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The Pierre Auger Research and Development Array (RDA) in southeastern Colorado – R&D for a giant ground array

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Abstract. The Pierre Auger Research and Development Array (RDA) was originally designed to be the precursor of the northern Auger observatory, a hybrid array of 4400 surface detector stations and 39 fluorescence telescopes deployed over 20,000 square kilometers. It is conceived as a test bed aiming at validating an improved and more cost-effective 1-PMT surface detector design and a new peer-to-peer communication system. The array of ten surface detector stations and ten communication-only stations is currently being deployed in southeastern Colorado and will be operated at least until late 2013. It is configured in such a way that it allows testing of a new peer-to-peer communication protocol, as well as a new surface detector electronics design with a larger dynamic range aiming at reducing the distance from the shower core where saturation is observed. All these developments are expected in the short term to improve the performance of the Pierre Auger Observatory and enable future enhancements. In the longer term, it is hoped that some of these new developments may contribute to the design of a next-generation giant ground array.

1. INTRODUCTION

From its original inception, the Pierre Auger Observatory was meant to comprise two sites, one in each hemisphere, to enable the study of the highest-energy cosmic rays impinging the Earth's atmosphere

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Table 1. Comparison of the Pierre Auger Observatory and the northern site design. The energy ranges for the efficiency refer to iron/proton primaries respectively.

	Pierre Auger Observatory	Northern site design
Location	35° S, 69° W	38° N, 102° W
Altitude	1,300 – 1,500 m a.s.l.	1,100 – 1,500 m a.s.l.
Area	3,000 km^2	20,000 km^2
Number of SD stations (total)	1,660	4,400
Pattern	Triangular	Square
SD spacing (regular array)	1.5 km	2.3 km ($\sqrt{2}$ mi)
PMT sensors / SD station	3	1
Communications network	SD-radio tower	peer-to-peer
SD array 50% efficient at	0.7/1 EeV	8/10 EeV
SD array 100% efficient at	3 EeV	80 EeV
FD sites	4	5
FD telescopes	27 ($4 \times 6+3$)	39 ($2 \times 12 + 2 \times 6 + 1 \times 3$)

from all directions in the sky. The southern site [1, 2] located near the town of Malargüe (Mendoza Province, Argentina) was officially completed in November 2008 and consists of an array of over 1660 Surface Detector (SD) stations and 27 Fluorescence Detector (FD) telescopes (including the three HEAT telescopes with an elevated field of view deployed more recently) located at 4 sites and overlooking the ground array. Based on the early results obtained at the southern site, a design for the Observatory's northern site to be located in southeastern Colorado was produced, based mostly upon the same detector concepts and technology that have succeeded at the southern site. To achieve a significant improvement in measurement sensitivity at trans-GZK energies, the SD array for the northern site was designed to cover an area of $20,000\,km^2$, nearly seven times the collecting area of the Pierre Auger Observatory. This was done by increasing the number of water Cherenkov stations, while reducing the station density by using a regular square $\sqrt{2}$ mile spacing grid. In total, the SD array was foreseen to have 4400 stations covering the whole area, including 400 in a denser 2,000 km^2 in-fill array, where stations were only placed one mile apart. The purpose of the in-fill array was to facilitate the integration of data between the two observatories. In order to maximize the hybrid aperture, the design called for 39 FD telescopes deployed at five separate sites across the array. A comparison between the parameters of the Pierre Auger Observatory and of the northern site design is given in Table 1. A more detailed description of the northern site design can be found in [3]. While the funding of the northern site of the Pierre Auger Observatory has been delayed indefinitely, a number of considerations and technical developments outlined in its design may be of interest in the development of a next-generation giant ground array.

