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The AMIGA detector of the Pierre Auger Observatory: an overview

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Abstract: The Pierre Auger Observatory is currently being enhanced with the AMIGA detector (**A**uger **M**uons and **I**nfill for the **G**round **A**rray) to bring the energy threshold down to 10^{17} eV and to enable the muon content of air showers to be determined. Its baseline layout consists of a 23.5 km^2 infilled area within the Pierre Auger Observatory array deployed with synchronised pairs of water-Cherenkov surface stations and buried scintillator counters that sample simultaneously the particles of air showers at ground level and at a depth of 2.3 m respectively. At present, both detectors are placed on a triangular grid of 750 m, half the spacing of the main array. In this work we present the status of AMIGA, the performance of the surface array and the analysis of the first data of the scintillator detectors.

Keywords: Pierre Auger Observatory, Low Energy Extensions, AMIGA

1 Introduction

The energy region from $\sim 10^{17}$ eV to $\sim 10^{18}$ eV is of the outmost importance to understand the origin of the high-energy cosmic-rays: it is the range where the transition from a galactic to an extragalactic dominated flux may occur. Measurements of the energy spectrum and the mass composition within that range are expected to enable discrimination between different astrophysical models [1, 2, 3]. The Pierre Auger Observatory has the unique characteristic of combining the observation of the fluorescence light induced by extensive air showers with the measurement of their secondary particles that reach the ground level. This hybrid approach allows cosmic ray observables to be interpreted with unprecedented precision.

The southern site of the Observatory, located in the Province of Mendoza, Argentina, spans an area of 3000 km^2 covered with over 1600 surface detectors (SDs) deployed on a 1500 m triangular grid. The SD array is overlooked by 24 fluorescence detector (FD) telescopes grouped in units of 6 at four sites on the array periphery. Each telescope has a $30^\circ \times 30^\circ$ elevation and azimuth field of view. The regular array of the Observatory is fully efficient above 3×10^{18} eV [4] and in the hybrid mode this range is extended to $\sim 10^{18}$ eV [5] which does not suffice to study the transition region.

The Auger Collaboration has already measured the energy spectrum of cosmic rays from 10^{18} eV to above 10^{20} eV [6]. The first enhancements of the Auger Observatory, AMIGA and HEAT (High Elevation Auger Telescopes [7]) aim at measuring the cosmic ray spectrum and its chemical composition components down to 10^{17} eV. Both extensions started in 2008 after the construction of the Observatory was completed. HEAT complements the Auger FD with three additional telescopes that are tilted upwards to extend the range of vertical viewing angles from 30° up to 60°. In turn AMIGA consists of an array of water-Cherenkov detectors (WDs) set out on a hexagonal spacing with sides of 750 m and 433 m (named *graded infill* array or simply *infill*) and an associated set of muon detectors (MDs) each of 30 m^2 buried at a depth of 2.3 m corresponding to 540 g cm^{-2}. Any impinging muon with energy $\geq$1 GeV propagates in the soil and is capable of reaching the buried muon detectors that are located near to the WDs as shown in Fig. 1. The new MD is the core of AMIGA that further develops the Auger Observatory as a multi-detector facility. Since the cosmic ray flux increases rapidly with the decreasing energy, the 750 m infill is laid out over an area of 23.5 km^2 while the planned 433 m array will cover only 5.9 km^2 within the larger area. The infill spacings allow cosmic rays to be detected with full efficiency down to an energy of 3×10^{17} eV and 10^{17} eV respectively.

In the following sections we will describe the status of the AMIGA project. A description of the detector performance is presented in [8, 9].

