The low-energy extensions of the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory was designed to measure ultra-high energy cosmic rays above $10^{18}$ eV with high accuracy using a hybrid air shower detection technique. A Surface Detector (SD) with 1600 water-Cherenkov stations on a 1500 m triangular grid covers an area of 3000 km\textsuperscript{2}. The atmosphere above the array is viewed by a Fluorescence Detector (FD) with 24 telescopes at 4 sites in the periphery of the SD. As an enhancement to this baseline design, in order to reach a lower energy threshold below $10^{17}$ eV, the Collaboration has implemented extensions to the Observatory. The SD extension is AMIGA (Auger Muons and Infill for the Ground Array), an infilled area with detectors at a smaller spacing than in the main array and with buried scintillator counters. The FD is complemented by HEAT (High Elevation Auger Telescopes), with 3 additional telescopes that are tilted upwards to extend the elevation range. The importance of these extensions of the Auger Observatory is that they allow to study the energy range where the transition from a Galactic to an extra-Galactic origin of cosmic rays may occur. The current status and initial results from these extensions are discussed.

1. Introduction

The origin and nature of the Ultra-high Energy Cosmic Rays (UHECR) has been a mystery since they were discovered in 1962 [1]. These cosmic rays reach energies above $10^{20}$ eV [2], questions about how and where they are accelerated, have been asked for decades. Our knowledge on Ultra High Energy Cosmic Rays is limited, one reason is the very low flux of UHECRs at Earth (see figure 1). Large detectors are needed to collect information of the Extensive Air Showers (EAS) produced by the primary cosmic ray particles in order to infer properties of the primary particle, such as its energy, its arrival direction, and its composition, with enough statistics. The flux of cosmic rays decreases with energy and can be described by a power law like $\frac{dN}{dE} \sim E^{-\alpha}$ with spectral index $\alpha$ between 2.6 and 3.2. One can find some small but relevant breaks at the energy spectrum, the knee at $\sim 4\times10^{15}$ eV, where $\alpha$ changes from 2.7 to 3.1, the second knee (slightly above $10^{17}$ eV) and the ankle at $4\times10^{18}$ eV (see figure 1) [3]. The transition from galactic to extragalactic cosmic rays may happen between the second knee and ankle, therefore, cosmic rays in this energy range are most likely generated by different astrophysical sources, and their composition may change as well.
2. The Pierre Auger Observatory

The Pierre Auger Observatory [5], is located near the city of Malargüe, Argentina, at latitude 35.2° South and an altitude of 1400 m.a.s.l. Its baseline design, inaugurated in November 2008, was completed in May 2008. The Observatory has been taking data since January 2004 during its construction phase. The Pierre Auger Observatory was designed to measure properties of cosmic rays with energy above $10^{18}$ eV such as their flux, arrival directions and mass composition with unprecedented statistics. The Observatory is a hybrid cosmic ray detector, that consists of two complementary detectors that can observe, in coincidence, the longitudinal development of the shower of particles with air-fluorescence telescopes and its pattern when it reaches the Earth surface, where they can be spread over several kilometres. The Surface Detector [6] determines the particle densities at ground. It is composed of 1600 Cherenkov stations separated by 1.5 km, covering a total area of 3000 km$^2$. Surface detectors use generally scintillators or water-Cherenkov stations as their detector stations. Water Cherenkov stations have broader angular coverage, compared to thin scintillators which are usually more difficult to build and deploy. Both methods are robust and reliable, well known, detectors adequate to instrument the required large areas. The Fluorescence Detector [7] consists of 4 buildings on the outskirts of the SD array, each one with 6 telescopes that overlook the array covering 30° in elevation and 180° in azimuth. It collects the fluorescence light emitted by atmospheric nitrogen molecules excited as the shower is crossing the atmosphere. The FD measures the longitudinal profile of the shower. Fluorescence detectors record the near UV light emitted by deexcitation of $N_2$ molecules previously excited by the shower particles. They provide a direct measurement of the longitudinal shower development. This is crucial, because the integral of the profile is a direct measurement of the energy deposited in the atmosphere. Moreover, the depth of the shower maximum is also a good indicator of the primary mass. Three factors limit the ability to study cosmic ray primary composition: intrinsic fluctuations on shower development, finite detector resolution and systematics and limited knowledge of high energy hadronic interactions. The layout of the Southern Observatory is shown in figure 2.

