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The AMIGA muon detectors of the Pierre Auger Observatory: overview and status

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Abstract: The muon detector of the AMIGA (Auger Muons and Infill for the Ground Array) extension of the Pierre Auger Observatory is currently finishing the construction of its engineering array phase. The engineering array consists of seven detectors in a 750 m regular hexagon with buried scintillator counters in each of its vertices and center. The muon counters are buried alongside each Auger surface detector station in the infill area. Two additional twin detectors are being built to study the muon counting accuracy and the design validation. An overview of the construction and deployment of the muon scintillation detector array is presented with an emphasis on the current data analyses.

Keywords: Pierre Auger Observatory, AMIGA, Ultra-high Energy Cosmic Rays, Muon Detectors.

1 Introduction

The AMIGA project [1] is an extension of the Pierre Auger Observatory [2] to provide full efficiency detection of cosmic rays down to $\sim 10^{17}$ eV through an infill of Water Cherenkov Detectors (WCD) of the Auger Surface Detector (SD). This energy region is of great importance because it is the range where the transition from galactic to extragalactic sources of cosmic rays is expected to occur. AMIGA will also improve the cosmic ray mass identification with 30 m^2 muon counters buried alongside the surface detectors in the infill to directly measure the muon content of the particle showers produced by the primary particle.

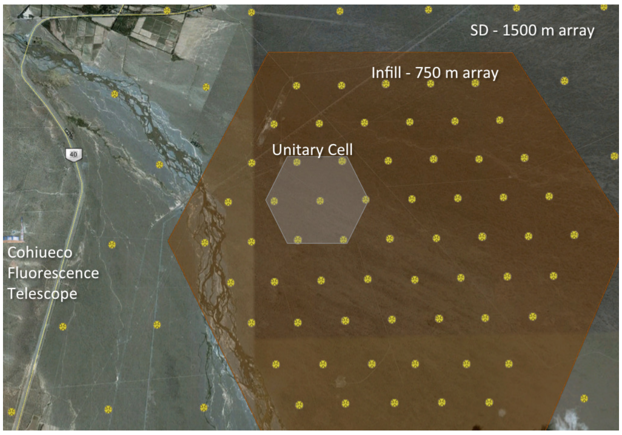

Fig. 1: Map of the AMIGA array with brown background. The engineering array positions, where muon counters are already deployed, can be seen highlighted in gray (also called the Unitary Cell).

The muon detectors of AMIGA are being deployed over the infilled area of $\sim$23.5 km^2 (fig. 1) which includes 61 stations. The first seven muon detectors are being deployed in an engineering array called Unitary Cell (UC), consisting of 30 m^2 counters to validate the detection technique and the detector design. In two positions, two identical 30 m^2 detectors are being deployed (the twins) to study the fluctuation in the counting rate for the detector design validation [3]. Finally, the rest of the 54 muon detectors will be deployed in the production phase.

Basically, the AMIGA muon counters have a modular design mainly because of the need to solve some engineering challenges. Therefore, the modules are designed to be water proof, easy, fast, and simple to manufacture, robust enough to resist long and hard transportation conditions, and small enough to fit into regular transportation trucks to reduce costs. Thus, the UC design (see fig. 2) consists of four modules covering the 30 m^2 divided into two modules with 10 m^2, and two with 5 m^2 detection area in each position.

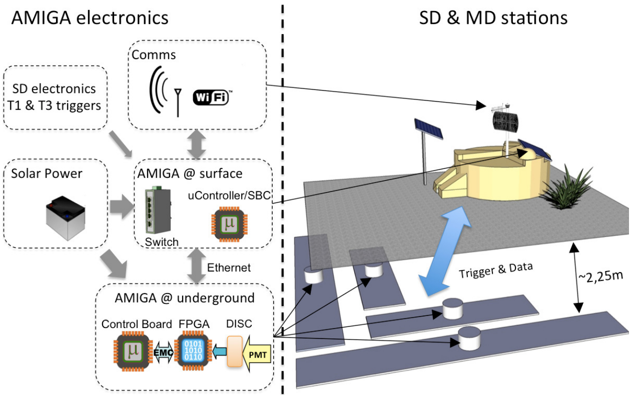

Fig. 2: Simple scheme of the AMIGA Unitary Cell muon detector and its electronics [6]. The discrimination levels of the signals from the PMT are adjustable by the calibration algorithm, expected to be set at $\sim$1/3 SPE (Single Photoelectron level).

