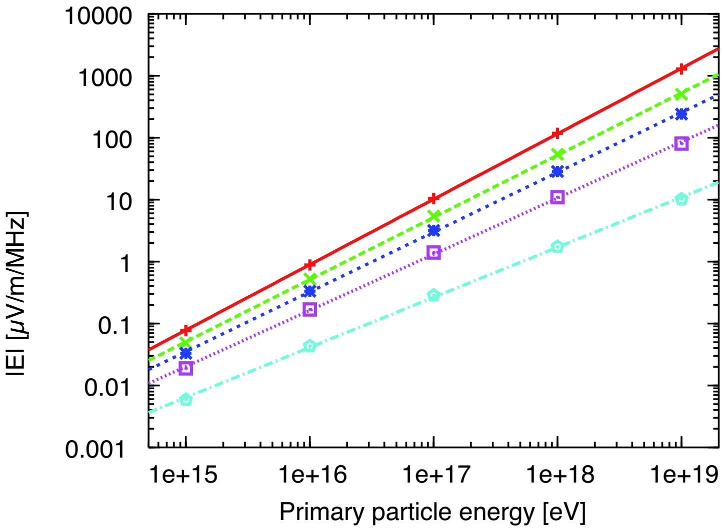

Figure 3: Scaling of the 10 MHz electric field emitted by a vertical air shower as a function of primary particle energy Ep with appropriately changing depth of shower maximum Xmax. From top to bottom: 20 m, 100 m, 180 m, 300 m and 500 m to the north from the shower center.

from a typical 10^{17} eV air shower as to be seen in Fig. 5. The comparison of parameterised (thin lines) and histogram binned (thick lines) Monte Carlo (MC) data shows that the spectra for histogram binned MC data are flatter and supports larger grid spacing ($> 500\,\mathrm{m}$) if the angle of incidence is not too steep and the energy is above 10^{18} eV.

Compared with earlier calculations based on parameterised showers, the simulations predict lightly weaker and in some cases narrower pulses. In addition, a pronounced East-West versus North-South asymmetry arises in the emission pattern, and the radio pulses become generally unipolar. Finally, we can study radio pulse shapes and their relation to shower characteristics such as the longitudinal air shower development.

4 Running Experiments: LOFAR, LOPES, CODALEMA

The LOw Frequency ARray (LOFAR) is the largest experiment now under construction observing radio emission for cosmology, bursting universe, cosmic rays and neutrinos above 10^{18} eV. In the phase 1 baseline design [10] more than 15,000 antennas will be distributed over 45 stations and a radius of 50 km. Two types of antennas will cover a frequency range of 30 - 80 MHz and 110 - 230 MHz and are connected by a high-speed digital network to a central IBM Blue Gene computer station. The first station is operational since end of 2006. Extensions of this array to North-Germany (Bremen and Limburg) are planned. The size of this array and the resulting sensitivity and angular resolution will have a very large discovery potential for astroparticle physics at the northern hemisphere.

In 2003, at the planning state of LOFAR, the collaboration LOPES collaboration was formed (LOfar PrototypE Station) to explore the radio emission of air showers. Coincident measurements with the air shower experiment KASCADE-Grande [7] are used as a test bed for LOPES. KASCADE-Grande covers an area of $0.5\,\mathrm{km}^2$ (Fig. 6) and therein gives a trigger of cosmic showers above 10^{16} eV with a rate of 1 per second. In a first step 10 and later additional 20 inverted V-dipole antennas (Fig. 7) were set up and externally triggered by KASCADE-Grande [11]. In this environment the background suppression was an ambiguous task to be learned at the beginning. In the unfiltered data in Fig 8a the coincidences could not be recognized. Only after Fourier transformation, Fig. 8b, and filtering off the narrow bandwidth emitters in the frequency space we got in the time space a clear correlation pattern between the antennas and

