GAP-98-006, Auger project technical note[1].

Auger: What, Why and How?

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Abstract. The Pierre Auger Observatories for the highest energy cosmic rays will be hybrid systems, employing water Čerenkov ground arrays over-looked by atmospheric fluorescence detectors. This will allow accurate reconstruction of primary cosmic ray energy and arrival direction in a cost effective manner, and without dependence on uncertain models. In this paper the design of the proposed instrument is reviewed, together with the simulations on which it is based, and the resulting performance predictions.

I WHAT?

The proposed Auger Observatories are of a hybrid design, employing fluorescence detectors overlooking ground arrays. During clear, moon-less nights all events will be observed both by the nitrogen scintillation light given off in the atmosphere, and also by particle detectors at ground level (this is 10% of the time). The remaining 90% of the time the ground arrays will work alone, aided by the data collected in the hybrid mode, collecting a large sample of events at energies above 10^{19} eV. Figure 1 shows the layout of an Auger observatory. Each ground array consists of 1600 water Čerenkov tanks arranged in a hexagonal grid with spacing of 1.5 km; three fluorescence eyes overlook each array. There will be two identical installations, one each in the Northern and Southern hemispheres, to obtain coverage of the complete celestial sphere.

Since this meeting has focused on the nitrogen fluorescence technique it is perhaps worthwhile to review the ground array method. Whereas a fluorescence detector measures the longitudinal profile of a shower as it grows and then diminishes while passing through the atmosphere, a surface array measures it in a single plane as the shower particles strike ground level.

When considering fluorescence detectors it is usually acceptable to treat the shower as a point source of light moving along the projection of the primary particle's trajectory at velocity c. Since the fall off of particle density at increasing distance from the axis is very steep, the numerical bulk of the particles are within

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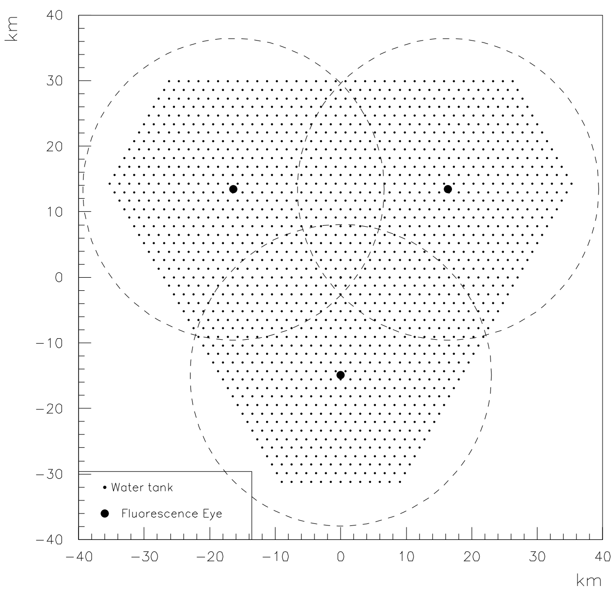

FIGURE 1. Layout of an Auger Observatory. The large circles indicate the approximate viewing range of the fluorescence detectors at 10^{19} eV.

≈ 50 m of the core. However, there is a measurable density of particles at distances up to several km. Figure 2 shows the longitudinal and lateral distributions of a single simulated shower.

It was using ground arrays that air showers were first measured, and it was at the Volcano Ranch Array in 1962 that the first event was observed which was claimed to have a primary energy of $\geq 10^{20}$ eV [1]. As they sweep down through the atmosphere, the shower particles form a curved disc normal to the primary cosmic ray's trajectory. The particle detectors which form a ground array take a number of "samples" of the shower front as it intersects the ground. The relative arrival time of the particles allow the shower direction to be inferred. The amount of signal recorded at each unit allows the core position and shower size to be reconstructed.

A fluorescence detector observes cosmic rays in much the same way as a video camera might observe meteor trails; the difference is that the air shower event is much fainter, and has a much greater angular velocity. A set of photomultiplier tubes view each small patch on the sky, and a series of hits allow the shower direction across the sky to be determined. The operation of hybrid air shower detector is illustrated in figure 3.

