Nuclear Instruments and Methods in Physics Research A 630 (2011) 171–176

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Measurement of radio emission from extensive air showers with LOPES

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ARTICLE INFO

Available online 25 June 2010

Keywords:
Cosmic rays
Air shower
Radio emission
Radio detection

ABSTRACT

A new method is explored to detect extensive air showers: the measurement of radio waves emitted during the propagation of the electromagnetic shower component in the magnetic field of the Earth. Recent results of the pioneering experiment LOPES are discussed. It registers radio signals in the frequency range between 40 and 80 MHz. The intensity of the measured radio emission is investigated as a function of different shower parameters, such as shower energy, angle of incidence, and distance to shower axis. In addition, new antenna types are developed in the framework of LOPES^{star} and new methods are explored to realize a radio self-trigger algorithm in real time.

1. Introduction

An intense branch of astroparticle physics is the study of high-energy cosmic rays to reveal their origin, as well as their acceleration and propagation mechanisms [1–3]. At energies exceeding 10^{14} eV cosmic rays are usually studied by indirect measurements—the investigation of extensive air showers initiated by cosmic particles in the atmosphere. Different techniques are applied, like the measurements of particle densities and energies at ground level, or the observation of Cherenkov and fluorescence light. An alternative technique has been recently revitalized—the detection of radio emission from extensive air showers at energies exceeding 10^{16} eV.

Radio emission from air showers was experimentally discovered in 1965 at a frequency of 44 MHz [5]. The early activities in the 1960s and 1970s are summarized in Ref. [6]. Only recently, fast analog-to-digital converters and modern computer technology made a clear detection of radio emission from air showers possible. LOPES, a LOFAR Prototype Station had shown that radio emission from air showers can be detected even in an

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doi:10.1016/j.nima.2010.06.058

environment with relatively strong radio frequency interference (RFI) [7]. Further investigations of the radio emission followed with LOPES [8–12] and the CODALEMA experiment [13,14], paving the way for this new detection technique, see also Ref. [15].

The LOPES experiment registers radio signals in the frequency range from 40 to 80 MHz [16]. In this band are few strong man made radio transmitters only, the emission from air showers is still strong (it decreases with frequency), and background emission from the Galactic plane is still low. An active short dipole has been chosen as antenna. An inverted V-shaped dipole is positioned about 1/4 of the shortest wavelength above an aluminum ground plate. In this way a broad directional beam pattern is obtained. LOPES comprises 30 antennas [17] located on site of the KASCADE-Grande experiment [18,19] one of the best air shower experiments operating in the energy range between 10^{14} and 10^{18} eV. The LOPES data acquisition is triggered by large air showers registered with KASCADE-Grande. The latter measures the showers simultaneously to LOPES and delivers precise information on the shower parameters, such as shower energy as well as position and inclination of the shower axis. All antennas, including the complete analog electronics chain, have been individually calibrated with a reference radio source [20].

Most likely, the dominant emission mechanism of the radio waves in the atmosphere is radiation due to the deflection of charged particles in the Earth's magnetic field (geosynchrotron radiation) [21–23]. In the frequency range of interest the wavelength of the radiation is large compared to the size of the emission region: the typical thickness of the air shower disc is about 1–2 m only. Thus, coherent emission is expected which yields relatively strong signals at ground level.

2. Radio signal and shower parameters

One of the primary objectives of LOPES is to investigate the measured radio signal as a function of parameters characterizing the extensive air shower. For this purpose the shower parameters measured simultaneously with KASCADE-Grande are irreplaceable. An empirical relation has been found to express the expected east–west component of the field strength at a distance R from the shower axis as a function of shower parameters [24]

$$\varepsilon = (11 \pm 1)[(1.16 \pm 0.025) - \cos\alpha]\cos\theta$$

$$\exp\left(-\frac{R}{(236 \pm 81)\,\mathrm{m}}\right)\left(\frac{E_0}{10^{17}\,\mathrm{eV}}\right)^{(0.95 \pm 0.04)}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right]. \quad (1)$$

