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The northern site of the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory studies cosmic ray extensive air showers with energies at and above the EeV range with a hybrid instrument consisting of a surface detector array and air fluorescence telescopes. Science results obtained with the southern observatory located near Malargüe, Province of Mendoza, Argentina, are the driving force to build a second observatory in southeast Colorado (USA) in the rural environment of Lamar. This Auger North Observatory will focus on measurements in the highest energy range above 50 EeV with the highest possible acceptance. As a consequence of the different energy range of the southern and northern sites, the designs of the instruments are different in some aspects. We present the proposed Auger North layout, the changes in the design of the detectors, and the current site activities with the Research and Development Array (RDA).

1 Introduction

Understanding the origin and nature of ultra-high energy cosmic rays above 10^{19} eV is a major challenge in astroparticle physics. It is known that the Greisen-Zatsepin-Kuzmin (GZK) effect (Greisen, 1966; Zatsepin and Kuzmin, 1966) reduces the energy of cosmic rays by interactions with the microwave background radiation. This effect limits the horizon for the highest energy particles to a maximum distance of about 200 Mpc. No sources are evident yet within this "GZK Sphere" .

The Pierre Auger Observatory is currently the largest experiment to study cosmic rays with energies above 10^{18} eV. It is a hybrid instrument composed of a surface detector (SD) and a fluorescence detector (FD) to determine the energy spectrum, the arrival directions, and the composition of ultra-high energy cosmic rays with unprecedented high statistics.

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The observatory was conceived with installations both in the southern and the northern hemispheres, named Auger South (AS) and Auger North (AN).

The first observatory (AS) was constructed close to the town of Malargüe, Province of Mendoza, Argentina. Completed in June 2008, it instruments an area of over 3 000 km^2 with 1 600 water Cherenkov detectors (Allekotte et al., 2008) together with 24 fluorescence telescopes in 4 buildings on the perimeter of the array (Abraham et al., 2010). Recently, the southern site was extended by three additional telescopes for the detection of showers at higher elevations and at close distances (Kleifges et al., 2009). In combination with a denser part of the SD array, these telescopes are particularly sensitive to low-energy showers with primary energies down to about 10^{17} eV.

Auger South started collecting physics data during construction, from January 2004. Important results for our understanding of the origin of UHE cosmic rays have been published. Most notable is the flux suppression at energies above 40 EeV (Pierre Auger Collaboration, 2010), which is compatible with the predicted GZK effect. An estimator for the mass of the primary particle is the depth of shower maximum X_{max}. It is determined by the fluorescence telescopes and possibly shows a trend to a heavier composition at the highest energies (Pierre Auger Collaboration, 2009b). Moreover, the arrival directions of cosmic rays observed with Auger South become anisotropic at energies above 60 EeV (Pierre Auger Collaboration, 2007, 2008, 2010). There is evidence that the arrival directions correlate with the positions of Active Galactic Nuclei listed in the Vèron-Cetty and Vèron catalog of astronomical objects (Vèron-Cetty et al., 2006). Some source models (called "top-down") do not accelerate particles at all, instead creating them by decays or annihilations of heavy particles. These schemes now are disfavored by Auger's stringent limits on the flux of cosmic ray photons (Pierre Auger Collaboration, 2009a) and neutrinos (Abraham et al., 2009).

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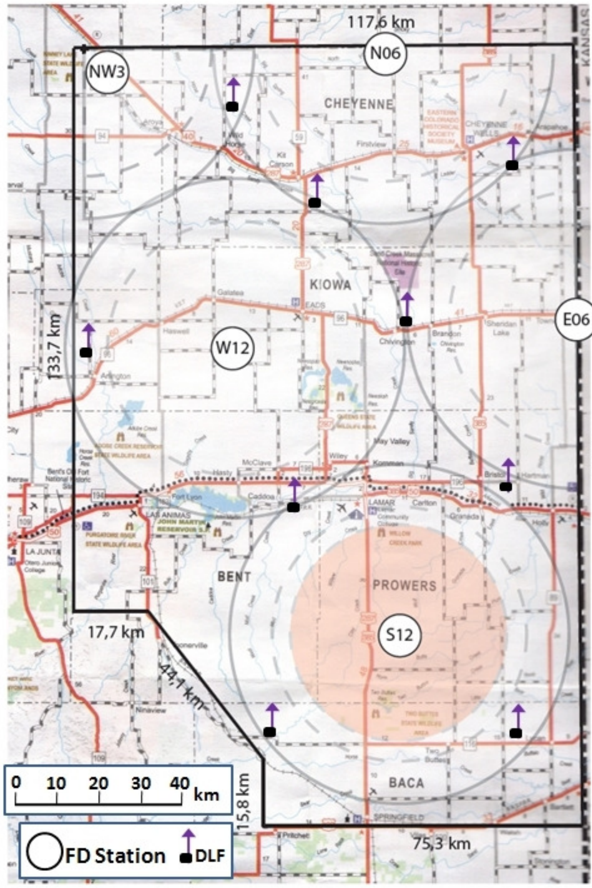