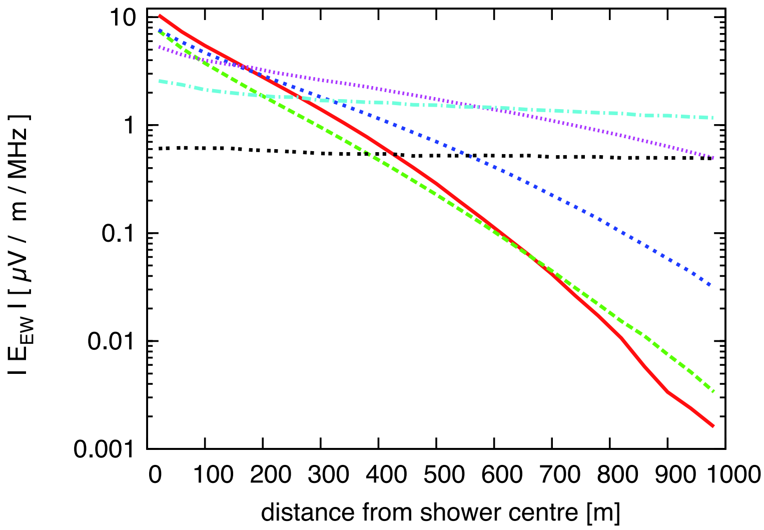

Figure 4: Dependence of the 10 MHz east-west electric field component emitted by a 10^{17} eV air shower coming from the south for different shower zenith angles as a function of distance to the north and for different zenith angles. Solid red: vertical shower, dashed: green 15°, blue 30°, violet 45°, turquois 60°, black 75° zenith angle.

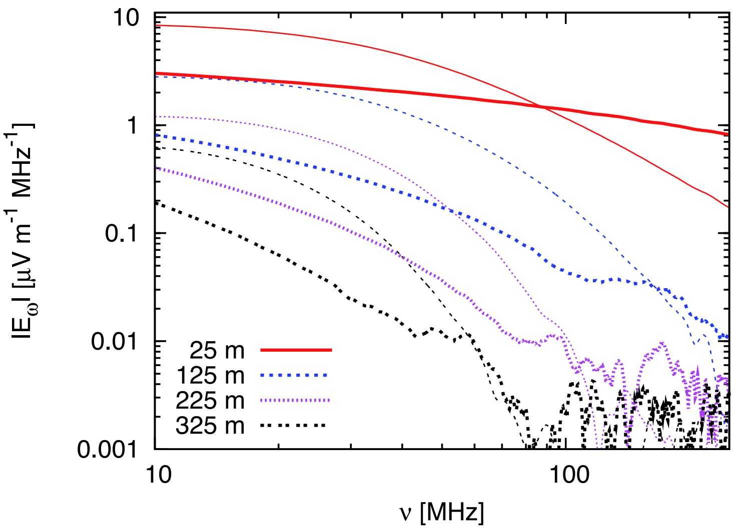

Figure 5: Overall change in the radio signal frequency spectra from a fully parameterised (thin lines) to a fully histogrammed (thick lines) air shower at various distances to the north from the shower centre.

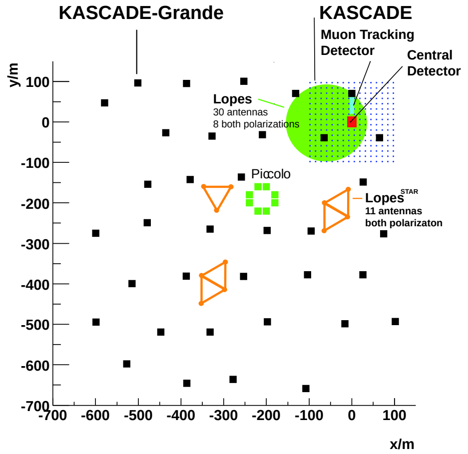

Figure 6: Layout and scheme of the KASCADE-Grande experiment with the original KASCADE experiment, the Grande array, and the Piccolo trigger array. The shadowed area contains 30 LOPES antennas and the equal lateral triangles are the new antennas of LOPES$^{\mathrm{STAR}}$.

Figure 7: V-dipole antenna as used in LOFAR and LOPES. The length of the arms are 1 m.

