Hybrid Performance of the Pierre Auger Observatory and Reconstruction of Hybrid Events

B. Fick,[1] for the Pierre Auger Collaboration,[2]
(1) The Enrico Fermi Inst., the University of Chicago, 5640 S. Ellis Av., Chicago, Illinois, USA
(2) Observatorio Pierre Auger, Av.San Martin Norte 304, 5613 Malargue, Argentina

Abstract

The Pierre Auger Observatory is a "hybrid" UHECR detector. The surface detector (SD) and air fluorescence detector (FD) of the observatory are designed for observation of cosmic ray showers in coincidence, with a 10% duty cycle. The resulting data are expected to be superior in quality to those of either the SD or FD operating individually. Hybrid operation, triggering, data acquisition, and event reconstruction were successfully demonstrated during the prototype phase of the project. This paper focuses on 75 hybrid events recorded during a four month period of running with the prototype detectors in late 2001 and early 2002. The geometric technique for reconstruction of the hybrid events is described and its advantages over the traditional FD-only method are demonstrated. A lateral distribution for the water Cherenkov signals, derived from these data, is presented.

1. Introduction

During the hybrid operating period the Auger engineering prototype observatory consisted of an array of 30 SD stations positioned on a triangular grid of 1.5 km spacing. Two prototype FD telescopes, located some 10 km away, viewed the volume of air above the array. The prototype was constructed to test the feasibility of the initial design and to discover any changes required for the complete observatory. The hybrid prototype has enabled us to test new concepts in triggering, data communications, merging, and reconstruction procedures. In particular we were able to establish the feasibility of the hybrid fitting scheme from an investigation of the data. Additionally, we were able to check to see whether we can construct a sensible average lateral distribution from the combination of FD and SD information.

2.   Hybrid Operation

The hybrid system was built with a "cross-triggering" capability. Data was recovered from both the FD and SD whenever either system was triggered. The SD data recorded as a result of an FD trigger was tagged accordingly. Hybrid events were built on the basis of this tag or time matching. In most cases the FD, having the lower energy threshold, promoted a subthreshold SD trigger. This is an important capability. It will be shown in the next section that timing information from even one SD station can improve the geometric reconstruction of a shower. The primary effect of this was to bring the hybrid energy threshold well below the design threshold of 10 EeV.

The hybrid prototype was operated on every available clear moonless night during the months of December 2001, January 2002, February 2002, and March 2002. At the time of these measurements neither of the detectors was satisfactorily calibrated but development changes on either instrument were held to a minimum during this period. 75 hybrid events were successfully recorded at a rate of approximately one every 1.5 hours. A number of potential hybrid events were lost during operation because of network and clock synchronization problems.

3.   Hybrid Geometric Reconstruction

FD shower axis reconstruction proceeds in two stages. First, the shower detector plane (SDP) is derived from the angular pattern of hit FD pixels. The SDP is the plane containing the shower axis and the FD. Second, the shower spot angular motion is used to determine the orientation and location of the shower axis in the SDP. The axis is most conveniently described in terms of the SDP normal $\hat{N}_{pl}$, the perpendicular distance from FD to shower axis R_p, the angle χ_0 that the axis make with the horizontal, in the SDP, and T_0 the time at which the shower passes closest to the FD. We call this the "mono" geometric reconstruction method because it relies on information from a single FD telescope. The details of this procedure are discussed elsewhere [1].

The mono procedure suffers from having to find three geometric parameters $(R_p, \chi_0,$ and $T_0)$ from a nearly linear relationship between spot position and time. The Auger hybrid procedure solves this problem by exploiting the time of shower front arrival at one or more SD stations. For any geometry specified by $(R_p, \chi_0,$ and $T_0)$, there is an an expected time when the shower front passes any position in space. The times recorded by SD stations are used to help pick out the best geometry by requiring that their times agree with the expected times at their locations.

We have done a bootstrap[2] analysis of a hybrid event to illustrate the situation in Figure 1. On the left we plot 1000 bootstrap core location solutions for mono and hybrid fits. On the right we plot the corresponding (R_p, χ_0) solutions.
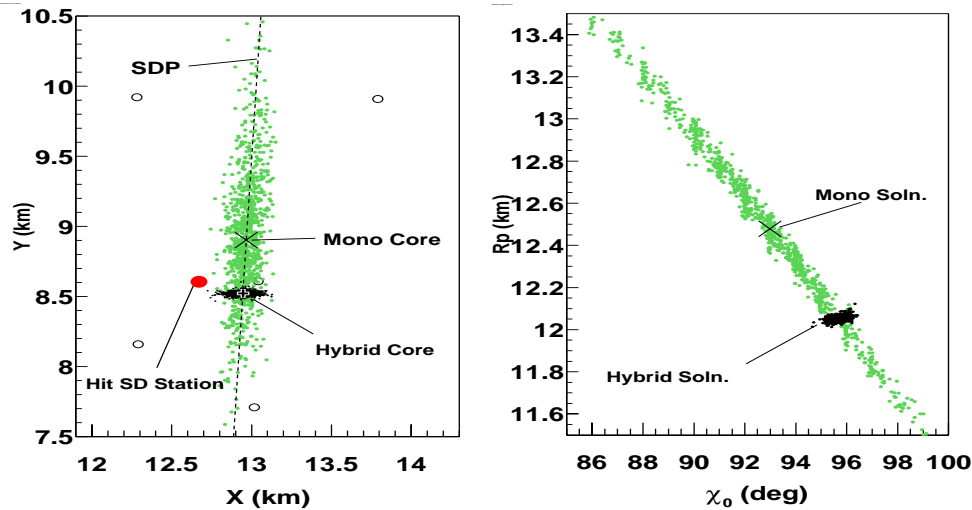
Fig. 1. Bootstrap solutions for mono and hybrid fitting procedures for a selected hybrid event.

