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Analysis of inclined showers measured with LOPES

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ABSTRACT

In the present study, we analyze the radio signal from inclined air showers recorded by LOPES-30 in coincidence with KASCADE-Grande. LOPES-30 consists of 30 East–West oriented digital antennas, which are amplitude calibrated by an external source.

Radio emission from air showers is considered a geomagnetic effect. Inclined events provide a larger range of values for geomagnetic angle (angle between shower axis and geomagnetic field direction) than vertical showers and thus more information on the emission processes can be gathered.

In order to have the geometry of the air shower we use the reconstruction provided by the KASCADE-Grande particle detectors array. Analyzing events observed by both LOPES and the extended part of the KASCADE array, Grande, gives the possibility to test in particular the capability and efficiency of radio detection of more distant events. The results are compared with a previous analysis of inclined events recorded by the initial 10 antenna set-up, LOPES-10, in coincidence with the Grande array.

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1. Introduction

Air showers have been proved to generate radio waves in the MHz domain [1]. Since the 1960s different emission mechanisms have been proposed and studied. Recently another theory explains the radio emission from air showers as a synchrotron emission in the Earth's magnetic field, named *geosynchrotron emission* [2,3]. In order to study this geomagnetic effect we use the radio antenna array, LOPES (LOFAR Prototype Station) [4,5] placed within the area

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covered by a particle detector array, KASCADE-Grande. The present analysis is concerned with the LOPES set-up consisting of 30 V-shaped East–West oriented antennas detecting radio waves in the range of 40–80 MHz. The set-up is absolutely amplitude calibrated.

KASCADE-Grande consists of 37 scintillator particle detectors covering an area of 0.5 km^2. The Grande array gives information on shower parameters in the energy range of $10^{16}-10^{18}$ eV. We use the reconstructed core position from Grande as input data for LOPES analyzes. This coincidence study presents the advantage that we have access to reconstructed showers with core distances up to 800 m from the radio array.

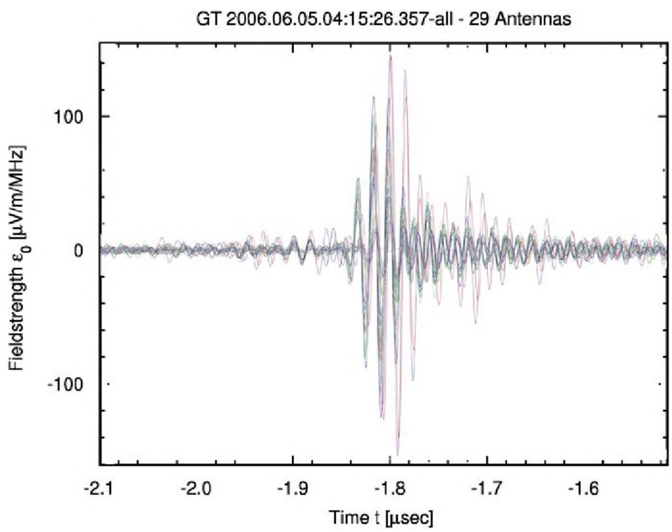

Fig. 1. Field strengths of individual antennas for a LOPES-30 event recorded on June 5th 2006, azimuth 211°, zenith 53° and geomagnetic angle 33°.

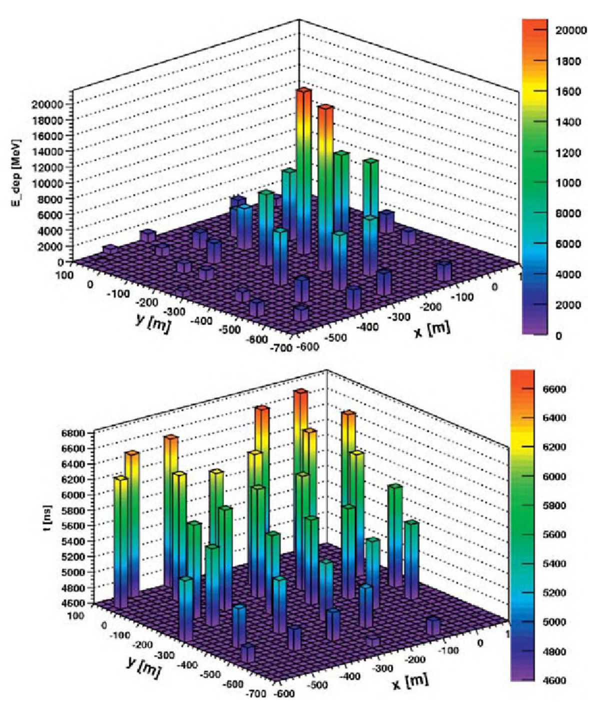

Fig. 2. Grande event reconstruction for the same event. The color code indicates magnitude of deposited energy in the upper plot and arrival time of shower particles to the detectors in the lower plot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The motivation of the study of inclined showers recorded by LOPES includes: the advantage to study correlations when information on a broader range of geomagnetic angles is available, test of radio detection at large angles and prospects for neutrino detection [6].