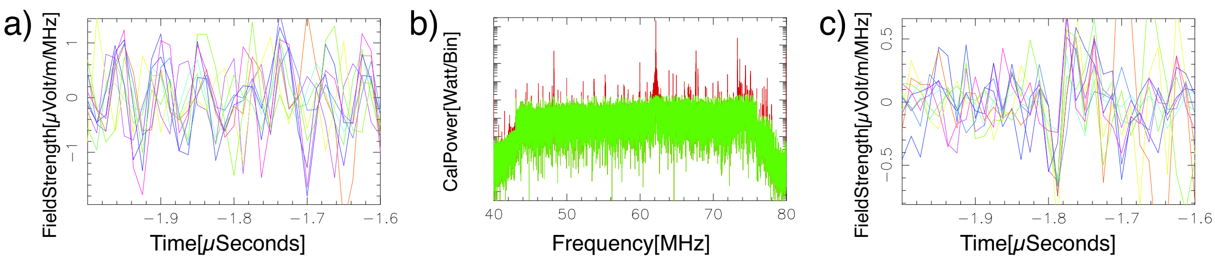

Figure 8: Unfiltered data with a trigger from KACADE-Grande; a) The different colours show traces from the different antennas, b) gain calibrated power spectrum of the antennas with a blocksize of 65536 samples. The red spikes above the noise floor are due to narrowband RFI, c) Filtered data, after filtering with a blocksize of 65536 samples. A coherent pulse at 1.78 μs is clearly visible.

to the KASCADE-Grande trigger. Finally in Fig. 8c after a correlation analysis, correcting for the instrumental and geometric delays, the block averaged radio emission as function of the time after beam forming the detected radio signal from the cosmic rays can be seen.

The energy normalised pulse height of the radio signal in Fig. 9a shows a clear dependence on the geomagnetic angle, indicating the geosynchrotron effect as source of the radio emission. The geomagnetic angle is defined as the angle between the shower axis and the geomagnetic field. By comparison of the radio signal of LOPES to the energy evaluated by the KASCADE-Grande experiment in Fig. 9b we got the result, that the radio signal is a good scale for energy and its emission is coherent due to the slope, the primary particle energy evaluated by KASCADE-Grande is proportional to the field strength at the antenna. By the multi correlation of 10 to 30 antennas we got a threshold of $6 \cdot 10^{16}$ eV at Karlsruhe.

The radial distribution of the radio signal as function of the distance of the antennas [12] to the shower core (Fig. 10) evaluated by KASCADE-Grande delivers an exponential fall off with a characteristic distance of 230 m. Due to our simulations as seen before that should be dependent on energy and angle of incidence. The low statistics of events until now allows no better analysis we have to wait a further year.

A strong indication for the improvement of reconstruction of KASCADE-Grande events by

Core position by	X_{core}[m]	Y_{core}[m]	$\varphi_{azimuth}[^\circ]$	$\theta_{elevation}[^\circ]$	Size of radio signal
Grande only	-142.9	40.3	302.2	41.6	0.8
Grande&LOPES	-137.9	30.3	301.6	41.0	2.8

Table 1: Effect of core position on the radio signal, optimised by using KASCADE-Grande and LOPES