II WHY?

The reason for building a cosmic ray detector with time-averaged aperture on the order of 10^4 km^2 sr is clear; there are events at energies $\gg 10^{20}$ eV and such an aperture will be required to observe a statistically meaningful number of them. The

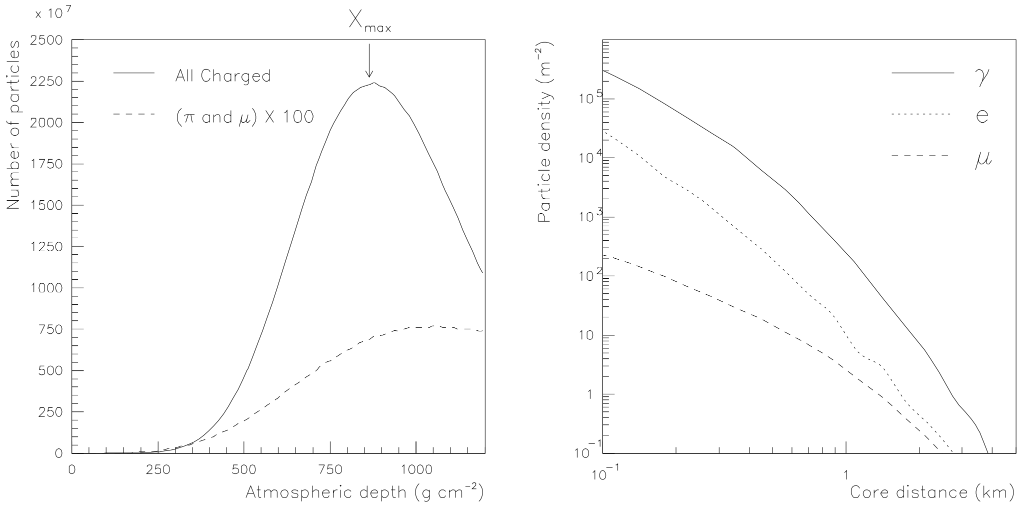

FIGURE 2. Simulated longitudinal and lateral profiles of a giant air shower. At left the number of charged particles is plotted against atmospheric depth. At right the lateral distribution is plotted for particles reaching ground level. The simulation is for a 3×10^{19} eV proton incident at 45° to the zenith, with ground level at 1450 m asl.

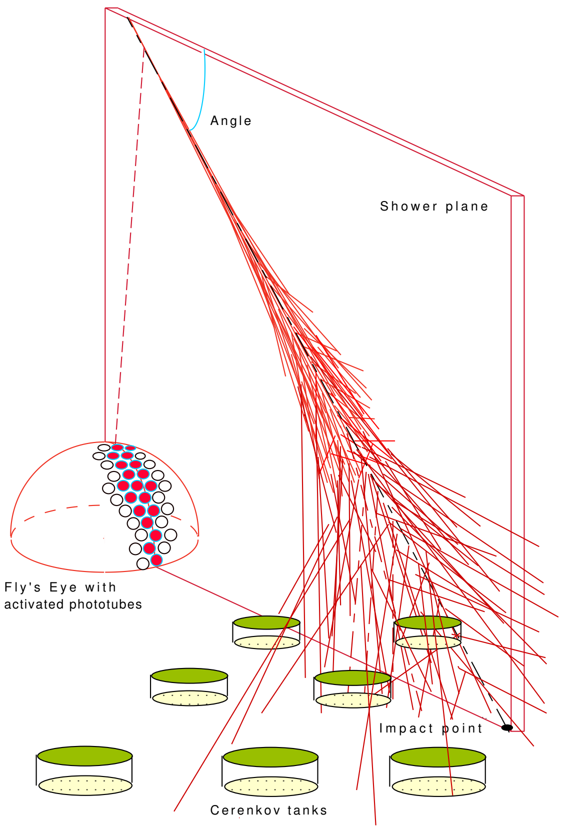

FIGURE 3. Illustration of the operation of a Hybrid air shower detector.