Figure 1. Energy spectrum of cosmic rays. The particle flux is scaled with $E^{-2.7}$ to evidence the spectral features (knee, second knee and ankle). The arrow starting from $10^{17}$ eV indicates the energy range where the Auger Observatory extends its studies of cosmic rays through HEAT and AMIGA. The figure was modified and taken from [4].
2.1. Surface Detector
The Surface Detector measures the front of the shower as it reaches ground. The detectors activated by the event record the particle density and the time of arrival.

The cell unit (see figure 3) of the Surface Detector of the Pierre Auger Observatory is a water Cherenkov counter. Each counter is a polyethylene station of cylindrical shape with size $10 \text{ m}^2 \times 1.2 \text{ m}$ filled with purified water. Cherenkov light produced by charged particles of the showers is detected by three 9" photomultipliers. Each unit is autonomous with a battery and a solar panel.

Stations are calibrated using the signals of atmospheric muons, a well known uniform background across the array. The signal of a muon is proportional to the geometric path length. A test station was used to establish the relation between the signal of down-going vertical and central muons (VEM) and the peak of the histogram obtained from omni directional muons crossing the station. Each station is calibrated matching the photomultipliers gain to obtain the expected trigger rate over a given VEM threshold. This procedure allows to calibrate the stations with respect to the absolute value of the VEM with an overall precision of 2% [8].

2.2. Fluorescence Detector
The fluorescence detector consists of 24 telescopes in four sites, located on small elevations on the perimeter of the array (figure 2). The telescopes measure the shower longitudinal development in the atmosphere by collecting the fluorescence light emitted by the atmospheric nitrogen molecules excited by the charged particles. Each telescope is composed by an aperture system, a spherical mirror, and a 440 photomultiplier camera at the focal plane. A schematic view of the arrangement can be seen in figure 4.
**Figure 3.** Schematic view of a water Cherenkov station (left) and photograph (right) of a Surface Detector unit.

**Figure 4.** Schematic view of a fluorescence telescope (left) and aerial view (right) of the FD building at Los Leones.
3. Low-energy Enhancements

3.1. The AMIGA Infill extension

The low-energy extension of the surface detector of the observatory is the Auger Muon and Infill for the Ground Array (AMIGA [11, 12]). The Infill array consists of an area of 23.5 km$^2$ with additional water-Cherenkov stations on a denser grid. The additional stations are set out forming an hexagonal spacing with sides of 750 m, compared to the spacing of 1500 m of the main array. This infilled array is close to and in the field of view of HEAT. Since September 2011 all the 61 surface stations planned for the 750 m infill have been deployed. Data taking with the Infill array still under partial construction began in 2008.

The analysis of the data collected, based on the algorithms developed for the regular array, is in an advanced stage. A scheme of Infill array is shown in figure 5.

In addition to the Infill array, AMIGA consists of an associated set of muon detectors (MDs). The MDs are scintillator counters buried close to the 61 infill stations under 2.3 m of soil. Each station consists of two scintillator modules of 10 m$^2$ and two smaller modules of 5 m$^2$. Their muon energy threshold is about 1 GeV. The MD is currently in its prototype phase, named the Unitary Cell (UC). The UC will consist of 7 buried detectors to be installed on one hexagon and on its centre. And is foreseen for early 2012.

The water-Cherenkov detectors used in the Infill array are the same used in the main array. Moreover, the Infill is embedded in the regular array and therefore similar strategies may be employed for the selection and reconstruction of the observed showers. The trigger efficiency, the aperture and exposure calculation, the event selection, the geometry reconstruction and lateral distribution functions used (LDFs), as well as the energy estimator and the energy calibration, all benefit from algorithms tested successfully over the past years for the main array of the Auger SD.

