Eur Phys J C **33**, s01, s947–s949 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1633-2

EPJ C direct
electronic only

Status and perspectives of the Pierre Auger Cosmic Ray Observatory

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Received: 20 October 2003 / Accepted: 22 January 2004 /
Published Online: 3 February 2004 –

Abstract. The problem of the origin of Ultra High Energy Cosmic Rays, that is those with an energy of the Primary above 10^{19} eV, is a challenging one. The expected flux at those energies is around 1/yr/km^2, thus requiring an unprecedented size of the detector in order to achieve consistent statistics. The Pierre Auger Observatory will be the largest cosmic ray detector ever built, consisting of two sites, one for each hemisphere, equipped with 1600 water Cherenkov detectors and four fluorescence detectors, covering each 3000 km ^{2}. The combination of the two techniques, referred to as the *hybrid* technique, results in unprecedented accuracy in the reconstruction of the air showers. The concept has been validated with an *Engineering Array* of 32 water tanks and two fluorescence telescopes, during which the apparatus demonstrated very good performances. This paper will summarize the features of the data, the reconstruction methods and the strategy toward completion of the full Observatory.

1 Introduction

In the past years, cosmic rays showers induced by primaries of energy above 10^{20} eV have been recorded by both fluorescence detectors and ground arrays. This energy region is interesting not only for the fact that an extremely efficient acceleration mechanism and large size of the accelerating source is required, but also because we expect that interaction with the CMB hinders sources farther than 50 Mpc (the GZK cutoff [1,2]). Present experiments did not collect enough statistics to confirm or reject the GZK hypothesis, while the accuracy and consistency of their energy measurement is a matter of debate.

The Pierre Auger Observatory will answer these questions by equipping a large area with a hybrid detector [3]. The Surface Detector (SD) gives information about the ground particles, while the Fluorescence Detector (FD) studies the shower longitudinal profile, giving a quasi calorimetric measurement of the energy.

2 Description of the detector

2.1 The surface detector

The SD of the southern observatory is constituted of 1600 water Cerenkov detectors arranged in a triangular grid with side length of 1.5 Km. Each unit [5] is a cylinder with 10 m^2 of top area and 1.2 m height filled with pure water, overlooked by three photomultipliers. Power is provided by solar cells, while communication is guaranteed by a wireless network. Timing is provided by a GPS based system.

The output of each photomultiplier is sampled at 40 Mhz by two 12 bit FADC devices, one connected to the last dynode and one connected to the anode. A custom system provides the local trigger and monitoring informations. The stations communicate with the Central Data Acquisition System which forms the event trigger when four stations claim a local trigger, reaching 100% efficiency at 10^{19} eV.

2.2 The fluorescence detector

The secondary particles of the shower, throughout its development, excite the Nitrogen molecules of the air, that in turn emit fluorescence light in the range 300-420 nm. This light is collected by the FD mirrors and focused onto a photosensitive device. Since the light flux is proportional to the energy deposit at a given time, this results in a calorimetric measurement of the shower energy.

Each of the four fluorescence detectors [4] that, in the southern observatory, overlook the SD is composed of six telescopes. Each of these units cover a region of the sky of 30 deg by 30 deg, and is made of a segmented mirror of approximately 3m x 3m and 3m focal length. Its focal surface is equipped with an array of 440 photomultipliers (pixels), each of those covering 1.5 deg^2 in the sky. An optical filter placed at the aperture of the unit selects photons in the fluorescence range. The signal from the photomultipliers is sampled at 10 Mhz with a resolution of 12 bit and a dynamic range of 15 bit. A first level trigger scans contin-

