Primary Particle Energy Calibration of the EAS Radio Pulse Height

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Abstract: LOPES is the pioneering experiment for the measurement of radio emission from air showers with digital radio receivers. It is set up at the site of the KASCADE-Grande air shower array and takes data in conjunction with it. This gives the unique possibility to combine LOPES and KASCADE-Grande data. In the first phase LOPES consisted of 10 antennas placed inside the KASCADE array. In its second phase it has been extended to 30 antennas, which increases the detection rate of well reconstructed events. Also a new, absolute calibration of the radio antennas is now available. By correlating the measured radio pulse height with air shower parameters measured by KASCADE-Grande, we have derived a formula that describes the radio pulse height as a function of air shower geometry and primary particle energy. Thus allowing us to estimate the cosmic ray energy from radio data.

Introduction

Measuring the radio pulses from air showers is a new method to measure high energy cosmic rays. Compared to other methods it has a number of advantages: Except during thunderstorm conditions one can measure day and night, giving a much higher duty cycle than, e.g., fluorescence telescopes. The radio waves are only very little attenuated in the atmosphere. Thus, even though one cannot image the track of the air shower, the radio signal is a quasi bolometric measurement of the whole air shower evolution. This makes radio measurements complementary to ground based particle detectors.

LOPES is a **L**OFAR **P**rototyp**e** **S**tation tailored to use digital technology to measure air showers. Thus, it is set up at the site of KASCADE-Grande overlapping with the original KASCADE array. LOPES uses quasi omnidirectional short dipole antennas for the frequency range of 40 to 80 MHz and does direct sampling of the radio signal. It is triggered by a large event trigger from KASCADE-Grande and stores 0.82 ms worth of raw data around each trigger.

In its first phase LOPES consisted of 10 antennas that were set up to measure the east-west polarized component of the radio signal. In the second phase parts of the electronics were updated and LOPES was expanded to 30 antennas. At first these antennas were also set up to measure the east-west polarized component. In the end of 2006 half of the dipoles were reconfigured to measure the north-south polarized component, allowing full polarization measurement. For the second phase of LOPES we also have an absolute calibration of the whole signal chain that allows us to convert the measured values to absolute field strength.

Determination of the Radio Pulse Height

Field Strength Calculation The values measured by LOPES are given in ADC samples from the receiver modules. These can be converted to the actual field strength at the antennas with the following formula:

$$\mathbf{E} = \sqrt{\frac{4\pi\nu^2\mu_0}{G_{(\theta,\phi,\nu)}c}\frac{1}{A_{ele(\nu)}R_{ADC}}}V_{ADC} \qquad (1)$$

Here ν is the observing frequency, $G_{(\theta,\phi,\nu)}$ is the gain[1] of the antenna, $A_{ele(\nu)}$ is the total gain of the electronics, V_{ADC} is the voltage measured by the ADC, and R_{ADC} is the input impedance of the ADC.

The calibration values needed for this conversion are the antenna gain and the amplification of the electronics. The ADC impedance and factors for the conversion of ADC samples to voltage are essentially free parameters as they are also used when measuring the electronics gain and thus cancel themselves out. For LOPES we get the direction and frequency dependent antenna gain from full EM-simulations of the antennas and their surrounding structure. These simulations were confirmed by partial measurements of the antenna gain pattern. For the first phase of LOPES the effective gain of the electronics was not well known due to the unknown match of the impedance of the dipole to the input impedance of the antenna amplifier. For the second phase of LOPES the amplification of the whole electronic chain was measured in one single process by placing a calibrated reference transmitter above the antennas and comparing the measured values to the expected values[4][5].