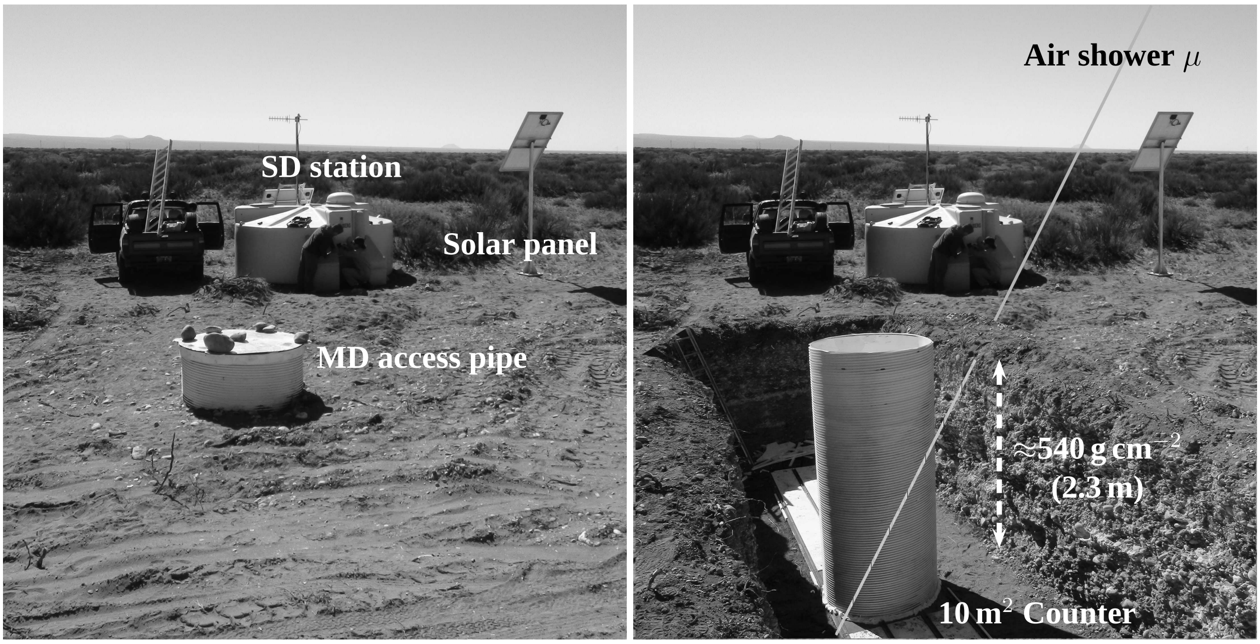

Figure 1: AMIGA concept: (Left) Surface infill SD station with its associated muon counter already buried. Once instrumented, the access pipe is filled with bags containing soil from the installation site. (Right) Photo-montage to depict the detector concept: any impinging muon with energy $\geq$1 GeV propagates in the soil and is capable of reaching the buried scintillator.

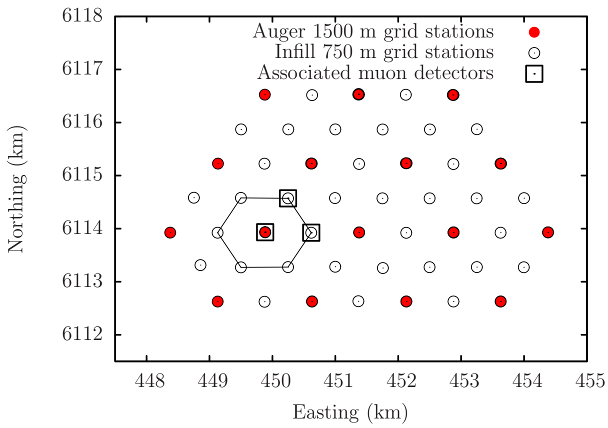

Figure 2: AMIGA array status in April 2011: the surface stations deployed on the 750 m grid are shown together with the associated muon detectors. The prototype MD will consist of 7 counters on the marked hexagon.

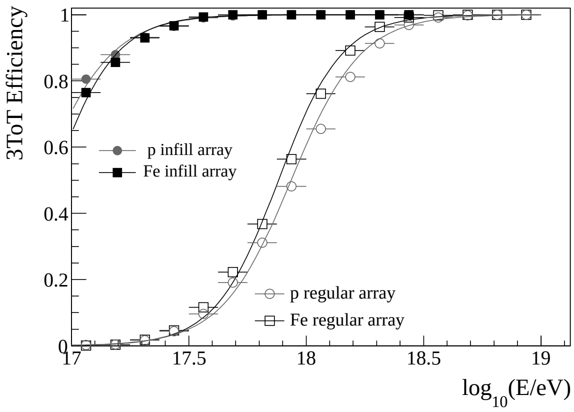

Figure 3: 3ToT trigger efficiency for the infill and regular array obtained from simulations of iron and proton primaries.

2 Surface Graded Infill

As of April 2011, 53 out of 61 surface stations planned for the 750 m infill have been deployed (see Fig. 2). For the smaller 433 m grid 24 new detectors will be installed after the completion of the 750 m array.

The water-Cherenkov detectors used in the infill array are identical to those used in the main array with the benefit of being a well-proven technology. Moreover, the infill is embedded in the regular array and therefore the same selection and reconstruction strategies may be employed to 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 regular Auger SD (for a detailed description see [8]). Any infill event with at least 3 stations forming a triangle and satisfying a local trigger of the type Time-over-Threshold (3ToT) [4] is accepted. The trigger efficiency as a function of energy for simulated 3ToT events with zenith angles below 55° is shown in Fig. 3 for both the regular and the infill array. As can be seen, the 750 m spacing of the infill allows cosmic rays to be detected down to an energy of 3×10^{17} eV with full efficiency. Integrating the instantaneous effective infill aperture over the time when the detector was stable, the exposure between August 2008 and March 2011 amounts to (26.4±1.3) km^2 sr yr. With the current configuration consisting of 16 hexagons the mean rate of 3ToT events is 55 events/day/hexagon out of which ~51% satisfy the fiducial selection that allows events that fall close to the boundary of the array to be rejected.