Each of the UC modules [4] are segmented in 64 scintillation bars produced at Fermilab. The generated light pulses are collected by a WLS (wavelength shifter) optical fiber and then propagated to a multi-anode PMT (Photomultiplier

Tube from Hamamatsu, H8804-200MOD) [5]. As sketched in fig. 2, the readout electronics consists of an analog front-end to amplify and discriminate the pulses coming from the PMT, and a digital board with a FPGA that samples the discriminated signals at 320 MHz to conform a 1-bit digitalization of the signals. Currently, the events consist of a block of 1024 words of 64 bits where each bit corresponds to a module channel and each word to the time bin [6]. The events are stored in a local memory when a first level trigger [7] is received from the surface detector. Finally, the data of the muon counter events are transmitted to the surface through a control and interface board when a third level trigger is broadcasted to the array and re-transmitted through a Wi-Fi system to the Central Data Acquisition System of the Observatory.

2 Deployment of the muon detector modules

The detector modules are mostly fabricated at Buenos Aires and then transported ∼1100 km to the Pierre Auger Observatory. Then, they are taken to the field and deployed ∼2.25 m underground (∼540 g cm^{-2} considering local soil) in an ”L” layout (fig. 3 and 4) in an effort to reduce the counting uncertainty produced by inclined muons that could cross two scintillators instead of one (clipping corners). The layer of soil above the detectors is used as a shielding against the electromagnetic component of the particle showers and it was simulated to be enough to avoid punch-through electrons. The modules are placed ∼5 m away from the surface detector to reduce any angular dependence due to a possible ”shading” and to avoid the removal of the surface detector to excavate the pits for the muon detector modules.

Fig. 3: Deployment of the first twin at Kathy-Turner when installing the service-tubes right before burying the modules.

As already mentioned in the previous section, in the case of the UC, the 30 m^2 muon detector is divided into four modules. The 5 m^2 ones provide better segmentation of the detector to make it suitable to measure particle showers closer to the core where the number of muons is higher, thus reducing the so called pile-up of muons.

From the engineering point of view, the modules and the deployment procedure are designed to provide an easy but safe installation both for the technicians and the module itself. As shown in fig. 3, the modules lay on a sand bed free of rocks in the pit to avoid damages. The pits are excavated with inclined walls at the top to reduce the possibility of collapse. The modules are also fully surrounded by polyfoam as a first protection layer against rocks but also against sun-light exposure that damages the PVC enclosure of the modules while deploying. Then, a ∼10 cm layer of fine sand is placed on top of the modules before proceeding to the final refilling of the pit.

Each of the modules has a service tube used to provide maintenance access to the electronics. The service tubes have a diameter of 1.3 m (comfortable enough for a technician). A special glue is used to connect them to the modules and provides water-tightness. The service tubes are covered with a cap to resist damage by animals, vandalism, and UV exposure. Finally, they are refilled with removable big sand bags (filled with local soil) to make a uniform shielding for the detector.

3 Current status of the Unitary Cell construction

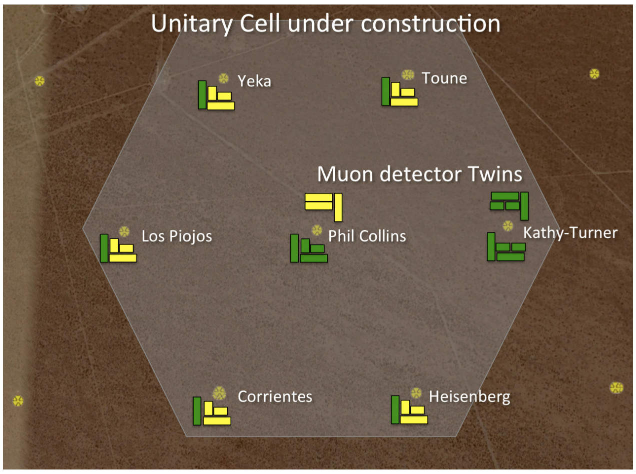

Fig. 4: Layout of the AMIGA Unitary Cell. The muon detectors already installed are represented in green, and those to be deployed in near future are shown in yellow. The twin muon detectors at Kathy-Turner are operating and those next to Phil Collins are still under construction. The twin detector at Phil Collins consists of three modules (10 m^2 each) instead of four to validate a three modules design for production.

