Technological developments for the Auger Engineering Radio Array (AERA)

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Abstract. The Auger Engineering Radio Array consists of 124 radio stations covering 6 km^2 installed within the low energy extension of the Pierre Auger Observatory in Argentina; this location allows a radio multi-hybrid measurement of air-showers with the fluorescence telescopes, the water-Cherenkov and the muon detectors. AERA detects the radio emission from cosmic-ray induced air showers above 10^{17} eV. The measured electric field is used to constrain the characteristics of the primary particle: arrival direction, energy and particle type (mass). These studies are possible due to an instrumentation development allowing externally-triggered in parallel with self-triggered measurements in the MHz domain and an improved understanding of the radio emission processes. We will present the main technological developments of AERA that have been realized since 2010, within the Pierre Auger Collaboration, to reach the requested quality allowing the accurate measurement of the electric field emitted by air showers. We will review the antennas and their low noise amplifiers (LNA), the trigger algorithm and the full acquisition chain up to the communication system.

Keywords: radio detection cosmic rays AERA Pierre Auger Observatory
PACS: 95.55.Vj, 96.50.sd, 07.57.-c

INTRODUCTION

One of the challenging questions related to cosmic rays concerns their nature. Improving our knowledge about the composition of the cosmic rays at the highest energies will allow one to constrain the models concerning their origin and their production mechanisms in the astrophysical sources. Several techniques exist to study the nature of cosmic rays. The most commonly used is the measure of the fluorescence light with UV telescopes, which give a direct access to the longitudinal profile of the shower, sensitive to the nature of the primary. But, due to its small duty cycle (around 14 %) [1], this technique suffers from a lack of statistics. It has been shown with simulations [2, 3, 4] and experimentally [5], that the electric field emitted during the shower development also gives access to the longitudinal profile, with a duty cycle close to 100 %. Since the middle of the 2000's, the Pierre Auger Observatory hosted several radio detection arrays in the MHz domain: RAuger [6], installed in 2006, and MAXIMA [7], installed in 2007. Taking benefit of its two pathfinders, the Auger Engineering Radio Array (AERA) was installed at the observatory in 2010. In this document we will review the different instruments composing an individual station. The main results of AERA are presented in [8] and the data reconstruction process is presented in [9].

AERA

AERA covers currently 6 km^2 with 124 radio stations measuring the horizontal polarization of the electric-field: east-west (EW) and north-south (NS). AERA-24, composed of 24 stations, has taken data since 2011 and constitutes the dense core of the array; the stations are located at 144 m from each others. AERA has then been extended in May 2013 to achieve the current status of the array. The stations of AERA-124 are spaced by 250 m or 375 m. Different instruments are used in the array following a continuous technological development in order to keep improving the measurement of the electric-field emitted by air-showers. The stations can be grouped in three categories based on the trigger system which is used:

- 77 stations are both self-triggered and externally-triggered (mainly by the surface and the fluorescence detector of the Pierre Auger Observatory (SD and FD);

- 6 stations are purely self-triggered;
- 40 stations are both self-triggered and triggered by small local scintillators.

For each station the detection of an event follows this chain: the electric-field emitted by the shower is firstly detected by an antenna and directly amplified by a LNA, the signal is then analogically processed, being filtered and amplified. Then the signal goes through a digital block whose main purpose is to digitize the signal and to apply the low level trigger algorithms for the self-trigger (level 1 trigger: T1 and level 2: T2). The data are then transferred from the local station (LS) in the field to the central data acquisition system (DAQ), located in a fluorescence detector (FD) building (Coihueco) close to AERA, this is done through communication antennas for AERA-124 and an optical fiber system via a central radio station and a wireless link for AERA-24. The stations are solar powered and are equipped with a GPS antenna (identical to the surface detector (SD) one) for precise time measurements.

THE ANTENNAS AND THEIR LNAs

Major components of a station are its antenna and its low noise amplifier (LNA) which have to be wide band, as sensitive as possible to the radio signal and induce the smallest signal dispersion. It also has to be robust as the site is exposed to high speed winds (up to 160 km/h). For the deployment of a large array, the antenna should be easy to install and should minimize the costs for production and maintenance. AERA is equipped with two antenna types.