2. Data

In the present study, we use data recorded from January to July 2006 by LOPES-30 in the East–West configuration in coincidence with KASCADE-Grande. For the purpose of studying only bright and inclined events we have made a cut for zenith angle $>50°$ and muon number, $N_{\mu}>10^5$. The core, direction and arrival time reconstruction have been checked to assure the quality of the parameters used as input for the LOPES beamforming. In order to be clear of any atmospheric electric field contribution we ignored the events which occurred during thunderstorms.

Figs. 1 and 2 show the digital radio beams for a LOPES-30 event recorded on June 5th 2006, azimuth 211°, zenith 53° and geomagnetic angle 33° and the corresponding energy deposits and particle arrival times at the Grande detectors. The reconstruction check of an event is the starting point of the analysis. Besides being well reconstructed an event must also have clear coherent

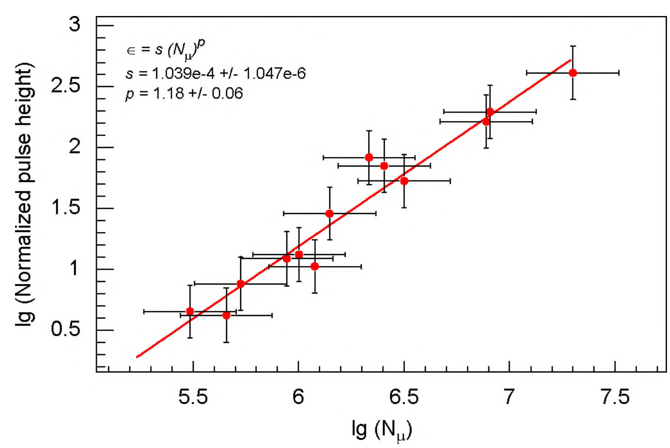

Fig. 3. LOPES-30. Normalized pulse height vs. muon number (primary energy estimator).

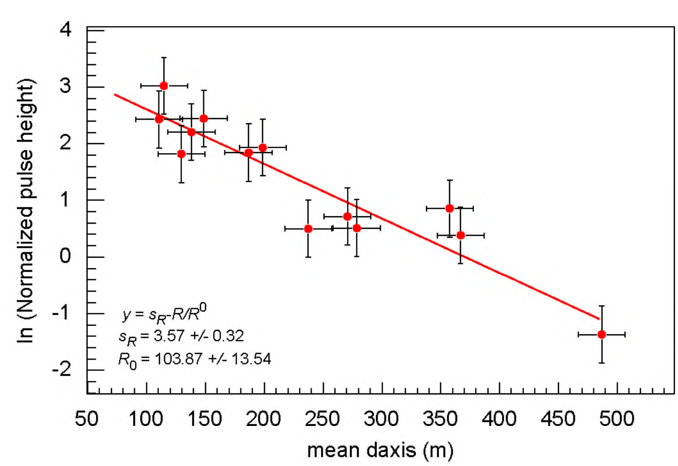

Fig. 4. LOPES-30. Normalized pulse height vs. mean distance from antennas to the shower axis.

radio signal. The analysis started with 268 events out of which only 14 had clear coherent radio signals.

The LOPES beam is digitally formed, meaning that signals from individual antennas are digitally added so reconstruct a single beam. After the initial beamforming an optimization has been performed both in radius of curvature of the wave front and core distance to take into account the uncertainties introduced by Grande, 1.5° in direction and 20 m in core position for inclined showers. The variation of the radius of curvature, even in small amounts, gives the most significant differences in the digitally formed signal, by contributing to the increase/decrease of the coherence, whereas the core position does not have much influence.

LOPES-10 events used for the comparisons were recorded from January to May 2004 with the original set-up of only 10 antennas and were processed the same way [7].

3. Correlations

The measured pulse height depends on three parameters: geomagnetic angle (angle between the shower axis and local magnetic field line), distance from the antennas/observer to the shower axis and shower size (related to primary energy). In order to study each dependence on its own we separate the parameters by doing separate fits in three iteration steps; in each step for one parameter the other dependencies are removed by dividing the result by the result of the fit from the previous iteration.

The errors used in the analysis are: 50% muon number error (due to the fact that the showers are inclined the reconstruction of the muon number is much more uncertain than for vertical showers) and 50% gain error, taken into account because the antenna model used in the calibration is based on simulations where the error is significantly increased for inclined showers.

Fig. 3 shows the normalized pulse height vs. muon number which is a good estimator for primary energy. If the pulse height (field strength) increases linearly with muon number then the signal power increases quadratically with the muon number (energy) as it is expected from a coherent radiation such as synchrotron radiation.

