Status and performance of the underground muon detector of the Pierre Auger Observatory

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Abstract: The Auger Muons and Infill for the Ground Array (AMIGA) is an enhancement of the Pierre Auger Observatory, whose purpose is to lower the energy threshold of the observatory down to $10^{16.5}$ eV, and to measure the muonic content of air showers directly. These measurements will significantly contribute to the determination of primary particle masses in the range between the second knee and the ankle, to the study of hadronic interaction models with air showers, and, in turn, to the understanding of the muon puzzle. The underground muon detector of AMIGA is concomitant to two triangular grids of water-Cherenkov stations with spacings of 433 and 750 m; each grid position is equipped with a 30 m^2 plastic scintillator buried at 2.3 m depth. After the engineering array completion in early 2018 and general improvements to the design, the production phase commenced. In this work, we report on the status of the underground muon detector, the progress of its deployment, and the performance achieved after two years of operation. The detector construction is foreseen to finish by mid-2022.

1. Underground muon detector (UMD)

73 station grid

73 × 3 buried modules (35% completed)

1 module:
- 10 m^2 scintillator detector
- 64 strips + optical fibers
- 64 silicon photomultipliers (SiPM)

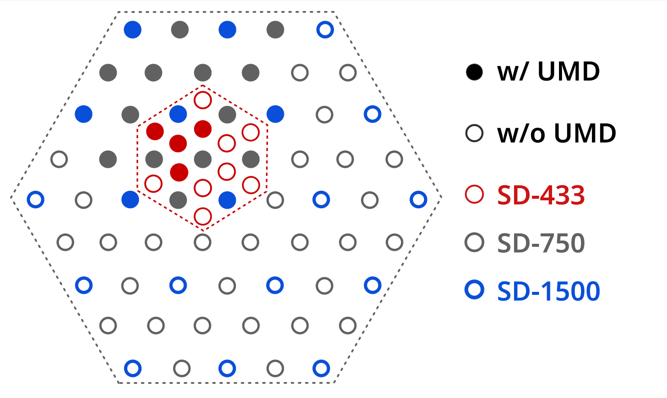

Figure 1: UMD array and deployment status

Figure 2: UMD module under construction and deployment

2. Traces

Binary acquisition mode:
- 64 traces with 2048 bits.
- 3.125 ns sampling time.
- Direct counting of muons.
- Low particle density

ADC acquisition mode:
- 2 waveforms with 1024 samples.
- 6.25 ns sampling time.
- Mean muon signal.
- High particle density

