Instrumentation for the Northern Site of the Pierre Auger Observatory

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Abstract

The Pierre Auger Observatory is a multi-national project for research on ultra-high energy cosmic rays. Science results from the Southern Auger Observatory motivate the completion and extension of the investigations begun there by constructing the Northern Auger Observatory, with a much larger acceptance for the extremely rare cosmic ray events above a few times 10^{19} eV.

This paper describes the layout and technical implementation of Auger North, highlighting advances with respect to the Auger South instrumentation that have been made to improve performance, reduce costs, and accommodate differences between the Southern and Northern sites.

Key words: Cosmic Rays, Auger North

1. Introduction

Since its inception it has always been envisioned that the Auger Cosmic Ray Observatory would have 2 sites, one each in the southern and northern hemispheres. Now that the Southern Auger Observatory (Auger South) has been completed and science results are flowing, planning for the Northern Auger Observatory (Auger North) has moved to the forefront.

2. Auger South

Auger South, located in the Mendoza province of Argentina was completed in 2008 with an instrumented area of 3,000 km^2. The modular nature of the detector has allowed physics data to be recorded since the beginning of 2004.

2.1. Layout

The Auger South Surface Detector (SD) consists of 1660 water Cherenkov stations on a 1.5 km triangular grid [1] (see Fig. 1). A Fluorescence Detector (FD) consisting of 24 telescopes divided into 4 stations views the atmosphere above the observatory on clear moonless nights [2].

Each SD station contains 1,200 liters of ultra-pure water viewed by 3 9" photomultiplier tubes (PMTs). The station electronics, which consume less than 10 W, are powered by a photovoltaic system. Timing is provided by a GPS receiver on each station. Trigger and data information are transported via a custom wireless network system (Comms) [3][4] to tower mounted base stations located at each FD station and from there to the central campus at Malargue via commercial microwave links.

2.2. Selected results

Initial physics results from Auger South provide strong motivation to proceed to construct Auger North.

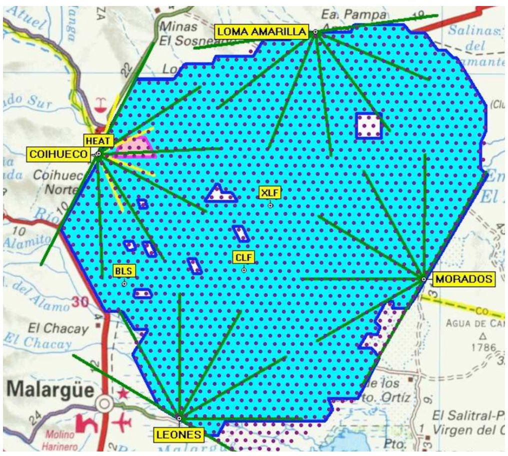

Figure 1: Layout and actual deployment status of Auger South as of April 2009. Each dot represents one surface detector station, those in the blue shaded area are operational. The fields of view of the four fluorescence telescope stations Los Leones, Coihueco, Loma Amarilla and Los Morados are indicated. The *High Elevation Auger Telescopes* HEAT are located close to Coihueco. Further elements are the *Central Laser Facility* CLF [5], the *Extended Laser Facility* XLF and the *Balloon Launching Station* BLS.

GZK suppression. Auger South has observed a suppression of the cosmic ray energy spectrum consistent with the expected interaction of high energy cosmic ray protons with the microwave background (the GZK effect) [6][7][8]. The GZK interaction limits the horizon (or GZK-sphere) for cosmic rays above 6×10^{19}eV (60 EeV) to less than 100 Mpc.

Correlation with local matter. In 2007 the Auger Collaboration published observation of a correlation of cosmic rays above 60 EeV with local matter in the universe [9][10], establishing that there are sources within the GZK-sphere.

Puzzling composition. The correlation with the local matter distribution leads one to infer that the cosmic rays above

60 EeV experience small deflections in the galactic and intergalactic magnetic fields, hence have a small charge, and are thus likely to be protons. However, measurements of shower development profile near 40 EeV [11] (below the 60 EeV that the correlation is observed) indicate a faster shower development than expected for protons, which could be an indication that the cosmic ray primaries are heavy nuclei (eg. Fe), or that the proton-air cross section is larger than predicted, perhaps signalling the onset of new physics.

2.3. *Event rates*

The profile measurements are made by the FD, and hence are only available for 10% of the data. We expect about 25 events per year above 60 EeV to be observed by the SD, and only 2 by the FD. A larger detector is needed to study these issues.

