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Auger@TA: In-situ Cross-Calibration of the World's Largest Cosmic Ray Observatories

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The Pierre Auger Observatory (Auger) and the Telescope Array (TA) are the world's two largest ultra-high-energy cosmic ray (UHECR) observatories. They operate in the Southern and Northern hemispheres, respectively, at similar latitudes but with distinct surface detector (SD) designs. A significant challenge in studying UHECR physics across the full sky is the apparent discrepancy in flux measurements between the two experiments. This discrepancy could arise from astrophysical differences and/or systematic effects related to their detector designs and sensitivities to extensive air shower components. To address this, the Auger@TA working group aims to cross-calibrate the two observatories with a self-triggering micro-Auger array within the TA array. This micro-array consists of eight Auger Surface Detector (SD) stations equipped with Water Cherenkov Detectors (WCDs) and AugerPrime Surface Scintillator Detectors. Seven SD stations, configured with a centered-1-PMT design, are arranged in a hexagonal pattern with one station in the center, with 1.5 km spacing, mirroring the Auger layout. The eighth station, which features a standard 3-PMT Auger station, is located in conjunction with a TA detector at the center of the hexagon, forming a triplet for high-statistics and low-uncertainty cross-calibration. A custom communication system that uses readily available components enables seamless communication between stations and remote access to each station through a central computer. The micro-array is now fully deployed, and initial data-taking is about to start. This presentation will detail the instrumentation, communication systems, central data acquisition system, expected performance of the micro-array, and preliminary results as appropriate.

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1. Introduction

The Pierre Auger Observatory (Auger) and the Telescope Array (TA) are the two largest cosmic ray observatories in the world, covering areas of more than 3000 km^2 and 700 km^2, respectively. Situated in the southern and northern hemispheres, they provide complementary views of the sky, enabling extensive studies of ultra-high energy cosmic rays (UHECRs). Despite using different detection techniques and calibration methods, both observatories have independently observed a suppression in the cosmic ray flux at the highest energies [1].

Determining cosmic ray energies by surface detector arrays is essential for accurately characterizing the spectrum. However, discrepancies have been recorded in the energy spectra reported by the two experiments. To investigate these differences, the Auger and TA collaborations formed an experimental joint working group called Auger@TA to understand and reconcile the observed spectral variations.

Auger and TA employ different surface-detector reconstruction approaches to estimate primary energies, reflecting their detector geometries and calibration techniques. At Auger, the signal at 1000 m from the shower axis, S(1000), is converted to a reference zenith angle of 38° via the Constant Intensity Cut (CIC) method and then directly correlated with the fluorescence detector (FD) energy, producing an SD energy-scale statistical uncertainty of about 1% at the highest energies [2].

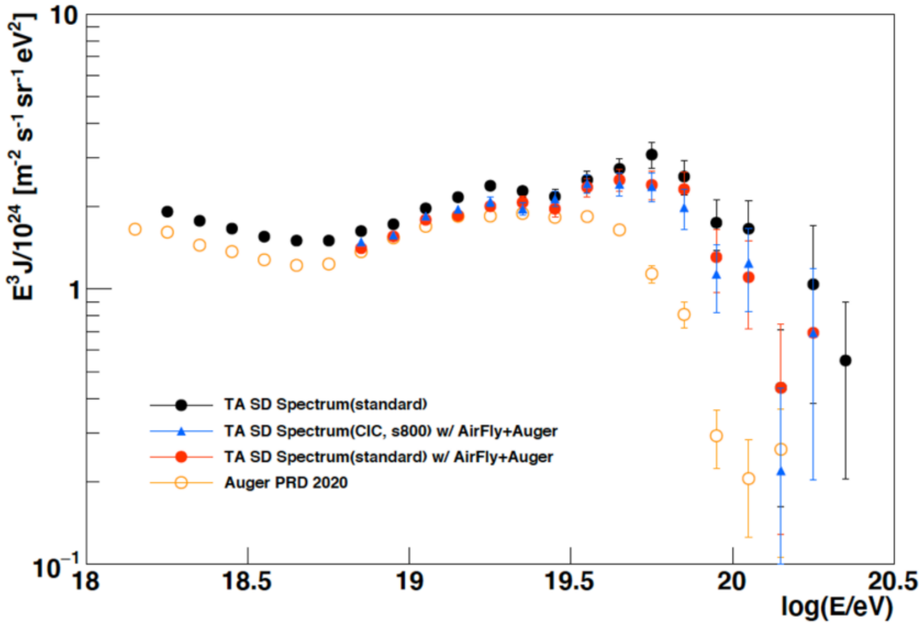

Figure 1: Comparison of the ultra-high energy cosmic-ray spectra measured by TA and Auger. Black points: TA standard analysis (14 years of SD data, TA fluorescence yield and missing-energy corrections). Red points: TA with AirFly fluorescence yield and Auger missing-energy correction (standard MC method). Blue triangles: TA with AirFly and Auger corrections using the CIC method. Orange open circles: Auger 2020 results [3].