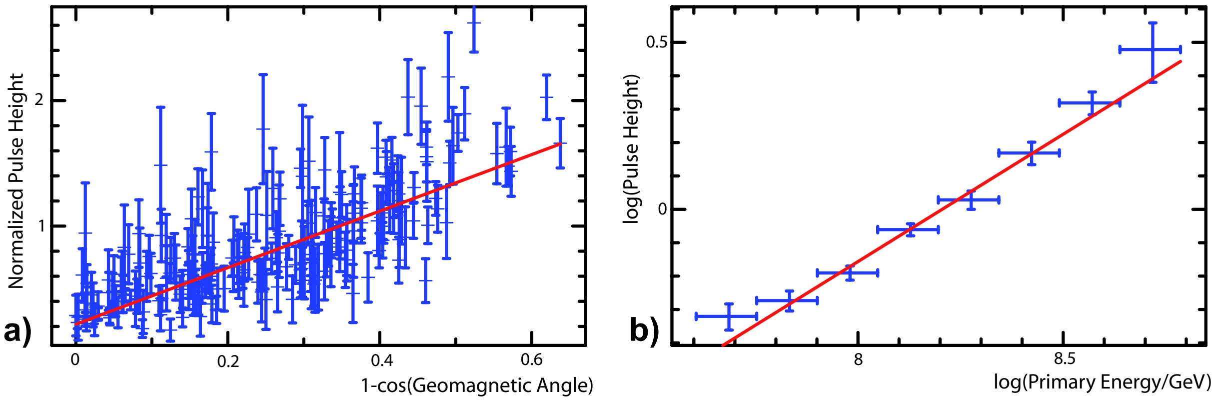

Figure 9: Pulse height distribution of detected radio events as function of (a) the cosine of the angle to the geomagnetic field and (b) the primary particle energy evaluated by KASCADE. In a) the pulse height is normalized to the number of muons and in b) corrected to the geomagnetic angle as given in a).

LOPES in precision of direction and core position may be seen in Tab. 1 for an example of an individual event. If we use the common core position of KASCADE and LOPES the correlation [3] of the radio signals improve the size of the radio signal by a factor 3. The increase in the radio signal is a strong indication, that the pointing resolution (error) at this energy is in the range of the

measured angular shift of 0.6°.

Finally we studied also the effect of thunderstorms and lightning on the radio signal [13]. Since the radiation mechanism is based on particle acceleration, the atmospheric electric field can play an important role. Especially inside thunderclouds large electric fields may be present. Under fair weather conditions field strengths of $E < 100\mathrm{Vm}^{-1}$ at ground level are known. For $E > 10\mathrm{kVm}^{-1}$ the force by the electric field dominates the magnetic field. Such field strengths may be exceeded within nimbostratus clouds by a factor 10. In thunderstorms local field strengths in the order of $100\mathrm{kVm}^{-1}$ are known. In both cases the radio emission of air showers could be affected [13]. Within the results of the LOPES experiment strong deviations from the energy correlation between KASCADE-Grande and LOPES are observed (Fig. 11), when weather with thunderstorms is reported. But that affects only less than 4% of the overall observation time and could be filtered out by field mills and lightning detectors. No amplified pulses were found during periods of cloudless sky or heavy cloudiness, suggesting that the electric field effect for radio air shower measurements can be ignored during non-thunderstorm conditions.

Another experiment looking presently for radio emission of air showers is CODALEMA, situated near to Nancay [14], see Fig. 12. The advantage of the CODALEMA experiment is, that the environment has a low radio background similar to many sites within Auger-South. It has not for calibration a large air shower experiment nearby as LOPES with KASCADE-Grande for calibration but recently some scintillators as trigger. The measured lateral distribution on single events is nearly exponentially falling off similar as LOPES and as expected in geosynchrotron theory. The absolute calibration of the radio signal is good but the extraction of the air shower parameters is as good or bad as the simple scintillation trigger detectors allow it.

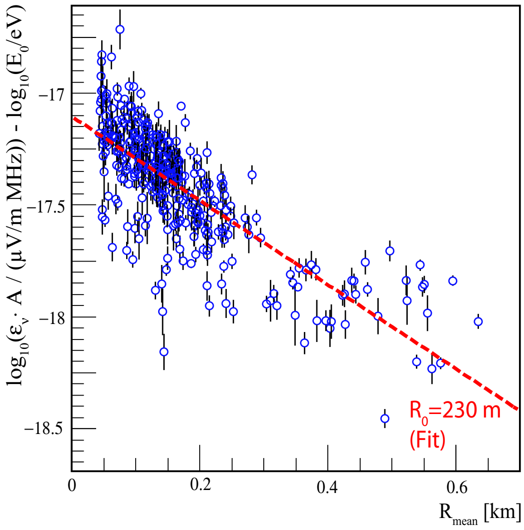

Figure 10: Correlation of radio signals normalized to primary energy from KASCADE as function of the mean distance of the antennas to the shower direction. The exponential fit gives a factor 2 higher scaling parameter R_0 than the formula of Allan (110 m).