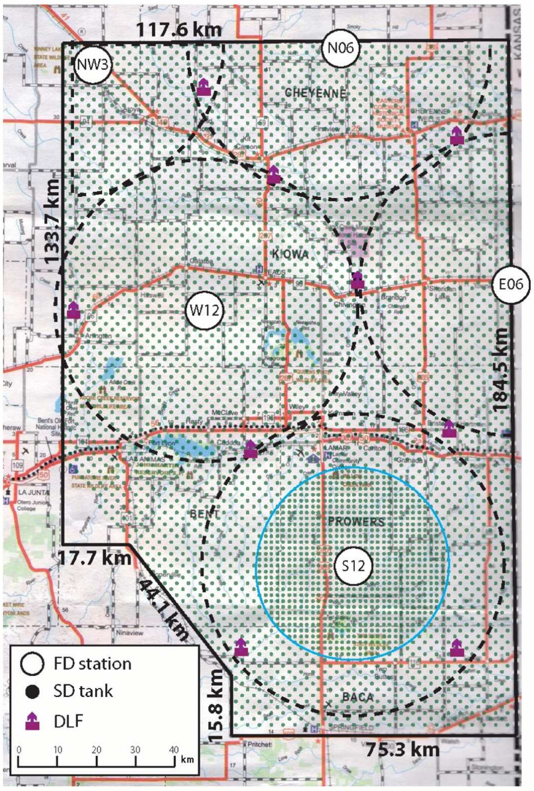

Figure 2: Auger North configuration. The SD detectors are arranged on a $\sqrt{2}$-mile square grid together with an infill (shaded) area of 1-mile spacing. Five FD sites, in combination with Distant Laser Facilities (DLFs), span the SD.

3. Auger North

Auger North, with a 7 times larger area, is designed to provide the next step in these studies.

The design for Auger North builds upon the same detector concepts and technology that have succeeded at the southern site in Argentina. To achieve a significant improvement in measurement sensitivity above 60 EeV, the surface detector (SD) will have an area of 20,000 square kilometers, nearly seven times the collecting area of Auger South.

	Auger South	Auger North
Location	35° S, 69° W	38° N, 102° W
Altitude	1,300 - 1,500 m a.s.l.	1,300 - 1,500 m a.s.l.
Area	3,000 km^2	20,000 km^2
Number of SD stations	1,660	4,400
SD spacing	1.5 km	2.3 km ($\sqrt{2}$ mi)
PMTs / SD station	3	1
Comms network	SD-radio tower	peer-to-peer
Comms band	902-928 MHz	4.650-4.694 GHz
SD 50% efficient at	0.7/1 EeV	8/10 EeV
FD stations	4	5
FD telescopes	24	39
	(4×6)	$(2 \times 12 + 2 \times 6 + 1 \times 3)$

Table 1: Comparison of the Pierre Auger Observatory sites. The energy ranges for the efficiency refer to iron/proton primaries respectively.

Challenge	Response
7X larger size	Increase separation between SD stations
	Reduce cost of each SD station
	Increase separation between FD stations
	Reduce cost of each FD station
Focus on higher energies	Increase SD station dynamic range
Larger separation of FD stations	Improve atmospheric monitoring
Colder climate	Insulate the SD station tanks
Terrain issues	Use new network paradigm
Radio spectrum contention	Use dedicated radio bands

Table 2: Summary of instrumentation challenges for Auger North.

Auger North will have 4,000 stations on a regular square $\sqrt{2}$-mile-spacing grid. Another 400 will fill in a dense sub-array of area 2,000 km^2 with one mile separation between nearest neighbors. The in-fill array will have an energy threshold close to the threshold of Auger South, yielding full understanding of threshold effects at Auger North.

Auger North will also have 39 air fluorescence telescopes, housed at five different stations. The fluorescence detector (FD) will make critical measurements of the atmospheric depth of maximum shower size for the study of the primary composition and hadronic interactions. Hybrid shower measurements by the SD and FD together provide a calorimetric energy calibration for the surface detector and also a direct measurement of its angular resolution and its accuracy in determining shower core positions.

The layout of the planned Auger North observatory is shown in Fig. 2. It will be located in the Southeastern corner of Colorado. Table 1 compares the major parameters of Auger South and Auger North.

4. Instrumentation Challenges

While the basic concepts for Auger North are based upon the proven technologies from Auger South, several instrumentation challenges are present. These are summarized in Table 2.

