Angular Resolution of the Surface Detector of the Pierre Auger Observatory

A. Creusot, for the Pierre Auger Collaboration

***Abstract*—the Pierre Auger Observatory measures Extensive Air Showers (EAS) induced by ultra high energy cosmic rays using a hybrid detector (fluorescence and surface detector). The angular resolution of the EAS reconstruction with the surface array is an essential parameter for the search of anisotropies in the sky. For this purpose, the angular resolution is estimated using several independent methods: on an event-by-event basis, with the hybrid events and with the events detected with special closed-by detectors.**

1. Introduction

THE Pierre Auger Observatory [1] measures EAS using two independent methods of detection [2]: the sampling of the shower particles at the ground level with an array of 1600 Cherenkov tanks and the detection of fluorescence light emitted by the air molecules (after excitation by the shower particles) with 24 telescopes. Some of the events, i.e. the hybrid events, can thus be detected by both components. Once the shower has been detected, the arrival direction and energy of the primary cosmic ray are estimated by reconstruction of the shower based on the measured data. The accuracy of the shower axis reconstruction is defined by the angular resolution, the angular radius that contains 68% of the reconstructed showers coming from a single point source.

Due to the higher duty cycle of the surface detector (SD), i.e. about 100% with respect to 10% of the fluorescence detector (FD), the bulk of EAS is detected by the SD only: for this reason it is important to know the angular resolution of the latter. The method used for this purpose is based on an event-by-event analysis. For some of the detected showers, redundant reconstruction of the arrival direction can be obtained either by a subsets of close-by detectors or by simultaneous observation by the FD (so called hybrid events). To check the validity of the event-by-event analysis, the space angle between the SD reconstruction axis and one of the two other reconstruction axes can be estimated. From the space angle measurement, the angular resolution can be extracted. The results obtained can then be compared with the measurement of the angular resolution with the SD. The angular resolution of the surface array reconstruction depends on the accuracy of the arrival time measurement of the particles in the surface detector. To determine this accuracy, a model of time variance has been developed [3]. This model will be presented and the SD angular resolution studied in the second section. The third section is dedicated to the simulation of the hybrid angular resolution. In the fourth section, the SD angular resolution is compared to the independent reconstructions.

Note that for this study, events from year 2004 up to 2008 were considered and the usual quality cuts were applied [4].

A. Creusot, University of Nova Gorica, Vipavska 13, PB 301, Rozna dolina, SI-5000 Nova Gorica, Slovenia (phone: +386-53315213; e-mail: alexandre.creusot@p-ng.si).

2. SD angular resolution

When a shower reaches the ground, the particles of the shower front are sampled by the SD. Each station measures the total signal and the arrival time of the particles in the detector. The shower axis (i.e. the estimated arrival direction of the cosmic ray) is determined by fitting the arrival time T_S of the first particle in each detector with a shower front model. The T_S measurement is the most important parameter in the estimation of the shower axis and thus in the estimation of the angular resolution. T_S is determined with a GPS clock and a detector internal clock. Consequently, the uncertainty on T_S is driven by the clock uncertainties and by the shower fluctuations.

A. Time variance model

In order to estimate the uncertainty of the time measurement, a model of time variance has been developed (for more details, see [3]). The model depends on typical signal properties: the equivalent muon number[1] n and the time interval T_{50} to reach half of the total signal. The time variance is written as

$$V[T_S] = a^2 \left(\frac{2T_{50}}{n}\right)^2 \frac{n+1}{n-1} + b^2 ,$$

[1] n is the total signal expressed in unit of Vertical Equivalent Muon (VEM) weighted by the inverse of the track length in the detector TL and by the height h of the detector,

$$n = \frac{S_{\mathrm{VEM}}}{TL} h .$$

For this calculation, two assumptions are made: the shower particles involved in the time estimate are mostly muons and the average zenith angle of the shower particles is assumed to be close to the shower zenith angle.

where a is a scale factor representing the uncertainty due to the shower fluctuations, expected close to the unity, and where b represents the uncertainty due to the timing, expected close to 12 ns since the GPS uncertainty is about 10 ns and the digitalization resolution about 7 ns.

The parameters a and b are adjusted by maximizing a likelihood function so that the model function fits the experimental data obtained with the doublet stations (closed-by stations 11 meters apart). The results of the likelihood maximization on 26992 events are

$$a = 0.60 \pm 0.01$$
$$b = 14.6 \pm 0.2 \text{ ns}.$$

This model of time variance is robust. a and b values are independent of the shower front model, be it spherical, parabolic or even planar. Furthermore, a and b values are close to the expectation.

Two tests were performed to check for the validity of the model. The first one concerns the stability of the model with respect to different shower characteristics, e.g. the zenith angle or the distance to the shower core. The second aims to show how the model reproduces the uncertainties in the arrival time of the particles in the station.

