Detecting Radio Pulses from Air Showers

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\begin{abstract}
Cosmic rays are energetic particles from outside the earth’s atmosphere. When a high energy cosmic ray hits the atmosphere it triggers a cascade of secondary particles produced in nuclear interactions, an air shower. Up to now the established methods of measuring air showers are detection of the particles that reach the ground level or optical observation of the Cherenkov or fluorescent light.

The measurement of radio pulses from air showers has a number of advantages: It gives a much higher duty cycle than measuring optical light, it measures the whole shower evolution thus being complementary to measuring the particles that reach the ground level, and it has the potential of giving a better direction estimate of the primary cosmic ray.

Historically these radio measurements have been plagued by man- and self-made radio interference. But the advent of fast digital computers and high bandwidth, high dynamic range ADCs enables us to use digital filtering and beam forming to suppress the radio interference. Online processing in fast FPGAs will even allow to trigger on air showers from the radio data alone.

LOPES was the first experiment designed to take advantage of this new technologies to measure radio pulses from air showers. It is a LOFAR Prototype Station for LOFAR, a new digital radio interferometer, that is being build in the Netherlands. LOPES consists of 30 dipole antennas operating in the frequency band of 40-80 MHz that are set up at the site of the KASCADE-Grande air shower array. At this site inside the Forschungszentrum Karlsruhe, there is significant radio interference present from RFI pulses. To test this technology and demonstrate its ability to measure radio pulses from air showers we built LOPES a prototype for the upcoming LOFAR radio telescope. LOFAR, the Low Frequency Array, is a new digital radio telescope designed to take advantage of the new technology. It will work in the frequency range of 10 to 270 MHz which is in the range of interest for cosmic

\end{abstract}

I. INTRODUCTION

The study of cosmic rays is one of the most active fields in astroparticle physics. Their origin, acceleration, and transport to the earth has been one of the unsolved problems in astrophysics for nearly 100 years. To resolve these questions, larger detectors with higher duty cycles and which combine multiple detection techniques are needed. We have investigated an alternative way to study cosmic rays: measuring the radio emission from cosmic ray air showers.

High energetic cosmic rays that hit the earth interact with the atmosphere and produce a cascade of secondary particles, an air shower. Radio pulses from air showers were first discovered by Jelley et al. in 1965 at 44 MHz \cite{1}. The results were soon verified and in the late 1960’s emission from 2 MHz up to 520 MHz was found. These historical experiments were limited by the existing technology. They could only measure with a relatively small bandwidth of a few MHz and they were limited to total power receiving systems. The latter includes that the radio signal is integrated with a time constant on the order of hundreds of nanoseconds, which also smears out the air shower pulse. A system like this is susceptible to RFI \cite{1}, it is impossible to filter out transmitter stations that leak into the frequency band and one cannot distinguish air shower pulses from RFI pulses. Consequently measurements were often only done at night when commercial TV and radio stations were turned off and access to the site could be restricted.

The advent of high bandwidth, high dynamic range ADCs allows us to digitize the whole radio frequency waveform and process the data with digital computers. This enables us to use digital filtering and digital beam forming to suppress the RFI and pick out air shower pulses. To test this technology and demonstrate its ability to measure radio pulses from air showers we build LOPES a prototype for the upcoming LOFAR radio telescope. LOFAR, the Low Frequency Array, is a new digital radio telescope designed to take advantage of the new technology. It will work in the frequency range of 10 to 270 MHz which is in the range of interest for cosmic radio frequency interference.\textsuperscript{1}
LOPES operates in the frequency range of 40 MHz to 80 MHz. This is a band with relatively little RFI in between the short-wave- and the FM-band. Additionally this frequency range is low enough that the emission from air showers is strong, but not so low that the background emission from the Galactic plane is too strong.

