



New technologies for the Pierre Auger Observatory – research and development in southeastern Colorado

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Abstract: The Pierre Auger Research and Development Array is conceived as a test bed aiming at validating an improved and more cost-effective one-photomultiplier surface detector design and a new communication system. The array of ten surface detectors and ten communication-only stations is currently being deployed in southeastern Colorado and will be operated at least until mid-2012. It is configured in such a way to allow testing of the peer-to-peer communication protocol and the new surface detector electronics that features an enhanced dynamic range aimed at reducing the distance from the shower core where saturation is observed. Atmospheric monitoring developments are also ongoing at the site and are presented in a separate paper. These developments are expected to improve the performances of the southern site of the Pierre Auger Observatory and enable future enhancements.

Keywords: Pierre Auger Observatory, Ultra-high energy cosmic rays, R&D for a future next-generation ground observatory

1 Introduction

The Pierre Auger Observatory [1, 2] aims at measuring the properties of the highest-energy cosmic rays using a large array of surface detectors combined with air fluorescence telescopes. From its original inception, the Pierre Auger Observatory was meant to achieve full sky coverage through the operation of two sites, one in each hemisphere. The southern site of the Observatory (Auger South), officially completed in November 2008, consists of an array of over 1660 surface detectors and 27 fluorescence telescopes (including the 3 elevated field-of-view HEAT telescopes [3]) deployed at 4 sites and overlooking the ground array.

The Pierre Auger Research and Development Array (RDA) in southeastern Colorado (USA) was originally conceived as a test bed for validating improved detector, communications and atmospheric monitoring techniques for the proposed northern site of the Observatory (Auger North) in

Colorado. Fiscal constraints in the US have delayed Auger North until the indefinite future. Much of the development resulting from the RDA, however, was also expected to extend the physics potential of Auger South, both by improving the performance of the current detector and by enabling future enhancements. Given the substantial investment by nearly all countries of the Auger Collaboration, the scope and goals of the RDA were slightly revised to be more aligned with specific needs of Auger South. In this context, the RDA has two major goals:

Validate a new surface detector design. A new surface detector is being developed that is more cost-effective to build and to operate. It is based on one central photomultiplier (PMT) design coupled to electronics with updated components yielding better resolution and dynamic range. Surface detectors built to the new design can be used for in-fill arrays that will provide more detailed cosmic ray measurements at energies below the ankle of the spectrum, provid-

ing a basis for understanding the transition from galactic to extragalactic sources.

Benchmark a new communication system. A new, versatile peer-to-peer radio-communication system will be tested at the R&D site. Originally designed to address the particular topology of the northern site, this new communication system can be used at Auger South as replacement or complement of the existing aging system in enhancements such as in-fills. Adding capacity to the communication system is critical to all future upgrades of the southern site, including, for example, large area radio arrays, if shown to be a viable alternative to air fluorescence for measuring the longitudinal profiles of cosmic-ray showers.

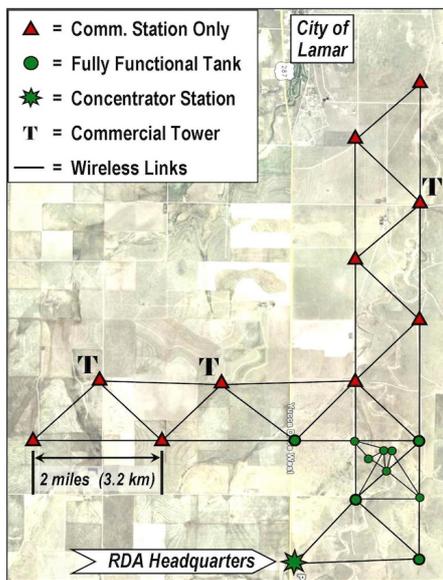


Figure 1: Layout of the R&D array in southeastern Colorado near the town of Lamar (see text for details).