If the model is independent from shower variables, then the variance of scaled time difference

$$X = \frac{\Delta T}{V[\Delta T]},$$

where ΔT is the time difference between the doublet stations with respect to the fitted shower front, should be constant and close to unity. This is shown in figure 1. In first approximation, the model is stable and does not depend on the shower characteristics.

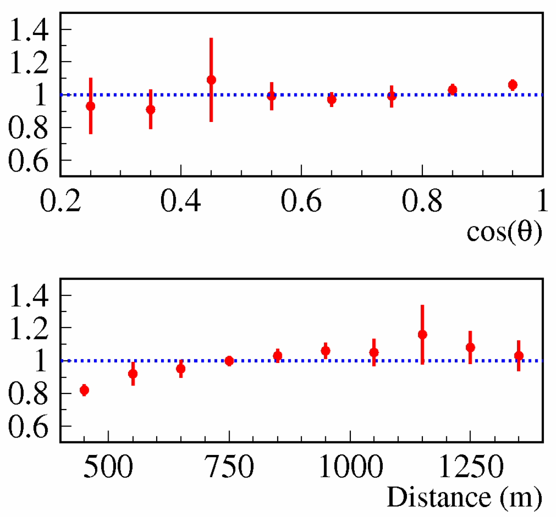

Figure 1 – Variance of the variable *X* as a function of the zenith angle (on the top) and as a function of the distance to the core (on the bottom).

The validity of the shower front fit is confirmed with the χ^2 probability. The figure 2 shows the χ^2 probability distribution for all events, for events with a zenith angle smaller than 55° and for events with a zenith angle larger than 55°. Except for low probabilities, the χ^2 probability distribution is constant for all events. The same remark can be done for the two zenith angle ranges, there is thus no compensation effect between the different populations. This test is a proof that the time variance model reproduces the time uncertainty well and that the shower front model fits the experimental data.

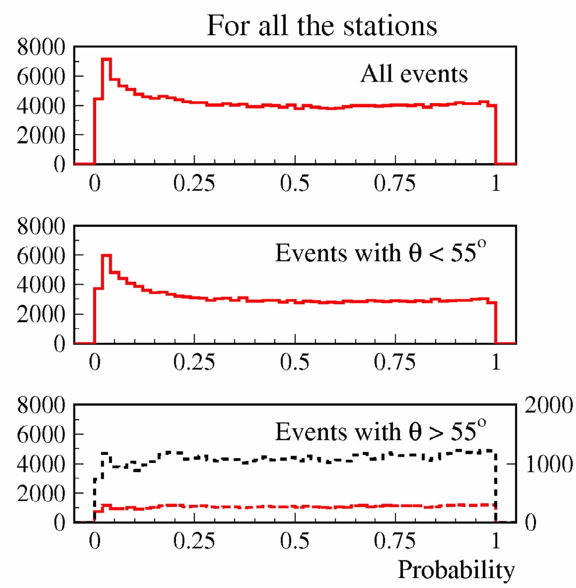

Figure 2 – χ^2 probability distribution for all events, for events with a zenith angle smaller than 55° and for events with a zenith angle larger than 55°. The dashed black line is just a rescaled of the red (gray) entries.

B. SD angular resolution on an event-by-event basis

Since the presented model of time variance is a good estimator of the time measurement uncertainty, the angular resolution of the SD can be estimated [5, 6] from the errors given by the Gaussian fit of the shower angle distributions.

The angular resolution AR is defined by

$$\text{AR} = 1.5\sqrt{\frac{1}{2}\left(V[\theta] + V[\varphi]\sin^2\theta\right)},$$

where $V[\theta]$ corresponds to the variance of the shower zenith angle θ and $V[\varphi]$ to the variance of the shower azimuth angle φ, assuming that θ and φ/sinθ have a Gaussian distribution. The figure 3 shows for different number of stations in the event, i.e. multiplicity, the angular resolution as a function of the shower zenith angle.

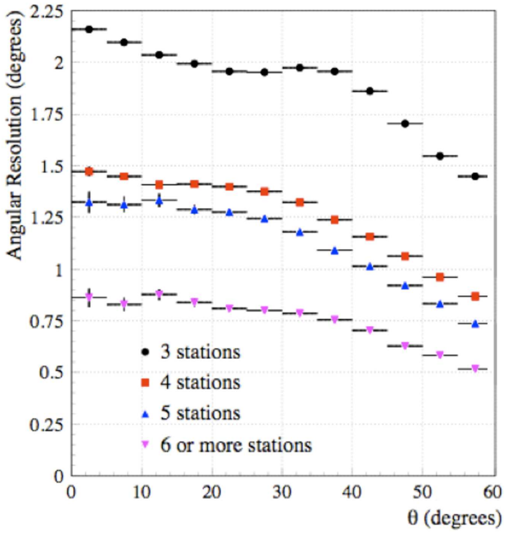

Figure 3 – The SD angular resolution as a function of the shower zenith angle θ. The SD angular resolution is estimated for several multiplicities: 3, 4, 5 and more than 5 stations.

