Hybrid Detection of UHECR with the Pierre Auger Observatory

MIGUEL MOSTAFÁ FOR THE PIERRE AUGER COLLABORATION

Physics Department, University of Utah
Salt Lake City, UT 84112, USA

Abstract
The Pierre Auger Observatory detects ultra-high energy cosmic rays by implementing two complementary air-shower techniques. The combination of a large ground array and fluorescence detectors, known as the hybrid concept, means that a rich variety of measurements can be made on a single shower, providing much improved information over what is possible with either detector alone. In this paper the hybrid reconstruction approach and its performance are described.

1 Introduction
The Pierre Auger Observatory was designed to observe, in coincidence, the shower particles at ground and the associated fluorescence light generated in the atmosphere. This is achieved with a large array of water Cherenkov detectors coupled with air-fluorescence detectors that overlook the surface array. It is not simply a dual experiment. Apart from important cross-checks and measurement redundancy, the two techniques see air showers in complementary ways. The ground array measures the lateral structure of the shower at ground level, with some ability to separate the electromagnetic and muon components. On the other hand, the fluorescence detector records the longitudinal profile of the shower during its development through the atmosphere.

A hybrid event is an air shower that is simultaneously detected by the fluorescence detector and the ground array. The Observatory was originally
designed and is currently being built with a cross-triggering capability. Data are recovered from both detectors whenever either system is triggered. If an air shower independently triggers both detectors the event is tagged accordingly. An example of this type of events, known as golden hybrids, is shown in Fig. 1.

![Figure 1](image1.png)

Figure 1: Example of an air-shower that independently triggers the fluorescence and surface detectors. *Left:* Fluorescence detector view. The pixel color indicates the timing sequence. The full line is the fitted shower-detector plane. The red squares represent the surface detectors. *Right:* Surface detector view. The size of the hollow circles is proportional to the logarithm of the signal in each tank. The dotted line is the intersection between the shower-detector plane and the horizontal. The full red line is the projection of the shower axis, and the star marks the location of the shower core.

There are also cases where the fluorescence detector, having a lower energy threshold, promotes a sub-threshold array trigger. Surface stations are matched by timing and location. This is an important capability because these sub-threshold hybrid events would not have triggered the array otherwise. One example is shown in Fig. 2.

![Figure 2](image2.png)

Figure 2: Example of a sub-threshold hybrid event. The trigger from the fluorescence detector is matched in time and location by only one of the water tanks. In the array view (right) the fluorescence detector is shown as a black semi-circle.

The Observatory started operation in hybrid production mode in Jan-
uary, 2004. Surface stations have a 100% duty cycle, while fluorescence eyes can only operate on clear moonless nights. Both surface and fluorescence detectors have been running simultaneously 14% of the time. The number of hybrid events represents 10% the statistics of the surface array data.

2 Hybrid Detection

A hybrid detector has excellent capability for studying the highest energy cosmic ray air showers. Much of its capability stems from the accurate geometrical reconstructions it achieves. Timing information from even one surface station can much improve the geometrical reconstruction of a shower over that achieved using only eye pixel information. The axis of the air shower is determined by minimizing a $\chi^2$ function involving data from all triggered elements in the eye and at ground. The reconstruction accuracy is better than the ground array counters or the single eye could achieve independently [1, 2]. Using the timing information from the eye’s pixels together with the surface stations, a core location resolution of 50 m is achieved. The resolution for the arrival direction of cosmic rays is $0.6^\circ$ [2]. These results for the hybrid accuracy are in good agreement with estimations using analytic arguments [3], measurements on real data using a bootstrap method [4], and previous simulation studies [5].

The reconstruction uncertainties are evaluated using events with known geometries, i.e. laser beams. The Central Laser Facility (CLF), described in Ref. [6], is located approximately equidistant from the first three fluorescence sites. Since the location of the CLF and the direction of the laser beam are known to an accuracy better than the expected angular resolution of the fluorescence detector, laser shots from the CLF can be used to measure the accuracy of the geometrical reconstruction. Furthermore, the laser beam is split and part of the laser light is sent through an optical fiber to a nearby ground array station.

