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LORA: A scintillator array for LOFAR to measure extensive air showers

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ABSTRACT

The measurement of the radio emission from extensive air showers, induced by high-energy cosmic rays, is one of the key science projects of the LOFAR radio telescope. The LOfar Radboud air shower Array (LORA) has been installed in the core of LOFAR in the Netherlands. The main purpose of LORA is to measure the properties of air showers and to trigger the read-out of the LOFAR radio antennas to register extensive air showers. The experimental set-up of the array of scintillation detectors and its performance are described.

1. Introduction

The search for the origin of the highest energy particles in the Universe is a big challenge in astroparticle physics [1–3]. From the experimental point of view, a precise measurement of the elemental composition of cosmic rays at the highest energies is crucial. The present work is part of an endeavor to establish a new method to measure air showers at high energies and determine the mass composition of cosmic rays with nearly 100% duty cycle: the radio detection of air showers [4]. To contribute to the measurement of radio signals from air showers with the LOFAR telescope [5], we have installed an air shower array in the LOFAR core.

High-energy cosmic rays impinging onto the atmosphere of the Earth induce cascades of secondary particles. The bulk of the charged particles is electrons and positrons. They are deflected in the magnetic field of the Earth, while in addition, there is an excess of negative charge. This yields the emission of coherent radiation with frequencies of tens of MHz, e.g. [6–9].

The feasibility of quantitative radio measurements of air showers has been demonstrated with the LOPES experiment (LOFAR prototype station) [10–12]. It has been shown that radio emission can be detected using low-noise amplifiers and fast digitizers in combination with sufficient computing power to analyze the registered signals.

Radio emission from air showers is detected with the LOFAR radio telescope in the framework of the LOFAR key science project *Cosmic Rays* [13]. The LOw Frequency ARray (LOFAR) is a digital observatory [5]. The main focus of the astronomy community is to observe the radio Universe in the frequency range of 10–240 MHz.

More than 40 stations with fields of relatively simple antennas work together as a digital radio interferometer, i.e. the measured signals are digitized with fast ADCs and correlations are formed in a central processing unit. The antenna fields are distributed over several countries in Europe with a dense core in the Netherlands. The latter consists of 24 stations on an area measuring roughly 5 km^2. Each station comprises 96 low-band antennas, simple inverted V-shaped dipoles, operating in the frequency range of 10–80 MHz. Each antenna has two dipoles, oriented perpendicular to each other. In addition, fields of high band antennas[1] cover the

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[1] The fields comprise 48 antennas in the Dutch stations and 96 in the European ones.

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frequency range of 110–240 MHz. The signals from the antennas are digitized and stored in a ring buffer (transient buffer board, TBB). A triggered read-out of these buffers will send the raw data to a central processing facility.

An ultimate goal is to independently detect radio emission from air showers with LOFAR. This requires a sophisticated trigger algorithm that analyses the digitized antenna signals in real time. To assist with the development of the trigger algorithm and to measure basic air shower parameters, an array of particle detectors has been at LOFAR.

The LOFAR Radboud Air Shower Array (LORA) is an array of scintillation counters, located in the innermost center of LOFAR, the *superterp*. It has been designed to register air showers initiated by primary particles with energies exceeding 10^{16} eV. Strong radio signals are expected from air showers in this energy region. This energy regime is also of astrophysical interest, as a transition is expected from a Galactic to an extra-galactic origin of cosmic rays at energies between 10^{17} and 10^{18} eV [2,3].

In the following, we describe the set-up of LORA and its properties. The experimental set-up is described in Section 2 and the detector calibration in Section 3. The various steps involved in the reconstruction of air shower parameters are described in Section 5 and in Section 6 the reconstruction accuracies are discussed, followed by a review of the array performance in Section 7.

2. Experimental set-up

LORA comprises 20 detector units, located on a circular area with a diameter of about 320 m. The positions of the detectors in the innermost core of LOFAR are illustrated in Fig. 1. The array is sub-divided into five units, each comprising four detectors. The detectors are located on circles with a radius of about 40 m around a central electronics unit, with a spacing of 50–100 m between the detectors.

Each detector unit contains two pairs of scintillators (NE 114) with the dimensions $47.5 \times 47.5 \times 3\ \mathrm{cm}^3$, read out via wavelength shifter bars (NE 174 A) through a photomultiplier tube (EMI 9902).[2] A detector unit, containing the two pairs of scintillators and two photomultiplier tubes, is sketched in Fig. 2. The detectors are installed inside weatherproof shelters.