4.1. *Atmospheric Monitoring*

The 80 km separation between FD stations will challenge the atmospheric monitoring program for Auger North. The ratio of distant lasers to FD stations will be increased from 2:4 in Auger South to 9:5 in Auger North. The distant lasers will use slightly

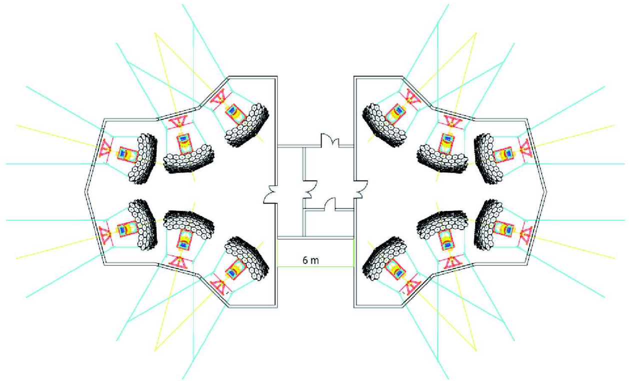

Figure 3: Telescope arrangement of a 360° FD site.

higher energy solid-state lasers in combination with robotic systems for absolute calibration of beam energy and polarization. GPS-disciplined rubidium oscillators will improve firing time stability. To reduce uncertainty in absolute photometric calibration, an automated independent nitrogen laser system (NAILS) will be installed near each FD site co-linear with the distant lasers.

4.2. Fluorescence Detector

Most of the innovations planned for Auger North FD telescopes have been tested in the HEAT enhancement recently constructed at Auger South.

FD electronics. The FD electronics architecture for Auger North is for the most part the same as the Auger South FD electronics system. However, the new system will replace obsolete components, implement a more convenient and compact backplane configuration, and increase the data sampling rate from 10 MHz to 20 MHz.

Telescope buildings. The FD buildings have been redesigned for Auger North to reduce cost. Each building will house either 3 or 6 telescopes depending on its location in the array (see Fig. 3). They will be built using steel frame construction covered with light weight insulating walls and roofs used in industrial buildings in the US.

4.3. Surface Detector

The surface detector stations are based on cylindrical polyethylene tanks of 3.6 m in diameter and 1.5 m high. The tank contains a Tyvek® liner filled up to a height of 1.2 m with purified water.

Tank design. To reduce costs, there will be only one PMT in each water tank. There will be one opening at the center of the tank for access to the PMT and electronics, and a second hatch at 1.2 m from the center for human and large components entry and for water filling operations (see Fig. 5).

Winters at the northern site are harsher than those in Malargüe, and the SD tanks in Colorado may freeze solid approximately once every 20 years if they are not insulated. Ongoing R&D on tank freezing in Colorado and Malargüe has

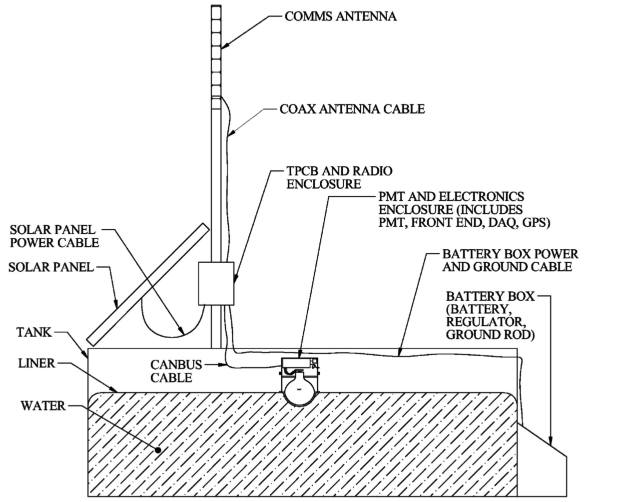

Figure 4: Conceptual drawing of the SD station, showing major components and interconnections.

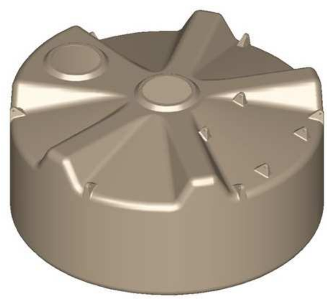

Figure 5: Proposed tank design for Auger North.

shown that significant heat flows into the tank from below in the winter, and that insulating the top and sides of the tank can significantly slow freezing and prevent catastrophic damage to the instruments.

Tests are being made to integrate polyethylene foam insulation on the inside surface of the tank during the rotomolding process. Another possibility is to cover the outside of the tank with a polyurethane foam, and paint it with an acrylic or polyurea layer for ultraviolet protection.