Although we chose a relatively quiet frequency band LOPES still has to deal with significant RFI (see fig. 8). But LOPES must also be able to detect faint radio pulses from air showers. This leads to two design goals for the hardware. The first is that the noise added by the hardware should be less than the background noise from the sky. As the average sky temperature in our frequency band ranges from 2000 K at 80 MHz to ~10000 K at 40 MHz this goal is relatively easy to meet. The second goal is that the dynamic range of the system has to be large enough to handle both the RFI and the small signals, i.e. distortions of the signal caused by the RFI in our electronics should be also less than the background noise. This puts a significant restriction on the kind of ADCs we can use, i.e. we cannot use 8-bit ADCs. The availability of ADCs with a sufficient dynamic range limited the bandwidth to 40 MHz and thus prevented us from using the range between 40 MHz and the short-wave-band.

The outline of the hardware used for LOPES can be seen in figure 1. It samples the radio frequency signal after minimal analog treatment without the use of a local oscillator.

1) Antenna: The antennas for LOPES are short dipole antennas with an “inverted V” shape. One of the LOPES antennas at the KASCADE-Grande site is shown in figure 2. The visible parts are commercial PVC pipes holding the active parts in place, while being transparent to the radiation. The radiator consists of two copper cables extending from the top down two thirds of two opposing edges of the pyramid. The PVC exterior of the antenna resides on an aluminum pedestal. This acts as a ground screen and protects the antenna from being damaged by lawn mowers.

This geometry determines the antenna pattern of the single antenna. The pattern, as obtained from simulations [4], is shown in figure 3. The half power beam width of the antenna ranges from ~ 85° in the direction parallel to the dipole (E-plane) to ~ 130° in the direction perpendicular to the dipole (H-plane). The four edges can be used for two orthogonal linear polarizations of the signal. If one measures both polarization directions one can do full polarimetry of the signal.

Inside the container at the top resides the active balun. Its main functions are balanced to unbalanced conversion, amplification of the signal and transformation of the antenna impedance to the 50 Ω impedance of the cable. The amplifier is a negative feedback amplifier, with a passive feedback net-
work. The feedback network is designed, so that the resulting input impedance is matched to the output impedance of the radiator over a wide frequency range. This gives sensitivity over a wide frequency range with good linearity and noise performance.

2) Receiver Module: Figure 4 shows one of the receiver modules for LOPES (RML). It consists of an amplifier (left), band-pass filter (top), ADC-board (bottom right, partially covered) and an optical transmitter board for the digital data piggybacked onto the ADC-board.

The amplifier is needed to bring the signal level from the antenna to the level needed for the ADC-module. The high background from the Galactic noise and the low absolute power result in relaxed requirements for noise and intermodulation performance of the amplifier. These could be achieved with a relatively cheap, off-the-shelf amplifier.

Next in the signal path is the anti-aliasing and band-pass filter. This filter should provide the largest usable bandwidth, while suppressing the strong transmitters outside our band of interest. Usable bandwidth is defined as the bandwidth in which we have significant power in our band and where contributions from outside the band are suppressed below the noise level. This requires high stopband attenuation and steep edges. The filters used for LOPES give us a usable frequency band from 43 MHz to 76 MHz for LOPES10 and from 43 MHz to 74 MHz for LOPES30. (Figure 7 shows the shape of the filters as part of the total electronics gain.)

The last analog device in the signal path is the A/D-converter board. It includes an amplifier, that matches the $50\,\Omega$ input impedance of the board to the impedance of the ADC. To detect weak pulses while not saturating the ADC with radio interference we need a dynamic range of about 60 dB. This is achieved by using 12-bit ADCs. The ADCs are running at a converter clock of 80 MHz. Thus we are sampling the signal in the second Nyquist domain of the ADCs. Piggybacked onto the A/D-converter board is an optical transmitter board. This changes the digital data of the ADCs from an electrical to an optical signal and transmits the data to the backend module.

3) Digital Backend and Clock Module: The digital data is transferred via fiber optics to the memory modules. These modules have standard PCI-connectors and fit into the front-end PCs. A module has 2 GByte memory and two inputs with $\sim 1.2$ GBit/sec each, which allows to store up to 6.25 seconds of data. Several of these modules can be used together by synchronizing them with a common synchronization-signal, which can be used to either start or stop writing the data into memory.