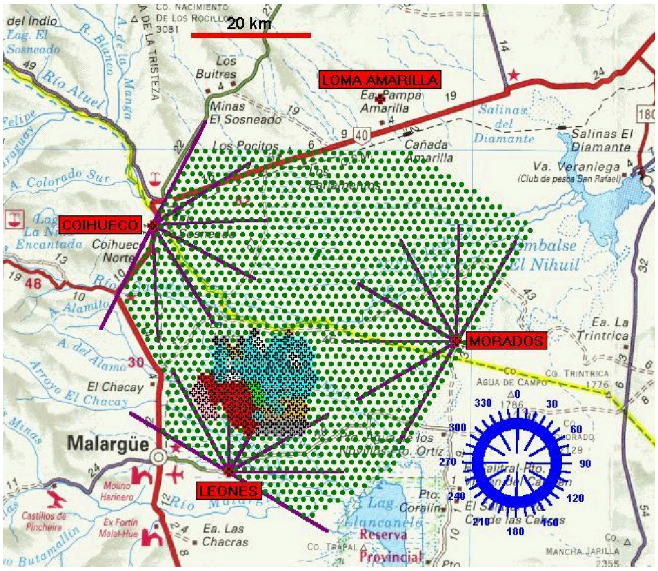

Fig. 1. Layout of the Southern Observatory. *Red labels* indicate the position of the fluorescence detectors, *crosses* the already deployed tanks

uously the FADC output to locate candidate fluorescence pulses in each pixel. A second level trigger scans the PMT matrix looking for patterns that are topologically consistent with a shower.

2.3 The advantages of a hybrid detector

The SD is made of simple and reliable devices and has 100% duty cycle. However, since only the ground particles are detected, the energy estimation relies somewhat on simulation. On the other hand, the FD provides a calorimetric measurement of the energy, tracks directly the development of the shower, but has only a 10 - 15 % duty cycle. Some uncertainties arise from the knowledge of the atmospheric transmission and scattering, and that is the motivation that lead the Auger collaboration toward the deployment of an extensive atmospheric monitoring program. The combination of the fluorescence and ground array techniques gives superior reconstruction of the event geometry, independent measurement of the energy, better control of systematics and cross calibration.

3 Status and plans

As mentioned before, the observatory has successfully completed an engineering phase (Dec 2001 – April2002) with 32 surface detectors and 2 fluorescence telescopes. During this run, 75 events hitting both the FD and the SD were recorded. The SD features 6000 triggers 600 of which were shower candidates with energy greater than 10^{18} eV and 120 events with more than 5 hit stations. The FD recorded about 1000 triggers, half of which are shower candidates, and 50 of which have a quality such that an energy estimate can be given.

The deployment of the full scale array is now taking place. The schedule foresees 400 tanks in operation by January 2004 together with 4 fluorescence telescopes, 2 at the Coihueco site and 4 at the Los Leones site (see Fig. 1). Completion of the observatory should be reached on December 2005.

4 Preliminary analysis of engineering array data

4.1 Geometrical reconstruction

The analysis of an event starts from the reconstruction of the shower geometry. When the SD is used alone, first the core of the shower is located. This is done by finding the barycenter of the stations that present a trigger weighted by the magnitude of the signal. Secondly, the direction of the shower axis is found using the arrival times of the shower front at the various stations. Timing is crucial for the accuracy of this method. A study conducted on engineering array data shows that the typical error is of the order of 20 ns, while the average error on the shower direction is of the order of 1 degree.

When the FD is used to reconstruct the shower geometry, the first step is the location of the Shower-Detector plane (SDP), which is defined as the plane in which the shower axis and the detector itself are contained. The standard procedure minimizes the angular distance of the vector perpendicular to a trial plane from the direction of the hit pixels, weighted by their signal. The error in the location of the SDP is of the order of a few tenths of a degree. The direction of the axis within the SDP must then be located. When data from a single FD is used, as in the case of most of the events recorded during the engineering array, the arrival time of the shower light at the different photomultipliers is used (the so called *time fit*). However, this method presents some ambiguities, as three parameters, i.e. distance of the shower from the detector, angle within the SDP and time of arrival, must be found by minimization of a function (the one that relates these parameters with the time of arrival at the tubes) which is essentially linear. The error on the angle can reach a few degrees. When informations from the SD can be used in conjunction, the accuracy improves dramatically. The time of arrival of the shower core at ground can be used to add a constraint to the time fit. In this case the average error reduces to half a degree [7]. Similar precision can be achieved when two FDs have different views of the same shower.

The geometrical reconstruction with the FD can be tested using a laser beam shot from different distances and at different angles. Such method has been used to study the detector systematics and estimate the errors by comparison of real and reconstructed geometries.

