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Radio detector array simulation
A full simulation chain for an array of antenna detectors

Stefan Fliescher

3.Physikalisches Institut A, RWTH Aachen University, Germany

For the Pierre Auger Collaboration[1]

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ABSTRACT

Recently radio signals originating from extensive air showers have been observed at the Pierre Auger Observatory. In this note we present software to simulate the response of an array of antenna detectors and to reconstruct the radio signals. With this software it is possible to investigate design parameters of an antenna array and to visualize the radio data. We show comparisons between measurements of radio signals from air showers and simulated data which were generated with the REAS2 generator and then processed with the detector simulation and reconstruction software.

1. Introduction

Besides the well-established observation techniques of cosmic ray induced air showers, it is possible to detect air showers due to their emission of electro-magnetic waves at frequencies in the radio regime [1,2]. This radio technique gives calorimetric information of the air shower with a high duty cycle and good precision in the reconstruction of the shower direction. An engineering radio setup [3] is currently in operation at the Pierre Auger Observatory [4,5].

2. Experimental setup

One of the used Radio Detector (RD) setups consists of three positions where antennas are mounted forming a triangle with an edge length of 100 m. On two positions logarithmic periodic dipole antennas (LPDA) [6] are employed. On the third position an inverted v-shaped dipole from LOFAR [7] is used. The East–West and North–South polarizations of the antennas can be read out separately. In combination with additional amplifiers and filters the setup is sensitive to frequencies in the radio regime between 40 and 80 MHz. Two scintillator plates provide an external trigger to readout the antennas. Details are described in Ref. [8].

3. Event data sets

3.1. Measured events

Radio data are recorded using an external trigger. They are compared offline with the shower reconstruction of the surrounding surface detector. Within its first year of data taking, 313 coincident events were recorded. The energies of these events range from 10^{17} to 10^{19} eV. The most energetic event observed so far had an energy of 1.1×10^{19} eV. The average uncertainty of the distance between core and antenna position in the measured data is $\sigma_d \approx 74$ m.

3.2. Simulated events

A simulation chain has been set up to produce simulated radio events having the same kinematic quantities as the 313 measured events. This chain consists of the generation of a CORSIKA [9] shower using the kinematic shower quantities as derived from the SD reconstruction. The shower particle content is then processed with REAS2 [10], which delivers the electric field at each antenna position. Finally, the electric fields are used by RDAS, the Radio Detector Array Simulation, to calculate the response of the antennas to the shower radio signal according to the characteristics of our setup. The content of the RDAS software will be described in Section 4 in more detail.

As the radio pulse amplitude is expected to decrease strongly with increasing lateral distance to the shower axis, the uncertainty of the shower core position needs to be taken into account when comparing data and simulations. To investigate the impact

E-mail address: stefan.fliescher@physik.rwth-aachen.de

[1] Av. San Martin Norte 304 (5613) Malargüe, Prov. de Mendoza, Argentina.

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of the core position on the simulated amplitude, we shift the shower core position 25 times within the reconstruction uncertainties.

4. Detector simulation

The RDAS detector simulation calculates the response of the antennas to the electric field of the shower pulse using the Nec2 antenna simulation program [11]. Additionally, the influence of amplifiers, cables, filters and the digitizer on the signal is calculated. Starting with the three-dimensional vector of the electric field coming from the REAS2 program (Fig. 1a), the result of the simulation is the voltage trace displayed in Fig. 1b. Furthermore in the RDAS program noise is added to the simulated traces starting with the parametrization of the galactic and extragalactic noise background done by Cane [12].

The RDAS software is set up in a modular way such that it can be adjusted to simulate different detector setups easily. The simulation modules access the data over a common data interface.

Also a reconstruction of the shower parameters is performed within the RDAS software. Starting with the timing and the amplitudes of a radio pulse in a set of antennas, the zenith and the azimuth angle of the shower are reconstructed with a plane fit. To find a radio signal within a given trace of a recorded or simulated antenna readout, a search for the maximum voltage amplitude A is performed. We use the signal-to-noise ratio:

$$S/N = \frac{A^2}{\sigma^2_{noise}} \tag{1}$$

to decide if a pulse originates from an air shower. The reconstruction of the RDAS program allows to impose a minimum signal-to-noise requirement which has to be fullfilled by a signal trace to be considered in the reconstruction. The reconstruction program will be used extensively in Section 6.