The SD angular resolution improves when the multiplicity increases since the shower front is estimated with a better accuracy with larger number of stations. The SD angular reconstruction improves also with increasing zenith angle. On the contrary, the core position estimation becomes less accurate with increasing zenith angle. This is the main reason of the small hump observed for 3 triggered stations around 35°. For more than 3 stations, the angular resolution is better than 1.5°. For more than 5 stations, i.e. for showers with energy larger than 10^{19} eV, the SD angular resolution becomes better than 1°.

3. Simulation study of the hybrid angular resolution

In order to compare the SD reconstruction with the hybrid reconstruction, the angular reconstruction of the hybrid events has to be studied.
An hybrid event is an event detected by FD with an additional station from SD. Figure 4 shows a special hybrid event (so called “golden event”) detected independently from SD and FD. The two axes can be seen, as well as the 14 triggered stations.

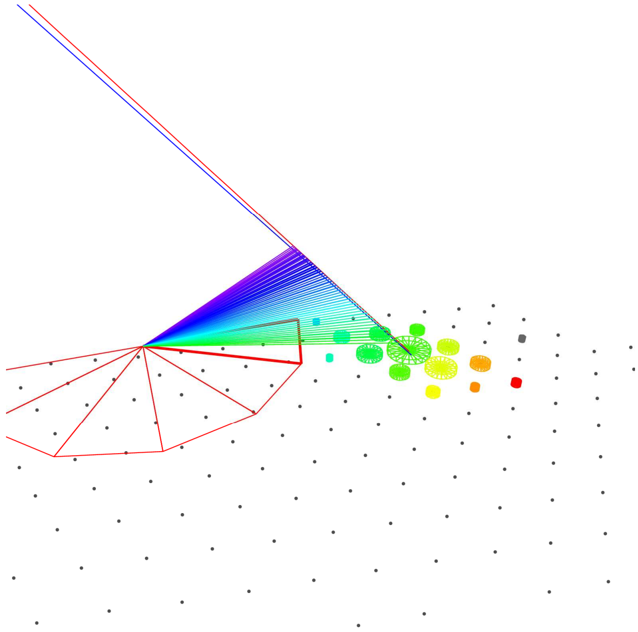

Figure 4 – Example of an event detected by both detector components of the Pierre Auger Observatory. The SD and hybrid reconstructed axes are shown. The color (gray) code is related to the arrival time.

The hybrid simulation is used to estimate the angular resolution of the hybrid reconstruction by shower simulation. If η_H is the space angle between the injected shower axis and the reconstructed axis then the hybrid angular resolution is equal to the value of η_H when the cumulative distribution function of η_H reaches 68% of its maximum. The hybrid angular resolution is shown as a function of the shower energy in the figure 5. The simulation sample consists of about 6000 proton Corsika [7] showers with zenith angle distributed as $\sin\theta\cos\theta$ (with $\theta < 60°$) and energies ranging between 10^{17} and 10^{19} eV in steps of 0.25 in the logarithmic scale. The showers have been generated using QGSJET [8] and FLUKA [9] for high and low energy hadronic interactions.

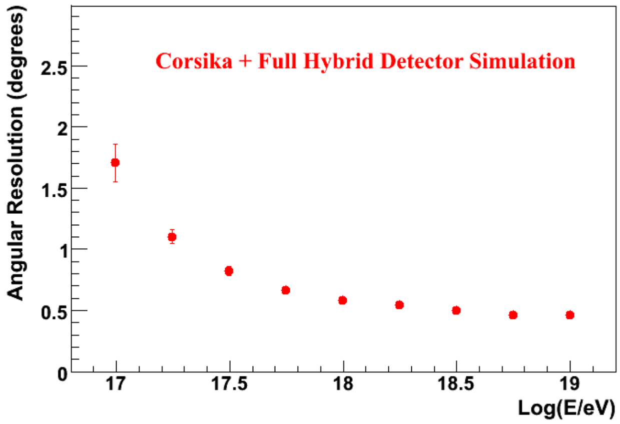

Figure 5 – Hybrid angular resolution estimated with the simulation. The shower development simulation is performed with "Corsika" software.

For energy larger than 10^{18} eV, the hybrid angular resolution extracted from Monte-Carlo simulations is better than 0.6°.

4. Comparison with independent reconstructions

Two independent reconstruction methods are used to validate the SD reconstruction and the estimation of the angular resolution. One method is based on the hybrid events, the other on the "super-hexagon" grid.