4.2 Estimation of the lateral distribution

Once the shower geometry has been reconstructed, the calibrated signal from the Cerenkov tanks is used to mea-

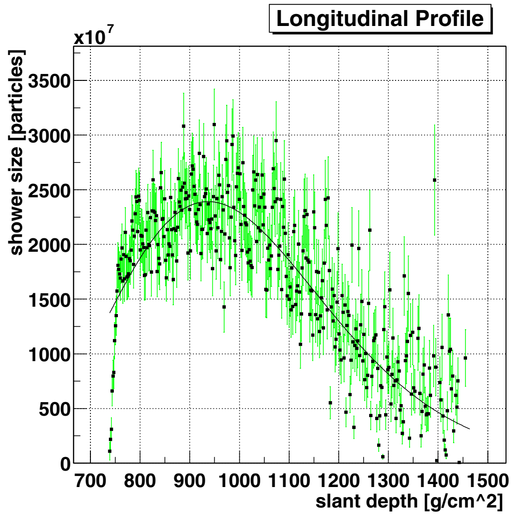

Fig. 2. The reconstructed longitudinal profile of a shower landing at 20 Km from the detector, with an estimated energy of $2.5\times10^{19}eV$

sure the lateral development. The density of particles at 1 Km from the core (S1000) is related to the primary energy. Figure 3 shows the lateral profiles obtained by superimposing different events in two angular regions [6]. A functional form such as the NKG function can then be used to fit the data.

4.3 Longitudinal profile reconstruction

Fluorescence light is emitted isotropically in the range 300-420 nm as the shower develops. Each electron yields four to five fluorescence photons per meter of track length, depending on electron energy, temperature and pressure and therefore on altitude. From the number of photons, one can infer the shower size at each atmospheric depth (X). The signal received versus time is a function of the fluorescence yield at the altitude of emission, of the number of particles at a particular X, of the distance of observation and of the atmospheric attenuation. The light received at the aperture of the FD is measured every 100 ns.Then the above relation can be used to estimate the number of particles at each atmospheric depth. A correction must be made to take into account direct and scattered Cerenkov light.

Once the shower size versus atmospheric depth is obtained, the experimental data points can be fit to a functional form, such as the Gaisser-Hillas function. The integral of this function is proportional to the electromagnetic energy of the shower. An example of a reconstructed longitudinal profile is show in Fig. 2.

4.4 Primary composition

The Auger observatory will have two independent ways of measuring the shower composition. With the SD, it can

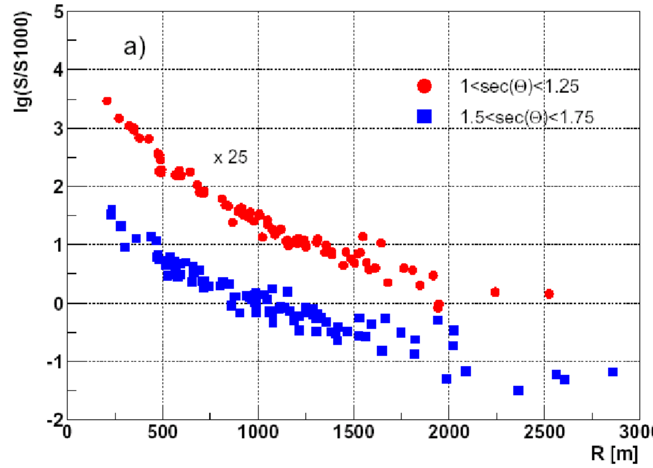

Fig. 3. Lateral distribution accumulated from 10 events in two regions of sec θ

be inferred from the muon content. Showers produced by heavy nuclei are richer in muons, which are separated from electrons using the different shapes of the signal recorder by the FADC traces. Muons show as sharp peaks arriving early in the event, while electrons are characterized by late arrival and broader distribution in time.

The atmospheric depth where the shower reaches its maximum X_{max}, is an indication of the primary composition as well. Heavy nuclei induced showers reach the maximum before proton induced showers. The FD can exploit this difference by measuring directly the shower development.

5 Conclusion

The Auger experiment is the best candidate for the investigation of Ultra High Energy Cosmic Rays. Its features are unique both because of the unprecedented size and of the accuracy in the reconstruction.

The *Engineering Array* phase was successfully completed, and proved that the design is solid and technical difficulties overcome. Analysis techniques were exercised, and the result have shown to be consistent, proving the good quality of data. We look forward toward completion of the full array.

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