Figure 1 shows the layout of the RDA located a few miles south of the city of Lamar, CO. Ten surface detectors (green circles) are concentrated in the southern part of the array within a triangle covering about 2 square miles with the detectors placed on the corners of a square-mile grid and additional in-fill positions comprising a doublet (two detectors 12 m apart) and two more detectors forming with the doublet a 575 m triangle. This configuration allows for the collection of a wide energy range of cosmic-ray showers to test the response of the new one-PMT surface detector. Ten communication-only stations (red triangles) are added to this array to specifically test the peer-to-peer communication system. The role of these stations is to simulate the broadcast of data from a large number of surface detectors upstream of the concentrator station located at the RDA headquarters (green star). The standard communication station is a standalone mast about 6 m high (the same height as that on the detectors). At three locations across the array (identified with an extra "T"), commercial towers about 12 m high are used to achieve line-of-sight with the neighboring positions.



Figure 2: (Left) The original 3-PMT surface detector used in Auger South. (Right) The central 1-PMT surface detector as assembled for the RDA.

In parallel, a vigorous R&D program in atmospheric monitoring is also proceeding at the site and is presented in a separate contribution to this conference [4].

2 The 1-PMT Surface Detector

2.1 Mechanical design

A surface detector station at the southern site [1] includes a rotationally molded polyethylene tank 3.6 m in diameter with a water height of 1.2 m and water inventory of 12,000 liters. An example of the assembled station is shown in figure 2 (left). The tank being developed for possible use at the northern site, shown in figure 2 (right), uses the same molding technology but was altered to have one PMT rather than the original three. It is constructed with more gradual slopes and more rounded corners on the top structure of the tank. The features on the tank top are required to maintain high stiffness to resist creep failure, especially with the heavier mast, antenna, and electronics structures supported on the tank top. The rounding and gentle slopes were incorporated to allow rotomolding of an extra foam insulation layer on the interior, a feature necessary to prevent the water from freezing solid in a particularly harsh cold snap sometimes observed in Colorado. A research program to develop this rotationally molded foam insulation layer was underway, when the objectives of the RDA were revised to address the needs in Auger South. It was then decided to include a simpler, low-cost insulation system of foam polyethylene sheets screwed to the interior walls of the tank which should be capable of preventing freezing damage for the short operating time required.

The water inside the tank is contained in an opaque, closed polyethylene liner with a Tyvek[®] inner surface. The liners used were surplus from the southern site and were modified to have a single PMT port instead of three. Screw caps on several small ports allow for water filling and the installation of LED flashers. A modified solar power system has been installed for the RDA using a single solar panel (80 Wp, compared to two 53 Wp panels at Auger South) and a single 105 Ah valve regulated lead acid absorbed glass mat (VRLA-AGM) lead-acid battery. The lower power consumption (possibly as little as 5 W when fully developed, compared to 10 W in Auger South) an-

anticipated for the RDA electronics allowed the reduced size of the power system, and the opportunity to compare performance of the AGM-type battery with the selectively-permeable-membrane flooded lead acid batteries used at the southern site is most welcome.

The single PMT is bonded to a thin, transparent polyethylene window with clear silicone rubber optical couplant, as at the southern site. The enclosure, however, is a new design that seals the PMT and its base away from exposure to the air inside the tank. Eventually, with production electronics of smaller size than the prototype electronics of the RDA, the electronics will be included inside this hermetically-sealed enclosure. This will result in more stable temperatures and more controlled humidity to reduce the possibility of corrosion. Rubber glands form seals where cables enter the sealed enclosures. For the RDA, the main electronics is enclosed in a separate sealed box inside the tank. The communication electronics and the Tank Power Control Board, used to monitor and provide some measure of control over the solar power system, are mounted in an enclosure outside the tank, clamped to the antenna mast behind the solar panel.

