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Radio detection of high-energy cosmic rays at the Pierre Auger Observatory

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Abstract: The southern Auger Observatory provides an excellent test bed to study the radio detection of extensive air showers as an alternative, cost-effective, and accurate tool for cosmic-ray physics. The data from the radio setup can be correlated with those from the well-calibrated baseline detectors of the Pierre Auger Observatory. Furthermore, human-induced radio noise levels at the southern Auger site are relatively low. We have started an R&D program to test various radio-detection concepts. Our studies will reveal Radio Frequency Interferences (RFI) caused by natural effects such as day-night variations, thunderstorms, and by human-made disturbances. These RFI studies are conducted to optimise detection parameters such as antenna design, frequency interval, antenna spacing and signal processing. The data from our initial setups, which presently consist of typically 3 - 4 antennas, will be used to characterise the shower from radio signals and to optimise the initial concepts. Furthermore, the operation of a large detection array requires autonomous detector stations. The current design is aiming at stations with antennas for two polarisations, solar power, wireless communication, and local trigger logic. The results of this initial phase will provide an important stepping stone for the design of a few tens kilometers square engineering array.

Introduction

The goal of the Pierre Auger Collaboration is to identify the origin of Ultra-High Energy (UHE) cosmic rays and to unravel the mystery of the physics behind the cosmic acceleration mechanisms, leading to events in the Earths atmosphere with energies far beyond those obtained at any human-made accelerator. To achieve this goal, not only a precise energy measurement, but also a high angular resolution and the capability to determine the composition of rays (γ-rays, neutrinos or leptons, and hadrons) are of paramount importance. The baseline detector system of the Pierre Auger Observatory consists of an array of 1600 surface detectors (SDs) complemented by 4 telescope buildings each housing 6 fluorescence detectors (FDs) [1]. Recently, the technique of detecting extensive air showers (EASs) with radio receivers has revived [2, 3, 4] after the initial measurements made in the 1960's [5]. Nowadays, there is more and more evidence that the underlying emission mechanism is geo-synchrotron radiation from electrons and positrons in the Earths atmosphere. Because close to the core, the thickness of an EAS induced by an UHE cosmic ray is less than about 5 m, this emission will be coherent if the detected frequency of the radio pulse is limited to about 100 MHz. For the detection of cosmic rays with an energy less than 10^{17} eV using radio techniques much progress has been made in recent years, especially because of the results obtained by the LOPES [6] and CODALEMA [7] collaborations.

In principle, the advantage of radio compared to other systems used for the detection of UHE cosmic rays is large: radio signals are not absorbed nor deflected on their path, the amplitude of the signal is proportional to the primary energy of the incoming event, and one can study the shower front in detail. In addition, radio can have a 100% duty cycle, which is a factor of ten higher than fluorescence detection. Furthermore, the technique may provide additional information which is complementary to that from SD and FD, as it determines directly the evolution of the electromagnetic properties of the shower in the atmosphere. This complementary information might open the possibility to study the composition of the primary event [8]. In addition, if one measures radio pulses with receivers distributed over a grid with a pitch size of many hundreds meters, a high angular resolution ($< 1°$) for the arrival direction of the event can be obtained. The high duty cycle will provide us with many more events which are needed for a statistical analysis to determine possible anisotropies, to identify point sources, and to get a better insight into the composition of these UHE cosmic rays.

Thus radio detection promises not only to be a bolometric measurement of the energy of the primary cosmic ray, but it can also give a precise determination of the arrival direction. Therefore, it might be a perfect additional tool for high-energy particle astronomy.

However, before radio detection of UHE cosmic rays can be regarded as a technique mature enough to deploy it over an area of the size of the Pierre Auger Observatories a substantial R&D program is required. This program will not only address the physics issues, but also the technological ones, and the investments and running costs. And it extends the continued efforts performed at the LOPES [6] and CODALEMA [7] sites in Europe.

