33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Measuring the accuracy of the AMIGA muon counters at the Pierre Auger Observatory

SIMONE MALDERA[1] FOR THE PIERRE AUGER COLLABORATION[2]

[1] *Osservatorio Astrofisico di Torino (INAF), Università di Torino and Sezione INFN, Torino, Italy*
[2] *Full author list: http://www.auger.org/archive/authors_2013_05.html*

auger_spokespersons@fnal.gov

Abstract: The AMIGA enhancement of the Auger Surface Detector consists of a 23.5 km^2 infilled area where the shower particles are sampled by water Cherenkov detectors accompanied by 30 m^2 of scintillator counters, buried 2.3 m underground. The accuracy of the muon counting obtained by the buried detectors is a basic element in the reconstruction procedure, and must be determined using experimental air shower data. To perform this measurement, twin muon counters (30+30 m^2) have been deployed in two infill locations; their mutual distance being about 10 m, they sample nearly the same region of the air shower. In this paper we discuss the basic properties of the modules as measured during the construction phase and the expected counting performances of the twin counters installed at the experimental site.

Keywords: Pierre Auger Observatory, AMIGA, ultra-high energy cosmic ray, muon detectors

1 Introduction

AMIGA (Auger Muons and Infill for the Ground Array) [1] is an enhancement of the Pierre Auger Observatory designed to lower the energy threshold of the Auger surface detector array by one order of magnitude, down to $\approx 10^{17}$ eV, i.e. the energy region where the transition from the galactic to the extragalactic component of the cosmic radiation is expected to take place. A detailed study of the features of the energy spectrum and of the mass composition of cosmic rays in that energy range is mandatory to discriminate among the different models proposed to describe that transition ([2] [3] [4]) and advance in the understanding of the origin of cosmic rays.

AMIGA consists of an "infill" of a portion of the Auger surface detector (SD) array, where the spacing between the detectors is reduced to 750 m (half of the spacing in the regular Auger array). Each infill SD station is accompanied by nearby buried muon counters to measure the muonic component of air showers, and to obtain information about the mass of the primary particle. While the infill surface detectors are already deployed and taking data [5], an Engineering Array of muon counters is being developed, consisting of a hexagon of six 30 m^2 modules plus one at the center (the "Unitary Cell", UC) [6].

The main goal of the muon Unitary Cell is the validation of the detector design and the complete understanding and optimization of the AMIGA muon counting performances. To evaluate the counting accuracy two complete modules are installed in a *twin* configuration in the Unitary Cell (see Fig. 1). The measurement will be performed by comparing the counts of two "doublets" of two 30 m^2 modules located at a short distance ($\approx$10 m) negligible with respect to the dimension of the shower at ground (of the order of 1 km at the energies of interest).

The first of the two twin counters is fully operational since March 18, 2013. In the following sections the basic properties of the muon detectors as measured during the construction of six modules in the mechanical workshop of INFN-Torino (Italy) and the expected counting performances of the twin counters installed at the experimental site will be discussed.

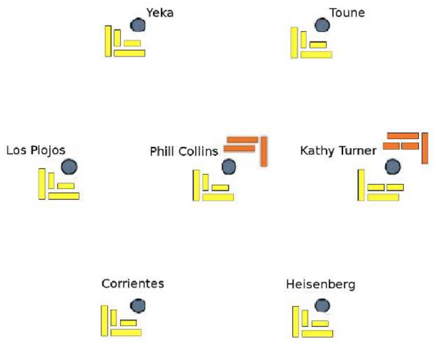

Figure 1: Planned layout of a Unitary Cell of muon detectors (in yellow) near the infill surface detectors (green circles). The additional muon counters making up the twins with the Phil Collins and Kathy Turner surface detectors are shown in orange. For information about the status of the deployment see [6].

2 Amiga muon detectors

Every muon counter of the Unitary Cell consists of four modules with a total active area of 30 m^2, split into two 10 m^2 and two 5 m^2 units. Each module is composed of 64 plastic scintillator strips 400 cm long (200 cm for the 5 m^2 ones), 4.1 cm wide and 1.0 cm high, lodged in a waterproof PVC casing.