2.2 Surface Detector Electronics

The signal in a surface detector varies dramatically both with time and with distance from the shower core, so a wide dynamic range is required. The system must accommodate signals from the photoelectron level for small electromagnetic signals far from the core to large currents due to the passage of peak particle intensity near the shower core. The design of the electronics for the new surface detector is based on the successful design used in Auger South [5]. At the southern site, two overlapping 10-bit flash ADCs are used per PMT, to digitize signals derived from the anode and the amplified last dynode to obtain a 15-bit (3×10^4) dynamic range. Nevertheless, saturated signals are observed near the core of high-energy events. The new surface detector electronics design is more highly integrated due to advances in field of programmable gate arrays (also called PLDs) and extends the dynamic range from 15 bits to 22 bits (4×10^6), thereby decreasing the distance from the core where saturated signals will be observed (from 500 m to 100 m for 10^{20} eV showers). The dynamic range extension is achieved by using signals derived from the anode and from a deep (5^{th} out of 8) dynode. The high voltage supply to the tube is designed so that space charge saturation in the last few dynodes does not feed back to the beginning of the dynode chain. This extended dynamic range also provides a more precise determination of the lateral distribution function for the highest energy events. The power consumption of the system will also be about half due to advances in low voltage CMOS components and the reduction of the number of photomultipliers from three to one.

As in Auger South, a hierarchical trigger is implemented with the Local Station Controller (LSC). The lowest level

(level 1) trigger is formed by the trigger PLD, which continuously monitors the PMT signals for shower-like signature. A local low power microprocessor applies additional constraints to form level 2 triggers, which are passed on to the observatory campus through the communication system for higher level trigger formation. The LSC is based on an ATMEL AT91RM9200 microcontroller, with 128 Megabytes of RAM, several USB interfaces (one used as a 4 Gigabytes file system), Ethernet 10/100, GPS Receiver M12M Timing used to time-stamp the events, slow control ADC AD7490 (12 bits, 16 channels), slow control DAC TI DAC7554 (12 bits, 4 channels), 3 dual channels syFlash Adc LTC2280 (10 bits, 100 MHz), and an Altera Cyclone III (canbus interface for connection to the radio system, Time Tagging and Trigger firmware). The front-end analog board performs 50-MHz lowpass filtering and signal duplication. The Anode, Anode x 30, Anode x 0.1 and Dynode signals are digitized and then routed to the Cyclone FPGA. The LSC runs a Linux Debian 2.6.27 Operating System, with I-Pipe and Xenomai 2.4.10 RealTime extensions. The software-based level 2 (T2) trigger reduces the T1 event rate from 100 Hz to 20 Hz. Only the time-stamps of the T2 and a rough evaluation of the energy received in the detector are sent to the Central Data Acquisition System (CDAS) every second. All the T1 events are stored locally in DRAM and the data sent to CDAS upon request when the CDAS has detected a multi station coincidence. A maximum of 2000 events are stored, corresponding to about 20 seconds of data taking. A continuous calibration of the detector is made locally using the muon data available from the front end, and the result of the calibration sent to CDAS along with the higher-level T3 data. In addition a LED flasher can also be used for that purpose.

The various electronics boards, namely the LSC and the LED flasher driver inside the tank, and the Tank Power Control Board and the communication electronics in the enclosure on the mast, are interconnected via a ISO standard Controller Area Network (CAN) bus, which provides power, distribution of GPS timing pulses, and transfer of event and monitoring data. This scheme is an improvement on the Auger South design, with both fewer cables and more robust data transmission.

3 The peer-to-peer communication system

3.1 Concept

At the southern site, each station communicates directly with one of four tower-mounted concentrator stations located on the periphery of the array. From there, data is forwarded via commercial microwave links to a fifth tower at the Observatory campus. This is possible because the terrain is remarkably flat, but surrounded by peripheral hills upon which to place the towers, affording a clear line-of-sight between each station and a tower. However, at the northern site, direct station-to-tower routing is infeasible due to the much larger surface area of the planned array,

the absence of convenient peripheral hills, and the presence of internal hills, ridges and gullies that impede station-to-tower line-of-sight. Therefore, it was decided to configure the Auger North surface detector communication system as a Peer-to-Peer Wireless Sensor Net (P2P-WSN). In a P2P-WSN, the transfer of data between a station and the concentrator is accomplished via multi-hop relaying of data between neighboring stations, rather than a single hop directly to the concentrator. The greatest disadvantage to P2P routing is reliability, because the failure of one radio will disconnect not only itself, but all stations upstream of that point (away from the concentrator). Thus, redundant routing and fault-tolerance must be present in the WSN. The particular WSN paradigm chosen for the northern site is the Wireless Architecture for Hard Real-Time Embedded Networks (WAHREN) [6]. WAHREN routes all messages via a second order power chain topology, in which each station, or node, communicates not only with its nearest, or first order, neighbors but also with its second-nearest, or second order, neighbors, providing the required redundancy.