Initial investigations started in 2006 and we aim to merge our set ups with the foreseen infill-detector array at the southern Pierre Auger Observatory [10, 11]. Starting in 2008, and for a period of 4 years we are planning to operate a 20 km^2 engineering array which will serve as a test bed to address these engineering and physics questions leading to the design of a many thousand kilometers square array.

R&D Program

The aim of the present research and development program is to optimise the hardware and software required for an area with a typical dimension of 20 km^2 which will be deployed at the southern site of the Pierre Auger Observatory. This array will provide its own trigger and read-out system and will thus operate independently from the baseline trigger and data-acquisition of the baseline detectors. The required correlation of events between the radio detection system and the baseline detectors will be performed using GPS time stamps. The optimisation of the whole read-out chain has various ingredients. It starts with the antenna design and operation, the preamplifier at the antenna station, the filters (analog and/or digital), the amplification, the receivers and digitisers, and the signal analysis.

The overall performance depends not only on a low system noise throughout the chain, but also on the capabilities for the suppression of Radio-Frequency Interferences (RFIs). These RFIs can be many fold: background from the Galactic sky, lightning from thunderstorms, carrier signals from radio and TV transmitters, and other human activities. It is known that strength of the man-made noise power can strongly depend on the site and that it rises steeply with decreasing frequency. Generally, the spectral power S integrated over the solid angle measured by one polarisation direction of a simple antenna with an effective aperture A can be expressed as:

$$\begin{aligned} S_\nu &= \frac{dP}{d\nu} = \frac{\int I_\nu A d\Omega}{d\nu} \\ &= \frac{\int \left(I_{\nu,man} + I_{\nu,sky}\right) A d\Omega}{d\nu} \end{aligned}$$

Here, the intensity I_ν of the induced power is written as the sum of the sky noise (mainly from Galactic and atmospheric origin) and noise induced by man-made sources. Both contributions are smoothly varying functions of the frequency ν, though both intensities increase going to lower frequencies. In quiet rural areas $I_{\nu,sky}$ dominates $I_{\nu,man}$ for $\nu > 10$ MHz. In addition to these smoothly varying contri-

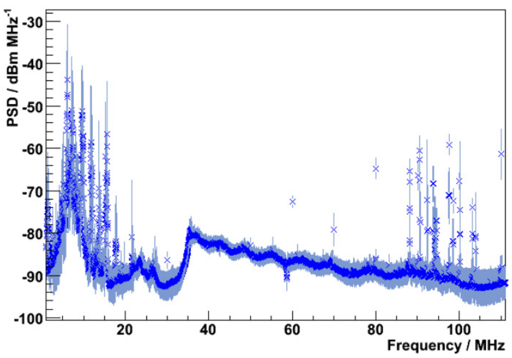

Figure 1: Spectral power density measured near the Balloon Launching Station using an LPDA and an Anritsu MS2711D spectrum analyser. The antenna signal was amplified using a low-noise amplifier [9] followed by an RG213 cable with a length of 160 m.

butions, we have to take into account the influence of strong transmitters used for radio and TV broadcasting. Finally, atmospheric noise can play an important influence on the ambient noise levels of the radio receivers. Atmospheric noise is caused by lightning, which at very low frequencies emits with a broad spectrum. A measurement of the ambient noise is shown in Figure 1. Transient noise, which can strongly fluctuate in amplitude and rate, can produce signals which look very much like those of cosmic rays; therefore, the reduction of this noise has to studied carefully.

The antennas which are being used in the present R&D program are various types of dipole antennas. One system uses a dual active fat dipole antenna (AFDA) which has a total length of 1.2 m mounted on a post of 1.0 m height, where two polarisations are measured. The AFDAs have a rather flat antenna gain over a large band [7]. Another design presently being tested, is a relatively large dual logarithmic periodic dipole antenna (LPDA). In this case, each antenna station has on one pole at a height of about 4 m two antennas, one for each polarisation. The antenna gain for these LPDAs drops relatively fast below 35 MHz, and is rather flat in the band between 35 and 90 MHz [9]. Finally, we use a dual inverted V-shaped dipole antenna (IVDA) [3], also mounted on a post at a height of 5 m. This antenna has a smoothly varying gain with a maximum around 60 MHz.