The scintillator strips are made of extruded polystyrene doped with fluors (PPO and PPOP), co-extruded with a diffusive titanium dioxide coating. Due to the short light attenuation length of the scintillator a wavelength shifter optical fiber (1.2 mm diameter), hosted in a groove in the middle of the strip, collects the scintillation photons. The scintillator strips are organized into two groups of 32 at each side of a central dome, where a multi-pixel photomultiplier (Hamamatsu H8004-200MOD) and the module electronics are placed. The 64 fibers from the two sides of the module are optically connected to the PMT. The readout electronics produces a digital output counting the pulses above a given threshold. The signal from each pixel is filtered and amplified at a nominal gain of -3.8, then discriminated, digitized with a sampling frequency of 320 MHz and stored in a circular memory. The discrimination level can be adjusted for each one of the 64 channels, and its default level is set to one third of the mean single photoelectron amplitude per pixel. When a trigger signal from the adjacent surface station is received, the digitized traces are transmitted to the central acquisition system. This method, besides strongly reducing the information to be sent to the Auger central data acquisition, is essentially independent of the PMT gain and its fluctuations and of the muon hitting position along the scintillator strip. The optimal depth for the muon detectors has been studied by means of numerical simulations. With a shielding layer of 540 g/cm^2 of soil ($\approx$2.3 m) the fraction of counts generated by the electromagnetic component of the shower, is lower than 5%, with an energy threshold for incoming muons of $\approx$1 GeV.

3 Characterization of the muon modules

During the construction phase the response of each module has been tested using both atmospheric muons and a radioactive source, using a setup similar to the one described in [7]. In fact a complete calibration of each scintillator strip with a cosmic-ray hodoscope needs about 12 hours of exposure, requiring the implementation of a reliable and fast calibration system for the module production.

After the assembly, the detectors have been exposed to a 0.84 mCi ^{90}Sr β radioactive source, placed at a distance of about 10 cm above the module. The X-Y position of the source was controlled by a robotic arm. A readout board multiplexes the signals from each pixel of the PMT to a charge amplifier and a dedicated data acquisition system. The 64 channels are read out within 100 ms, allowing continuous monitoring of all the scintillator strips.

The source is moved along the direction perpendicular to the strip length at a fixed distance from module median. The signal of each pixel increases as the source is approaching the strip, reaches a maximum value when it is in the center and then decreases. The resulting time profile is fitted with a Gaussian function to get the height of the maximum. Performing such "transversal scans" at different distances to the PMT the light attenuation profile can be derived (see Fig. 2).

The response of the AMIGA modules to through-going muons has been studied using two small detectors consisting of a piece of scintillator (4x10 cm^2) and a photomultiplier, placed above and below a given strip. The coincidence of the two small scintillators generates a trigger for the FADC (1 GHz sampling rate, 10 bits) reading the PMT signals from the module. An acquisition time of about one day allows a good measurement of the charge spectrum of the acquired signal. To increase the statistics larger trigger scintillators (10x80 cm^2) were also used, allowing more strips to be measured at the same time. In this case a huge background peak appears in the charge spectrum. About 100 measurements on different modules, strips and at different distances from the PMT (computed along the optical fiber) have been performed, allowing one to normalize the results obtained with the radioactive source to the mean collected charge when a muon crosses the detector vertically. Fig. 3 shows the ratio between these two quantities, taken on the same scintillator strip and at the same distance from the PMT.

Finally the number of photoelectrons (*n.p.e.*) produced

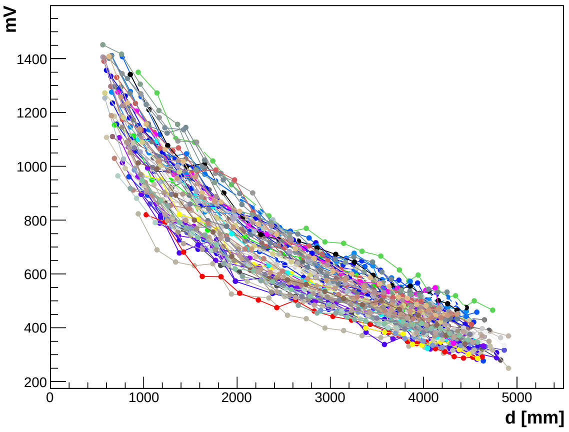

Figure 2: Results of the scan with a radioactive ^{90}Sr source for one 10 m^2 module. The maximum of the signal from each scintillator strip is shown as a function of the distance from the PMT (along the fiber).