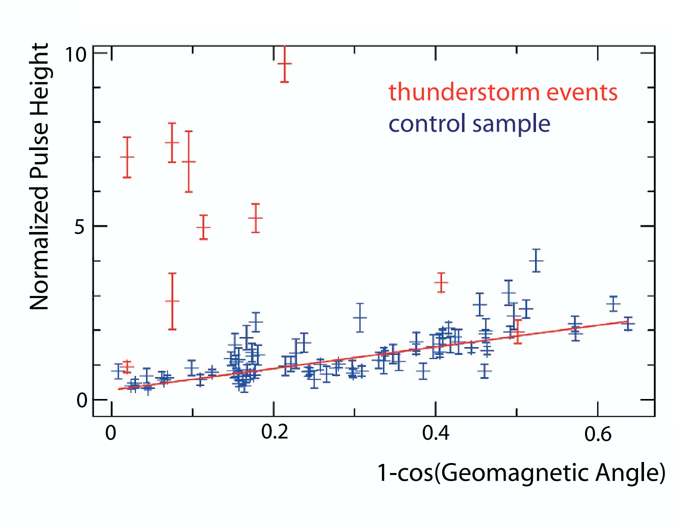

Figure 11: Normalized pulse height of the events taken at fair weather conditions (control sample) and those detected during thunderstorms plotted against the geomagnetic angle.

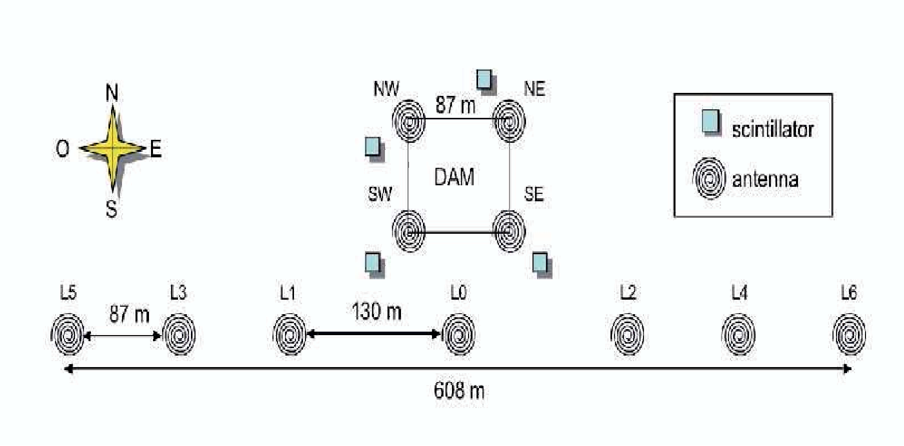

Figure 12: Current Codalema setup. The scintillators serve as 4-fold cosmic particle trigger for the radio antenna signals.

5 Future for radio at KASCADE-Grande and Auger

The future of radio at large experiments as the Pierre Auger observatory or at smaller size at KASCADE-Grande depends strongly on the cost effectiveness and additional value for air shower detection. And that starts with the simplicity and effectiveness of considered antennas: V-dipole or Tri-pole (LOFAR and LOPES), Active dipole (CODALEMA), and Logarithmic periodic dipole antenna (LOPES$^{\mathrm{STAR}}$). LOPES$^{\mathrm{STAR}}$ is the acronym for LOPES Self Triggered Array of Radio detectors and was developed at the Research Centre of Karlsruhe (IPE). The different types of antennas have especially different selectivity, noise immunity, and sensitivity to environment conditions (e.g. conductivity of the ground). For first measurements and optimisation of trigger a small array of 10 pairs of LOPES$^{\mathrm{STAR}}$ antennas for both possible polarisations are placed in the field of KASCADE-Grande and taking data. Shower data could be triggered.