Fig. 1. Layout of the northern Auger site in southeast Colorado. The proposed positions of the 5 FD buildings are shown with their 40 km field of view (circles).The purple symbols indicate positions of distant laser facilities (DLF) used for calibration and monitoring. The red circle around FD building S12 indicates the area of the infill array.

In summary, the results of Auger South favor a scenario of cosmic rays coming from extragalactic sources within the GZK sphere. However, the low flux constrains the event rate of the Southern Observatory to only about 25 events per year at trans-GZK energies. This is inadequate for the identification of individual sources of highest energy cosmic particles. To attain the goal of single source identification, Auger North is optimized for the largest possible statistics at the highest energies. The detailed study of cosmic showers at those energies, especially particle identification, requires the construction of a hybrid instrument with both surface detectors and fluorescence telescopes. In the following we describe the overall layout, the design of the key components and the expected performance of the proposed Northern Observatory.

2 Design of the northern observatory

The design of Auger North is based on well-proven detector technology developed for Auger South. The focus on the most interesting highest energy range demands instrumentation of the largest conceivable area. This is only possible with a rather sparse array of surface detectors. Research and development work aims at improving the instrument's performance over Auger South at the same or lesser production and operation cost-per-event. Some design changes are also necessary, due to the different climate and topography of the sites in Argentina and in the USA. Other changes, especially in the electronics design, reflect the progress in technology from 1997 to 2005 (the start times for Auger South and Auger North designs respectively). After the design optimization, the expected costs for Auger North are about 2.5 times higher than Auger South, but the aperture at the highest energies increases by a factor of abou 7.

2.1 Auger North Layout

The location around the city of Lamar in southeast Colorado was selected in 2005 as the best site for Auger North. With an average altitude of about 1300 m above sea level and an almost flat and wide open landscape it is perfectly suited for cosmic shower detection. The designated layout shown in Fig. 1 is almost rectangular. It extends 185 km to the north and south and 118 km east and west. The southwest corner is clipped because that area is crossed by mountain ranges and canyons making the deployment of tanks difficult. The useful area is more than 20 000 km^2. Further extensions into Kansas are possible.

A very important criteria for the decision in favor of the Colorado site was the existence of infrastructure, especially the presence of country roads spaced on a regular 1-mile grid covering a large fraction of the area. The deployment of the 4 000 surface detectors is much simplified by placing them with a spacing of $\sqrt{2}$ miles (2.3 km) at alternating intersections of roads.

A 10% fraction of the total array will be covered by 400 additional surface detectors at a denser spacing of 1 mile (1.6 km). This infill array is located within 25 km of one of the fluorescence buildings (red circle in Fig. 1). The reduced spacing of the infill lowers the energy threshold to about the same as for the Auger South array. Thus, the subset of events measured with the infill provides an easy comparison with data measured at Auger South events.

An 80% coverage of the SD array will be achieved with 39 fluorescence telescopes, anticipating a usable viewing distance of 40 km. This range is indicated by the solid circles in Fig. 1, the dashed lines corresponding to 30 km radii. The locations of the telescopes have been chosen carefully to maximize the aperture by avoiding overlapping fields of view from different telescopes. In addition, locations are preferred when they are close to the existing electricity grid, have access to roads, and are near to an optical fiber network.