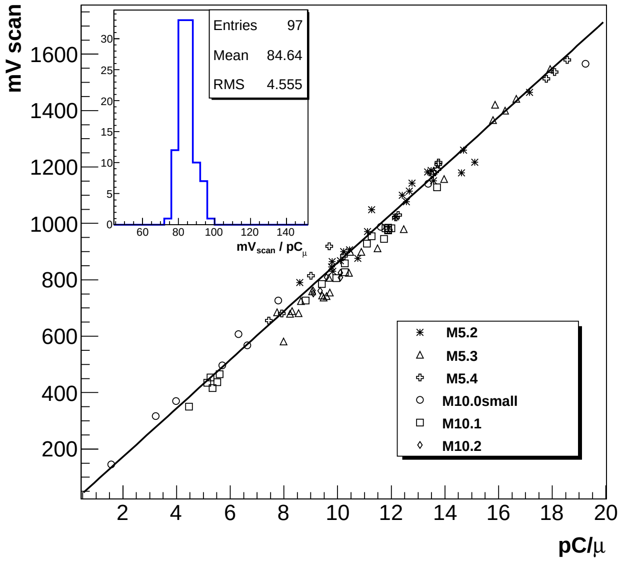

Figure 3: Normalization of the signal measured with the radioactive source to the average charge collected per muon crossing the detector vertically, measured on the modules built in Torino (four 5 m^2 modules and two 10 m^2 ones labeled as M5 and M10 respectively). The histogram of the ratios between all those measurements is shown in the top left corner. The width of this histogram gives the uncertainty in the normalization value.

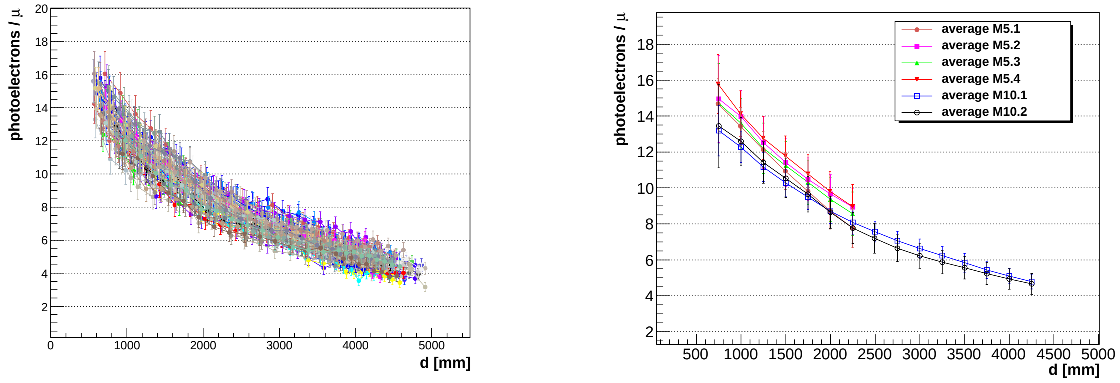

Figure 4: **Left:** Number of photoelectrons per muon crossing the detector vertically for the 64 strips of one module, obtained from the measurements with the radioactive source. **Right:** Number of photoelectrons produced by vertically crossing muons, at different distances from the PMT, Each point represents the average of the 64 strips of the module, error-bars correspond to the RMS of their distribution.

at the PMT photocathode by a through-going muon can be derived as:

$$n.p.e. = \frac{Q_\mu}{G_{pixel} \cdot e} = \frac{V_{scan}}{R} \cdot \frac{1}{G_{pixel} \cdot e}$$

where e is the elementary charge, G_{pixel} is the gain of the specific pixel of the PMT, V_{scan} is the signal generated by the radioactive source read out through the charge amplifier, and R is the normalization factor (given by the ratio shown in Fig. 3). The gain of each PMT pixel has been measured using the single photoelectron technique, with an uncertainty of about 7%. In Fig. 4 we show the result of the conversion of the measurements with the radioactive source to the number of photoelectrons, according to the formula above. The uncertainty in the measured $n.p.e.$ is about 12%, and has been derived from the combination of the uncertainties in the peak voltage obtained with the source (about 2%), in the normalization factor (8%), and the quoted uncertainty in the pixel gain.

