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Measurement of the cosmic-ray energy spectrum above 10^{16} eV with the LOFAR Radboud Air Shower Array

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ABSTRACT

The energy reconstruction of extensive air showers measured with the LOFAR Radboud Air Shower Array (LORA) is presented in detail. LORA is a particle detector array located in the center of the LOFAR radio telescope in the Netherlands. The aim of this work is to provide an accurate and independent energy measurement for the air showers measured through their radio signal with the LOFAR antennas. The energy reconstruction is performed using a parameterized relation between the measured shower size and the cosmic-ray energy obtained from air shower simulations. In order to illustrate the capabilities of LORA, the all-particle cosmic-ray energy spectrum has been reconstructed, assuming that cosmic rays are composed only of protons or iron nuclei in the energy range between $\sim 2 \times 10^{16}$ and 2×10^{18} eV. The results are compatible with literature values and a changing mass composition in the transition region from a Galactic to an extragalactic origin of cosmic rays.

1. Introduction

The quest for the origin of cosmic rays is one of the most fundamental problems in Astroparticle Physics [1–3]. Since the discovery of these highly energetic particles more than a century ago, numerous measurements of several of their properties have been made, using sophisticated instruments (see e.g. Ref. [4] for a review). However, the exact nature of their sources still remains an open question. The search is mainly hindered due to the fact that cosmic rays, being charged particles, are scattered or deflected by the Galactic and inter-galactic magnetic fields during their propagation to the Earth, making it extremely difficult to reconstruct the direction of their sources. Nevertheless, observed cosmic-ray properties like the energy spectrum and composition have been used to understand and characterize the properties of the sources such as their Galactic or extragalactic nature, the cosmic-ray production spectrum and the power injected into cosmic rays (see e.g. Refs. [5–11] for recent reviews).

LOFAR, the LOw Frequency ARray, is an astronomical radio telescope [12]. It has been designed to measure the properties of cosmic rays above $\sim 10^{16}$ eV by detecting radio emission from extensive air showers in the frequency range of 10–240 MHz [13]. One of the main goals of the LOFAR key science project Cosmic Rays is to provide an accurate measurement of the mass composition of cosmic rays in the energy range between $\sim 10^{16}$ and $\sim 10^{18}$ eV, a region where the transition from Galactic to extragalactic cosmic rays is expected. This is being carried out by measuring the depth of the shower maximum ($X_{\max}$), using a technique based on the reconstruction of the two-dimensional radio intensity profile on the ground [14,15]. Another focus of the LOFAR cosmic-ray measurements is to understand the nature and production mechanisms of the radio emission from air showers. This is done by measuring various properties of the radio signals in great detail such as their polarization properties, the radio wave front and relativistic time compression effects on the emission profile [16–18].

In order to assist the radio measurement of air showers with LOFAR, we have built a particle detector array LORA (LOFAR Radboud

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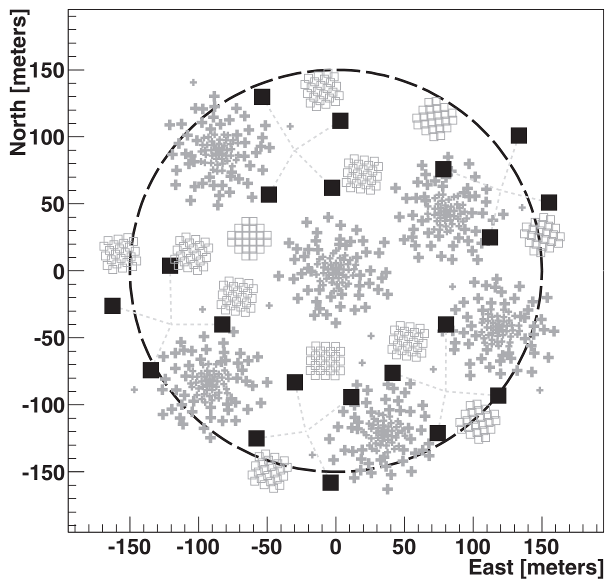

Fig. 1. Layout of the LORA array in the LOFAR core. The filled black squares represent the LORA detectors, the crosses the LOFAR low-band antennas and the empty squares the high-band antennas. The dashed circle in the figure illustrates the fiducial area of a radius of 150 m, which is used in the analysis.

Air Shower Array) in the center of LOFAR [19]. Its main objectives are to trigger the read-out of the LOFAR radio antennas to register radio signals from air showers, and to provide basic air shower parameters such as the position of the shower axis as well as the energy and the arrival direction of the incoming cosmic-ray. These parameters are used to cross-check the reconstruction of air shower properties, based on the measured radio signals. Currently, given the lack of an absolute calibration of the radio signals, the cosmic-ray energy is estimated through the reconstruction of the particle data. Therefore, an accurate energy reconstruction with LORA is essential for a proper understanding of the air showers measured with LOFAR.