The laser light from the CLF produces simultaneous triggers in both the surface and (three) fluorescence detectors. The recorded event times can be used to measure and monitor the relative timing between the two detectors. The time offset between the first fluorescence eye and the surface detector has been measured in this way to better than 50 ns [7]. The contribution to the systematic uncertainty in the core location due to the uncertainty in the time synchronization is 20 m.

Hybrid events can be well reconstructed with as little as one surface station. Thus, the energy threshold of hybrid events is lower than it is
for surface array only events, where at least three stations must be trig-
gerated. Sub–threshold hybrid events have a lower energy distribution, while
the angular resolution is still 0.6°. Another important consequence is the
additional number of events. Approximately 60% of the total hybrid events
have fewer than three stations, i.e. for each event that can independently
trigger both the surface array and one fluorescence detector there are two
extra low energy events.

Figure 3: Status of the Pierre Auger Observatory on May 10, 2006. Each color dot
represents a surface station: red means a proposed location, yellow a deployed tank,
orange a tank with water (but without electronics), and green a fully operational
tank. Each fluorescence site is shown as a white circle.

The status of the Observatory on May 10, 2006 is summarized in Fig. 3.
There were 953 fully operational tanks at that time. The first two fluores-
cence sites (Los Leones and Coihueco) were fully operational, i.e. running
six telescopes each, in June, 2004. The third site (Los Morados) started
operation on March 18, 2005. The fourth and last site (Loma Amarilla) is
currently under construction and is scheduled to start operation by the end
of this year. The present average rate is 50 hybrid events per night per eye,
for a total of 40000 events up to June, 2006. At this rate, 4000 hybrid
events per month are expected when the Observatory is completed.

3 Hybrid Measurements

Due to the much improved angular accuracy, the hybrid data sample is ideal
for anisotropy studies and, in particular, for point source searches. Results
on a search for a point–like source in the direction of the galactic center
using these hybrid events were presented in Ref. [8].
Many ground parameters, like the shower front curvature and thickness, have always been difficult to measure experimentally, and were usually determined from Monte Carlo simulations. The hybrid sample provides a unique opportunity in this respect. As mentioned, the geometrical reconstruction can be done using only one ground station, thus all the remaining detectors can be used to measure the shower characteristics.

The combination of the air fluorescence measurements and particle detections on the ground provides an energy measurement almost independent of air shower simulations. The fluorescence measurements determine the longitudinal development of the shower, whose integral is proportional to the total energy of the electromagnetic particle cascade. At the same time, the particle density at any given distance from the core can be evaluated with the ground array. The conversion from particle density to the energy of the shower is where the fluorescence measurements become important. Hybrid events that can be independently reconstructed with both techniques are used to establish an empirical rule for the energy conversion. The procedure to determine the energy of each event is explained in more detail in Ref. [9]. It is important to note that both techniques have different systematics, and results are preliminary at this stage while the Observatory is under construction. The possibility of studying the same set of air showers with two independent methods is valuable in understanding the strengths and limitations of each technique. The hybrid analysis benefits from the calorimetry of the fluorescence technique and the uniformity of the surface detector aperture.

4 Conclusions

We have tested the performance of Pierre Auger Observatory in its hybrid configuration. Operation started in January, 2004 and over 40000 hybrid events have been successfully reconstructed up to now. It is important to note that the Observatory is under construction and that results are preliminary. It is already clear that the combination of fluorescence and ground array measurements provides reconstruction of the geometry of the shower with much greater accuracy than is achieved with either detector system on its own. Unprecedented core location and direction precision leads to excellent energy and shower development measurements. Several Auger measurements profit from the hybrid capability of the Observatory, including the angular resolution [2], energy spectrum [9], and photon limits [10].
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