The Medium Access Control (MAC) layer of WAHREN is a Spatial Reuse Time Division Multiple Access (SR-TDMA) protocol. SR-TDMA divides time into constant-length transmission slots. A fixed number of slots are then grouped into a TDMA Window. Within each window, each node is assigned one slot in which it is allowed to transmit. If two nodes are outside of interference range from each other, then they can be assigned to the same slot (hence the term Spatial Reuse). WAHREN employs a systolic broadcast scheduling protocol, shown in figure 3.

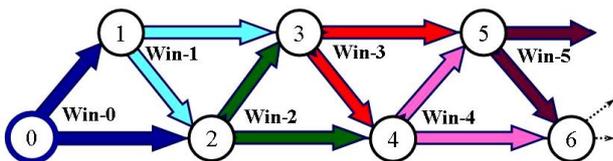


Figure 3: Schematic of single-source systolic broadcast along a second-order power chain.

In this example, node 0 transmits its own message in window 0. Then, in each subsequent window, k , node k forwards the message received during the previous window to two downstream neighbors ($k+1$ and $k+2$). Except for the initial transmission from node 0 to node 1, all nodes receive two copies of the message from two different sources. In the single-source example above, each node transmits in only one window. This observation makes it possible for every node in the system to transmit its own original message simultaneously (each within its assigned slot of window 0). Then, in each subsequent window, all messages are forwarded at the rate of one node per window.

Power chains can turn a sharp corner in a manner that is transparent to the graph topology. Such a structure is called a Möbius Fold. This allows the surface detector array to potentially be partitioned into several sectors, in each of

which, several side chains intersect a backbone chain at a right angle. The RDA layout shown in figure 1 features such a structure with a backbone running north-to-south and a side chain running west-to-east. The WAHREN paradigm has been verified by a variety of formal verification methods and testbed systems. However, the RDA will permit extensive end-to-end testing to be done in-situ on a full-scale grid with the hardware. RDA testing will include: (1) interference, signal strength, and bit and packet error rate studies; (2) fault injection experiments wherein nodes are purposely put into a failure mode; (3) tests of trigger packet transmission and read out of data from stations; (4) traffic studies wherein fake traffic is introduced to study system behavior at saturation.

3.2 Hardware implementation

To avoid the excessive overhead and RF band restrictions imposed by commercial standards such as IEEE 802.11 (WiFi), custom circuit boards were designed to directly implement the WAHREN protocol over four licensed, dedicated channels in the 4.6 GHz band. The surface detector station radio is split into a baseband board and an RF daughter card, both of which can be customized to other applications. Primary control of the radio is provided by an Altera Cyclone III FPGA. Its configuration includes modulator/demodulator circuitry, as well as dual NIOS II processor cores, one serving as the main CPU and the other as an input/output processor (IOP). The interface to the RF daughter card uses a Maxim 19707 ADC/DAC chip. The final component on the baseband board is a TMS470 microcontroller, serving as a channel guardian. It independently monitors transmitter output and system timing.

4 Projected timeline

The RDA is expected to be operational in the Fall of 2011 and will collect data until at least June 2012.

References

- [1] I. Allekotte *et al.* for the Pierre Auger Collaboration, *Nucl. Instr. and Meth. A*, 2008, **586**: 409-420
- [2] J. Abraham *et al.*, Pierre Auger Collaboration, *Nucl. Instr. and Meth. A*, 2010, **620**: 227-251
- [3] T.H.J. Mathes for the Pierre Auger Collaboration, paper 0761, these proceedings
- [4] L. Wiencke for the Pierre Auger Collaboration, paper 0742, these proceedings
- [5] T. Suomijärvi for the Pierre Auger Collaboration, *Proc. 30th ICRC, Mérida, Mexico 2007*, **4**:311-314. arXiv:0706.4322v1 [astro-ph]
- [6] R.M. Kieckhafer for the Pierre Auger Collaboration, *Proc. 17th IEEE-NPSS Real Time Conference, Lisboa, Portugal 2010*, 1-8