The two photomultipliers in one detector unit share a common high-voltage channel. To match the gain of the two tubes, we use a resistor network to adjust the voltage correspondingly. The signals of the two photomultiplier tubes in each detector are read out via RG223 coaxial cables and a passive connection into a single digitizer channel. 12-bit ADCs are used, which sample the incoming voltage with a time resolution of 2.5 ns[3] [15]. A field programmable gate array (FPGA) provides a trigger signal in real time.

Four detectors form (electronically) a unit, comprising two digitizer units (with two electronic channels each) [15,16], controlled by a Linux-operated, single-board mini PC. The two digitizer units operate in a master and slave combination like a four-channel oscilloscope, where the master generates a common trigger for both the digitizer units. The master digitizer contains a GPS receiver (Trimble, Resolution T), which provides GPS time stamps to both the digitizer units. Each digitizer contains a 200 MHz clock counter to assign a time stamp with nanoseconds accuracy to each triggered signal.

The pulse per second signals (1PPS) from this type of GPS receiver can introduce a timing uncertainty of up to a maximum of

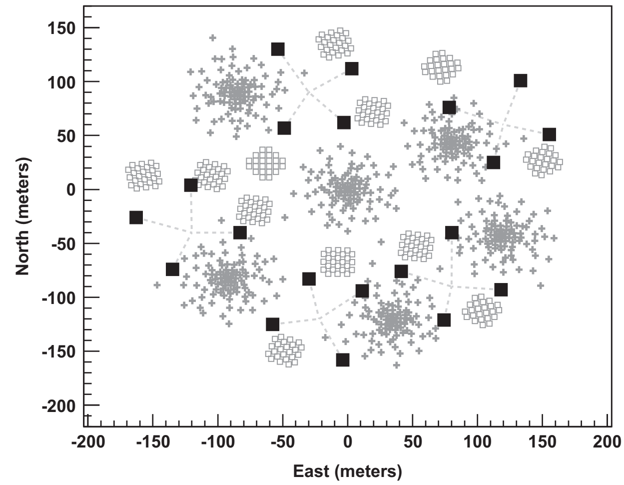

Fig. 1. Layout of LORA in the dense core in the center of LOFAR. The squares represent the positions of the particle detectors. The crosses and open squares represent the two different types of LOFAR radio antennas. The dotted lines indicate the grouping of the detectors for the data acquisition.

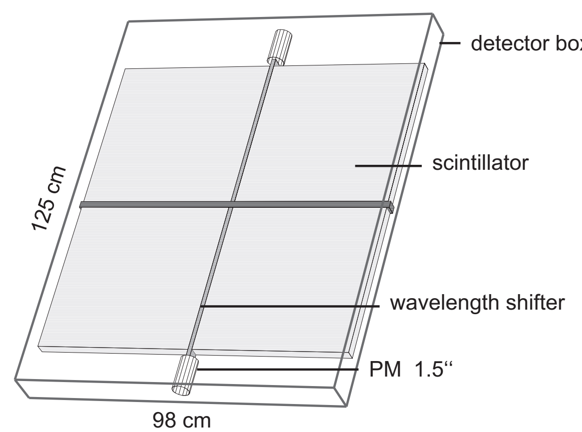

Fig. 2. Schematic view of a scintillation detector. Sheets of plastic scintillator are read out by photomultiplier tubes via wavelength shifter bars [14].

20 ns. This error is stored every second during the data taking. It is corrected for the event time stamp in the offline data analysis using a proper correction formula [17]. The time stamp calculation also takes into account the fluctuations in the number of clock periods of the 200 MHz clock counter between two PPS signals.

The two digitizers are connected to the PC through an USB interface. The PC also controls a four-channel high-voltage supply through one of the digitizer units. The FPGA inside the digitizer unit controls an input–output register, which is connected to the high-voltage supply, allowing to set the individual voltages on the four channels remotely. A block diagram of the electronics components is depicted in Fig. 3.

When the four input signals from the PMTs in an electronics unit satisfy a local trigger condition, usually three out of four detectors in coincidence within 400 ns the digitizers send the data to the local computer. The data from the five mini PCs consequently are sent via Ethernet to a central, Linux-operated master computer, where the main data acquisition (DAQ) runs. Within 100 ms all data are collected from the other electronics units. The received time stamps, which are each assigned according to the first threshold crossing in a detector, are checked for coincidences (500 ns window) and are combined to an event file that is stored locally. A simple analysis is performed on these data, which reconstructs arrival direction and core position to allow for

[2] The detectors were previously operated in the KASCADE calorimeter [14].

[3] Internally, two ADCs are used per channel, sampling the same input signal at 200 MHz with an offset of half a clock cycle.