4 Simulation of the detector response

The laboratory measurements and results described above have been used to simulate the detector counting performances (similarly to [8]). The energy deposited by a muon in the buried scintillator strip is simulated by means of Geant4 ([9]), and then converted to a number of photoelectrons generated in the PMT given by:

$$n.p.e_{sim} = \frac{E_{dep}}{< E^{\mu}_{dep} >} \times N_{p.e/\mu}(d)$$

being E_{dep} the deposited energy, $< E^{\mu}_{dep} >$ the average energy deposit of a vertically crossing muon (obtained by simulation), and $N_{p.e/\mu}(d)$ the measured average number of photoelectrons per vertically crossing muon (Fig. 4). To reproduce the measured distribution a Poissonian fluctuation is applied to the photoelectron number obtained with the quoted formula. Given the total number of photoelectrons, a corresponding signal shape is extracted from a sample of traces (organized in bins of $n.p.e.$) obtained from the measurements with atmospheric muons described above. To match the conditions of the readout electronics of the muon module, such traces are convolved with a digital low-pass filter with a cutoff frequency of 140 MHz (while the bandwidth of the digitizer used in the laboratory is 500 MHz) and down-sampled to 320 MHz with a simple decimation algorithm. Each time bin of the resulting trace is discriminated at a threshold corresponding to 33% of the photoelectron amplitude, producing a digital data stream similar to the one expected from the real detectors.

Using this simple simulation, the detection efficiency for different counting strategies and discrimination thresholds can be estimated. Fig. 5 shows the ratio between the number of counts obtained with two different counting algorithms and the total number of injected muons, as a function of the distance from the particle position to the module

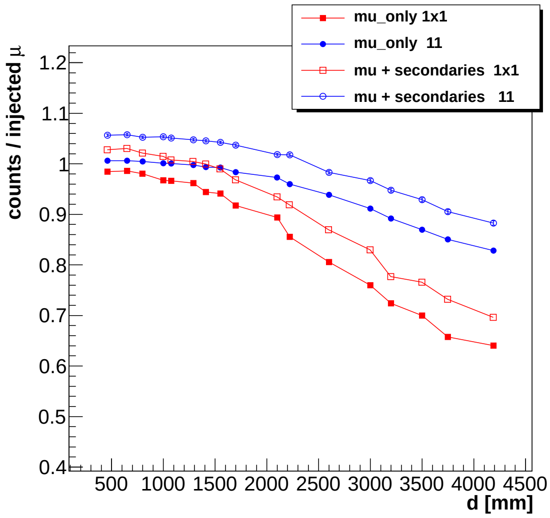

Figure 5: Ratio between the number of counts obtained from the module simulation and the total number of injected muons as function of the distance from the particle position to the PMT. Vertical muons of 5 GeV have been considered in the simulation (see text).

center. Two different counting strategies have been used, one requiring two adjacent positive samples (labeled as *11*), the other one requiring two positive samples spaced by one positive or negative bin (labeled as *1x1*).The results are shown first taking into account only the muons that hit the detector and then considering also the hits of secondary electrons generated in the propagation of muons in the ground. The overall ratio is about 93% for the *11* counting strategy and 82% for the *1x1* strategy considering only muon hits, rising to 98% and 88% respectively when the hits of secondary particles are included.

5 The muon counting accuracy

The muon modules have been doubled at two positions of the UC (as shown in Fig. 1) to directly measure the accuracy in the muon counting. Such accuracy must be determined experimentally using real events measured by the detector. In fact, shower fluctuations are extremely difficult to simulate, due to the large number of particles in the cascades ($> 10^{11}$) and the uncertainties in the numbers of muons, electrons and gamma-rays, which depend on the hadron interactions and on the primary particle type. Moreover, the measurements in the field include environmental and instrumental effects (e.g. background from soil radioactivity and residual punch-through particles, PMT gain fluctuations and other noise effects) which are difficult to be correctly estimated in the simulation.