The further analogue RF (radio frequency) front-end and trigger will now be discussed at the example of LOPES$^{\mathrm{STAR}}$ with a first running self-trigger system. After pre-amplification signal-to-noise ratio is no large problem. Galactic and extra-galactic background in the used frequency range of 40 - 80 MHz can be seen - a 32th order band pass filter cuts off the disturbing short-wave and FM-radio frequencies. These filters are at the same time the necessary Nyquist filter for the direct radio analogue-to-digital conversion with only 80 MHz sampling rate. As trigger we use a simple envelope trigger consisting of the absolute quadratic sum of both polarizations performed by a stabilised transfer function of Si-diodes. Why do we drive the trigger with rectified RF? The rectifier is a squaring device: multiplication in time domain corresponds to convolution in frequency domain. At the rectifier output man made radio frequency interferences (RFI) without or with low frequency modulation turns into DC or low frequencies and may be separated from pulse spectrum by a high pass filter. After summing both polarisations we apply a 500 kHz high pass. The principle of this trigger is demonstrated in Fig. 13. This background suppression fails partly, if several mono frequent RFI superimpose and generate high beat frequencies, which can not be suppressed by the high pass filter. But filters in the frequency space can further reduce this background. The obtained trigger rate at each antenna was then lower than some kHz at a threshold corresponding to $5 \cdot 10^{17}$ eV at Research Center Karlsruhe and to $3 \cdot 10^{17}$ eV at Auger-South.

To allow self-triggering we demand as minimum the coincidence of 3 neighbouring antennas. At KASCADE-Grande we take a distance of 65 m between the antennas and at Auger-South 100 m. Assuming a plane wave as incoming wave front we get also a pointing information for the radio source. Radio interference from the horizon may be recognized by their large delay as can

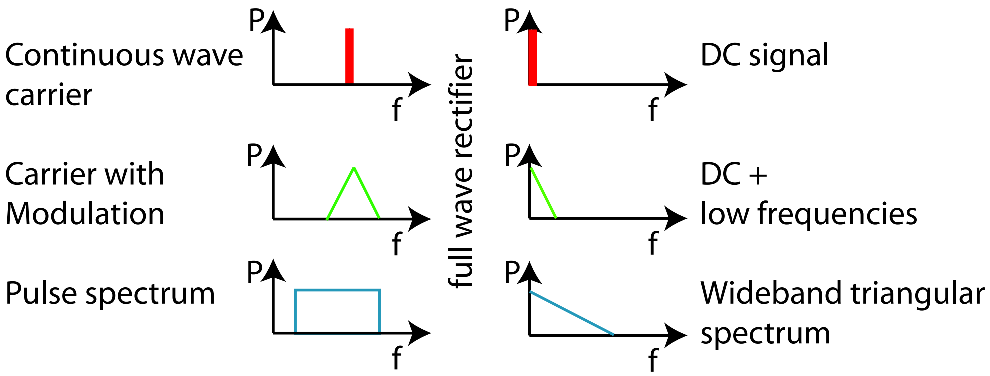

Figure 13: Trigger after full way rectifier. Man made RFI turns into DC or low frequency and may be separated from pulse spectrum by high-pass filtering.

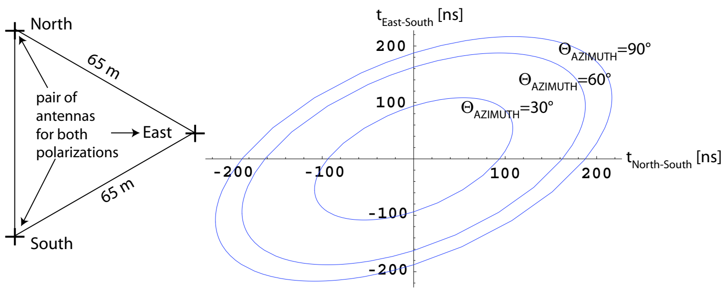

Figure 14: Pointing information in time space evaluated by using the difference times in a equilateral triangle $t_{ES} = t_{East} - t_{South}$ and $t_{NS} = t_{North} - t_{South}$. The given times for different azimuth angles are given for a side length of 65 m as used in Karlsruhe.

be seen in Fig. 14. By the size of the ellipse in the difference time space we can limit the accepted zenith angle range. For a more precise determination of the direction we have to consider the curvature of the incoming pancake of cosmic particles, all particles have nearly the same speed near to c, and that needs minimal 4 antennas. Fig. 15 shows one of the logarithmically periodic dipole antenna of LOPES$^{\mathrm{STAR}}$ within KASCADE-Grande at the Research Centre of Karlsruhe.