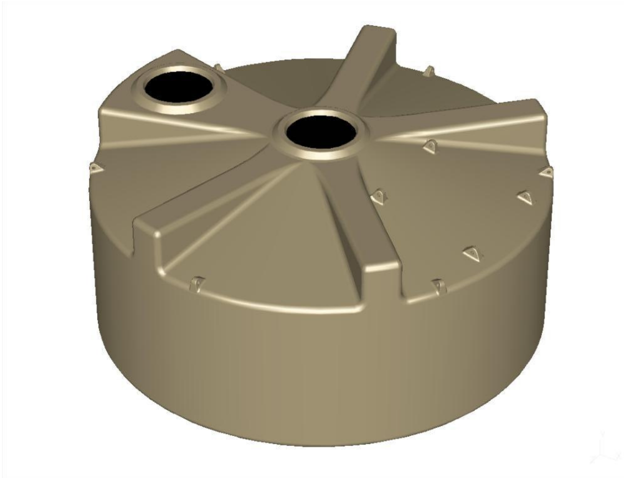

Fig. 2. A prototype surface detector tank for Auger North.

2.2 Auger north surface detector

The Auger North surface detectors are cylindrical water Cherenkov tanks with 3.6 m diameters and 1.5 m heights, as shown in Fig. 2. The fabrication process for the tanks will be identical to the one used for Auger South, i.e. a high-density polyethylene resin will be processed by a rotomolding process. Colder temperatures expected in Colorado winters (down to $-35\,^{\circ}$C) demand additional thermal insulation by polyethylene foam integrated from inside during fabrication. The tanks will be filled with $12\,\mathrm{m}^3$ of ultra-pure water to guarantee a low absorption of Cherenkov light during the expected 20 year lifetime. The water will be contained in a flexible, laminated liner with an inner Tyvek® surface for diffuse reflection of the Cherenkov light.

The Auger South tanks are equipped with three large 9” photomultipliers (XP 1805) viewing the water from above. For Auger North, only one central PMT will be used. To allow recording of showers even at close distance to the tanks without saturation, the dynamic range will be increased from 15 bits at Auger South to about 22 bits at Auger North. Tests with pulsed LEDs have verified that the extended range can be achieved by recording the anode signal as well as the signals from the fourth and sixth intermediate dynodes.

The electronics for Auger North have been redesigned, taking into account the experience gained with Auger South and employing up-to-date components. Signal digitization will be performed at 100 MHz by commercial 10-bit ADCs. The first level trigger will be implemented in FPGA logic as a combination of a simple threshold and a digital time-over-threshold trigger. A single FPGA of the Cyclone III family will generate the trigger and provide time tagging functions on the front-end board. Internal RAM memory of the FPGA will hold shower traces, muon buffers and monitoring data. Higher level functions of the electronics will be carried out on the local station DAQ board shown in Fig. 3.

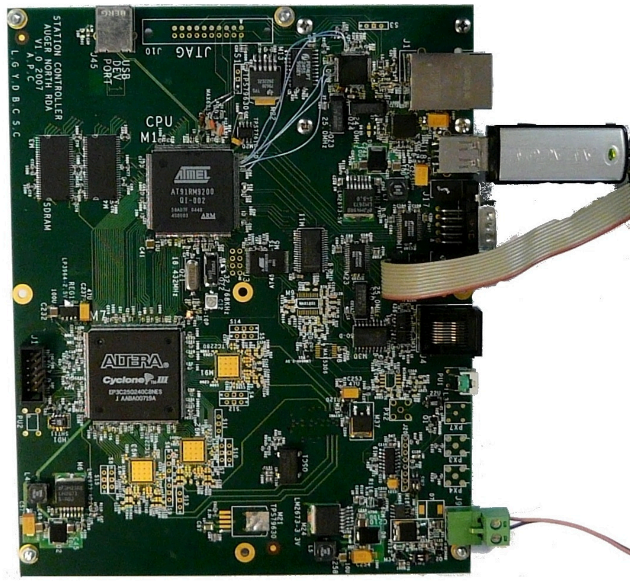

Fig. 3. First prototype version of SD DAQ board.