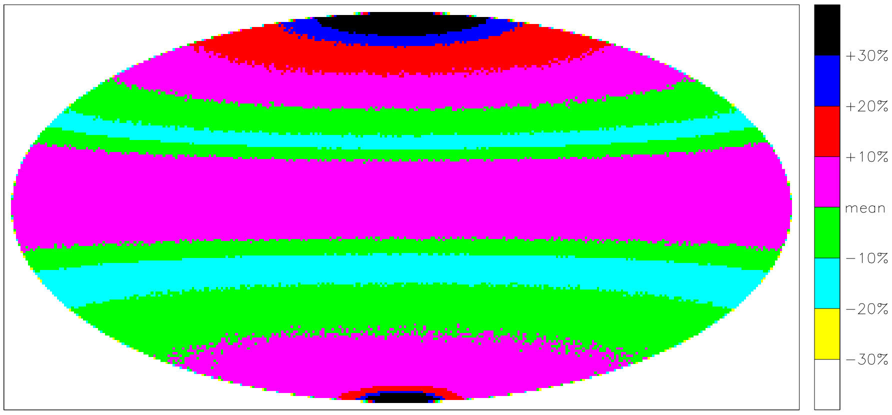

FIGURE 4. Relative all sky exposure of the Auger Observatories.

previous and current experiments, Fly's Eye and AGASA, both had apertures of the order of 10^2 km^2 sr, and each observed one event well in excess of 10^{20} eV [2,3] during a period of approximately 5 years (AGASA is still running). The next generation HiRes detector will achieve 10^3 km^2 sr, but this will still not be enough to settle the formidable questions posed by the existence of such events.

It is difficult enough to construct plausible theories of acceleration to $\gg 10^{20}$ eV even when the most extreme astrophysical objects are invoked (such as AGN's). However, due to interactions with the all-pervading CMB radiation, the search volume must be limited to on the order of 100 Mpc, and there are few, if any, suitable candidates. To compound the mystery, the extra-galactic magnetic fields do not seem strong enough to deflect a proton propagating such a distance by more than a few degrees. Therefore one expects the events to point back towards their sources; there are no obvious candidates so far [4].

The Auger project aims to provide the necessary event statistics, to do it in a cost effective way, and furthermore to be a conservative detector which makes all-important experimental cross checks and inter-calibrations.

The need for sites in the Northern and Southern hemispheres is clear; since the phenomenon under study is so poorly understood it is necessary to survey the complete celestial sphere. A water Čerenkov ground array can reconstruct events at up to 60 degrees from the zenith, while a fluorescence detector can go nearly to the horizon. Even in the latter case it is not possible to observe the entire sky from a single site with acceptable uniformity. Figure 4 shows the relative all sky exposure for the Auger water Čerenkov arrays; variation is on the order of $\pm 20\%$ over the bulk of the celestial sphere.

The combination of a surface array and fluorescence detector characterizes showers to a greater degree than either technique alone. The decision to use the two techniques together is based upon a set of related considerations which can be grouped into the four categories below.

- **Energy Spectrum Measurement:** The two methods have different problems when measuring the intensity of cosmic rays. To do this one must know both the number of events at a given energy, and the effective detection aperture at that energy. A fluorescence detector has an (in principle) direct energy calibration, but the aperture is uncertain. A ground array has a known aperture, but a more indirect energy calibration.

The energy calibration of a ground array comes (in most cases) from calculations of shower development, either analytic or Monte Carlo. Since the first few cascade generations are above the energy range which has been studied with accelerators, large systematic errors could result [2] —this is the Achilles heel of ground array detectors.

The aperture of a ground based fluorescence detector grows with energy as brighter events can be seen from further away. The detection aperture also varies as a function of night sky background, and hence from night to night, and can only be determined by a detector Monte Carlo which includes the details of the trigger electronics.

By combining the two techniques it is possible to have the best of both worlds. The 10% sub-sample of events collected in hybrid mode will allow the energy calibration constants for the ground array to be extracted. The ground array data can then be analyzed without model dependence, and with a well known aperture.