Fig. 4 shows the exponential dependence of the normalized pulse height on distance from antennas/observer to the showers axis.

The geomagnetic origin of the radiation is supported by the increase in pulse height with geomagnetic angle, Fig. 5. The form of the dependence is yet to be established after more statistics is available. Other effects are expected to be superimposed on the dominant geosynchrotron process, which can explain the non-zero values for the very low geomagnetic angle events.

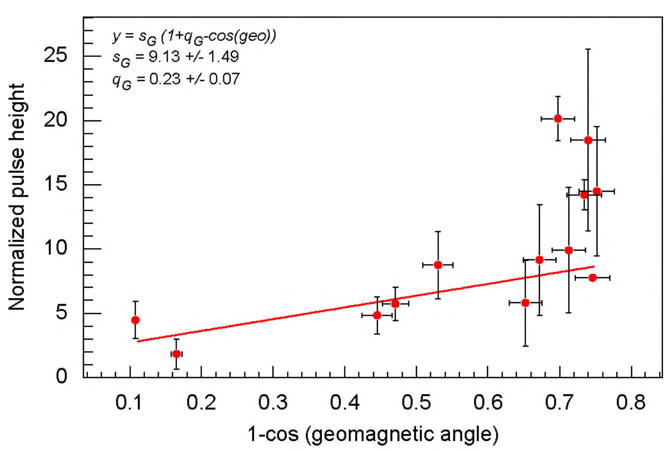

Fig. 5. LOPES-30. Normalized pulse height vs. geomagnetic angle.

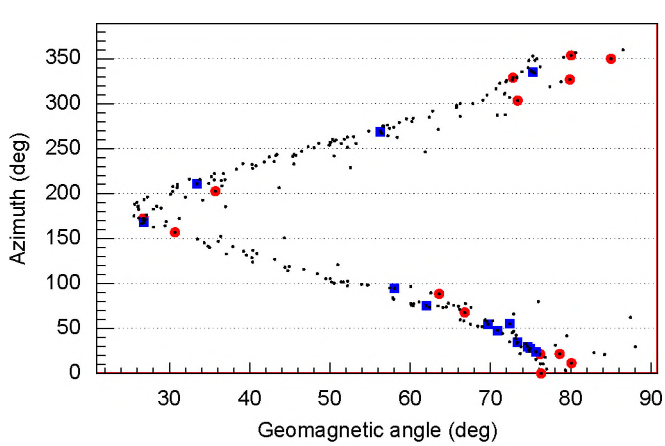

Fig. 6. Azimuth vs. geomagnetic angle. North = 360°/0°, East = 90°; black dots represent all events that are well reconstructed from the Grande data and also have radio data recorded while red circles represent only coherent radio signals from LOPES-10 data and blue squares coherent signals from LOPES-30. (For interpretation of the references to colors in this figure legend, the reader is referred to the web version of this article.)

4. Comparison with LOPES-10 data

Both sets of inclined showers investigated, LOPES-30 and LOPES-10 data, show a predominance in arrival direction North and rare East/West events, see Fig. 6. This is consistent with the geosynchrotron approach because the larger the geomagnetic angle the higher the radio pulse is and thus more showers are detectable; for Northern Europe the Northward arrival direction has the largest geomagnetic angle.

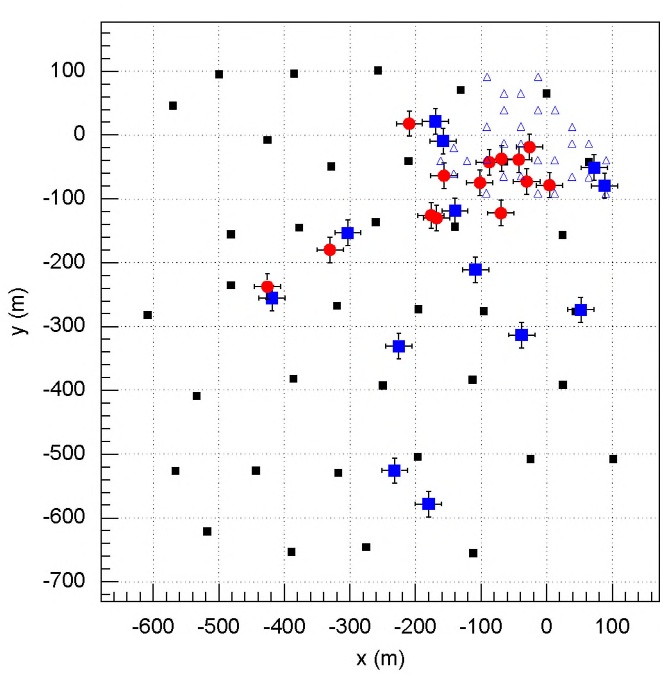

Fig. 7. Shower cores reconstructed by Grande for LOPES-30 and LOPES-10 radio events (colors and symbols same as the previous figure). Blue empty triangles are the radio antennas positions and black squares are the Grande detectors positions. (For interpretation of the references to colors in this figure legend, the reader is referred to the web version of this article.)