Different experiments use different bandwidth. But as the pulses are rather short in time their spectrum is relatively flat. So in order to get a value that is comparable between experiments the values given are the field strength divided by the effective bandwidth: $\varepsilon_\nu = \frac{\mathbf{E}}{\Delta\nu}$

Beam Forming To increase the signal to noise we combine the data from all available antennas. The data streams from all antennas are shifted in time and then combined. This process, called *beam forming*, implements a spatial filtering, i.e., it makes the resulting data more sensitive to signals coming from one direction and less sensitive to signals from other directions. To get the best performance we calculate what we call the CC-beam in the following way:

$$cc[t] = \pm\sqrt{\left|\frac{1}{N_{Pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i[t]s_j[t]\right|} \qquad (2)$$

With N the number of antennas, $s_n[t]$ the time shifted data from one antenna, and N_{Pairs} is the number of unique pairs of antennas. The sign for each sample is the sign it had before taking the square root.
The difference between normal beam forming (adding of the data samples) and the CC-beam is the same difference as between a phased array and interferometry in radio astronomy.

1. Or directivity as it is also called.

Pulse Height To get a robust value for the radio pulse height we smooth the beam formed data by block averaging over 3 samples and then fit a Gaussian to the resulting peak. The height of this fitted Gaussian is then used as the pulse height in the further analysis.

Pulse Height Parameterization

Event Selection For this analysis the data from LOPES10 between January 2004 and September 2004 and LOPES30 between November 2005 and September 2006 were combined. From this we selected events for which we have good data from the KASCADE array (including cuts on array processor status, shower core position, and reconstructed shower age) and had a minimum shower size[2]: $\log(N_\mu) > 5.2$

From these we selected events with at least six working antennas, a zenith angle smaller than 50 degrees, which were not taken during a thunderstorm, and in which a radio peak from the direction of the air shower was detected. This left 207 LOPES10 events and 346 LOPES30 events for the following analysis.

Parameterization Formula The radio pulse height measured by the east-west polarized antennas of LOPES can be parameterized as a function of the angle to the geomagnetic field, the zenith angle, the distance of the antennas to the air shower axis and the size of the air shower given either by the muon number or an estimate of the primary particle energy calculated from KASCADE-Grande data[6],[7]. The separated relations for the LOPES30 events can be seen in figure 1.

The fit is done in two steps. First the fits to the geomagnetic angle, the distance to the shower axis, and to the shower size are done separately with the LOPES30 events. Then in a second step the LOPES10 and LOPES30 events are combined and the results from the separate fits are used as starting parameters in a combined fit. As there is no absolute calibration available for the LOPES10 events, this fit also includes a free parameter for the height of the LOPES10 events. Thus the absolute height is set by the LOPES30 events, but the LOPES10 events contribute to the determination of the other

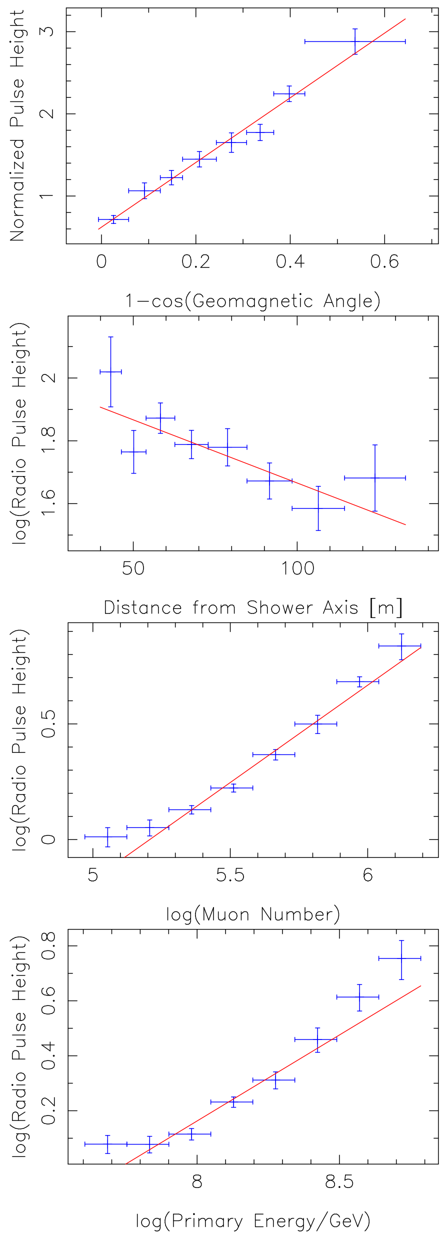

Figure 1: Normalized radio pulse height plotted against (from top to bottom:) the angle to the geomagnetic field, the mean distance of the antennas to the shower axis, the muon number, and the estimated primary particle energy. The normalization is done by dividing by the fits to the other parameters (geomagnetic angle, distance or shower size).