- **Direction measurement:** The direction resolution of a stereo fluorescence detector is somewhat better than that of a ground array. However, optical detection is only possible on clear, moon-less nights (10% duty cycle). Hence the aperture waxes and wanes as a function of both lunar and seasonal cycles. A ground array runs 24 hours a day, 365 days a year, giving a constant aperture. Ground array data is much more straightforward to interpret when investigating the arrival direction distribution.

- **Composition Sensitivity:** A fluorescence detector measures directly the depth of shower maximum (X_{max}). This is a powerful composition parameter, but it is important to note that its interpretation is model dependent. A ground array measures semi-independent composition parameters. A hybrid detector therefore offers the best chance of being able to both select a reasonable shower model, and deduce the primary composition, simultaneously and independently.

- **Practical Considerations:** We believe our design to be highly competitive in terms of dollars spent per shower detected above 10^{20} eV. However, cost considerations do not control the ratio of the apertures of the fluorescence and ground array components. The fact that the bulk of the data is recorded in

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[2] In fact on closer examination, it turns out that even quite radical changes to the high energy interaction model have small effects when trying to determine shower energy [5]. Room for maneuver is limited when one considers the existing accelerator data [6].

ground-only mode is simply because the optical detectors can operate only 10% of the time (clear, moon-less nights).

III HOW?

The proposed Auger fluorescence detectors are similar in design to the Fly's Eye / Hi-Res [7]. The surface array is made up of water Čerenkov tanks, and resembles the array successfully operated by the Haverah Park group for more than twenty years [8] (although on a much larger scale). The tanks are to be cylindrical with 10 m^2 top area, and 1.2 m deep. They will be lined with a highly reflective material, and filled with purified water. Large photomultiplier tubes (pmts) will view the water volume vertically downwards from above; when an event trigger is generated the pmt waveforms will be recorded by a flash-ADC system. Figure 5 shows an artist's impression of a ground array station. The detectors will be semi-autonomous, relying on battery-backed solar power, radio data communications, and obtaining time synchronization from the Global Positioning Satellite (GPS) system.

There will be 3 fluorescence eyes per site, each viewing an elevation range of 30 degrees, with a complete circle in azimuth. Pixel size will be 1.5 degrees, with 48 mirror units per eye, each unit covering a 15 degree by 15 degree region of sky. A sketch of a possible fluorescence detector unit is shown in figure 6; there would be 12 such units per eye. Sites have been chosen for the Observatories in Utah, USA, and Mendoza Province, Argentina. A large international collaboration has been formed (more than 250 people), and funding is being organized.

Extensive simulations have been carried out to predict the performance of the proposed instrument. The first step is the generation of simulated air showers. These are then passed through simulations of the ground array and fluorescence detectors. The fake data thus generated is reconstructed, and the results compared to the input shower parameters to determine the experimental resolutions. In this work the Mocca shower simulation code [9] is used, with the Sibyll high energy hadronic interaction generator [10]. Individual events from the shower simulation are input to the detector simulation stage. Hence shower-to-shower fluctuation effects are fully included, and if anything, are over estimated.

The fluorescence and ground array detectors are simulated in great detail so that measurement fluctuation effects should be fully included. Figure 7 shows some example Flash-ADC waveforms for tanks taking part in a ground array event.

The hybrid data is reconstructed using a similar method to that described in [11]. The arrival time of the shower particles in the ground array detectors is used in combination with the track orientation on the sky as seen by the fluorescence eye(s). The result is geometrical reconstruction accuracy which is equal to that of stereo fluorescence. Angular error is $\sim$ 0.3 degrees, and energy error $\sim$ 10% for primary energies above 10^{19} eV (68% bounds). A caveat here is that the atmospheric attenuation is assumed to be perfectly known, and hence perfectly correctable.