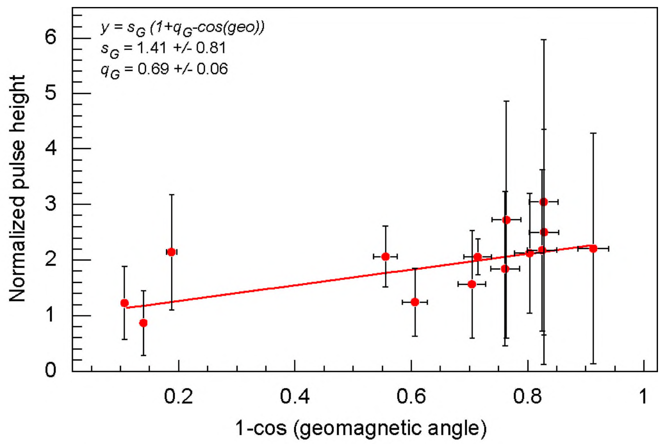

Fig. 8. LOPES-10. Normalized pulse height vs. geomagnetic angle.

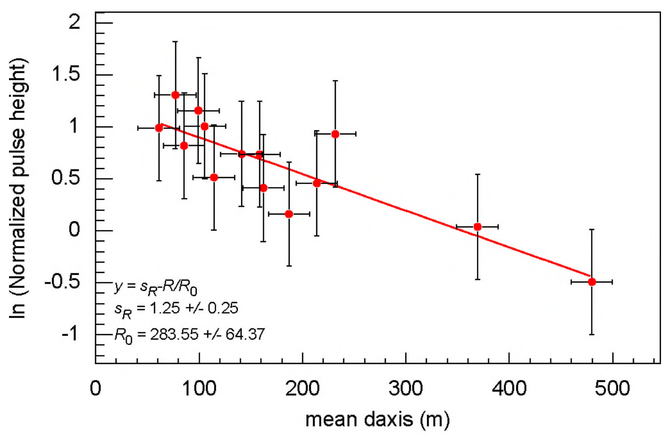

Fig. 9. LOPES-10. Normalized pulse height vs. mean distance from antennas to the shower axis.

The LOPES-10 data used in this comparison were taken in 2004 when the smaller antenna array did not have an absolute calibration which was performed in 2006 [8], therefore, due to the unknown real gain, there is a difference between pulse heights obtained in the two configurations. But, the correlations that involve the pulse height can still be investigated and compared as only the amplitude and not the shape of the dependencies would be influenced.

For the LOPES set-up with only 10 antennas (2004) the detected showers were closer to the array than for the extended LOPES-30 set-up (2006), due to the attenuation (see Fig. 7).

The correlations of the normalized pulse height with various parameters, for the LOPES-10 data set, are shown in Figs. 8–10. The features are the same as discussed for Figs. 3–5; therefore

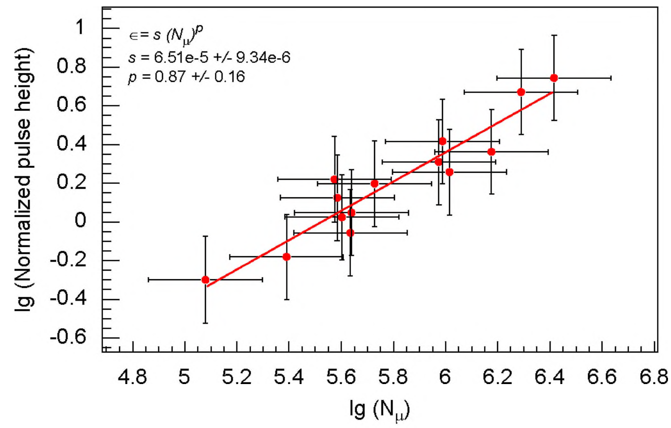

Fig. 10. LOPES-10. Normalized pulse height vs. muon number.

LOPES-30 data (now absolute amplitude calibrated) confirms the statements published in Ref. [6] obtained from LOPES-10 data.

5. Conclusions

The features observed in the correlations of pulse height vs. geomagnetic angle, distance and muon number in the LOPES-10 data are the same in the LOPES-30 data set. The changes in amplitude are due to the calibration of set-up . The predominance of Northward showers and the increase of pulse height with geomagnetic angle point to the geomagnetic origin of the radio emission in EAS as a dominant effect. Also, a power law with exponent 1 in the pulse height vs. muon number is expected for a coherent emission such as is the case of the geosynchrotron emission.

Acknowledgment

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