To be able to do beam forming with the data, the ADCs have to use the same conversion clock. Even small differences in the frequency of the conversion clock lead to offsets of several samples during the time of one dataset. Also the clock for the ADCs not only needs to be stable over long times, but also over short times. This is particularly true if one uses 2nd Nyquist sampling of the signal, as jitter on the sample-clock distributes part of the power from narrow band RFI over all frequency channels. Sending the clock signal over the optical transmission path added too much jitter, thus we distribute the clock via coaxial cables. To achieve this the clock for the ADCs is generated with a low noise crystal on a central master clock module and then distributed via slave modules to the receiver modules. They also distribute a synchronous clock for the memory modules and the synchronization-signal.

A clock card provides an accurate time-stamp and interfaces to the trigger from KASCADE-Grande.

B. LOPES at KASCADE-Grande

1) Layout: The layout of the LOPES antennas inside the KASCADE array can be seen in figure 5. In the first phase, named LOPES10, it had 10 antennas in a cross like pattern around the electronics station with the receiver electronics. In the second phase, called LOPES30, we have 30 antennas, of which 26 are inside the KASCADE array and 4 are outside on a meadow next to the KASCADE array. In the first two
phases all antennas were configured to measure the east-west polarization component. In the third phase half of the antennas were reconfigured for north-south polarization measurement.

The electronics are housed in three racks, each in the electronic station of a different cluster (in clusters 2, 6, and 10). Each station houses a slave clock module, ten receiver modules, five memory modules in three front-end PCs and support electronics (power supplies etc.).

The position of the antennas in relation to each other has been measured with high precision with a differential GPS system\(^2\). The accuracy of these positions, as given by the software, is better than 10 cm with less error in the horizontal plane than in the height.

2) Data Acquisition: The data acquisition is done with one master PC and nine front-end PCs connected via standard Ethernet. The front-end PCs house the memory modules and the clock the clock card. The DAQ software consists of a master program running on the master PC and one client program for each memory module and the clock card running on the front-end PCs. After a trigger has been received, the master program collects the data from all clients, writes out an event file, starts all memory modules and then frees the veto on the clock card.

3) Trigger: To get good frequency resolution \(\sim 0.82\) ms of data is saved for each trigger, giving a frequency resolution of \(\sim 1.2\) kHz. The data is selected so that the air shower signal is in the center of the data.

LOPES is triggered by a large event trigger from KASCADE-Grande. This is either a 10 out of the 16 coincidence of the KASCADE array clusters, or a coincidence of 3 trigger hexagons of the Grande array. This results in a trigger rate of \(\sim 2\) triggers per minute. Considering a dead time of LOPES of \(\sim 1.5\) seconds this means that about 5\% of the events are lost to the dead time.

III. CALIBRATION OF LOPES

A. Delay Calibration

In order to be able to do beam forming, the instrumental signal delays of the different antennas has to be known with good accuracy. Even small errors in the relative delays of the antennas with respect to each other degrade the coherence.

Tolerances of the electronics, unequal aging of the parts and different temperatures can cause a variation of the delay for the different channels. Additionally the digital electronics can cause the time index of a channel to be off by two samples, due to a glitch in the relative timing of the boards.

1) Calibration on the Sun: During solar bursts the sun becomes by far the brightest source in the sky at our frequencies. It can even become so bright, that only the strongest RFI sources are visible in a single antenna spectrum. Due to the low spatial resolution of LOPES the sun is seen as a single point. This allows us to use the bursting sun as a calibration source for the relative delays.

The result of this is a relative delay calibration for this event. After correcting for this delay, going to the frequency domain, and calculating the relative phases of an antenna to the reference antenna one can get additional calibration information:

- At the frequencies where the power is dominated by the solar burst, the relative phases give the phase difference of the electronics.
- At the frequencies dominated by the TV transmitter one can get the reference values for the second calibration method.

2) Calibration on a TV-Transmitter: By monitoring the relative phases of a TV transmitter we can monitor the phase stability of our system and get time delay calibration values for every day. As the position of the TV transmitter does not change, the relative delays and thus the relative phases of its signal in the different antennas remains constant. Additionally, its picture carrier and the two audio sub-carriers are strong enough that they are visible in every antenna and can be easily identified.