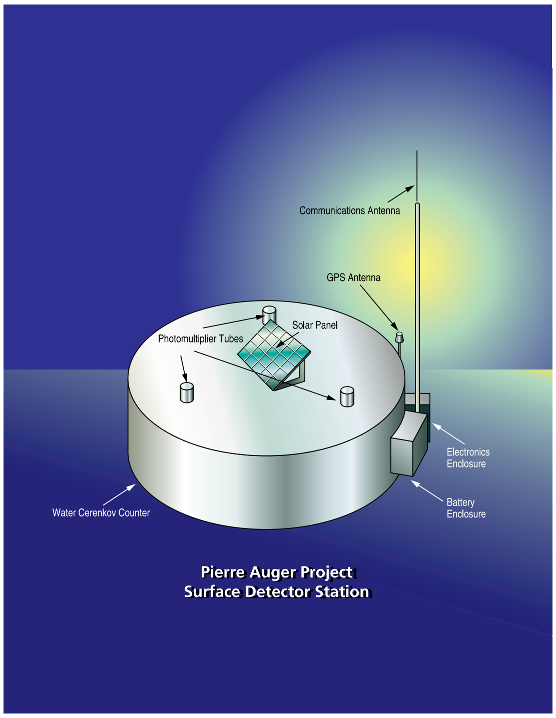

FIGURE 5. An Auger ground array station.

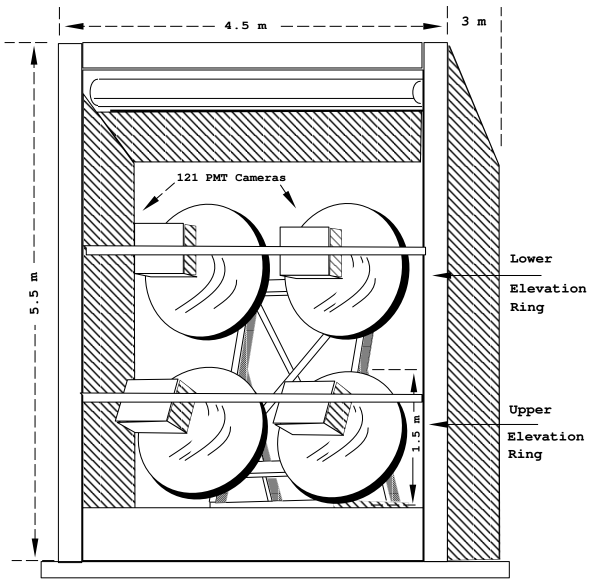

FIGURE 6. Possible fluorescence detector enclosure.

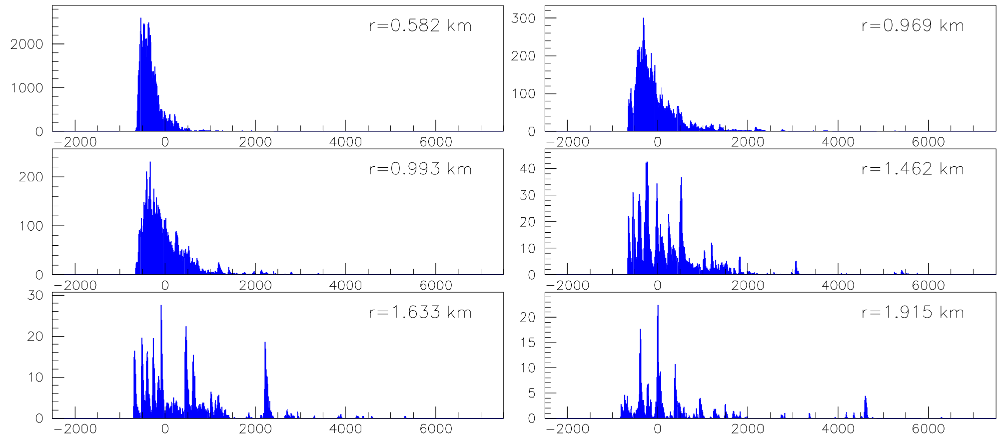

FIGURE 7. Simulated pmt output for six tanks taking part in a ground array event. Note the very different vertical scales; a single muon has an amplitude of approximately 20. The horizontal scale is time in nanoseconds, and distance from the shower axis is noted on each trace.

Note that the hybrid reconstruction does not use the signal size information from the ground array detectors, only the trigger times. This is vitally important as it allows us to overcome a major problem of stand-alone giant arrays. To reconstruct ground array data it is necessary to know the form of the lateral distribution function (ldf); how the particle density varies with axial distance to the shower core. For a sparse array it is difficult to determine the ldf and the shower core positions simultaneously; there is insufficient data. An assumed shape is required, either extracted from lower energy data, or determined by analytic or Monte Carlo calculations.