SD electronics. 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. Auger South employs two overlapping 10-bit flash ADCs per PMT, digitizing signals derived from the anode and amplified last dynode to obtain a 15-bit (3×10^4) dynamic range [12]. This results in saturated signals for high energy events. For Auger North the dynamic range will be extended from 15 bits to more than 20 bits using signals derived from the anode and from one or more deep (4th or 5th) dynodes.

The various electronics boards are interconnected via a CANbus cable, which provides power, distribution of GPS timing pulses, and transfer of event and monitoring data among the station radio, the data acquisition board (DAQ), and the tank

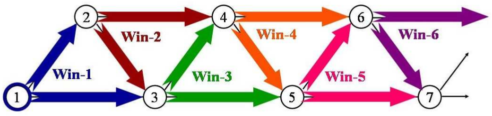

Figure 6: Systolic broadcast protocol in a second-order power chain

power control board (TPCB). This scheme is an improvement on the Auger South design, with both fewer cables and more robust data transmission. This is shown in Fig. 4.

4.4. Communications System

Although the altitude variations across the Auger North site are small on average, local variations of a few meters impose constraints on line-of-site communication links. Together with the absence of hills outside or within the surface detector array, these small local altitude fluctuations make the tower-based communication scheme of Auger South, in which each tank transmits to a distant collection point, impractical for Auger North. Consequently, a new communication scheme was designed for Auger North, whereby data are passed from detector to detector and on to the collection point using a real-time wireless protocol. Fundamental principles of the Auger South design are retained: (1) Spatial Reuse Time Division Multiple Access (SR-TDMA) radio network; (2) radio hardware optimized for Auger; (3) custom network protocol optimized for real-time reliable transport of trigger packets.

Network description. The Auger North design employs the *Wireless Architecture for Hard Real-Time Embedded Networks* (WAHREN) [1] paradigm to provide reliable hard real-time delivery of trigger (and data) messages.[2] The basic infrastructure topology is a second-order power chain as illustrated in Fig. 6. Each node communicates with both its nearest pair of neighbors and its second nearest pair of neighbors, providing resiliency to the loss of a single node.

A power chain can make a sudden right angle bend with no disruption in the data flow. This permits the entire array to be interconnected by a series of backbones and side-chains (Fig. 7). Furthermore, this ability supports much more complex routing paths, including multiple backbones, and hierarchical layers of backbones and side-chains, allowing the network to be mapped onto amorphous shapes, and to route data around holes or obstacles to RF propagation.

WAHREN uses a strict SR-TDMA communication between nodes, wherein every node may transmit in its assigned slot within a communication window. A systolic broadcast protocol is employed, in which all nodes initiate a broadcast simultaneously, in their assigned TDMA slots of the same window. Then, in each subsequent window, each node forwards messages received during the previous window (Fig. 6).

[1] While it has other applications, WAHREN has largely been developed by Auger collaboration members in the context of Auger North.

[2] A small portion of the bandwidth is available for non-real-time communication traffic, for use by “off-grid” devices such as FD calibration lasers or repair trucks.

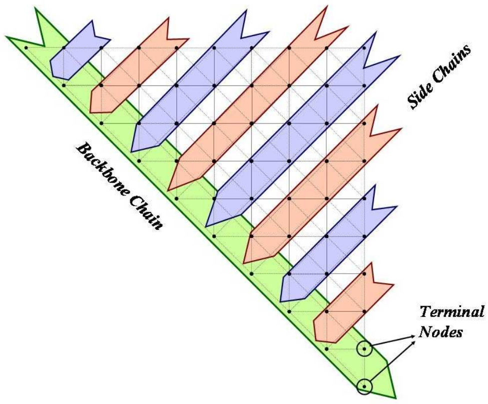

Figure 7: Backbone and side chain example.

Incoming messages from the SD stations converge on a set of concentrator stations (and diverge from them for outgoing messages). The concentrators manage end-to-end error checking and re-transmission, reformat the messages into TCP/IP data packets, and forward them via fiber optic links to the Central Data Acquisition System located at the Observatory Campus. The reverse sequence of operations is performed for outgoing messages.

Data rate and RF band. In Auger South each SD station is guaranteed 1200 bits/second hard real-time data rate. This has proved to be sufficient, but puts constraints on diagnostic information. In Auger North we plan to double that.

The Auger South communication system uses the 902-928 MHz ISM band, in which an Argentine federal government decree gives Auger priority on the site and surrounding area. In Auger North the Communications System will use a dedicated band at 4.650-4.694 GHz, part of the radio spectrum reserved for US government use, ensuring no contention from other users.

Acknowledgments

The author gratefully acknowledges the support of the US Department of Energy Office of Science for this work.

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