As was done for the 1.5 km array, measurement uncertainties have been derived from data [10]. The angular resolution of the 750 m array was found to be 1.3° for events with at least 4 stations. To reconstruct the events, the distribution of SD signals on ground as function of their distance to the shower axis is fitted with a LDF, S(r). The optimum distance, $r_{\rm opt}$, where the signal fluctuations are minimised depends on the array spacing. The signal S($r_{\rm opt}$) is the ground parameter eventually used to obtain an energy estimator. For the regular array $r_{\rm opt}$=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 3×10^{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. As an example the LDF of a well-contained infill event of 2.7×10^{18} eV impinging with zenith angle of 27° is shown in the top panel of Fig. 4. The same event reconstructed using stations from the regular array alone is illustrated in the bottom panel. Both reconstructions are compatible. 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 ~22% at 10 VEM to ~13% at 100 VEM. The energy of an event is estimated from the ground parameter independently of the zenith angle of the air shower by means of the *Constant Intensity Cut* (CIC) method [11]. The method allows S(450) to be evaluated at a reference angle of 35° (S_{35}). S_{35} is calibrated using the events simultaneously observed by the SD and the FD. The infill array was found to be fully efficient from S_{35}~20 VEM.

3 The Array of Muon Detectors

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. Once completed, the UC will be composed of 30 m^2 scintillator counters. Each counter will consist of two 10 m^2 plus two 5 m^2 modules associated to a single water-Cherenkov detector. In turn each module is made up of 64 scintillator strips 4.1 cm wide × 1.0 cm high. The length of the strips is 4 m and 2 m for the 10 m^2 and 5 m^2 modules respectively [9]. At present, three 10 m^2 detectors have been deployed in the positions shown in Fig. 2 with prototype electronics

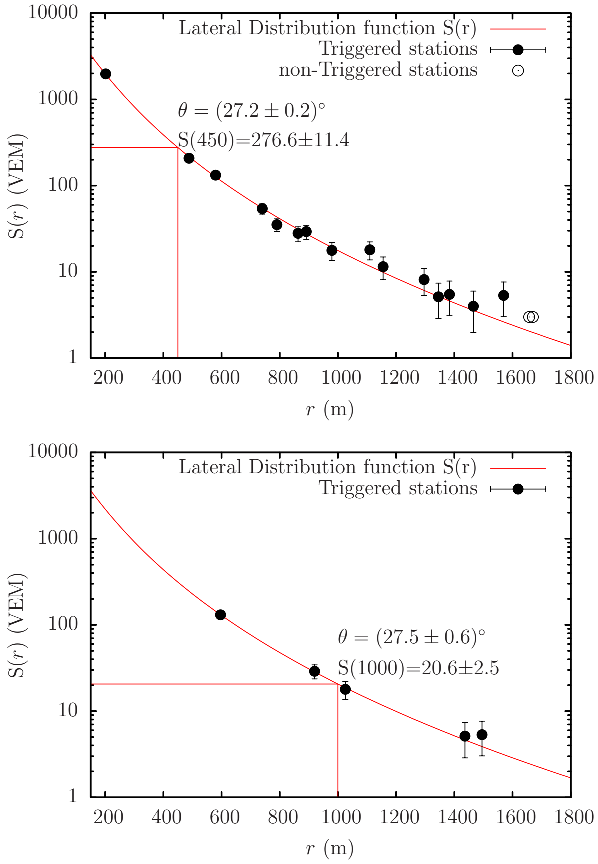

Figure 4: The same event reconstructed with the infill (top) and the regular (bottom) array. Solid and open circles are triggered and non-triggered stations respectively.

sampling every 12.5 ns (80 MHz). At the hexagon centre, an additional 5 m^2 module was also installed.

Although the MD has an internal stand-alone trigger mode of operation for monitoring and self-calibration purposes (see [9] for details), the buried scintillation detectors are triggered by signals from the associated WD station. The event geometry and the primary energy of the showers detected by AMIGA are reconstructed by means of the SD data alone as explained in the previous section. Once the shower parameters are established, the MD data are analysed [9] to provide the number of muons of the observed event. As of April 2011, the surface stations provide their lower-level trigger (T1, in single mode) to the associated scintillation detectors. The electronics required to link the MD data with the SD higher trigger levels is under development and therefore, is not yet possible to include the muon data in the shower reconstruction chain.

We will now describe the observed correlation, at T1 level, between the MD acquisitions and its associated SD station.