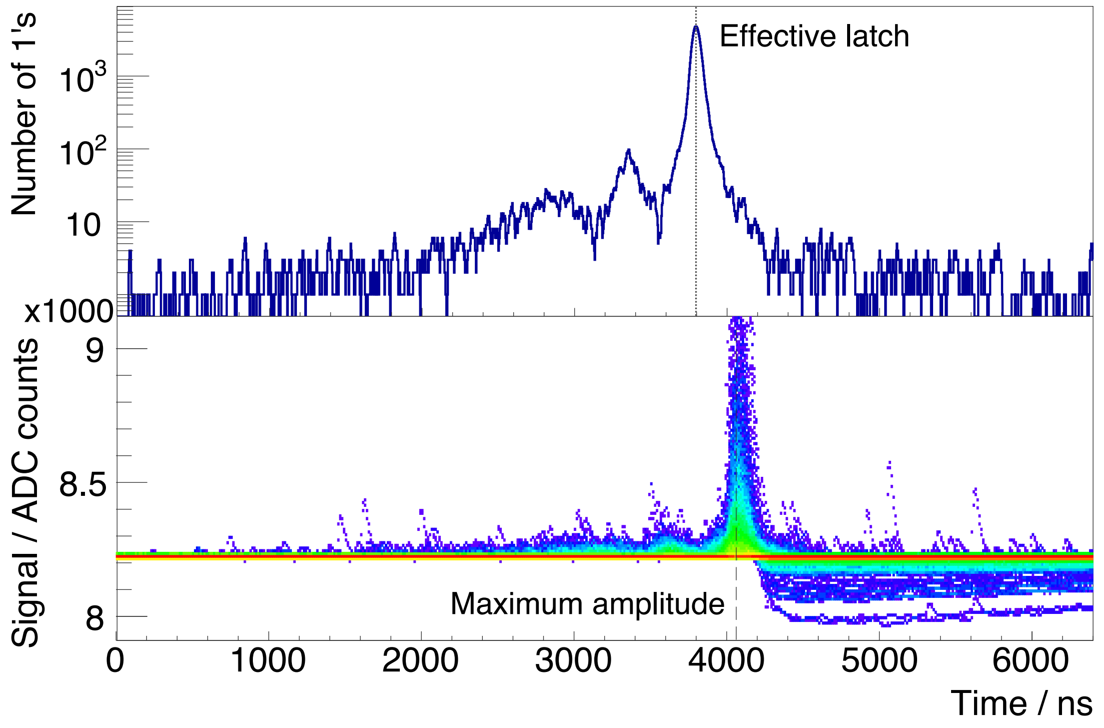

Figure 3: Addition of binary traces (top) and ADC traces overlap (bottom)

3. Calibration

Photo-equivalent (**PE**) amplitude determined from dark-count rate.

PE amplitude = 0 → Reverse-bias voltage (**V$_{bias}$**) = minimum voltage for Geiger mode (**V$_{br}$**)

Binary calibration: Amplitude threshold at 2.5 PE

ADC calibration: determination of single-muon charge with background

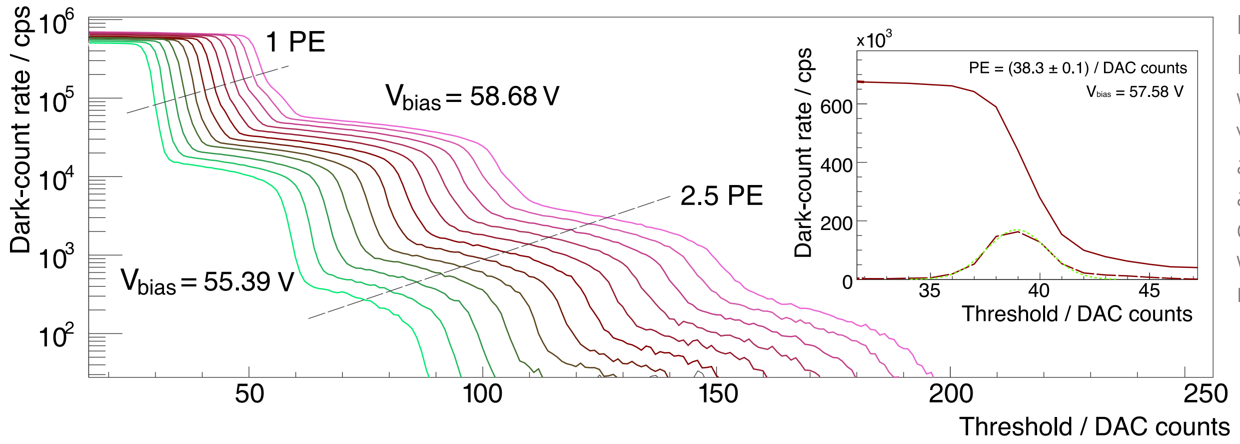

Figure 4: Dark-count rate with different values of V$_{bias}$ and PE amplitude determination with dark-count rate

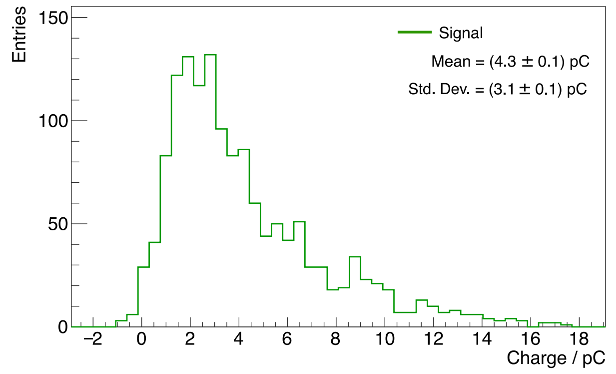

Figure 5: ADC calibration histogram

4. Calibration parameters

ADC charge calculation depends on trace features:
- Effective latch in binary channel.
- Delay between binary start time and ADC maximum.