The trigger system of the Infill array is adopted from the regular Auger array [8]. An event
is accepted when at least 3 stations forming a triangle (see figure 6) satisfy a local trigger of the type Time-over-Threshold (3ToT event). The smaller spacing between stations of the Infill leads to an increase of the trigger efficiency at low energy, as illustrates figure 7 for zenith angles < \(55^\circ\), for both Infill and regular array. As is shown, the 750 m spacing of the Infill allows cosmic rays to be detected with efficiency of 100\% for energies above \(3 \times 10^{17}\) eV.

Figure 6. Event accepted when at least 3 stations forming a triangle satisfy a local trigger of the type Time-over-Threshold (3ToT event).

The 3ToT trigger rate is around 55 events/day/hexagon out of which around 28 events/day/hexagon satisfy the fiducial event selection that requires 6 working stations to surround the station with the highest signal, i.e. a working hexagon. This condition assures a good reconstruction and allows for a simple geometrical calculation of the aperture. Integrating the instantaneous effective area over the time when the detector was stable, the acceptance between August 2008 and March 2011 amounts to \(26.4 \pm 1.3\) km\(^2\) sr yr.

As was done for the principal array (1500 m separation) measurement uncertainties have been derived from data. The angular resolution of the 750 m array was found to be 1.3\(^\circ\) for events with at least 4 stations. To reconstruct events, the distribution of SD signals on ground as a function of the distances to the shower axis, \(S(r)\), is fitted with a Lateral Distribution Function LDF. The optimum distance, \(r_{opt}\), is the ground parameter eventually used to obtain an energy estimator. For the regular array \(r_{opt} = 1000\) m whereas for the 750 m Infill was found to be 450 m. Besides the uniform treatment of data from the highest energies down to \(3 \times 10^{17}\) eV, an additional advantage of having the Infill within the regular array is that it is possible to make cross checks of results in the overlap region. From event to event, the main statistical sources of uncertainty in the parameter \(S(450)\) are the shower-to-shower fluctuations, the finite size of the detectors and the sparse sampling of the LDF. There is also the systematic contribution due to the lack of knowledge of the LDF. The total \(S(450)\) uncertainty derived from the Infill data goes from \(~20\%\) at 10 VEM (Vertical Equivalent Muon) to \(~10\%\) at 100 VEM. The energy of an event is estimated from the ground parameter accounting empirically for the shower attenuation in the atmosphere (that depends on the zenith angle) with a constant intensity cut method. The equivalent signal at a reference zenith angle of \(35^\circ\) (\(S_{35}\)) is used to infer the energy. \(S_{35}\) is calibrated using hybrid events, and correlates with the energy measured with the FD, as illustrated in figure 8. The number of events as a function of \(S_{35}\) is illustrated in figure 9 for different zenith angle intervals, and the Infill array was found to be fully efficient from \(S_{35} \sim 20\) VEM, the trigger threshold.
Figure 8. The correlation between $S_{35}$ and energy.

Figure 9. The distribution of events as a function of $\log_{10}(S_{35}/\text{VEM})$ for different zenith angle intervals.

3.2. HEAT

The low-energy extension of the fluorescence detector of the Observatory are the 3 High Elevation Auger Telescopes (HEAT) \cite{13} (figure 10), which operate on the same principles as the standard fluorescence telescopes of the Observatory.

Figure 10. Photo of the 3 HEAT telescopes tilted upward. In the background the telecommunication tower of Coihueco is visible.

HEAT telescopes are located near the FD Coihueco building, overlooking the Infill array and additional water-Cherenkov stations installed to further increase the effective Infill area for low energy shower measurements (HEAT Low Energy Trigger, HEATLET). The HEAT telescopes are very similar to the FD telescopes but are housed in three individual buildings, which can be tilted hydraulically by 30 degrees to cover the range from 30 to 60 degrees above horizon, so HEAT has two modes of operation: Down Mode (figure 11) and Up Mode (figure 12). The horizontal mode of the HEAT telescopes, which is used for installation, commissioning and maintenance of the hardware, is also the position in which the absolute calibration of the telescopes takes place. In this position the field of view of the HEAT telescopes overlaps with those of the Coihueco telescopes. This offers the possibility of doing special analyses of events recorded simultaneously. In addition, these events can be used to check the alignment of the
new telescopes and provide a cross-check of their calibration constants.