The mono cores are spread out along the line of the SDP whereas the hybrid cores are well contained in a smaller region with greatest extent in the direction perpendicular to the line of the SDP. The expected ambiguity in the mono determination of R_p and χ_0 is illustrated in the right plot. There is a strong correlation between these two parameters. The hybrid solutions are more tightly confined and show no correlation between the parameters. The hybrid axis is much better determined.

We have done a bootstrap analysis of a subset of the hybrid data set. The data consisted of 38 events with estimated energies above 1 EeV. Please refer to [3] for an explanation of FD energy reconstruction. But for the energy cut these events represent a random sample of hybrid triggers that are not optimized for favorable mono fitting. This is shown in Table 1. The hybrid procedure determines geometries with greater precision. To investigate the sensitivity to

Table 1. Bootstrap uncertainties for geometric reconstruction.

Method	$\langle \delta R \rangle$ (m)	Max δR (m)	$\langle \delta \chi_0 \rangle$ (°)	Max $\delta \chi_0$ (°)
Mono	921	2600	8.05	24
Hybrid	20.95	86	0.24	0.7

poor timing we introduced timing errors into the hybrid reconstruction chain and determined the effects on geometry for 68 hybrid showers. The mean change of FD core distance R per 100 ns clock offset was 39 m. 90% of the events changed

by less than 70 m. The mean change in χ_0 was 0.26°. 90% of the events changed by less than 0.5°. We conclude that even with a clock accuracy of 100 ns we will get geometric reconstructions exceeding our original design specification.

4. Combined LDF

We have combined information from both the FD and SD to form an average lateral distribution. The geometry of each event was found using the hybrid fitting method described above. Events with as few as one triggered SD stations are included. Information from SD stations were included based on the following criteria : $\delta R < 100m$, $\delta X_{core} < 100m$, $\delta E/E < 0.2$, and $\theta < 60°$. For each qualifying SD station we plot , in Figure 2, the observed particle density normalized by the FD energy versus its distance to the core. Horizontal Error bars come from a bootstrap analysis of the hybrid-derived geomety . Vertical error bars are a combination of uncertainies in SD calibration and FD energy. A curve representing a power law form for the lateral distribution function, $S(r) = kr^{-\nu}$ with $\nu = 2.99$ has been drawn through the points. The agreement in shape between data and model is apparent.
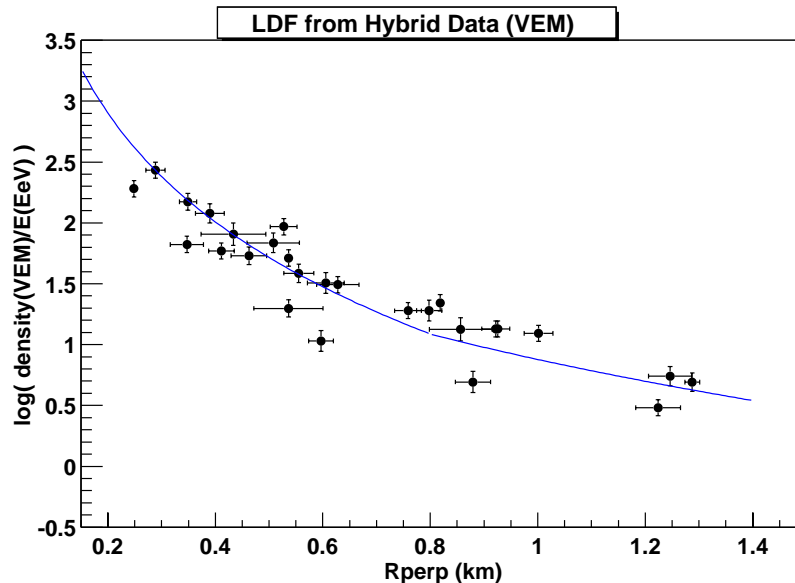

Fig. 2.   Average lateral distribution of normalized sd station densities.

1. P.Privitera for the Pierre Auger Observatory, these proceedings
2. Efron,B., et. al., "An Introduction to the Bootstrap", Chapman and Hall(1986).
3. S.Argirò for the Pierre Auger Observatory, these proceedings