The signal from the TV transmitter does not have enough fine structure to allow us to directly get the relative delay via the cross-correlation. Checking the relative phases of just a single frequency cannot detect larger shifts due to the ambiguity of the phase. But by checking three frequencies this ambiguity can be reduced so far that not only delays by a small fraction of a sample time but also shifts of an integer number of samples can be detected.

The resulting delay corrections for one antenna over a few days are shown in figure 6. The three spikes belong to events where the algorithm failed. The delay-axis is given in sample times, so even without the correction the delay error stays within the \(\pm 0.1\) sample times range.

B. Gain Calibration

With a setup like LOPES the directly measured values are ADC-counts. The values of interest are the field strength of the radio pulse. To get from the recorded ADC-values to values for the field strength one has to consider the properties of the ADC, the gain and attenuation of the electronic parts in the signal chain and the gain of the antenna.

1) A/D-Converter: For single samples the "power into the ADC" can then be calculated with the formula for DC-currents: \(P_{ADC} = \frac{U_{ADC}^2}{R_{ADC}}\). The actual value of the input impedance of the ADC does not need to be known,
as is accounted for by our measurements of the gain of the electronic parts.

2) Electronic Gain: We measured the gain of all electronic parts together by suspending a calibrated reference transmitter above the antennas and recording the data from the ADC. With the information about the reference transmitter, its distance to the antenna and the antenna gain we can calculate the power received from the transmitter for every frequency. By comparing this to the power measured by the ADC we can determine the amplification of the electronics: \( V_{ele} = P_{ADC}/P_{rec} \). The process is described in detail in [5], the results for all antennas can be seen in figure 7.

3) Antenna Gain: The gain of an antenna \( G(\theta, \phi) \) in a given direction \( (\theta, \phi) \) is defined as the ratio of the power transmitted or received in that direction to the power an isotropic radiator would radiate in receive from that direction:

\[
G(\theta, \phi) = P(\theta, \phi)/P_{iso}.
\]

This antenna gain has been calculated from electromagnetic simulations of the geometry of the antenna [4], and the resulting antenna pattern can be seen in figure 3. Measurements at LOPES with the reference transmitter [5], and at LOFAR-ITS, which uses a similar hardware [6], have shown that these simulations are generally quite reliable. Deviations are mostly at higher zenith angles, for zenith angles less than 50° the error is less than 10%.

4) Calculating the Field Strength: The power picked up by the antenna is proportional to the square of the electric field strength\(^3\). If the bandwidth of the signal is larger than the bandwidth of the receiver, one measures only parts of the signal, so the measured values depend on the receiver bandwidth and may depend on the receiver frequency. To get values that are better comparable between experiments with different bandwidth, one can divide the measured peak field strength by the effective receiver bandwidth.

Together with the results from the previous sections one can calculate the field strength per unit bandwidth from the measured ADC values:

\[
\mathcal{E}_\nu = \frac{|E|}{\Delta \nu} = \frac{1}{\Delta \nu} \sqrt{\frac{4 \pi \nu^2 \mu_0 c^2}{G(\theta, \phi) G_{ele} R_{ADC}}} \frac{1}{U_{ADC}^2} \frac{U_{ADC}^2}{R_{ADC}}.
\]

\(^3\)Full calculations can be found in [2].

Here \( \Delta \nu (= 33/31 \text{ MHz}) \) is the bandwidth, \( \nu (= 59.5/58.5 \text{ MHz}) \) is the observing frequency, \( G(\theta, \phi) \) is the (direction dependent) gain of the antenna, \( V_{ele} \) is the (frequency dependent) gain of the electronics, \( U_{ADC} \) is the voltage measured by the ADC, and \( R_{ADC} (= 50 \Omega) \) is the input impedance of the ADC, that was used when calculating the correction values (In brackets the values for LOPES10 and LOPES30). As the same antenna gain values are used here as for the reference measurements, any error of the simulated antenna gain is canceled out at least for the direction of the reference measurements. One also has to keep in mind, that the field strength calculated that way is just the field strength in the polarization direction of the antenna.