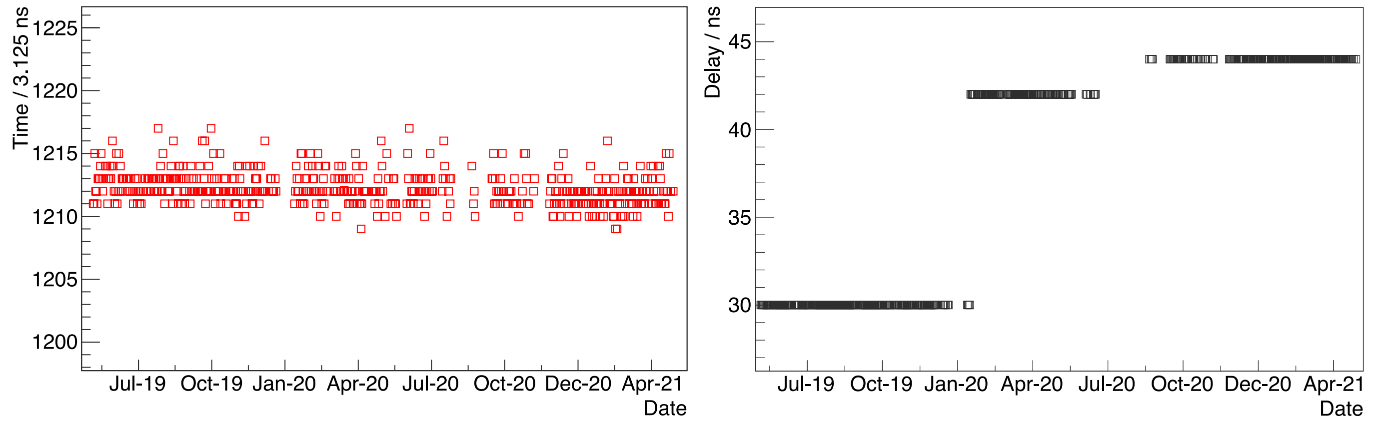

Figure 6: effective latch (left) and delay between binary and ADC (right)

5. Performance

Dark-count rate modulated by temperature

10-20% probability of "1" in 6.4 μs.

5% overcount probabilty in 6.4 μs.

Seasonal modulation in number of detected background muons.

ADC charge calibration stable in time (1.3% fluctuation).