Since the shower footprint is of the order of several square kilometers, these modules (separated by 10 m, as described above) are virtually measuring the same region of the shower. The muon counting accuracy will be derived from the comparison of the counts in two adjacent counters. In particular the relative fluctuation in the muon number can be defined as:

$$\Delta = \sqrt{2} \cdot \frac{M1 - M2}{M1 + M2}$$

where M_i corresponds to the number of muons measured by the i-th counter of the pair. The relative accuracy of a single module is then given by the width of the Δ distribution, $\delta\Delta = \sigma/M$, where σ is the accuracy of a single module. To obtain this expression, it has to be assumed that $M_1 \approx M_2$ and that $\sigma_1 \approx \sigma_2$; quality cuts will be used to ensure that the modules are measuring real EAS events. The detectors are in principle identical, therefore their accuracies should be similar.

The expected results on the counting accuracy of the AMIGA muon modules have been studied by means of simulations. Given the energy threshold of the infill array (full trigger efficiency at $\approx 3 \times 10^{17}$ eV) one year of data taking will allow deviations from a Poissonian behavior (expected for an ideal detector) of the order of 10% to be detected at a level of 2σ. In addition the comparison between the counts in the 5 m^2 and the 10 m^2 modules will allow us to study the counting efficiency and the effect of pile-up (due to the finite segmentation of the modules).

The first data from the twin counters at the *Kathy Turner* position are shown in Fig. 6. Requiring that the associated SD station is part of an event with reconstructed energy above 10^{17} eV, about 280 events have been collected in two month of data taking. The preliminary comparison of the counts of the two counters, already gives a first indication that the detectors are working as expected, allowing the muon counting accuracy to be accessed in the near future.

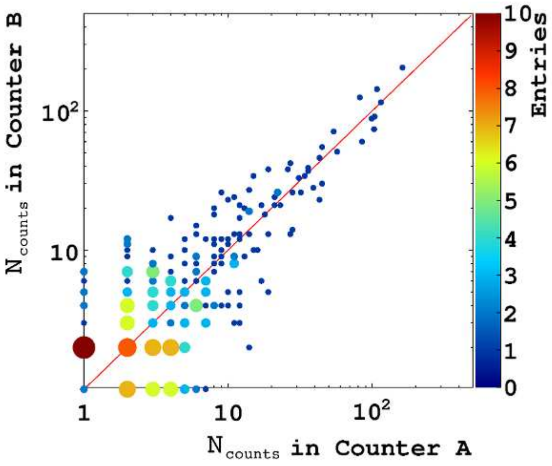

Figure 6: Comparison of the counts registered by the two muon counters at the *Kathy Turner* position after the application of the *1x1* counting strategy, for the first two months of data taking (18 March - 18 May 2013). The color code and the dot size are proportional to the number of events in each bin.

6 Conclusions

The AMIGA muon Unitary Cell, being deployed at the experimental site, will allow us to validate of the detector design and performances. The counting accuracy will be studied by a couple of twin muon counters buried near the same SD station. The first twin has been taking data since March 2013.

The muon module response has been carefully studied during the construction phase, and the results for the modules built at INFN-Torino have been reported. In particular the average number of photoelectrons in the PMT for a vertical muon crossing the detector has been measured to be between ≈15 and ≈5 according to the position at which the particle crosses the detector.

The laboratory measurements and their results have been used to implement a simple simulation of the detector response, allowing the expected counting performances of the modules to be estimated. Such simulations will be used to further study and optimize the reconstruction algorithm.

References

[1] A. Etchegoyen for the Pierre Auger Collaboration, Proc. 30th ICRC, Mérida, Mexico, **5** (2007) 1191.
[2] M. Hillas, J. Phys. G Nucl. Part. **31** (2005) R95.
[3] V. Berezinsky *et al.*, Phys. Rev. D **74** (2006) 043005.
[4] D. Allard *et al.*, Astropart. Phys. **27-1** (2007) 61.
[5] D. Ravignani for the Pierre Auger Collaboration, paper 693, these proceedings.
[6] F. Suarez for the Pierre Auger Collaboration, paper 712, these proceedings.
[7] M. Platino *et al.*, JINST **6** (2011) P06006.
[8] B. Wundheiler for the Pierre Auger Collaboration, Proc. 32th ICRC, Beijing, China **3** (2011) 84, arXiv:1107.4807.
[9] S. Agostinelli *et al.*, Nucl. Instrum. Meth. **506** (2003) 250.