TA, by contrast, derives its SD energy scale using Monte Carlo–derived lookup tables mapping the measured density at 800 m, S(800), to primary energy and zenith angle; an independent

CIC-based reconstruction validated this simulation-based scale at about the 3% level [4]. Since the Auger–TA Energy Spectrum Working Group convened in 2012 to cross-calibrate the two observatories, TA has investigated Auger's fundamental analysis choices with the laboratory-measured AirFly model, which would lower TA energies by about 14% when matched to Auger's calibration [5], switching to Auger's experimentally derived missing-energy correction, and applying the CIC procedure to normalize S(800) to 38° exactly as Auger does for S(1000).

These combined alternatives appear to tighten the overall energy-scale offset from about 9% to below 1% for energies below $10^{19.5}$ eV (Figure 1), demonstrating that consistent fluorescence-yield and invisible-energy treatments may be adequate to bring the two spectra into near agreement, and motivating the Auger@TA project both to probe the remaining residual differences and to validate the robustness of these cooperative calibration procedures.

Moreover, studies report an 8σ significance in the variation of the UHECR energy spectrum between the northern and southern hemispheres, indicating possible differences between the northen and southern skies [6]. This observation raises some other critical questions: Are these spectral differences due to fundamental variations in the UHECR sky, or do they derive from unresolved systematic uncertainties between the two experiments? The Auger@TA micro-array is designed to probe whether local detector effects, or reconstruction alternatives can account for this residual difference.

This work presents the design, deployment, and early performance of a 7-station micro-array built to cross-calibrate the Auger and TA responses to the same ultra-high-energy cosmic ray showers. First, we describe a dedicated Central Data Acquisition System (CDAS) tailored to Auger@TA. Although it borrows many software components from the regular Auger CDAS, our version incorporates a trigger logic optimized for a smaller configuration. Second, we successfully commissioned one of the hexagon's triangular segments, which is currently operating with four fully functional stations. Finally, we outline significant enhancements to the communications network—hardware and firmware—that ensure robust data transmission. We conclude with an outlook on completing the full hexagonal micro-array deployment, a comprehensive calibration strategy, and joint Auger–TA spectral analyses to resolve the remaining discrepancies in the UHECR spectrum.

2. The Auger@TA Project

The Auger@TA project was created with the goal of addressing the already cited discrepancies, focusing on a joint calibration effort between the two observatories. An Auger standard hexagonal micro-array, comprising seven stations equipped with single photomultiplier tubes (PMTs), was deployed within TA. At the center of this array, a triplet of stations was set for calibration purposes: a regular Auger station with a three-PMT setup, the Auger@TA station with one PMT, and an independent TA station, each being about 12 meters apart from one another. This setup aims to enable direct cross-calibration and to identify any underlying detector-based causes of the spectral discrepancies by comparing the same events with both detection approaches.

Both Auger and TA detect extensive air showers (EAS) using surface detector (SD) arrays, but each employs distinct mechanisms to collect particle signals. Auger uses Water Cherenkov Detectors (WCD), cylindrical tanks filled with ultra-purified water and equipped with PMTs. Charged particles from air showers generate Cherenkov radiation upon crossing through the water, producing a detectable light signal captured by the PMTs. Auger then calibrates the WCD signals using the Vertical Equivalent Muon (VEM), defined by the signal of a single vertical muon passing through the detector [8]. Additionally, Auger stations are also equipped with a Scintillator Surface Detector (SSD) installed on top of the WCD, providing complementary measurements and enhancing detector sensitivity.

In contrast, TA uses plastic scintillator detectors, where charged shower particles excite the plastic scintillator material, causing it to emit scintillation photons that are collected by wavelength-shifting fibers and guided to PMTs for detection [9]. Their calibration employs the Minimum Ionizing Particle (MIP) as its calibration standard, corresponding to particles depositing the same amount of energy within the scintillator [10]. To investigate and reconcile possible discrepancies, the intention is to simultaneously measure and reconstruct the same air showers with both detectors in situ. Auger@TA will enable detailed event-by-event cross-calibration, likely reducing systematic uncertainties, and facilitating a joint flux measurement.