A. Hybrid events

Since the Pierre Auger Observatory is a hybrid detector, the angular resolution estimated with only the SD events can be cross checked, for some subsets of events, with the hybrid events. The principle is to reconstruct in parallel the SD and the hybrid events, and to compare the two reconstructed axes. Since the hybrid angular resolution extracted from Monte-Carlo simulation is smaller than the SD angular resolution, the hybrid reconstruction is considered as the reference.

If η is the space angle between the SD and the hybrid reconstructed axes then the angular resolution $AR_{SD\text{-}H}$ can be written

$$AR_{SD\text{-}H} = \sqrt{AR_\eta^2 - AR_H^2} ,$$

where AR_η is the value of η when the cumulative distribution function of η reaches 68% of its maximum and where AR_H is the value of the hybrid angular resolution as obtained from simulations, i.e. 0.6°.

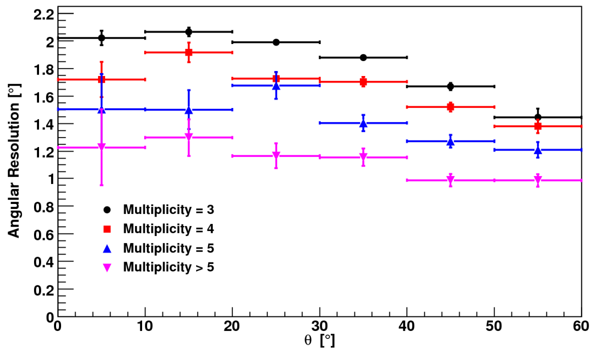

Figure 6 – Shower zenith angle dependence of the angular resolution of the SD reconstruction when hybrid reconstruction is considered as a reference. The same multiplicities are shown as in figure 3. Additionally, the statistical errors are given.

The figure 6 shows the angular resolution of the SD reconstruction when hybrid reconstruction is considered as a reference as a function of the shower zenith angle and for several multiplicities. As in the event-by-event estimation, the shower axes are reconstructed with more accuracy when the multiplicity is large. The accuracy also improves with increasing shower zenith angle. For very high energies (above 10^{19} eV), the angular resolution becomes close to 1°. The agreement between the two methods of estimation is quite good for three tank events. The slight disagreement for higher multiplicities is the subject of further studies and could be eventually used to set a limit to systematic errors.

B. Nearby station events

Within the regular SD array, a "super-hexagon" grid (see figure 7) has been added for comparison of the measurements. It allows the reconstruction of particular showers with two independent networks of stations. The method of estimating the angular resolution is similar to the method used for the hybrid events: the reconstruction of the same shower with two independent detectors and the comparison of the angular results. If η_D is the space angle between the axes reconstructed with the regular grid and with the doublet station grid, the angular resolution of the SD reconstruction by comparison between embedded networks is equal to η_D when the cumulative distribution function of η_D reaches 68% of its maximum.

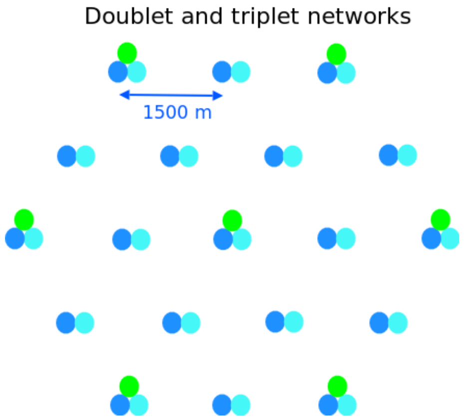

Figure 7 – Configuration of the "super-hexagon" grid. Close to the regular stations, additional doublet stations are installed (11m apart), allowing independent measurements.

The table 1 represents the results obtained with the "super-hexagon" grid, compared to the event-by-event values. The results are presented for two different zenith angles due to the fact that the angular resolution slope (see figure 3) is different below and above 35°. Note that the quoted numbers have the statistical errors only. The results obtained with the two methods are in good agreement.

multiplicity	θ	AR_D	AR
4	10-35°	1.31 ± 0.01	1.29 ± 0.06
4	35-60°	0.87 ± 0.01	0.84 ± 0.05
≥5	10-35°	0.76 ± 0.03	0.96 ± 0.10
≥5	35-60°	0.63 ± 0.02	0.70 ± 0.07

Table 1 – Comparison of the angular resolution measured with the "super-hexagon" grid (AR_D) and on an event by event basis (AR). Two ranges of multiplicity and two ranges of shower zenith angle θ are given.

5. Conclusion

The angular resolution of the surface detector of the Pierre Auger Observatory has been determined from experimental data. On an event-by-event basis, it is lower than 1.5° for more than 3 station events. For high energy events, the angular resolution becomes better than 1°. This angular resolution has been cross checked with two independent reconstruction methods. The results obtained are consistent for both methods, be it with the hybrid events or with the "super-hexagon" grid.

References

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