Nuclear Instruments and Methods in Physics Research A 615 (2010) 277–284

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

New method for the time calibration of an interferometric radio antenna array

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ARTICLE INFO

Article history:
Received 19 October 2009
Received in revised form
20 January 2010
Accepted 22 January 2010
Available online 2 February 2010

Keywords:
LOPES
Radio detection
Cosmic ray air showers
Calibration
Timing

ABSTRACT

Digital radio antenna arrays, like LOPES (LOFAR PrototypE Station), detect high-energy cosmic rays via the radio emission from atmospheric extensive air showers. LOPES is an array of dipole antennas placed within and triggered by the KASCADE-Grande experiment on site of the Karlsruhe Institute of Technology, Germany. The antennas are digitally combined to build a radio interferometer by forming a beam into the air shower arrival direction which allows measurements even at low signal-to-noise ratios in individual antennas. This technique requires a precise time calibration. A combination of several calibration steps is used to achieve the necessary timing accuracy of about 1 ns. The group delays of the setup are measured, the frequency dependence of these delays (dispersion) is corrected in the subsequent data analysis, and variations of the delays with time are monitored. We use a transmitting reference antenna, a beacon, which continuously emits sine waves at known frequencies. Variations of the relative delays between the antennas can be detected and corrected for at each recorded event by measuring the phases at the beacon frequencies.

1. Introduction

For the study of ultra-high energy particles from the cosmos the measurement of the radio emission from secondary particle showers generated in air or dense media is evolving as a new technique [1]. First measurements of the radio emission of cosmic ray air showers had been done already in the 1960's [2], but with the analog electronics available at that time, the technique could not be competitive with traditional methods like the detection of secondary particles on ground or the measurement of fluorescence light emitted by air showers. Recently, the radio detection method experienced a revival because of the availability of fast digital electronics. Pioneering experiments like LOPES [3] and CODALEMA [4] have proven that radio detection of cosmic ray air showers is possible with modern, digital antenna arrays. Due to the short duration of typically less than 100 ns of the air shower induced radio pulse, the experimental procedures are significantly different from those of classical radio astronomy.

The main goal of the investigations is the detailed understanding of the shower radio emission and the correlation of the measured field strengths with the primary cosmic ray characteristics. The sensitivity of the measurements to the direction of the shower axis, the energy and mass of the primary particle are of particular interest. Radio antenna arrays can derive the energy of the primary particle by measuring the amplitude of the field strength, and reconstruct the direction of the incoming primary particle by measuring pulse arrival times—with the remarkable difference to other distributed sensor networks, that with LOPES, the arrival direction is reconstructed using digital interferometry which demands a precise time calibration. Another goal is the optimization of the hardware (antenna design and electronics) for a large scale application of the detection technique including a self-trigger mechanism for stand-alone radio operation [5,6].

LOPES was built as a prototype station of the astronomical radio telescope LOFAR [7,8] aiming to investigate the new detection method in detail. LOPES is a phased array of radio antennas. Featuring a precise time calibration, it can be used for interferometric measurements, e.g. when forming a cross-correlation beam into the air shower direction [9]. Thus, LOPES is sensitive to the coherence of the radio signal emitted by air showers, allowing to perform measurements even at low signal-to-noise ratios in individual antennas.

This paper describes methods for the calibration and continuous monitoring of the timing of a radio antenna array like LOPES and

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doi:10.1016/j.nima.2010.01.072

shows that it is possible to achieve a timing accuracy in the order of 1 ns by combining these methods for such kind of arrays. Beside the measurement and correction of group delays and frequency dependent dispersion of the setup, we use a transmitting reference antenna, a beacon, which continuously emits sine waves at known frequencies. This way, variations of the relative delays between the antennas can be detected and corrected for in the subsequent analysis of each recorded event by measuring the relative phases at the beacon frequencies. This is different from the time calibration in other experiments, like ANTARES [10], ANITA [11] and AURA [12] which determine the arrival times of pulses emitted by a beacon. In addition, AURA has the capability to measure frequency shifts of constant waves for calibration [13]. The use of phase differences of a continuously emitting beacons is reported for ionospheric TEC measurements [14], where the measurement of phases of a beacon signal is used for atmospheric monitoring, not for time calibration. Where the individual methods described in this work are more or less standard in sensor based experiments, their combination to achieve the possibility of interferometric measurements is new and applied for the first time in LOPES.