IV. ANALYZING AIR SHOWER EVENTS

The goal of the processing of air shower events is to reconstruct the radio field strength of the pulse emitted by the air shower. Processing of air shower events proceeds in the following steps:

1) Correlation between LOPES and KASCADE-Grande
2) Selection of interesting events
3) Fourier transforming the data to the frequency domain
4) Correction of instrumental delays from the TV-transmitter
5) Frequency dependent gain correction
6) Suppression of narrow band RFI
7) Flagging of antennas with high noise
8) Correction of trigger delay
9) Beam forming in the direction of the air shower
10) Quantification of peak parameters
11) Optimizing the direction
12) Identification of good events

A. Correlation between LOPES and KASCADE-Grande

The KASCADE-Grande data is routinely analyzed with the KASCADE-Grande air shower reconstruction program. A selection that contains all events that satisfy the conditions for the large event trigger for LOPES is written into a special file. The data from these files is then merged with a list of all LOPES events from the same span of time. This results in a list with air shower parameters reconstructed from KASCADE-Grande data and the filename of the corresponding LOPES events.

B. Event selection

This off-line correlation is done for all events. The next steps (steps 3–11) are done in an automatic pipeline. As this pipeline takes a few minutes per event only selected events are processed. These events are selected by KASCADE-Grande data according to the goals of the analysis.

C. Fourier Transform

Fourier transforming a finite time series generates leakage, in which power is shifted from one frequency bin to neighboring bins. To reduce leakage the time domain data is scaled with a modified Hanning window, that is flat in the center. This has the advantage of reducing the leakage while not changing the central part of our data with the pulse from the air shower.
D. Delay and Gain Correction

The algorithm used for the determination of instrumental delays is described in section III-A2. The delay corrections obtained this way are added to the other delays and applied during the beam forming process.

The gain calibration values from section III-B2 are multiplied to the data. In this step the frequencies outside our band are multiplied by a smaller number, thus effectively removing them.

E. Suppression of Narrow Band RFI

Narrow band RFI occupies only few channels in frequency space, while a short time pulse is spread over all frequency channels. So by flagging the channels with RFI one can greatly reduce the background without affecting the air shower pulse much. Figure 8 illustrates the effect of this. Panel a) shows a section of unfiltered data with traces for all antennas. Panel b) shows the power spectrum of one antenna before and after the filtering. After filtering the RFI lines stay in the region of the noise. Panel c) shows the time domain data after the filtering. A coherent pulse at $-1.78\,\mu s$ is clearly visible (i.e. all the traces fall onto each other). Panel d) shows the effect of insufficient frequency resolution. Less frequency resolution has two effects. The first is that with each filtered line a greater portion of the radio pulse is cut away. The second is that RFI is more prone to be hidden in the noise and thus not filtered. In this example the second effect is dominant, the amplitude of the signals is only a little lower than in the unfiltered data.

F. Flagging of Antennas

Antennas are flagged and not used if:

- They have an unusual amount of noise, i.e. their peak value is significantly larger than those of the other antennas.
- They have an extremely small signal, e.g. because they were not connected.
- They are standing next to the muon tracking detector and the shower core falls on top it. In this case lots of particles penetrate the shielding of the detector and the detector generates a large amount of RFI.
- The antenna is manually deselected.

G. Beam Forming

The essence of beam forming is to add the signals from different antennas in order to achieve sensitivity to one direction. This direction is determined by time shifts of the signals from the antennas. As an example figure 9 shows the geometry of the source and two antennas. A pulse originating at the source will first arrive at antenna 2 and then at antenna 1. To have the pulse at the same position in both datasets the dataset of antenna 1 has to be shifted in relation to the one from antenna 2 by the delay that corresponds to the distance from antenna 1 to point A. If both datasets are then added up, the pulse will be enhanced in the resulting data, while a pulse from another direction will be smeared out. We choose the reference position for the calculation of the geometric delays so that the radio pulse is always at about the same array index in our time series.