**Figure 11.** Down Mode: horizontal mode for service and cross-calibration.

**Figure 12.** Up Mode: data-taking mode in tilted orientation.

**Figure 13.** Limited field of view on reconstruction of standard FD: Showers approaching the telescope have much higher reconstruction probability than those departing.

**Figure 14.** Extended field of view by combination of Coihueco+HEAT.

The fluorescence technique is best suited to determine the cosmic ray composition by a direct measurement of the shower depth maximum $X_{\text{max}}$. HEAT allows to lower the energy threshold for these measurements. As the fluorescence light signal is roughly proportional to the primary particle energy, low energy showers can be detected only at close distances. The field of view of the baseline design of the FD is limited to $30^\circ$ above the horizon (see figure 13). At close distances only the lowest few kilometres of the atmosphere are in the field of view, but, low energy showers reach their maximum of development at higher altitudes. Thus, the crucial region around the shower maximum is generally not observable. The small fraction of the shower development, which falls within the field of view, is mostly insufficient to determine the depth of shower maximum $X_{\text{max}}$. In addition, this cut-off effect also depends on primary mass and shower direction. A plain reconstruction of the shower profile using raw data would yield biased results with respect to zenith angle and mass composition.
With HEAT in the tilted position (mode up), the combined HEAT-Coihueco telescopes cover an elevation range from the horizon to \(60^\circ\) (figure 14). This extended field of view enables the reconstruction of low energy showers for close-by shower events and resolves ambiguities in the \(X_{\text{max}}\) determination. The improved energy resolution and \(X_{\text{max}}\) determination is especially visible in the low energy regime.

An example of one of the low-energy showers recorded with HEAT and Coihueco is shown in figure 15 (Camera image of the recorded signal) and figure 16 (Reconstructed energy deposit profile). The energy of this event is \(\sim 1.07 \times 10^{17}\) eV.

Since June 2010, the data taking and data quality reached a satisfactory performance level. The alignment of the regular fluorescence telescopes is obtained from star tracking. In addition to this method, a new one was introduced to determine the alignment of HEAT telescopes. Given a reference geometry from any number of sources (SD, hybrid, reconstruction from other sites, laser shots) and the observation of the corresponding light traces in a HEAT telescope, the developed algorithm determines the optimal pointing direction for the telescope. The accuracy of the method increases when applied to several events. This method results in a statistical accuracy of 0.3° or better for elevation and azimuth. For the HEAT telescope 1, which has the Central Laser Facility (CLF) in its field of view, accuracies of better than 0.1° can be achieved.

For shower reconstruction it is desired to combine the data from HEAT and Coihueco. However, in the standard reconstruction chain the data from each building is used separately. Thus, the official software (Offline) has been generalized. The different telescopes can then be combined in any desired form to build a virtual site.

3.2.1. HEATLET (Heat Low Energy Trigger tanks), consists of 5 additional water-Cherenkov stations forming an array of 9 Infill stations (see figure 17), very close to HEAT, in order to get the best low-energy hybrid event reconstructions. The timing information from at least one triggered surface station in a hybrid event enables showers at low energies to be reconstructed with good accuracy. The single station trigger probability needed for such hybrid measurements depends on the detector spacing, as well as on the energy, zenith angle, and mass of the primary particle. In figure 18 an example of an event as described above and recorded with the HEATLET array is displayed.
4. Conclusions
The Infill array, part of the AMIGA enhancement of the Pierre Auger Observatory, has been operating in good conditions since its deployment. It extends the energy range for the surface detector of Pierre Auger Observatory down to $3\times10^{17}$ eV. The integrated exposure between August 2008 and March 2011 is $(26.4\pm1.3)$ km$^2$ sr yr, with resolution in S(450) varying from 20% at 10 VEM to 10% at 100 VEM, at the highest energies.

The HEAT telescopes have operated since September 2009 and are producing high quality data in a stable manner since June 2010. These new telescopes improve significantly the quality of data for energy and mass composition analyses at low energies. The enhancements to the baseline of the Pierre Auger Observatory also include, in addition to AMIGA and HEAT, arrays for detection of radio and GHz emission from air showers [14, 15, 16]

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