2. THE PIERRE AUGER RESEARCH AND DEVELOPMENT ARRAY (RDA)

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 as a precursor of the northern site. From the start, it was however also envisioned that much of the development resulting from the RDA could be used to extend the physics potential of the Pierre Auger Observatory, both by improving its performance and by enabling future enhancements. Some aspects of the R&D may also represent technological advances useful for the development of a next-generation giant ground array concept. The RDA has two main objectives. The first one is to test a new, more cost-effective, one-PMT surface detector largely based on the three-PMT detector used in Argentina but coupled to a faster electronics providing better resolution and larger dynamic range. The second objective is to validate a new, versatile peer-to-peer radio-communication system. Originally

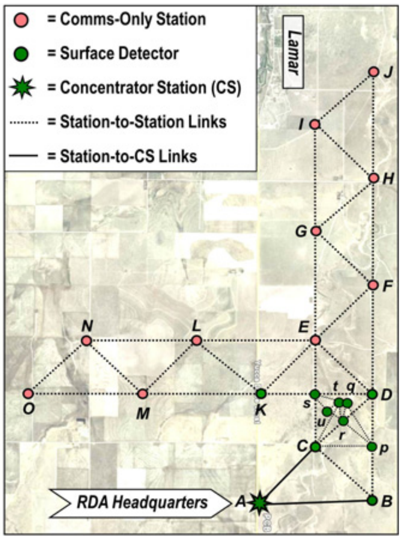

Figure 1. Layout of the RDA in southeastern Colorado near the town of Lamar (see text for details).

designed to address the topology of the northern site, the new system can be used to add capacity to the communication system at the Pierre Auger Observatory, especially for future upgrades such as large radio arrays for example. A peer-to-peer communication system such as the one being tested at the RDA will also likely be required in any future ground array concepts that include a sizeable number of SD stations spread over a large area. A vigorous R&D program in atmospheric monitoring was carried out in parallel at the site and is presented in a separate contribution [4].

Figure 1 shows the arrangement of stations deployed in the RDA a few miles south of the city of Lamar, Colorado. Ten SD stations (green circles) are located in the southern part of the array within a 2-square mile triangle including detectors on the corners of the square-mile grid and additional in-fill positions comprising a doublet and two more detectors forming a smaller 575 m-triangle with the doublet inside the larger triangle. The configuration allows for the collection of cosmic-ray showers with a wide range of energy ensuring that enough statistics can be collected to test the new surface detector. The stations identified with lower case letters are off the main grid as defined by the communication system structure. In addition, ten communication-only stations (red circles) are added to the array to simulate the broadcast of data from a large number of SD stations upstream of the Concentrator Station (CS) located at the RDA headquarters (green star) and are used to specifically test the performances of the peer-to-peer communication system. Figure 2 shows a picture of each of the elements of the RDA deployed in the field, namely the new 1-PMT surface detector (left), the standard standalone communication station (middle) and the commercial tower (right) used as the concentrator station and at specific locations (positions H, N and L), where the topology of the site requires a higher mast to achieve communication line-of-sight. All the stations with their power system, but without electronics, were deployed in the field over the course of last year, in part to assess their behavior over the 2011–2012 winter.

2.1 The 1-PMT Surface Detector station

The tank developed for use at the northern site uses the same molding technology than the one used at the Pierre Auger Observatory, but was altered to have only one central PMT position instead of three. As it needs to support a heavier external structure comprising the 6 m antenna mast, the electronics

Figure 2. Elements of the RDA: *Left*: the new 1-PMT surface detector used in Auger South. *Middle*: the standard communication-only station. *Right*: the commercial tower used for the concentrator station and selected locations within the array.