The engineering array is currently growing to form the UC (fig. 4), and it is important to solve the engineering challenges of logistics, to develop the facilities and the module construction procedures for a reasonable construction rate, to finish the mechanical design, to develop the corresponding calibration methods, and to register a reasonable amount of events. Exploiting the UC data, we will be able to get an experimental output to confirm the simulated parameters used as the base-line design of the modules such as the number of muons per shower and their distribution in time and space. A detailed analysis of these events is thus mandatory before getting into the production phase.

The UC also includes two twin positions, i.e. there are two infill surface detectors each one associated with two 30 m^2 muon detectors running independently. Currently, one of the two twins is already deployed and taking data; more details about the data analysis of the events registered by the twins can be found in [3].

4 First muon counter events

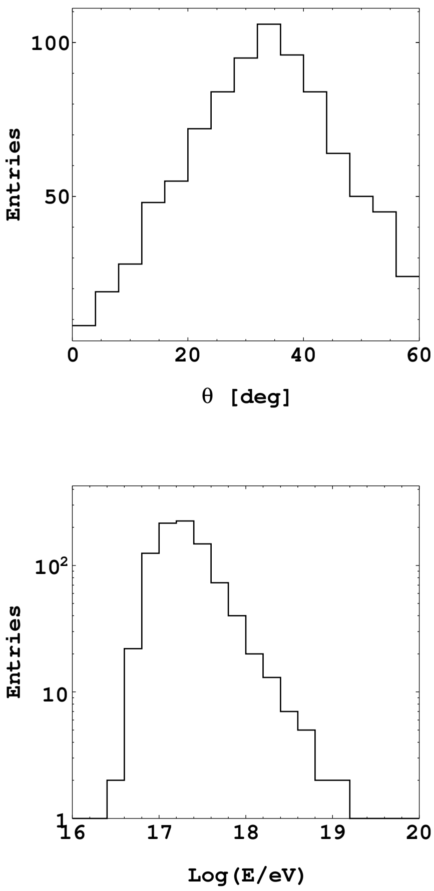

Fig. 5: Angular and energy distribution of recorded AMIGA events since Marh 18th 2013

Data taken by the AMIGA muon counters and by the WCD are transmitted to the Central Data Acquisition System where they are merged. The recorded events are analysed with the Offline software to reconstruct the shower parameters using the SD data alone and to extract the number of muons from the buried counters. This is done by applying a certain counting strategy that can be adjusted in order to reduce the miscounting produced by the systematic uncertainties of the detector (e.g. after pulses, channels cross-talk, dark-pulse rate) [9]. On Marh 18th 2013, the UC started the first stable AMIGA acquisition period with parameters of the baseline design, and 901 forth level trigger events were registered with zenith angle below 60° up to May 31st. As expected, most of them (671) are low energy events and only 230 are above the infill full efficiency energy 3×10^{17} eV (see fig.5). The footprint on the MD hexagon of a 2.7×10^{18} eV shower impinging with $\theta = 39.9°$ zenith angle can be seen in fig. 6.

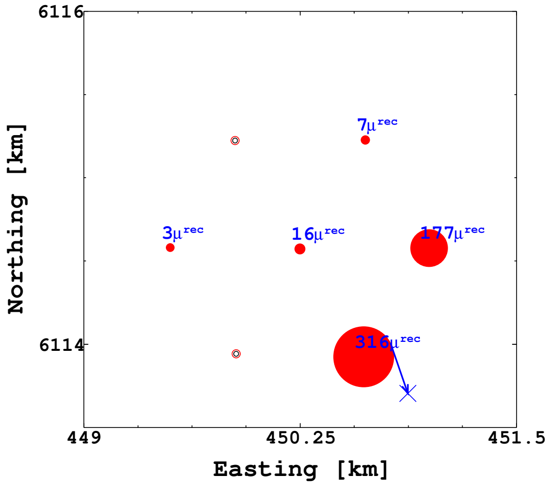

Fig. 6: Example of a 2.7×10^{18} eV shower impinging with an zenith angle of $\theta = 39.9°$ that hit the border of the muon counters engineering array under construction. The reconstructed core position is marked with the cross sign and the impinging direction is indicated with the arrow. The sizes of the red dots are proportional to the reconstructed number of muons (in blue) per station. Open red circles indicate a *silent* counter, i.e, counters that received the SD triggering signal but counted less than three muons. Open black circles are untriggered counters. The *twin* MD counter is the rightmost vertex of the hexagon. As can be noticed, the 60 m^2 area of this counter are responsible for the 177 reconstructed muons, roughly ten times more of its closest 10 m^2 companion at the centre of the hexagon. The hottest counter (bottom right vertex), with 10 m^2 is saturated (see fig. 7), i.e. more than 21 muons where simultaneously measured in a time window of 25 ns.