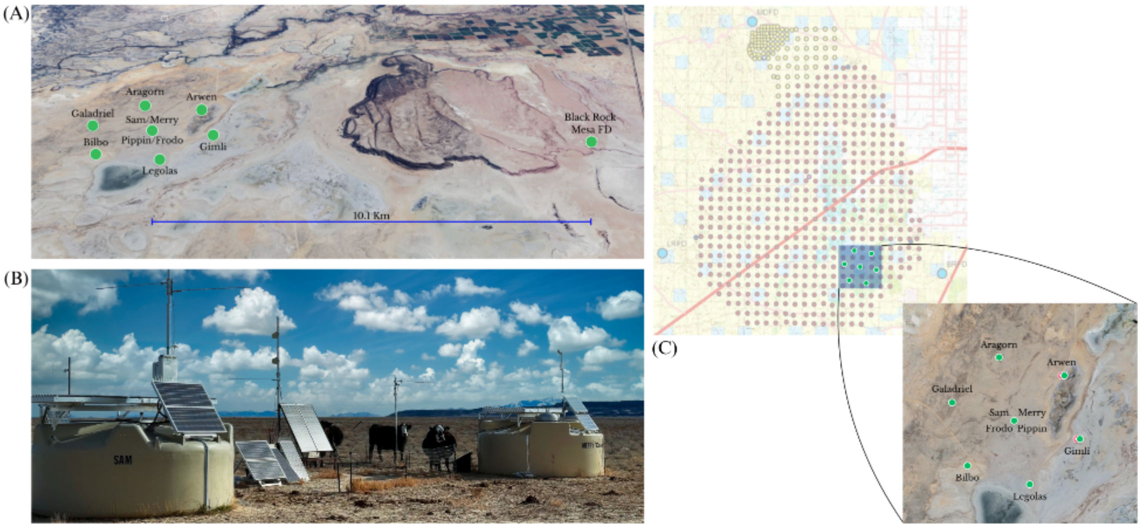

Figure 2: (A) Micro-array location in relation of TA's Black Rock Mesa FD, (B) The Auger@TA central stations, (C) Location of micro-array within TA's site.

The main infrastructure of the micro-array comprising the tanks, water, and major structural components were deployed starting in late 2022, southwest of the Telescope Array FD. The deployment area relative to Black Rock Mesa FD, central stations, outrigger antennas, communication base and the location of the micro-array are shown in Figure 2.

The stations are designed to closely replicate the specifications of standard Auger stations. A detailed explanation of the modifications, along with a summary of the newly integrated components, can be found in [7], and Figure 3 illustrates the layout of the Auger@TA station. Currently, the key distinctions between an Auger@TA station and an Auger station include the use of a single centrally located PMT, a slightly altered shell design, a custom-built communication system composed of commercially available components, and a PMT board — responsible for distributing and regulating the high-voltage supply to the Photomultiplier Tube (PMT) — handmade for the Auger@TA project due to a slightly different mounting mechanism to the central PMT.

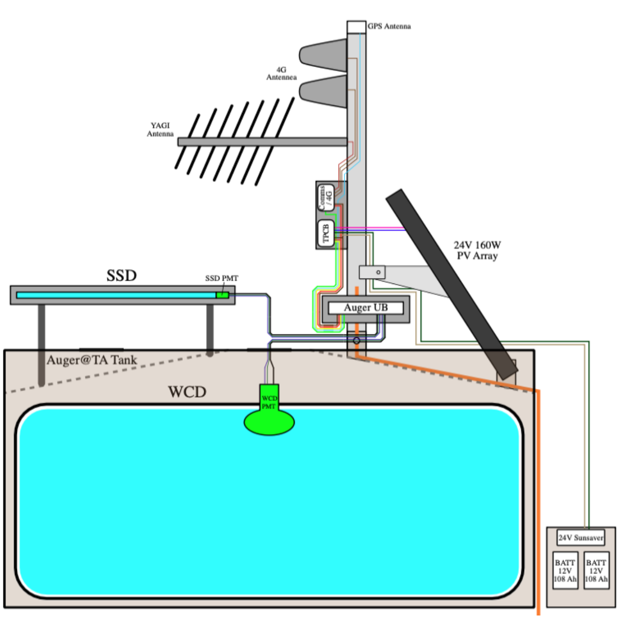

Figure 3: Auger@TA Station.

Additionally, all seven stations are equipped with AugerPrime Surface Scintillator Detectors (SSDs), extending the original goal of the deployed pre-upgraded Auger stations and providing enhanced capabilities for cross-calibration.

3. Communication Systems and Data Handling

The detector stations communicate with CDAS via radio. For Auger@TA, each station uses a Raspberry Pi 4 for communication purposes and to have a user-friendly system. The Pis are connected to the Unified Board (UB) and integrated with an XBee daughter board connected directly to the Pi to enable radio communication between the station and the central computer where CDAS is run.