For AERA-24, the choice of the antenna was based on the immediate availability of a sufficient number of antennas to build the dense core of the array. The antennas are Log-Periodic Dipole Antennas (LPDA) which were used for MAXIMA. Each of them is composed of two independent planes measuring 4 m $\times$ 4 m, placed at 3.4 m from the ground. Each antenna has a dedicated LNA: an Infineon amplifier with BGA420 MMIC [10]. The LPDA provides good data for AERA-24 together with a stable acquisition.

For AERA-124, a detailed study of different antenna types was done to find the one that fits best the requirements of a large-scale array [11]. The performances of the LPDA were compared to the ones of the Butterfly antenna, designed and developed at Subatech for the CODALEMA experiment [12], and the antenna currently used for the Tunka-Rex experiment [13]. The Butterfly antenna is composed of two active bowtie antennas measuring 2 m $\times$ 2 m associated to a LNA ASIC - AMS BiCMOS 0.8 μm [12]. The Butterfly was used for RAuger and allows one to measure the signal on a wide frequency range due to the dependency of its LNA on frequency.

The data measured with an antenna and its LNA are the convolution of the incoming electric field with the antenna and the electronics responses. The latter must be well known to allow an efficient deconvolution of the incoming signal. The antennas were tested in the 30-80 MHz range corresponding to the radio quiet band of the AERA site. Their responses to a transient signal, presented in figure 1, were compared to a bandwidth-limited Dirac pulse corresponding to an ideal antenna with only a bandwidth limitation applied. We can see that the pulse measured with the Butterfly is very similar to the Dirac one both in time and in amplitude, contrary to the pulse measured with the LPDA. This latter presents an offset of around 70 ns and a diminution of the amplitude. These effects have to be removed from the data before analysis. The second main important parameter of the combination antenna/LNA is its sensitivity to the radio signal, indeed it is this combination that determines the signal-to-noise ratio of the antenna. The sensitivity of the two antenna types to the main continuous radio contribution, the galactic radio background, has been compared. Continuous spectra have been measured with the antennas during four days at the radio-astronomy station of Nançay. The results of the measurement campaign are shown in the figure 1. The rise and fall of the galactic plane are visible with both antennas but with different sensitivities. The most precise measurement is obtained with the Butterfly antenna.

Among the studied antennas, the one that minimizes the signal dispersion and that presents the best sensitivity to the radio signal is the Butterfly antenna which has logically been chosen for AERA-124. Moreover, the Butterfly antenna is robust, compact and convenient for the installation. After the pre-amplification of the signal with the LNA, the signal is sent to the electronics block.

THE ACQUISITION CHAIN

Analog signal processing. The first step of the signal processing consists of a filter/amplifier block. As noted before, the 30-80 MHz range is the radio quiet frequency band available at the AERA site. Below 30 MHz we found

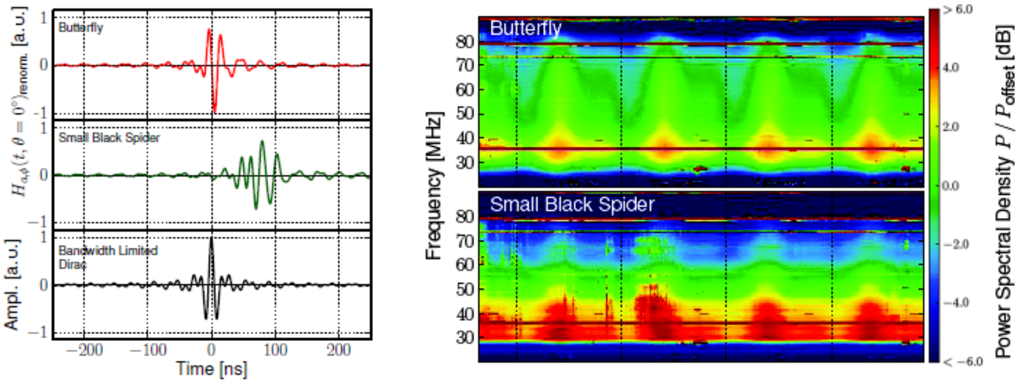

FIGURE 1. Left: normalized responses of the two antenna types to a transient signal to their respective maximum peak value which would be realized without dispersion in the antenna, in red for the Butterfly, in green for the LPDA. A bandwidth limited Dirac pulse is shown, in black, for comparison. Right: continuous spectrum measured with the two antennas during four days at Nançay. Each spectrum is scaled with a constant offset value to have a common scale of the power axis.

short wave transmitters and above 80 MHz, the FM ones. To remove these contributions, a 30-80 MHz band-pass filter is applied, the signal is then amplified and sent to the digital block.