Given the geometry and the energy of the shower by the SD, a KASCADE-Grande like muon lateral distribution function (MLDF) [10] is fitted to the measured muon densities.

$$\rho_\mu(r) = \rho_\mu(450)\left(\frac{r}{r_0}\right)^{-\alpha}\left(1+\frac{r}{r_0}\right)^{-\beta}\left(1+\left(\frac{r}{10r_0}\right)^2\right)^{\gamma} \quad (1)$$

The fitting parameters are $\rho_\mu(450)$ and β while the others are fixed at $\alpha = 1$, $\gamma = 1.85$, and $r_0 = 150$ m.

5 Data analysis

Although the muon component in the showers is attenuated much less than the electromagnetic component, the shielding of ~2.25 m of soil adds 540 g cm^{-2} of vertical mass (roughly 60% more than the whole atmosphere at the level of the Auger Observatory, namely, 870 g cm^{-2}). However, a detailed study of attenuation is not possible yet due to the low statistics so far achieved. Nevertheless, averaging over all MLDFs normalized to their fitted parameter $\rho_\mu(450)$ allows a qualitatively inspection of the dependence of the β

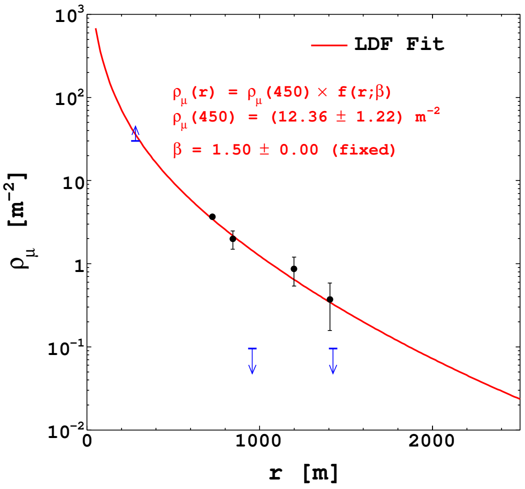

Fig. 7: Muon LDF fit (equation 1) corresponding to event of fig. 6. Blue upward and downward arrows are saturated and silent counters respectively.

parameter with the zenith angle θ of the impinging shower. In fig. 8 the mean $\rho_\mu(r)/\rho_\mu(450)$ are shown for three angular bins evenly separated in $\cos(\theta)\sin(\theta)$.

6 Conclusions

The construction of the AMIGA muon detector array is proceeding through the Unitary Cell deployment, and it is growing smoothly. Advances in the engineering of the muon counters fabrication, logistics, procedures, and deployment technique have been achieved with remarkable results concerning the mechanical design and the stability of the detector modules. No mechanical damages nor loss of modules were suffered so far during the construction of the project.

The muon content of the particle showers is being measured with the Unitary Cell under construction and a first collection of events has been analysed. Preliminary muon LDFs have been obtained. A stable and good performance of the AMIGA scintillation modules can be inferred from the analysis of the first events registered.

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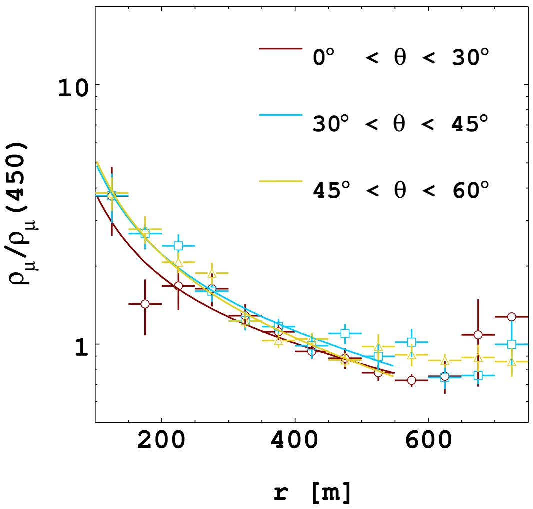

Fig. 8: Averaged $\rho_\mu(r)/\rho_\mu(450)$ of 230 measured MD events where at least two counters detected more than two muons above the full efficiency detection. Although still preliminary, the radial dependence of the muon densities with the decreasing zenith angle can be appreciated for the three angular bins evenly separated in $\cos(\theta)\sin(\theta)$.

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