The XBee module operates in a 900 MHz band and is paired with an L-COM Yagi antenna at each station. The Yagi antenna is a highly directional device designed to amplify signal strength in a specific direction, and when paired, they significantly enhance the range and reliability of the XBee module, enabling long-range communication. Together, the XBee module and the L-COM Yagi antenna create a highly efficient communication system.

CDAS is a critical element of Auger, which is responsible for collecting, processing, and storing the data recorded by each detector station. CDAS runs on a Linux-based operating system and is designed as a modular architecture comprising multiple specialized processes communicating through TCP/IP protocols. Each individual detector station runs its own local station data acquisition system, which handles the digitization of signals, triggering, and local storage before transmitting data to CDAS [11].

Each SD continuously watches for pulses of light in its PMTs. When a pulse exceeds a basic threshold (T1), the station applies a secondary threshold (T2) in which the frequency is set to match the expected rate of cosmic ray signals to the WCD before sending anything to the central system.

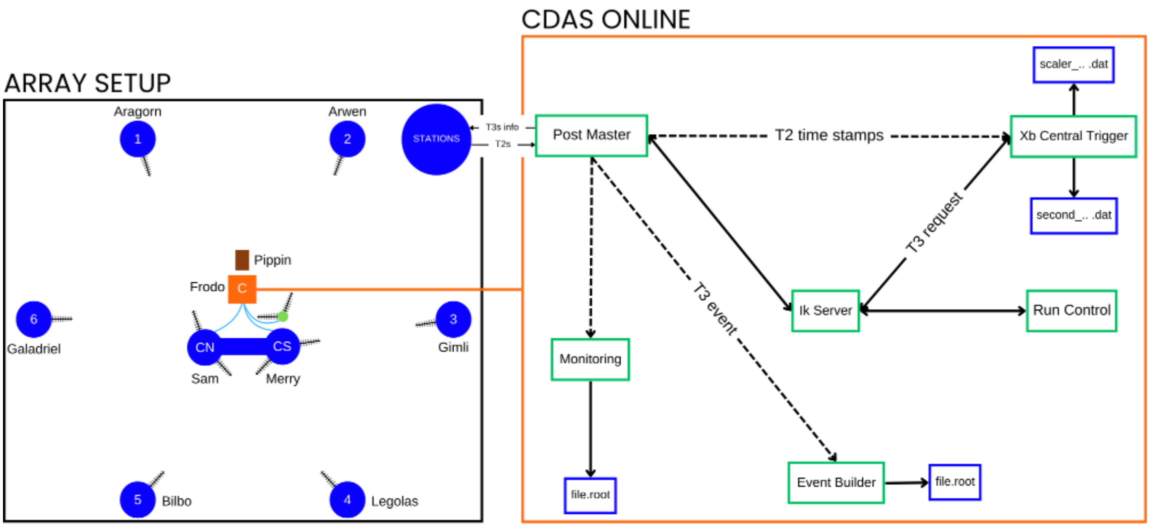

Figure 4: The left side shows the hexagonal micro-array with its nine stations (eight Auger stations and one TA station). Each station communicates with the central computer through a radio antenna installed on a mast on each station. The right side shows CDAS installed and running on Frodo, the central computer and each of the processes and their schematics.

This two-step verification keeps each station's reported rate from around 100 to around 20 hits per second, ensuring the sent signal has a higher chance of coming from an actual cosmic ray event. All T2 triggers - sent every second - are communicated to the central CDAS, allowing it to look for event-level coincidences across multiple detector stations, checking patterns in time and space that match a real cosmic-ray shower. If three stations report a time-over-threshold (ToT)-T2 within a few milliseconds, the system issues a T3 trigger, and CDAS requests detailed event data from relevant stations. This way, a T3 selects actual shower events, which are recorded and saved in a database at a much lower frequency [12].

The CDAS software structure involves many key processes. To cite some, there is the Post Master (Pm) that collects and reconstructs incoming fragmented data packets, forwarding them to the appropriate internal clients; the Xb Central Trigger (Xb) searches for event-level coincidences to generate T3 triggers; the Event Builder (Eb) saves the event data from stations; and the IkServer (Ik) acts as an internal routing service, broadcasting messages based on their source and destination specifications. A schematic of the micro-array and CDAS processes can be seen in Figure 4.

In the Auger@TA project, a slightly simplified version of the Auger CDAS was developed, tailored to the smaller scale and specific calibration goals of the micro-array. This version of CDAS employs fewer processes than the main Auger CDAS, reducing system complexity and enhancing reliability in our smaller-scale deployment.