The heart of this board will be a microcontroller (ARM family ATM91RM920) running on RealTime Linux. Equipped with interfaces to a DRAM, a flash EPROM, a USB port and a serial $\mathrm{I^2C}$ bus for the connection of slow control devices, the board will monitor and control the high voltages for the PMT, and monitor internal and external voltages and temperatures. It also will parameterize the i-Lotus M12M GPS receiver, the successor model of the Motorola Oncore UT+ used in the Auger South electronics. The 1-PPS signal of the M12M receiver is stable enough to ensure uniform timing across to SD array with better than 10 ns accuracy.

Using low current components, the average power consumption of the SD electronics has been reduced to less than 5 W (compare with 10 W at Auger South). Power is provided by an off-the-shelf solar panel, buffered by one 12 V lead-acid battery of about 100 Ah capacity. The number of cables between the various electronics component is reduced to only one CANbus cable. It provides power, distributes the 1-PPS timing signal and transmits event and monitoring data between the DAQ board, the subscriber for wireless communication and the tank power control board.

2.3 Auger north fluorescence detector

The configuration of Auger North telescopes is shown in Fig. 1: buildings S12 and W12 comprise 12 telescopes each with a 360° view, buildings E06 and N06 provide 6 telescopes at the perimeter, and building NW3 has 3 telescopes at the northwest corner. A floor plan for a 12 telescope building is shown in Fig. 4. Low construction costs are achieved by the special shape of the building, allowing a very compact telescope arrangement. The construction will be based on

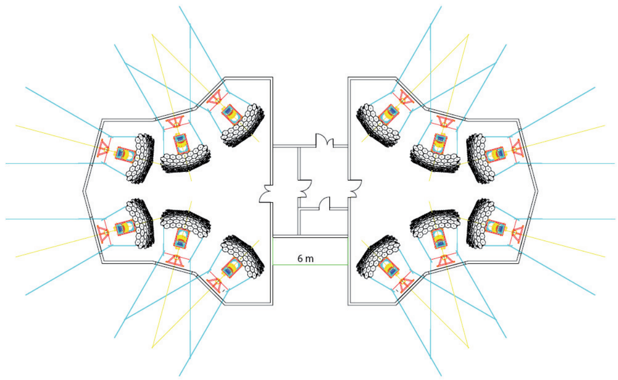

Fig. 4. Layout of a FD building with 12 telescopes: two parts for 6 telescope enclosures face each other with a service building for common infrastructure in between.

a steel frame covered with lightweight insulating walls and roofs used in US industry.

The principal designs of the optics and mechanics is identical to Auger South. The aperture system is protected by a robust commercial shutter working like a garage door. Background light from stars is reduced by UV-transmitting filter glass (Schott M-UG6) with high absorption in the visual range fitted in the aperture. The Schmidt optics provides a 2.2 m diameter wide entrance window, which is fitted with an annular shaped corrector ring element. Light passing through the aperture is reflected by a 14 m^2 spherical mirror made from 60 hexagonal glass pieces with a reflectivity above 90% in the relevant UV range. The camera in the focal surface of the optics is composed of 440 PMTs, arranged in a matrix of 22 rows and 20 columns. The hexagonal PMT XP3062 used in Auger South are no longer available and will be replaced by the round Hamamatsu type R9020 which currently is being tested. The use of super bialkali material at the cathodes will enhance the quantum efficiency from 25% to about 35% at 350 nm.

Electronics connected directly behind each PMT provide high-voltage biasing through an active voltage divider and a differential driver for signal transmission. The front-end subrack processing the camera signals has been redesigned to improve the performance and to avoid problems with obsolete components. The sampling rate has been enhanced to 20 MHz and the readout is now 20 times faster, leading to a universal DAQ system applicable in other projects, too. The DAQ system provides 20 Analog Boards for signal adaptation and amplification, 20 First Level Trigger boards for a 12-bit digitization and one Second Level Trigger board for triggering on light tracks from cosmic rays and data readout. The pixels are marked as triggered as long as a running sum of 20 successive ADC values exceeds an adjustable threshold. Individual pixel triggers are combined by the second trigger stage to find track segments of at least 5 adjacent pixels. Traces are stored in 64 event buffers with 2 000 samples per pixel for readout without dead time. The trigger algorithm is implemented in FPGA firmware. It is followed by further software trigger stages running on a CPU daughter board integrated on the SLT and connected through a PCI bridge (see Fig. 5).