α is the angle between the shower axis and the direction of the Earth magnetic field (geomagnetic angle), θ the zenith angle of the shower, and E_0 the energy of the shower inducing primary particle. It is interesting to note the absolute values of some parameters: the exponential fall-off has a characteristic length of about 240 m, much larger than the classical Molière radius of electrons in air (≈ 80 m). This indicates that the lateral distribution of the radio component is flatter as compared to the electromagnetic component, an important fact to build large-scale radio arrays with an economic antenna density. The measured radio signal is almost directly proportional to the shower energy ($[0.95 \pm 0.04] \approx 1$). Such a behavior is expected for a coherent emission of the radio waves from the air showers. This calibration of the measured radio signal is a first important step towards the application of the radio detection as independent method to register extensive air showers.

Recently, the lateral distribution of the measured radio signals has been investigated in more detail [4]. A function of the form:

$$\varepsilon = \varepsilon_0 \exp\left(-\frac{R}{R_0}\right) \quad (2)$$

has been fitted to the measured field strength as a function of the distance to the shower axis R_0. The measured field strength as a function of the distance to the shower axis is presented in Fig. 1 for a typical event. The characteristic length R_0 for this example is of order of 100 m.

The investigations reveal that there are different types of air showers. Most of them have a lateral distribution which is characterized by a constant $R_0 \approx 100-200$ m, like the example shown in Fig. 1. On the other hand, there are few showers with relatively flat lateral distributions and corresponding values for R_0 as high as 1000 or 1200 m. A closer look indicates that the steepness of the fall-off R_0 depends on the mean distance to the shower axis R_{mean} and the zenith angle of the showers θ. The reconstructed scale parameter R_0 is plotted as a function of the relation $(1-\sin\theta)R_{mean}$ in Fig. 2. A correlation between the two quantities can be recognized. Large values for R_0 are obtained for showers with large zenith angles and a small average distance between the shower axis the antennas. But as not all events with small R_{mean} show a flattening—the reason is still unclear and further investigations with larger statistics are required.

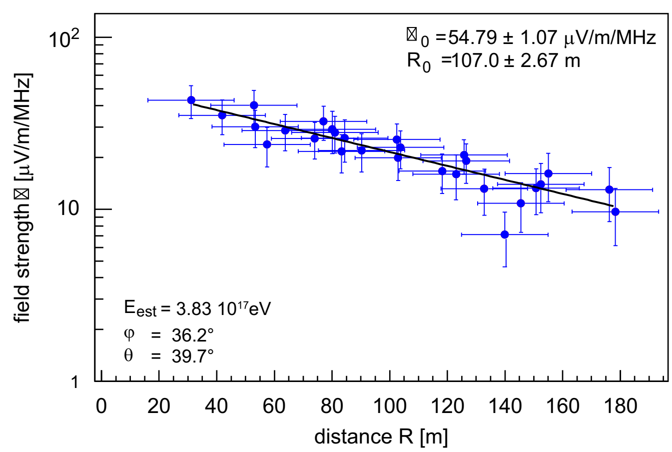

Fig. 1. Measured field strength as a function of the distance to shower axis for an individual shower [4].

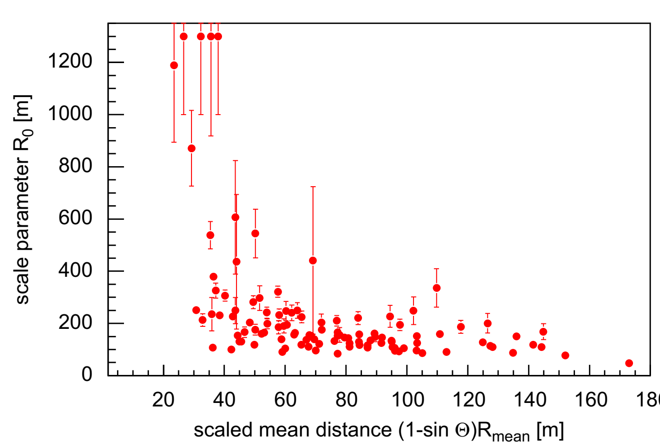

Fig. 2. Scale parameter R_0 as a function of the zenith angle times the mean distance to the shower axis [4].