enclosure and the solar panel and its mount, the tank top was constructed with more gradual slopes and more rounded corners. The tank was originally designed to receive an internal foam insulation layer to prevent the water from freezing in the not-so-unusual cold periods experienced in southeastern Colorado. The choice of the best foam insulation that can be incorporated in the rotomolding process was due to be the subject of a R&D topic pursued at the RDA. However, the scope of the R&D program was eventually downscaled and a simpler insulation scheme using polyethylene sheets screwed to the interior walls of the tank was used. This design change resulted in some of the tanks to show signs of creep after several months in the field due to the missing internal foam insulation, which was to add stiffness to the tank top. Also, after the 2011–2012 winter, dislodged insulation was found in two tanks. This was likely the results of a water leak, which induced the lifting of the insulation sheets by buoyancy. The two tanks were repaired and an improved drainage scheme was devised at the bottom of the tanks to prevent the water to creep under the insulation sheets. The water inside the tank is normally contained in an opaque, closed polyethylene liner with a Tyvek inner surface. The liners were obtained from the surplus of the Pierre Auger Observatory and were modified to have a single PMT port (at the center) instead of three. Screw caps on several small ports allow for water filling and for the LED flashers, which have been installed in every SD stations of the RDA. The response of the detector can be monitored by the LED flasher system. It consists in two blue LED flashers and a digital controller, connected through CAN Bus to the Local Station (LS) controller. Using the two flashers, it is possible to check the linearity of the PMT over the whole dynamic range. In addition they can be fired simultaneusly in different stations to check the trigger chain. The solar power system uses one 80 Wp solar panel and one 105 Ah valve regulated lead acid absorbed glass mat (VRLA-AGM) lead-acid battery. The single PMT is bonded to a thin, transparent polyethylene window. The enclosure is designed to seal the PMT and its base to prevent exposure to the air inside the tank. Rubber glands form seals where cables enter the sealed enclosures. The main electronics is enclosed in a separate sealed box inside the tank and connects via a CAN Bus cable to the communication electronics and the Tank Power Control Board located in an enclosure outside the tank, clamped to the antenna mast behind the solar panel.

The design of the electronics for the new surface detector is based on the successful design used at the Pierre Auger Observatory [5]. The new 100 MHz electronics design is more integrated and extends the dynamic range from 15 bits to 22 bits (4×10^6), thereby decreasing the distance from the core

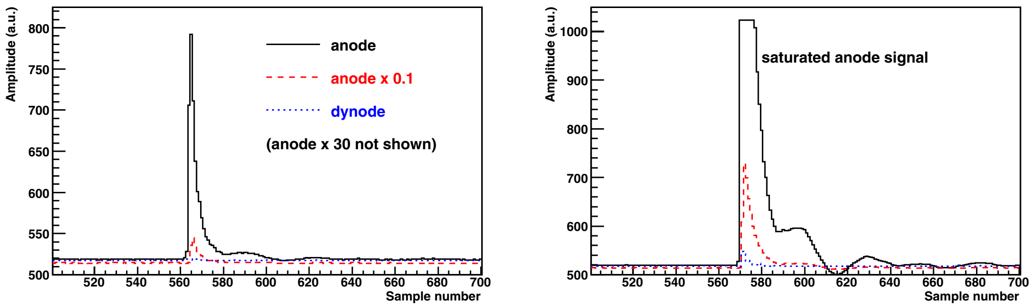

Figure 3. Two cosmic-ray events triggered by a local threshold trigger implemented in the LS controller.

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 ($\times 0.1$, $\times 1$ and $\times 30$) and from a deep (5^{th} out of 8) dynode. A hierarchical trigger similar to the one used in Argentina is implemented in the LS controller. The first level trigger is created within the LS by continuously monitoring the PMT signals for shower-like signatures. A local low power microprocessor applies additional constraints to build a second level trigger, which is communicated to the RDA headquarters to potentially form higher level triggers. Figure 3 shows a couple of cosmic-ray events recorded using a local threshold trigger in the LS to illustrate the dynamic range of the signals collected. The second event (on the right) has a saturated anode signal, but the same signal remains useable when processed through a lower gain amplifier. The barely noticeable dynode signal in these two events will be used in SD stations closer to the shower core. More information about the RDA SD electronics can be found in [6].

In the spirit of carrying out R&D for possible enhancements at the Observatory or for a future ground array, it may prove valuable to obtain better identification of muons and better time resolution for studies of both hadronic interactions and cosmic ray composition. Studies performed on a water Cherenkov detector prototype early in the planning for the Pierre Auger Observatory indicated a black top, as compared to a Tyvek top, reduced the photomultiplier pulse produced by a vertical muon from approximately 39 ns to 19 ns. No comparable studies were performed on general cosmic ray showers which produce light due to both muonic and electromagnetic components in the detectors, so the amount of improvement to be expected in muon identification in a realistic shower environment is not experimentally known. A Tyvek® top was selected because the black top provided pulses of only 40% as many photoelectrons. Experience in Argentina indicated that the water clarity remains good enough that the number of photoelectrons is more than sufficient for good pulse resolution and the idea of the black top is again under consideration. The RDA already has 100 MHz digitization, compared to 40 MHz in Argentina, so it will be possible to study the advantages of the shorter muon pulse width effectively. In order to test the black-top tank option, we plan to insert lightweight, black foam polypropylene beads to a depth of 10–20 mm. The beads will float to the surface of the water and are expected to largely cover the surface, eliminating light reflection from the top part of the liner. Initial tests with one of the twin tanks (labelled "t" and "q" in Fig. 1) will allow a direct comparison with the reflective-top station in identical environments within the shower. If the results are encouraging, we could increase the number of tanks with the black foam beads.