Also for the readout chain, different techniques are being used. In all cases, low noise amplifiers are mounted at the front end of the antenna. In the present R&D stage, the signals are transported over relatively short (< 10 m) or long (160 m) cables. In the case where the cables are short, digitisation takes place close to the antenna station and the data are transferred by a wireless link to a nearby central system. Here, the power for the antenna stations is being generated by solar power units. The digitisers in this case are either a system based on the simultaneous digitisation of 3 slightly overlapping frequency bands each with a sampling rate of 40 MS s^{-1} and a dynamic range of 10 bits or a system which has a rather broad band with a width of 250 MS s^{-1} and a dynamic range of 8 bits. For the antennas which are connected by the relatively long cables to the data-acquisition system, bias-tees connected to the available infrastructure in the Balloon Launching Station of the Observatory are used to power the pre-amplifiers. For these antennas, digitisation systems with a relatively large dynamic range (12 bits) are being used. One of these 12-bit systems has a rate of 40 MS s^{-1}, the other one has a rate of 400 MS s^{-1}. Triggers for these systems are based on signal-over-threshold (SoT) or using an external trigger. This external trigger is generated by an external pulser (P) or by a trigger of the SD array (T3). When an external pulser is used the ambient background can be measured with these data-acquisition systems. To avoid false triggers, when operated in the signal-over-threshold mode, pass filters are used to suppress the received power for the regions below about 25 MHz and beyond 80 MHz. The power suppression is typically 80 to 100 dB. Table 1 summarises the various parts used in the present stage of the R&D program.

To increase the number of events which can be observed with the baseline detectors, an infill SD station has been deployed near both sites

system	antenna type	antenna band width (MHz)	wireless	total gain (dB)	trigger	pass filter (MHz)	DAQ sampling rate (MS s^{-1})	dynamic range (bits)
1	AFDA	0.1 – 200	yes	35	SoT	0.1 – 90	250	8
2	LPDA	35 – 90	yes	<75	SoT/T3	13 – 85	40	10
3	LPDA	35 – 90	no	55	SoT	41 – 79	40	12
4	LPDA	35 – 90	no	53	SoT/P	25 – 75	400	12
5	IVDA	35 – 80	no	53	SoT/P	25 – 75	400	12

Table 1: Configurations used in the present R&D phase (see text for details).

used for our radio R&D program, one site near the Balloon Launching Station, the other near the Central Laser Facility. In this way the SD-trigger rate is increased by a factor of 20, yielding about 2 events with an energy larger than 0.3 EeV per day within a radius of 500 m from our test sites.

To evaluate the different systems, we define a signal-to-noise ratio (R) based on the power measured by each of the different systems:

$$R = \frac{P_{max}(signal)}{\int_{\nu_1}^{\nu_2} S_\nu(noise)d\nu} \qquad (1)$$

where $P_{max}(signal)$ is the interpolated maximum power of a radio signal induced by an EAS in the frequency band between ν_1 and ν_2 and $S(noise)$ is the power of the noise spectrum integrated over the same bandwidth. The value of R will be a leading factor in the decision for the design and construction of an engineering array of about 100 - 150 antennas, which we plan to deploy in the engineering array. Antenna stations of this array have to operate on solar power and data transmission will be based on wireless communications.

Conclusions

We have started an R&D program for the detection of UHE cosmic rays within the Pierre Auger Observatory. Presently, our main aim is to optimise our signal-to-noise ratio, testing several antenna concepts and read-out systems. The results of this initial phase will be used to design and construct a larger array with a dimension of about 20 km^2.

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