The geometrical delays and the delay corrections are added to give the final delays. The shift itself is done by multiplying a phase gradient to the frequency space data before transforming it back to the time domain. From the shifted data we calculate several so called beams, that combine the data in different ways:

- The data from all antennas is added pixel by pixel, but then normalized by the number of antennas to have values comparable to a single antenna.

$$ f[t] = \frac{1}{N} \sum_{i=1}^{N} s_i[t] \tag{2} $$

Where $F[t]$ is the unnormalized field strength of the formed beam, $f[t]$ is the normalized field strength, $N$ the
number of antennas, $s_i[t]$ the time shifted field strength of the single antennas, and $t$ the time or pixel index. This is the normal beam forming process. With this the parts of a coherent pulse can have both positive and negative sign, so to see a peak one has to look at the absolute values.

- For comparison the squared values of all antennas are averaged and then the square root is taken, called the power-beam.

$$
p[t] = \sqrt{\frac{1}{N} \sum_{i=1}^{N} s_i^2[t]} \tag{3}
$$

This gives a peak if there is lots of power in the antennas, independent of it being coherent or incoherent.

- The data from each unique pair of antennas is multiplied, the resulting values are averaged, and then the square root is taken while preserving the sign.

$$
cc[t] = \pm \sqrt{\frac{1}{N_{Pairs}} \sum_{i=1}^{N-1} \sum_{j>i}^{N} s_i[t]s_j[t]} \tag{4}
$$

$N_{Pairs}$ is the number of unique pairs of antennas. The negative sign is taken if the sum had a negative sign before taking the absolute values, and the positive sign otherwise.

We call this the cross-correlation beam or CC-beam. The advantage of this is that a peak from a coherent pulse always has a positive sign. Peaks from incoherent pulses can also have a negative sign, e.g., if one antenna has a large value but the other antennas have values with opposite sign.

- To better bring out the significance of a pulse in the presence of rapidly changing noise, the CC-beam is weighted by the absolute value of the relation of the smoothed CC-beam to the smoothed power-beam.

$$
x[t] = cc[t] \cdot \left| \frac{cc[t]}{p[t]} \right| \tag{5}
$$

As coherent peaks have the same height in both beams they are not changed much, but incoherent peaks usually have a larger value in the power-beam than in the CC-beam, so they are reduced. This is called the excess-beam or X-beam.

Figure 10 shows the different kinds of beams. Panel (a) shows the data from all antennas, while panels (b)–(d) show the field strength, the CC-beam, and the X-beam, all together with the power-beam. The peak from the coherent pulse at $-1.8\mu\text{s}$ is seen in all panels with about the same height. The incoherent noise between $-1.75\mu\text{s}$ and $-1.3\mu\text{s}$ produces significant peaks in the field strength, smaller peaks in the CC-beam and no significant peaks in the X-beam.

H. Quantification of Peak Parameters

The response of the analog electronics to a short pulse is an oscillation over a short time. The major contribution to this oscillation comes from the anti-aliasing filter. Filtering of the lower frequencies causes an oscillation around zero, while the finite bandwidth broadens the pulse. Sampling such a signal with an ADC gives a certain fine structure inside the pulse that is not part of the original pulse but is caused by the electronics. To suppress this fine structure the data is smoothed by block averaging over 3 samples. Although the pulse shape is not really Gaussian, fitting a Gaussian to the smoothed data gives a robust value for the peak strength. Other methods, like e.g., the maximum of the peak or the sum over the pixels of the peak, can change their values when the data is shifted in time or suffer from problems in determining where the pulse starts and where it ends.

I. Direction Optimization

The beam-forming direction is optimized in three parameters: azimuth, elevation, and radius of curvature. The radio pulse of an air shower does not arrive on the ground as a plane wave, but it has some curvature. For the distances of LOPES the shape of the wavefront can be represented by a sphere with a finite radius of curvature. Figure 11 shows the difference between plane wave beam forming and beam forming with an optimized radius of curvature.