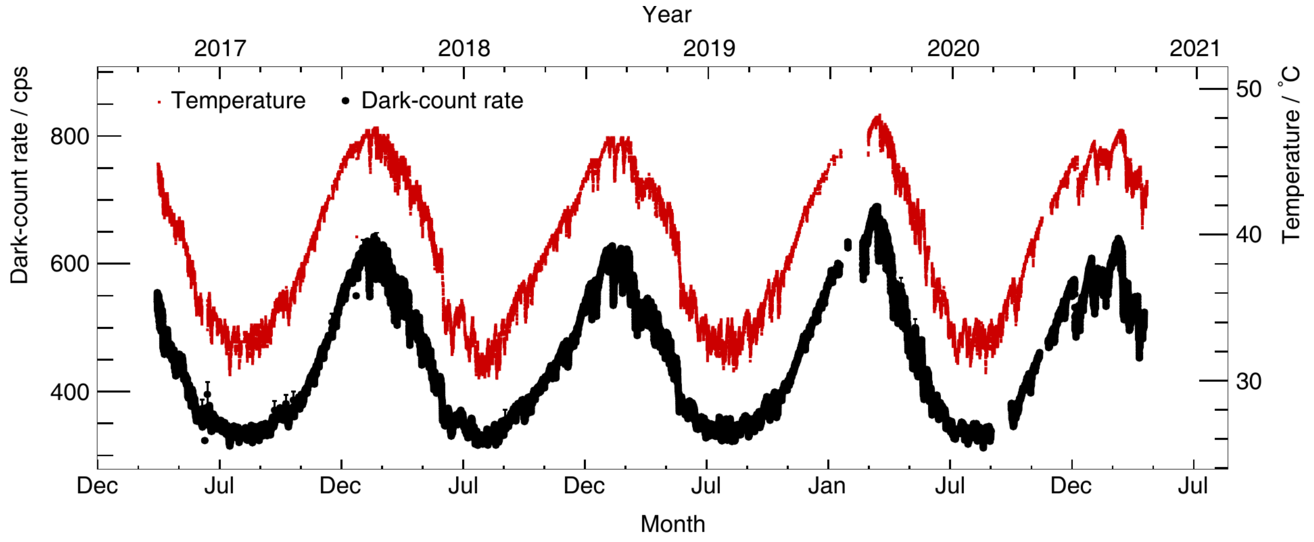

Figure 7: Dark-count rate with amplitude > 2.5 PE and temperature

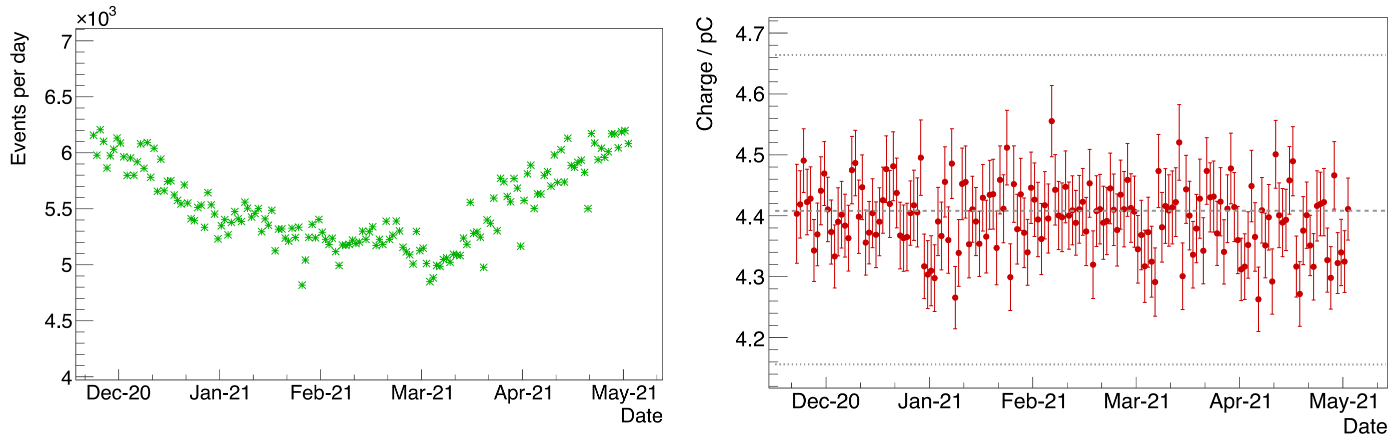

Figure 8: number of background muons (left) and ADC muon charge (right)

6. Uniformity

Dark-count rate per module: × 2 between summer/winter

ADC calibration running stably in whole UMD array

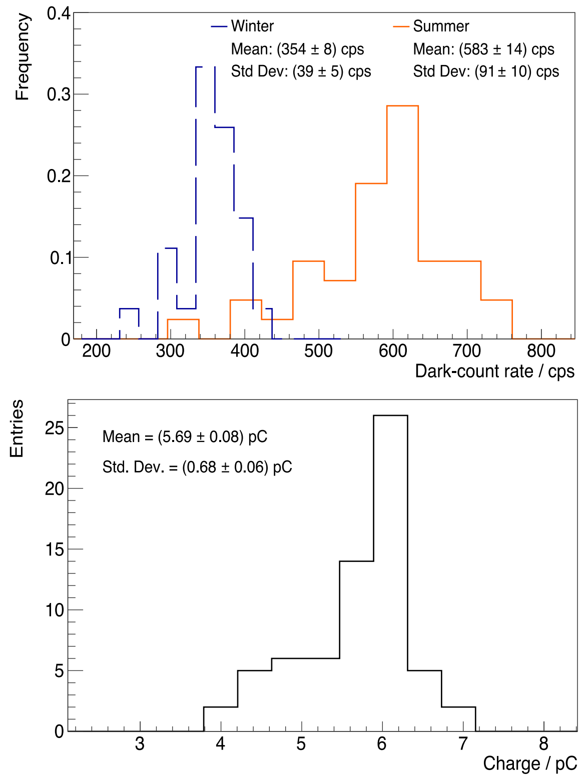

Figure 9: mean dark-count rate (top) 0 and ADC charge (bottom) for UMD array

Summary

- UMD deployment undergoing (35% complete)
  - SiPM, binary and ADC calibration achieved.
  - Calibration parameters stable in time.
  - Stability and uniformity of background parameter assessed.
- UMD full-scale array to be completed by mid-2022.
- More information and references here