2. The LOPES antenna array

The main component of LOPES consists of 30 amplitude calibrated, inverted V-shape dipole antennas [15,16]. The antennas are placed in co-location with the particle air shower experiment KASCADE-Grande [17,18] (Fig. 1). KASCADE-Grande consists mainly of stations equipped with scintillation detectors on an area of $700 \times 700\,m^2$, where 252 stations compose the KASCADE array, and further 37 large stations the Grande array. Besides the 30 LOFAR-type antennas, LOPES consists also of newly designed antennas forming the LOPES^{STAR} array [19]. The main purpose of LOPES^{STAR} is to optimize the hardware for an

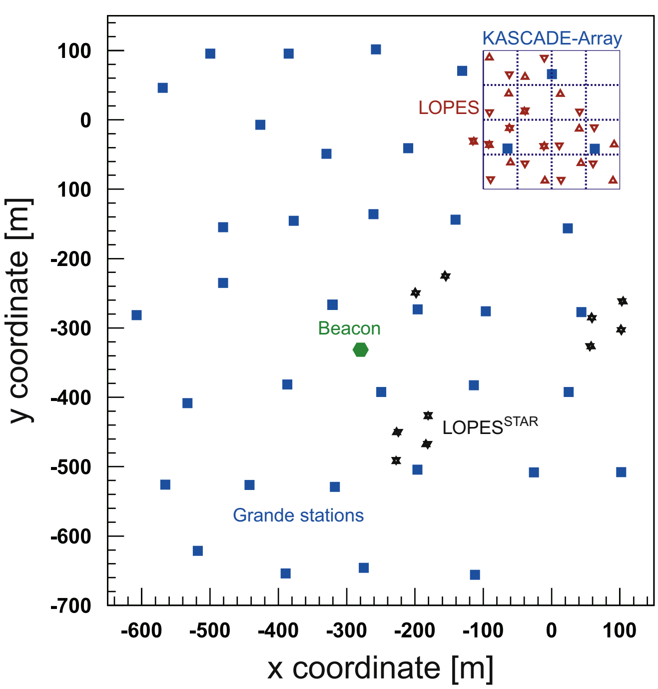

Fig. 1. Current setup of the LOPES experiment which is co-located with the KASCADE-Grande experiment at Karlsruhe Institute of Technology, Germany. Upward triangles mark east-west oriented antennas, downward triangles north-south oriented antennas, respectively. A star indicates an east-west oriented and a north-south oriented antenna at the same place.

application of this measuring technique to large scales, e.g. at the Pierre Auger Observatory [20]. All antennas are optimized to measure in the range of 40–80 MHz which is less polluted by strong interference than, e.g. the FM band. The positions of the antennas have been determined by differential GPS measurements with a relative accuracy of a few cm.

Whenever KASCADE-Grande measures a high-energy event, a trigger signal is send to LOPES which then stores the digitally recorded radio signal as a trace of 2^{16} samples with a sampling frequency of 80 MHz, where the trigger time is roughly in the middle of the trace. As a band-pass filter is used to restrict the frequency band to 40–80 MHz, LOPES is operating in the second Nyquist domain and contains the complete information of the radio signal within this frequency band. Recovery of the full information is possible by an up-sampling procedure, i.e. the correct interpolation between the sampled data points which is done by a zero-padding algorithm [21–23]. This way, sample spacings of 0.1 ns can be obtained within reasonable computing time, which is considerably smaller than the uncertainties of the timing introduced by other sources (see below). Thus, the sampling rate does not contribute significantly to systematic uncertainties.

More details of the experimental set-up, the amplitude calibration, the operation, and the analysis procedures of LOPES can be found in references, e.g. [9,16].

3. Need for a precise time calibration

The angular resolution, respectively source location, of LOPES is limited to about 1° [24] due to the uncertainties of the emission mechanism of the radio pulse, and thus, by the uncertainties in the shape of the wave front of the radio emission. Consequently, for LOPES, improving the accuracy of the time calibration to about 1 ns is not expected to significantly improve the angular resolution. Instead, this good timing resolution is a necessary requirement to enable the use of LOPES as a digital radio interferometer. Hence, this is the most important among several reasons why a precise time calibration with a relative accuracy in the order of or below 1 ns is desirable for a radio air shower array:

- Interferometry: A timing precision which is at least an order of magnitude better than the period of the filter ringing ($\sim$ 17 ns for LOPES) allows one to perform interferometric measurements if the baselines of the interferometer are adequate for the angular scale of the observed source. As the distance of the source of radio emission from cosmic ray air showers to the LOPES antenna array (several km) is much larger than the extension of the source region and the lateral extension of the array ($\sim$ 200 m), the angular extension of the source is small. Hence, one expects that every antenna detects the same radio pulse just at a different time. Thus, LOPES should see coherent radio signals from air showers on the ground, which has been experimentally verified [3], and can be exemplarily seen in Fig. 2. This coherence is measurable, e.g., by forming a cross-correlation beam into the air shower direction [25], and can be used to distinguish between noise (e.g. thermal noise and noise originating from the KASCADE particle detectors) and air shower signals.

  The requirement of a timing precision in the order of 1 ns for the interferometric cross-correlation beam analysis, can be quantitatively verified by adding an additional and random timing uncertainty to each antenna, and studying the influence on the reconstructed cross-correlation beam which is a measure for the coherence. This has been done for the example event (Fig. 2) by shifting the traces of each antenna