5. Event display

An event display has been developed to provide standard visualization methods for the data. In Fig. 2 the positions of the antennas are displayed. The strength of the signal is given in terms of signal to noise as defined in Eq. (1) by the size of the bars separately for the East–West and the North–South direction of the antennas. The timing information are marked with the color code.

The event display accesses the data by means of the same data interface that is used in the detector simulation.

6. Benchmark of simulated radio event with recorded data

We compare the simulated data described in Section 3.2 with the recorded radio events. Fig. 3 displays a direct comparison of a simulated and a recorded trace [8].

6.1. Angular resolution

We investigate the angular distance between the shower angles from the SD reconstruction and the corresponding values of the RD for both the simulated and the recorded radio events:

$$\Delta\theta = \theta_{\mathrm{RD}} - \theta_{\mathrm{SD}} \tag{2}$$

$$\Delta\phi = (\phi_{\mathrm{RD}} - \phi_{\mathrm{SD}})\sin\theta_{\mathrm{SD}} \tag{3}$$

where the factor $\sin\theta_{\mathrm{SD}}$ results from the treatment in spherical coordinates. The mean energy of the air showers in the measured data set is $\sim 6.7\times10^{17}$ eV. In case of such low energies events the precision of the SD reconstruction is in the order of 1.9° in zenith and azimuth angle [13]. To take the angular resolution of the SD into account, we randomly shift the angles of the SD reconstruction within their uncertainties, when the distributions from Eqs. (2) and (3) are calculated for the simulated radio events. The uncertainty of the antenna positions does not give a major contribution to the angular resolution and has been neglected in the calculation.

The resolution of the RD is deduced requiring a S/N above 14. Within an angular distance of $\pm 20^\circ$ the distributions are displayed in Fig. 4.

6.2. Lateral detection efficiency

We investigate the detection probability of radio signals at different distances perpendicular to the shower axis. We select the two antenna positions of the RD, where LPDAs are mounted. For each of the externally triggered 313 radio events observed in coincidence with the SD, we calculate the distances of the shower core to the two antenna positions perpendicular to the shower axis. In this contribution, we define the detection efficiency in the following way: we count the number of radio pulse amplitudes observed at the different distances from the shower core. An amplitude is identified as a radio pulse, when its signal-to-noise

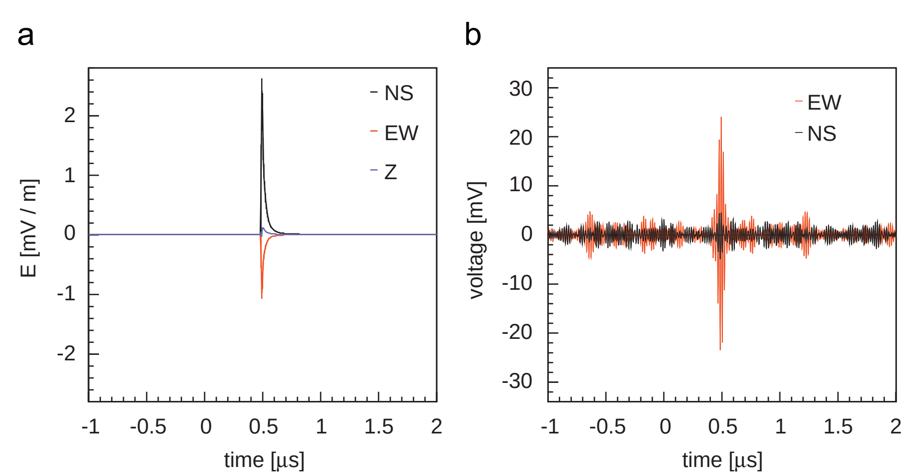

Fig. 1. (a) The starting point for the detector simulation is the simulated electric field at each antenna position. (b) The RDAS software simulates the detector response and adds noise to the signal.