2.2 The peer-to-peer communication system

The Pierre Auger Observatory site in Argentina is exceptional in the sense that the SD array sits on a remarkably flat terrain conveniently surrounded by hills, where microwave communication towers are located. When considering larger ground arrays, the condition to maintain line-of-sight with distant towers becomes very drastic and eventually impossible to fulfill, even at the Colorado site which enjoys

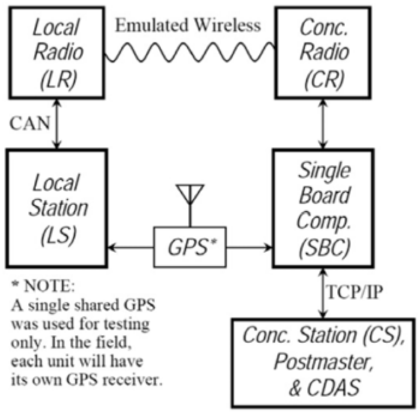

Figure 4. Schematic of the integration test carried out in August 2011.

a rather gentle topology. In this context, the communication within the ground array becomes a critical aspect of the design. At the RDA, we will test a Peer-to-Peer Wireless Sensor Net (P2P-WSN) structure called Wireless Architecture for Hard Real-Time Embedded Networks (WAHREN) [7]. In a P2P-WSN, the transfer of data between a SD station and a concentrator station is achieved using multi-hop relaying of data between neighboring stations. WAHREN routes the data of one given station not only to its nearest neighbors but also to its second-nearest neighbors, providing the redundancy required to bypass a station gone "dark". More information about the implementation of the WAHREN structure at the RDA site can be found in [6, 7].

During August 2011, a series of integration tests of the RDA SD communication system was performed. The goal of this exercise was to test and debug the entire SD communication chain from a LS controller, through the Central Data Acquisition System (CDAS). As illustrated in Figure 4, the path comprised seven interacting processes running on five computing platforms, including:

– A LS controller to generate simulated second-level triggers and routine monitoring data, and to forward that data over a wired CAN Bus connection to the Local Radio (LR),
– A WAHREN Baseband Board (BB) serving as a LR for a typical tank,
– A second BB serving as a Concentrator Radio (CR) for the sector CS,
– A Single Board Computer (SBC) interface between the CR and the CS,
– A Computer running the CS, Postmaster (PM), and CDAS software.
– A fully functional GPS receiver to synchronize timing between the LR and CR.

For this indoor testing, no radio frequency (RF) daughter cards were needed. Rather, the wireless link between the LR and CR was emulated by a ribbon cable carrying the analog signals that would normally run between each baseband board and its RF daughter card. During testing, end-to-end communication was successfully established. The system was cold-started from a completely shut-down condition. First, the CR established two-way communication with the CS computer via the SBC. Then, the LR established communication with the CS via the CR and SBC, and was integrated into the running system. Finally, the LS began generating simulated second level trigger messages, which were successfully relayed to the CDAS software. In addition, error-injection code was written that exercised some of the fault-detection and response mechanisms in the CS computer. Specifically, the CR was programmed to corrupt a specified fraction of second level trigger messages en route to the CS. Whenever an incorrect second level trigger message was received by the CS, it issued a Negative Acknowledgement (NACK) message which was properly relayed to, and received by the LR.

The last elements of the communication electronics, the RF boards, are currently being tested and will likely go in production over the summer 2012.

3. PROJECTED TIMELINE

At the time of writing, only the communication electronics remains to be deployed in the field. The RDA is expected to start operation late in the Fall of 2012 and collect data until at least the end of 2013.

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