Digital signal processing. The first purpose of the digital block is to sample the received signal. It also allows the storage and the transmission of the traces or of their GPS time at the DAQ. The AERA stations are equipped with two different types of digitizers both equipped with 4 channels and with Altera Cyclone 3/4 Field Programmable Gate Arrays (FPGA). One of the digitizers has a sampling frequency of 180 MS/s and a resolution of 12 bits. The second one samples the signal at 200 MS/s and has a resolution of 14 bits. These digital blocks are very efficient with a fast response and a low total power consumption compatible with solar power supply (10.8 W for the first one and 6-7 W for the second one). Some filters can be used before the trigger decision to reduce the background as it is the case for the second digitizer which uses Infinite Impulse Response Filters (IIR).

The digital block is also implemented with the low level rejection algorithms (T1 and/or T2) used for the self-trigger, where the stations are mostly triggered by anthropic background. A lot of work has been done to develop low-level triggers to identify real shower radio signals. The T1 consists of signal to threshold comparison in the time domain. A processing of the signal in the frequency domain is applied before this comparison to suppress RFI[1]. The T2s are mainly pulse shape analyses. Despite of these different rejection algorithms, the proportion of accidental self-triggering is still high. It has thus been decided to select the self-trigger events at the DAQ level, out of the LS ; and to add an external trigger.

Communication system. The last step of the signal in the LS is the communication system which allows communication between the LS and the DAQ at Coihueco. For AERA-24, an optical fiber communication system was used but given the high number of stations deployed now, this system was not relevant any more for AERA-124. Instead of the optical fibers, two Wi-Fi systems are tested in the array:

- a customized TDMA[2], fitting the needs of AERA. This system is used for mobile phones. It uses the 2.4 GHz band with a bandwidth of 5.5 Mb/s and can carry out up to 55 stations per channel.
- a commercial 802.11n system[3], commonly used for the commercial Wi-Fi, with a TDMA. This system uses the 5 GHz band with a bandwidth of 80 Mb/s and can carry out up to 100 stations per channel.

These two Wi-Fi systems work currently without problem in the array. No bandwidth limitation has been encountered.

[1] Radio Frequency Interference
[2] Time Division Multiple Access
[3] Bullet

DATA ACQUISITION SYSTEM

The data acquisition system is located in the FD building Coihueco and is composed of three modules: the PostMaster, ensuring the communication between the local stations and the central DAQ, the T3Maker that selects the self-triggered events and processes the external-triggers and the EventBuilder which constructs the raw data files.

On average each LS sends 500 T2s per second (self-trigger) that are received by the PostMaster which transfers them to the T3Maker. The T2s are sorted by increasing time and lists of stations are made. For each event the arrival direction is computed and events reconstructed with the same incoming direction in a short time slot are rejected. The T3Maker processes also the T3 requests send by the external triggers. These requests are sent by the FD located close to the array or by the SD. Several controlled triggers also exist for the monitoring. T3s lists are constructed with the selected self-trigger events and the T3 requests, and are sent by the T3Maker with an average of 2-5 Hz to the PostMaster and to the EventBuilder. The PostMaster asks then to the stations for the traces of the selected events and transfers them to the EventBuilder. This latter checks the compatibility of the received traces with the T3 list and write the data to disk with an average of 1 Mb/s.

CONCLUSION

AERA is a radio array with different instruments operating together. These continuous technological developments allow one to keep improving the measurement of the electric field induced by air-showers. The feasibility of measuring the vertical polarization of the electric-field and also inclined showers are currently tested, see [14].

The stage 2 of AERA is installed at the Pierre Auger Observatory since May 2013, covering now 6 km^2 with 124 radio stations. The 100 new ones are equipped with Butterfly antennas which are more sensitive to the radio signal and which induce small signal dispersion. Powerful electronics, communication system and central DAQ have been developed and permit an efficient and fast data processing. The self-triggered events are now selected at the central DAQ level and the local stations are externally-triggered. All these developments allow high quality measurements of extensive air-showers.

Acknowledgments

IFIN-HH, Bucharest produced the PCU in the frame of the ĂIJANCS/CNDI-UEFISCDI Partnership project 194/2012.

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