In our adapted CDAS, we replace the standard Auger long-range radio network with an emulator link to talk directly to each UB. This emulator connection allows us to send commands, simulate event-trigger messages, and check data flow and integrity without the complexity and infrastructure of the full Auger radio system.

These adaptations aim to provide a robust yet lightweight DAQ solution for Auger@TA, reliable reconstruction of air showers, and an independent cosmic ray flux measurement. Moving forward, the simplified CDAS framework and emulator capabilities will allow us to rapidly integrate additional stations and efficiently manage data as the full Auger@TA hexagonal micro-array comes online.

4. Preliminary Observations and Future Prospects

Following several technical challenges, including humidity-induced cable corrosion, malfunctions in the PMT bases, communication system implementation issues, and the commissioning of certain electronic components, the micro-array is now nearing completion. All stations have been structurally assembled, with only a few PMT bases remaining to be installed, final adjustments to the new base enclosures needed, and integration of the SSDs on top of each tank.

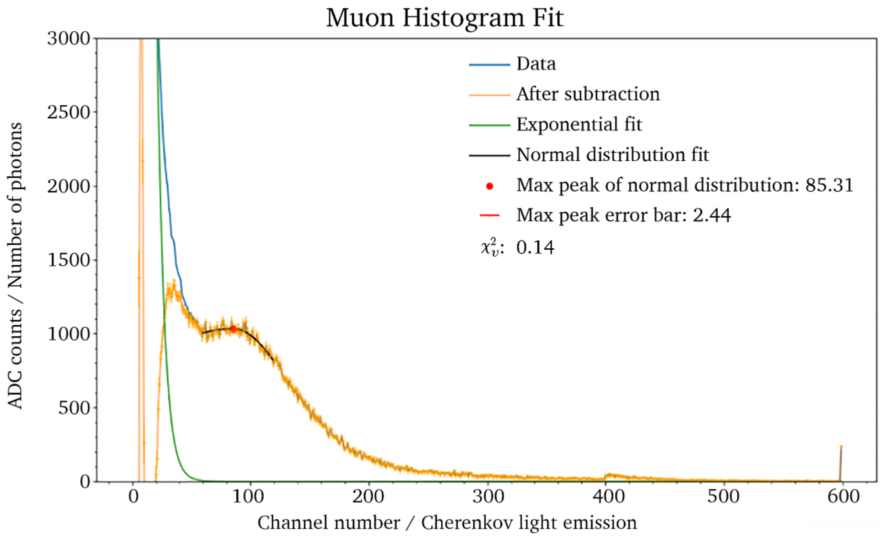

Figure 5: An obtained muon charge histogram for station *Sam*.

At present, both Auger stations in the central triplet are fully operational, along with two additional stations that together form a functional triangular sub-array. All installed PMTs are working as expected, passing all tests. An example of a typical charge histogram taken from Sam used for VEM calibration is shown in Figure 5. Raw signal traces have been successfully recorded from these stations, including the central triplet and two outer detectors, along with the corresponding T2 and T3 data.

	Data acquisition (Jan. 2025 - Feb. 2025)	
T2s	20-30 per second per station	
T3s	8 events recorded with 3 stations	4 events recorded with 4 stations

Table 1: Rate of T2 and T3 events recorded during the first test period.

The dedicated communications network explicitly developed for this experiment has proven reliable. As an added precaution, the stations have automatic reboot capabilities if connectivity is lost. All stations except *Legolas* are communicationally operational. The central communication station, *Frodo*, was upgraded in February 2025 with a more robust, watertight enclosure containing a powerful *Intel NUC* mini-PC, that operates the Auger@TA control CDAS.

Data collection is active, for the four operational stations connected to CDAS. As discussed, event detection requires simultaneous triggers from at least three stations arranged in a triangular configuration, such as the existing *Merry/Sam–Galadriel–Bilbo* formation. Thus far, 12 T3 events have been identified, as shown in Table 1.

Efforts are underway to explore methods to analyze coincident signals from the central doublet stations (*Merry/Sam*), which is essential for comparing Auger@TA signals to standard Auger signals. Daily connectivity checks are conducted by exchanging a verification file between the field PC and our data server. Automated scripts monitor this exchange, initiating reboots if communication lapses are detected. Additionally, the CDAS PC generates bi-daily reports detailing temperature, operational uptime fraction, station status, and network connectivity. Lastly, collaboration with the TA team continues at the local TA station, intended for the central triplet configuration. This station is currently being upgraded with new TAx4 electronics. A fully operational micro-array is anticipated by the end of the year.

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