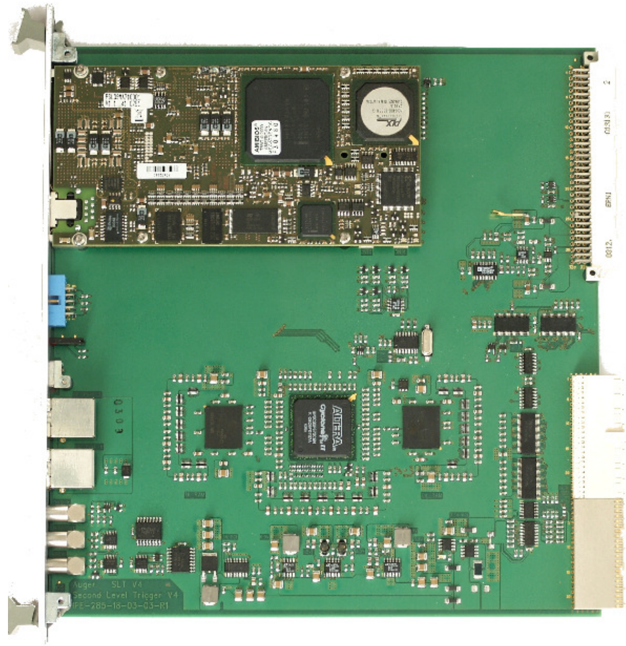

Fig. 5. The SLT board: the mezzanine card with the Intel-based CPU is plugged on at the top left.

2.4 Auger north communication

The data recorded by the SD and the FD must be transmitted to the Central Data Acquisition system (CDAS). While the FD buildings are connected to a pre-existing fiber network, the SD will transmit its data through wireless telecommunications. The topographical flatness and the vast size of the array make it impractical to adopt the Auger South scheme of point-to-point transmission to an elevated telecommunication towers. The alternative solution for Auger North is a wireless sensor network (WSN), in which data are passed from detector to detector until finally a concentrator point with access to the fiber network is reached. The network is based on the second-order power chain shown in Fig. 6, i.e. each detector receives from, and transmits data to, the nearest and second nearest pair of neighbor detectors. The scheme provides inherent fault-tolerance against single tank failures, which is a requisite for high reliability.

To cover the whole array, the site is divided into communication sectors of triangular shape. Within a sector, the communication follows along a set of side chains that connect to a common backbone, as illustrated in Fig. 7. Unlike in dynamic ad hoc WSN, the Wireless Architecture for Hard Real-

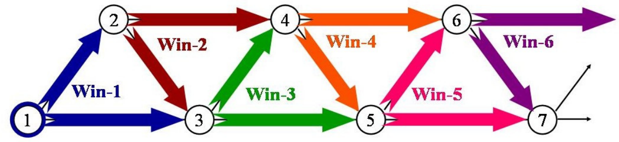

Fig. 6. Scheme of a systolic broadcast protocol in a second-order power chain. Different colors indicate transmission of the same message at different time windows.

time Embedded Networks (WAHREN) developed for Auger North strictly follows a Spatial Reuse Time Division Multiple Access (SR-TDMA) protocol adapted for a network of fixed installed nodes. Every node is only allowed to transmit data in its assigned time slots. A systolic protocol initiates a broadcast of all nodes in their assigned slots at the same time window. Then, in subsequent time windows, previously received messages from other nodes are forwarded.

The radio transmitter is custom-made, consisting of a baseband motherboard with an FPGA and a microcontroller, and a mezzanine RF- board with commercial radio ICs. This modular design allows developing RF-boards for several frequency bands. The Auger North communications system will use the dedicated band at 4.650 – 4.694 GHz, which was obtained from the US government to avoid contentions from other users. Compared to Auger South, the data rate will be doubled to a guaranteed 2 400 bits/s for each detector. Simulation software based upon digital elevation maps predicted, and measurements with a radio link on site verified, that an antenna mast of 6 m height is in 90% of cases sufficient to establish a stable link to neighbor nodes. Only in rare cases will a higher mast be needed or will a tank need to be moved by up to 100 m from its nominal position.