2. The value used is the so called truncated muon number from KASCADE-Grande[1].

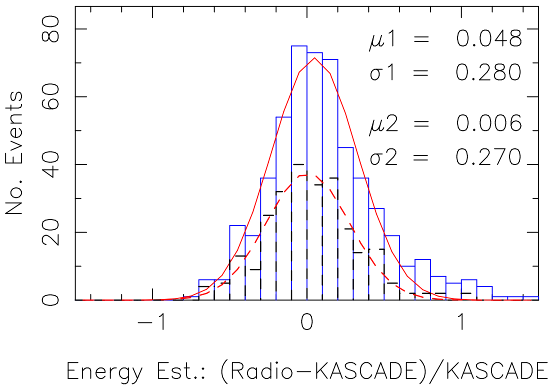

Figure 2: Spread between the energy estimated from radio data using the inverse of equation 4 and the primary energy provided by KASCADE-Grande. For all selected events (top, solid lines) and for events $> 10^{17}$eV (bottom, dashed lines).

parameters. This results in analytical expressions for the radio pulse height, one based on the muon number and another based on the estimated primary energy:

$$\epsilon_{\text{est}} = (53 \pm 4.9)\,(1.09 \pm 0.017) - \cos\alpha)$$
$$\exp\left(\frac{-\mathrm{R_{SA}}}{(221{\pm}62)\,\mathrm{m}}\right)\left(\frac{\mathrm{N}_\mu}{10^6}\right)^{(0.99\pm0.04)}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right] \quad (3)$$

$$\epsilon_{\text{est}} = (11 \pm 1.)\,(1.16 \pm 0.025) - \cos\alpha)\cos\theta$$
$$\exp\left(\frac{-\mathrm{R_{SA}}}{(236{\pm}81)\,\mathrm{m}}\right)\left(\frac{\mathrm{E_p}}{10^{17}\mathrm{eV}}\right)^{(0.95\pm0.04)}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right] \quad (4)$$

(With: α the geomagnetic angle, θ the zenith angle, $\mathrm{R_{SA}}$ the mean distance of the antennas to the shower axis, N_μ the truncated muon number, and $\mathrm{E_p}$ the primary particle energy. The given errors are the statistical errors from the fit.) Eq. 3 does not contain a $\cos\theta$ term as the Muon number already depends on the zenith angle.

Equation 4 can also be solved for the primary energy. With this one can then estimate the energy of the primary cosmic ray particle only from geometrical parameters and the measured radio pulse height. Figure 2 shows the spread between the energy that was estimated this way from the radio data and the value for the primary particle energy provided by KASCADE Grande. This spread is the convolution of the error of the radio measurement and the error of the KASCADE-Grande value. In events with low signal to noise[3] the reconstructed pulse height can contain a significant noise contribution which then leads to an overestimation of the energy (seen as excess events at positive ΔE in fig. 2). At high primary energies this ceases to be a problem.

Conclusions

One issue that has to be kept in mind is that this analysis is only made with the east-west polarized component. This is probably the reason for the uncommon $1 - \cos\alpha$ dependence on the geomagnetic angle, which is neither predicted by theory nor seen in the historical experiments as presented in [2].

Nevertheless we have derived an analytical formula to estimate the height of the radio pulse from only the air shower geometry and the primary particle energy. As the shower geometry can also be determined from radio data [3] the inversion of this formula allows one to estimate the primary particle energy from radio data alone. The combined statistical spread for the estimation of the energy of single events from LOPES data and KASCADE-Grande data is 27% for strong events. This is in the same range as the fluctuations in measurements with particle detector arrays alone.

References

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3. And thus with little influence on the fit.

4. `http://www-ik.fzk.de/~ralph/CREAM.php`