The surface stations have two independent T1 trigger modes [4]: a mode based on threshold discrimination (TH-T1), and a mode where the signal above threshold must be maintained over more than 325 ns (ToT-T1). The rate of triggers which satisfies the TH-T1 condition in the WD is

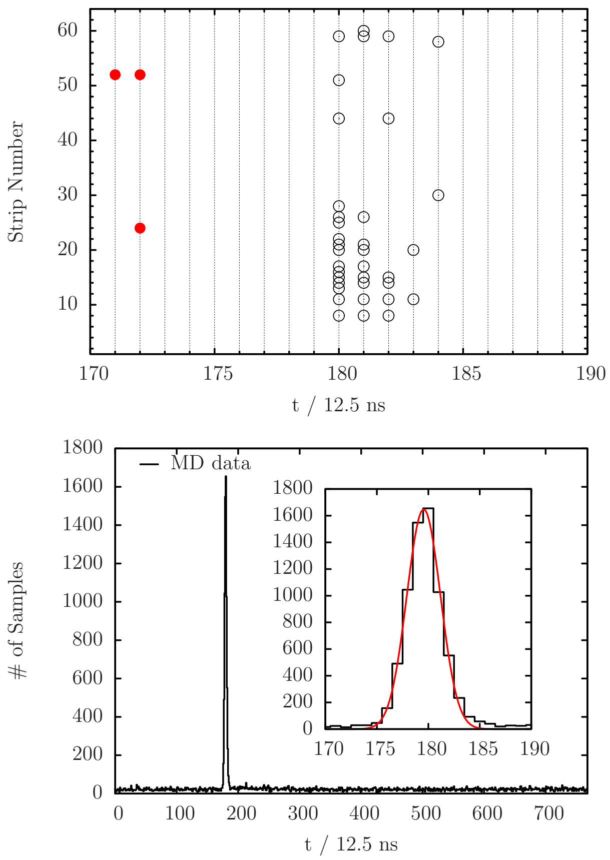

Figure 5: (Top) Two superimposed T1 events in the MD: a typical one with low-multiplicity (solid circles) and an unusual one with high-multiplicity (open circles). The low-multiplicity events account for around 95% of the T1 events. (Bottom) Projection over the time axis of the logical 1s of MD events triggered by WD T1s.

around 100 Hz while the rate of those satisfying the ToT-T1 is ~1.5 − 2 Hz. Once the MD is triggered, it records the digital signal of each one of the 64 scintillator strips in a local memory. Each signal has 768 logical samples and up to 1024 events can be stored. Within each signal, a logical 1 is stored every time the corresponding pulse is above a certain (adjustable) discrimination threshold.

Only 1% of the WD T1 events also have data in the MD. The rate of these events is around 1.6 Hz. Furthermore, within this small fraction, in 95% of the cases fewer than 4 strips were struck. These low-multiplicity events spread in time across 1 or 2 intervals of 12.5 ns. In the top panel of Fig. 5 two T1 events, as recorded by the MD, are shown superimposed as an example. One is a typical low-multiplicity event while the other is a rather unusual event with high-multiplicity. The projection over the time axis of the logical 1s of all non-empty MD events triggered by the WD T1s is shown in the bottom panel of Fig. 5. The discrimination threshold was set to ~80% of the mean single photo-electron pulse height. Around 40% of these events contribute to the well-defined Gaussian peak illustrated in the inset, showing a time correlation with the WD T1s and therefore indicating a common physical source. The remaining 60%, which constitutes the histogram baseline, is most likely atmospheric background given that it is uniformly distributed in time. The same results were obtained with different discrimination levels.

4 Discussion and Conclusion

The AMIGA enhancement of the Pierre Auger Observatory is being built. It comprises both, SD stations identical to the ones used in the main array of the Observatory deployed over an infilled area, and buried scintillation detectors that are used to count muons. The deployment of the SD infill component started in 2008 and more than 85% of the 750 m array has already been deployed. The prototype phase of the MD consists of 30 m^2 scintillation counters to be associated to 7 SD infill stations corresponding to one 750 m hexagon and to its centre. At present, four scintillator modules have been deployed. The uncertainties of the AMIGA infill have been studied with data and simulations using well-proven algorithms developed for the regular array during the past years. The total S(450) uncertainty goes from ~22% at 10 VEM to ~13% at 100 VEM. At the highest energies, the main driver of the uncertainties are the shower-to-shower fluctuations. The angular resolution of the infill array is below 1.3° for events with at least 4 SD stations. The first data from the muon detectors being triggered by the lowest level trigger signal of the associated WD station were analysed. Although it is still preliminary, a time correlation between the T1 trigger of the water-Cherenkov stations and the muon detector events was shown indicating a common physical source of both signals. The analysis of the MD events is on-going.

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