2.5 Expected performance

It is important to verify that the performance of Auger North is appropriate for the measurement of cosmic rays above 50 EeV. The detection efficiency of the SD was obtained from the data of Auger South by using sub-configurations of SD stations with densities similar to the Auger North design. The results reproduce predictions based on a lateral trigger probability function from shower simulation programs. For iron and proton primaries the detection efficiency reaches 90% around 20 EeV and 30 EeV, respectively, which is at the low end of the energy range of interest.

The accuracy in the determination of the arrival direction depends mainly on the number of triggered SD stations. This number increases with energy and the zenith angle. The angular accuracy was estimated using Monte-Carlo simulations and comparing the reconstructed arrival directions with the simulated ones. Demanding 5 or more stations in an event we estimate the angular resolutions to be about 1° to 2° at 50 EeV (see Table 1). These values are only slightly worse

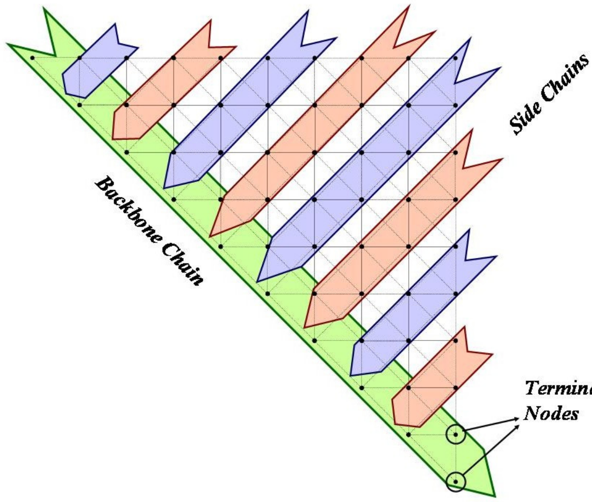

Fig. 7. Backbone and side chain example.

Table 1. Expected performance of Auger North (for SD and FD) as given in Suomijärvi et al. (2010) and Blümer et al. (2010).

Performance	Value	Comment
SD detection efficiency (90% threshold)	4 EeV 30 EeV 20 EeV	infill grid, protons regular grid, protons regular grid, iron
SD angular resolution (68% probability) at 50 EeV	about 2.2° about 1.2° below 1°	at 25° zenith angle at 45° zenith angle at 60° zenith angle
FD X_{max} resolution	≤ 20 g cm^{-2}	
FD energy	15%	system. uncertainty
FD acceptance	40 000 km^{2}sr	at 100 EeV

than for Auger South, except for very vertical showers.

The FD performance was estimated with a ray tracing program that takes into account the changes in the telescope design and the different atmospheric aerosol contaminations. Values given in Table 1 refer to an average of summer and winter conditions.

3 Current activities at AN site

Work now is ongoing to construct a Research and Development Array (RDA) close to US highway 287/385, south of Lamar. The goal of the RDA is to reconstruct cosmic ray showers with prototype detectors, to bring as many components to the pre-production stage as possible, and to test the