In this article, we describe in detail the various steps of the energy reconstruction and present the cosmic-ray energy spectrum above $\sim 10^{16}$ eV as measured with LORA. The article is organized as follows. A short description of the setup will be given in Section 2 followed by a description of the data analysis technique in Section 3. The various steps involved in the Monte-Carlo simulation studies of the array will be described in Section 4, and a comparison between measurements and simulations for some of the air shower properties will be given in Section 5. In Sections 6 and 7, the energy calibration, the uncertainties in the reconstructed energies, and reconstructed cosmic-ray intensity will be described. The measured cosmic-ray spectrum and a comparison with the measurements of other experiments will be presented in Section 8, followed by a short conclusion and a future outlook.

2. LORA experimental setup and operation

LORA (the LOFAR Radboud Air Shower Array) consists of an array of 20 plastic scintillation detectors of size $\sim 0.95\,\mathrm{m} \times 0.95$ m each, distributed over a circular area with a diameter of ~ 320 m in the center of LOFAR [19]. The array is subdivided into 5 units, each comprising of 4 detectors. The detectors have a spacing between 50 and 100 m, and have been designed to measure cosmic rays with energies above $\sim 10^{16}$ eV. The array is co-located with six LOFAR stations.[1] The layout of the array is shown in Fig. 1. The data acquisition in each unit is controlled locally. A local trigger condition of 3 out of 4 detectors is set for each unit, and an event is accepted for a read-out of the full array when at least one unit has been triggered. A high-level trigger for the LOFAR radio antennas is formed when at least 13 out of the 20 detectors have measured a signal above threshold. More technical details can be found in Ref. [19].

3. Data selection and analysis

Data collected with the LORA array since its first science operation in June 2011 until October 2014 are used. Only data collected in periods with all 20 detectors in operation will be considered. This amounts to a total of 706.9 days of data. For the analysis, only showers that trigger a minimum of 5 detectors will be considered, which corresponds to a total of 1,861,045 air showers.

For every measured shower, the signal arrival time and the energy deposit in each detector are recorded. The relative signal arrival times between the detectors are used to reconstruct the arrival direction of the primary cosmic ray. The energy deposits are used to reconstruct the position of the shower axis and the shower size (the effective number of charged particles at the ground). The latter is determined in terms of the number of vertical equivalent charged particles, which may also include converted photons in addition to the dominant charged particles – electrons and muons. The shower axis position and the shower size are determined simultaneously by fitting a lateral density distribution function to the measured two-dimensional distribution of particle densities, projected into the shower plane. The particle density in each detector is obtained by first dividing the track-length-corrected[2] energy deposition by the energy deposition of a single particle obtained from calibration, and then by further dividing by the projected area of the detector in the shower plane. The lateral density distribution of an air shower is generally described by the Nishimura–Kamata–Greisen (NKG) function which is given by [20,21]

$$\rho(r) = N_{\mathrm{ch}} C(s) \left(\frac{r}{r_{\mathrm{M}}}\right)^{s-2} \left(1 + \frac{r}{r_{\mathrm{M}}}\right)^{s-4.5}, \tag{1}$$

where $\rho(r)$ represents the particle density in the shower plane at a radial distance r from the shower axis, N_{ch} is the shower size, s is shower age or lateral shape parameter and r_{M} is the radius parameter which is basically a measure of the lateral spread of the shower. The function $C(s)$ is given by

$$C(s) = \frac{\Gamma(4.5 - s)}{2\pi r_{\mathrm{M}}^2 \Gamma(s) \Gamma(4.5 - 2s)}. \tag{2}$$

In the case of LORA, the value of r_{M} is determined from the fit along with N_{ch} and the position of the shower axis. The parameter s is kept constant at a value of 1.7 throughout the fitting process. Simultaneous fitting of both r_{M} and s results in fits of poorer quality. Simulation studies have shown that keeping s constant gives better results than keeping r_{M} constant [22]. The fitting procedure is repeated three times with the output of each fit taken as starting values for the next iteration. Details about the minimization procedure and the choice of starting values as well as the reconstruction of the arrival direction of the primary particle are described in Ref. [19].

All showers that trigger at least 5 detectors with a minimum of 1 particle m^{-2} are allowed to pass through the reconstruction algorithm, and their shower parameters are calculated. Furthermore, only showers whose reconstructed position of the shower axis falls within 150 m from the center of the array are selected. The normalized distribution of r_{M} values for the selected showers with reconstructed sizes $\log_{10} N_{\mathrm{ch}} > 6.40$ and reconstructed zenith angles in the range of 0–15° are shown in Fig. 2 (left panel). The inset shows a

[1] Each LOFAR station consists of 96 low-band and 48 high-band antennas, operating in the frequency range of 10–80 MHz and 110–240 MHz, respectively.

[2] The measured energy deposit in each detector is corrected for the increase in the path length of the incident particles through the detector by multiplying by a $\cos\theta$ factor where θ is the zenith angle of the reconstructed arrival direction of the primary cosmic ray.