The optimization is done in two steps. In the first step the pulse height is evaluated on a small grid around the pulse, while the finite bandwidth broadens the pulse. Sampling such a signal with an ADC gives a certain fine structure inside the pulse that is not part of the original pulse but is caused by the electronics. To suppress this fine structure the data is smoothed by block averaging over 3 samples. Although the pulse shape is not really Gaussian, fitting a Gaussian to the smoothed data gives a robust value for the peak strength. Other methods, like e.g., the maximum of the peak or the sum over the pixels of the peak, can change their values when the data is shifted in time or suffer from problems in determining where the pulse starts and where it ends.
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So one cannot select events with air shower pulses just by the air shower there can be an incoherent noise peak that is as high as an average air shower peak, even in the X-beam.

\[ \text{Fig. 12. Left: Field strength of the single antennas of the first unambiguous radio pulse from an air shower detected with LOPES. Right: The formed beam of this event. One can clearly distinguish between the coherent radio pulse at } -1.8 \, \mu\text{s} \text{ and the detector RFI between } -1.7 \, \mu\text{s} \text{ and } -1.4 \, \mu\text{s.} \]

J. Event Identification

Not every selected air shower is accompanied by a radio pulse that is detectable by LOPES. If there is no pulse from the air shower there can be an incoherent noise peak that is as high as an average air shower peak, even in the X-beam. So one cannot select events with air shower pulses just by the height of the fitted Gaussian, but has to classify events in an extra step. Simple methods using only a small number of parameters turned out to have a significant number of false classifications. The low absolute number of events makes it desirable to have the lowest number of false classifications that is possible. But it also allowed us to classify all selected events by eye, which turned out to be the most effective way for now.

V. First Detection

The first unambiguous radio pulse from an air shower detected with LOPES was taken on the 12. January 2004. Figure 12 shows the field strength of the single antennas and the block averaged CC-Beam for this event. It showed, that the contribution between $-1.7 \, \mu\text{s}$ and $-1. \mu\text{s}$ matches the noise expected from the particle detectors and that at $-1.8 \, \mu\text{s}$ there is an additional, coherent signal that was then identified as the radio pulse from the air shower itself. This event was taken during a thunderstorm which increased its radio signal [7]. This made this particular event unusable for a quantitative analysis, but it showed us how to distinguish air shower pulses from detector RFI.

A first analysis based on this discovery used a rather restrictive set of events with relatively high signal to noise [8]. Using events from the first half year of operation, starting January 2004, all events were selected with a shower core within 70 m of the center of LOPES, a zenith angle $< 45^\circ$, and the muon number $N_\mu > 4 \times 10^5$, selecting 15 events in total. In all of those events we detected a radio pulse from the air shower, proving that indeed there are indeed radio pulses associated with air showers and that it is possible to measure them, even in radio loud environments, with a digital radio telescope. The analysis of the pulse heights of these events showed that there is a dependence of the pulse height on the angle of the air shower axis to the geomagnetic field and an independent, nearly linear dependence on the muon number. In particular the geomagnetic dependence is of interest, as it supports our theory of a geosynchrotron emission process.

VI. Summary and Outlook

LOPES is a digital radio telescope aimed at the detection of radio pulses from cosmic ray air showers. It directly samples the radio waveform in the frequency range of 40 MHz to 80 MHz with fast analog to digital converters, after only minimal analog treatment of the signal. Digital processing of the stored data then allows us to form a beam after an air shower has been recorded.

LOPES is set up at the site of the KASCADE-Grande experiment, and triggered by a large event trigger from the particle detectors. In the first two phases 10 resp. 30 antennas measured the east-west polarized signal, currently 15 antennas measure the east-west polarization and 15 antennas measure the north-south polarization. For the air shower analysis the data is offline correlated with data from KASCADE-Grande array, radio interference is digitally filtered, and a beam in the direction given by KASCADE-Grande is formed.

LOPES was the first experiment to unambiguously detect radio pulses from air showers with the new technology. Thus demonstrating that it is possible to measure radio emission from air showers even in a radio loud environment. This initial success of LOPES has led to a revival of this topic with a growing community. The effort to measure air showers with the LOFAR telescope is the direct continuation of LOPES. The high sensitivity and precise calibration of LOFAR will allow a detailed view on single air showers. Another project is working on adding radio detection capability to the Pierre Auger Observatory.

REFERENCES