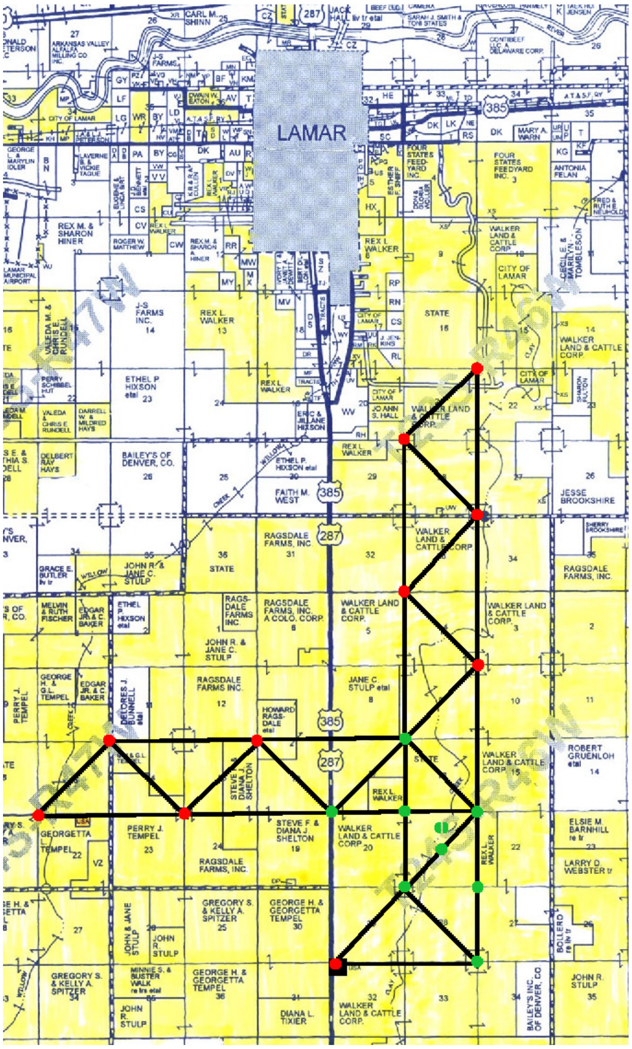

Fig. 8. Map of the RDA: the black lines indicate the communication links between communication-only (red dots) and fully instrumented tank stations (green dots). The concentrator station is at the southernmost red circle, the Powers Country building along highway US 287.

new WSN communication. The plan is to deploy 10 Auger North surface detectors and 10 stations that have only communication equipment. The overall layout in Fig. 8 shows the positions of real tanks as green points and communication-only stations in red. The configuration includes a short backbone and one side chain of sufficient length to test (1) interference, signal strength, bit and packet error rates; (2) trigger packet transmission and readout of data from stations; (3) fault tolerance, via fault injection experiments where nodes are purposely put into a failure mode; and (4) network capacity, via the introduction of fake traffic.

In parallel, an atmospheric monitoring program will accumulate a more complete database than the earlier measurements. Data taking will be carried out over at least one

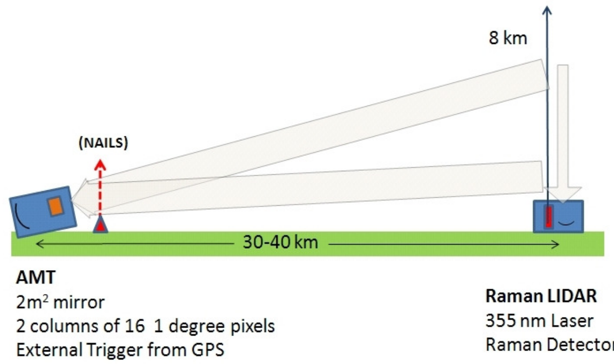

Fig. 9. Sketch of the setup to measure atmospheric parameters with AMT and Raman LIDAR.

year. The accumulated data will be used to refine simulations and reconstruction algorithms in advance of Auger North site construction. The vertical atmospheric optical depth will be determined by recording tracks from a distant vertical pulsed 355 nm laser of known intensity. The Atmospheric Monitoring Telescope (AMT) is a simplified FD telescope, located at 38.8 km distance for this purpose (see Fig. 9). It is equipped with a 4-column PMT camera and the new FD electronics modules. The laser and the AMT are synchronized by GPS timing. The laser system will also include a back-scatter Raman LIDAR receiver to compare two methods of aerosol retrieval. The AMT will be calibrated using a portable nitrogen vertical laser system (NAILS) operated at close distance. For tests, the AMT can also be equipped with the higher quantum-efficiency PMTs anticipated for Auger North.

4 Conclusions

Results from Auger South point to very interesting physics questions in the field of astro- and particle physics for the highest energy cosmic rays. To address these questions, the northern site of the Pierre Auger Observatory is planned in Colorado, USA, as a hybrid detector of total 39 fluorescence telescopes and 4 400 surface detector stations spread over 20 000 km^2. Focusing at energies above 50 EeV, the observatory will increase the acceptance at highest energies dramatically, while keeping the performance and resolutions similar to Auger South. The design of Auger North benefits from the experience gained in constructing and operating Auger South. The two instruments are very similar in design, with necessary changes to be carefully tested with the RDA.

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