2006 we started also the radio tests at Auger-South. All type of antennas will be tested in respect to their performance, noise immunity, trigger (rates and obtainable threshold), and communication under the rough environment of the Pampa Amerilla at the site of the Pierre Auger Observatory. Then in case of a positive review we will build an engineering array on one to several $10\,\mathrm{km}^2$. The results of this engineering array will then again decide by a review on an add-up to Auger-South & -North.

6 Conclusions

LOPES is running in coincidence with the air shower experiment KASCADE-Grande. The first results are very promising with respect to the proof of detection of radio flashes from cosmic rays. LOPES events with primary energies even below 10^{17} eV were detected in the radio domain, which is remarkably low considering the noisy environment at the experimental site and the missing measurements of the second polarisation direction. One of the most interesting results

Figure 15: Logarithmic periodic dipole antennas used for LOPES$^{\mathrm{STAR}}$ optimized for the frequenzy band from 40 to 80 MHz and azimuth angles smaller than 80°.

of the LOPES data analysis is the presence of clear EAS radio events at more than 500 m distance from the shower axis for primary energies below 10^{18} eV [12].

The angular resolution seems to be better than that of KASCADE-Grande and the discovery of point sources with $\Delta\Theta < 1^\circ$ and decreasing with more antennas seems to be feasible. The measurement of energy is bolometric and correlated with the geomagnetic angle. By this new method we get complementary information to fluorescence and surface detectors. Thunderstorms make an effect and have to be considered, but can be discriminated easily.

The analysis of polarisation is under progress and we may get a lever arm for composition by the time development of the radio signal [8], see Fig. 16.

Finally the Pierre Auger Collaboration installed 2006 several antennas in Argentina. But much has to be done before you can apply radio detection as tool for UHECR to Auger-North. Auger-South is the necessary and best test environment for the future of radio.

In addition, the clear correlation of the measured radio pulse with the geomagnetic angle suggests a geomagnetic origin for the emission mechanism. Finally, the found quadratic dependence of the radio power on the primary energy due to the coherent nature of radio emission will make radio detection a cost effective method of detection of UHECRs and probably also cosmic neutrinos. With LOPES and LOPES$^{\mathrm{STAR}}$ we will be able to follow the main goal of the LOPES project: The understanding and calibration of radio emission in extensive air showers.

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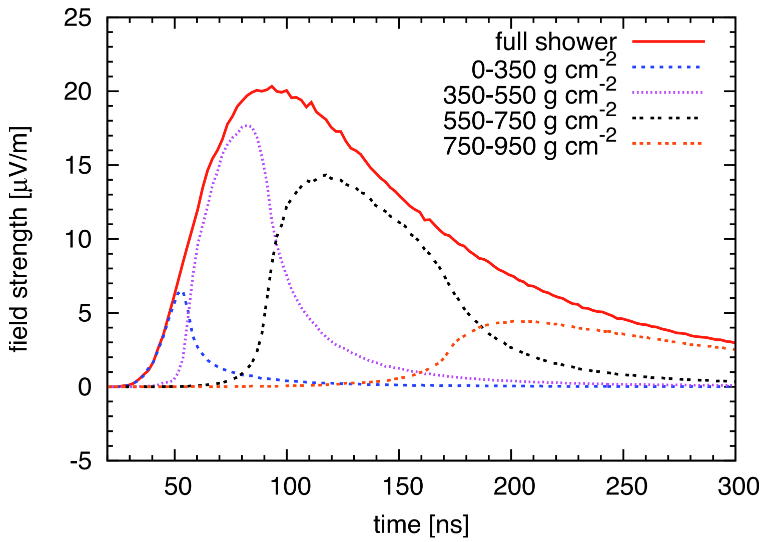

Figure 16: Simulated time development of a shower as tool to analyze the longitudinal structure of a shower.

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