Hybrid reconstruction will determine the core position to within 50 m. The lateral distribution function can then be accurately measured event-by-event using the independent surface detector density information. This measured ldf will then be used in the reconstruction of the 90% of the data which is ground only. This resolves the first major problem with conventional ground arrays.

The second major problem of ground arrays is how to infer the primary energy from ground level observations. In this work $\rho(1\ km)$ is used as the energy parameter; the interpolated signal density in a water Čerenkov detector at 1 km from the shower core. According to shower simulations this parameter has small fluctuations, and corresponds almost linearly with primary energy. The shower size on axis reaches maximum somewhat above ground level at the Auger sites (since the ldf is approximately a power law, the total number of particles is dominated by those close to the axis). However, for a vertical event, $\rho(1\ km)$ is still growing at ground level; it is maximal for events which arrive at approximately 40 degrees zenith angle. Within the zenith angle range 0 to 60 degrees fluctuations in $\rho(1\ km)$ are minimal since the gradient of this quantity is small.

The important thing to note is that it does not matter if the Mocca-Sibyll predictions of X_{max} etc. are exactly right; the freedom allowed by existing data from the Fly's Eye is not enough to qualitatively alter the situation. The exact form of the relationship between $\rho(1\ km)$ and primary energy will be determined in the final experiment by exploiting the pseudo-calorimetric energy measurements available from the fluorescence detectors for the 10% of the data where hybrid observations are made. This process has been fully implemented in the simulation — the hybrid reconstruction results are used to extract the (2) parameters of a simple model relating primary energy to $\rho(1\ km)$ and shower zenith angle. In all cases *reconstructed* parameters are used to make the process realistic.

Angular error is ~ 1 degree for vertical events, falling with increasing zenith angle. Energy error is $\sim 25\%$ for a worst case scenario where the primary particles are an equal mix of protons and heavy nuclei, and no correction is made. Using hybrid cross calibration the mean energy error is always zero, so if the primary beam is not mixed this figure reduces to 15%. The energy error distribution does not have a high side tail — see figure 8. These resolution figures are entirely appropriate to the problem at hand. The normal assumption is that the primaries are charged particles; if so they will be subject to random magnetic deflections greater than the angular resolution. Likewise the energy resolution will not significantly degrade

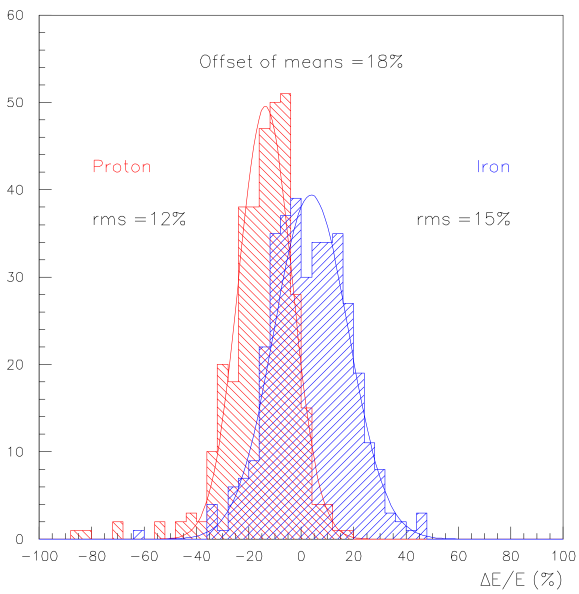

FIGURE 8. Energy error distribution of ground-only events.

spectral measurements. What is needed to make progress is event statistics with a well known aperture; high resolution is not required.

IV CONCLUSIONS

The proposed Auger Observatories of cosmic rays above 10^{19} eV have been described. The background to the project has been outlined, and the reasoning behind the hybrid experimental design given. Finally event simulation and reconstruction has been discussed, including the way in which hybrid data will be used to free ground array data from the problems to which it is normally subject. We believe this experiment to be the logical next step in the exciting field of ultra high energy cosmic rays.

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