The angular resolution of the Pierre Auger Observatory

C. Bonifazi\textsuperscript{a} for the Pierre Auger Collaboration\textsuperscript{b}

\textsuperscript{a}LPNHE, Université Paris VI-VII – CNRS/IN2P3. 4 place Jussieu, 75252 PARIS CEDEX 05, France
\textsuperscript{b}Pierre Auger Observatory, av. San Martín Norte 304, (5613) Malargüe, Argentina

We discuss the angular resolution obtained for events registered with the surface detector alone and for hybrid events, i.e., those observed simultaneously by both the surface and fluorescence detectors. The angular accuracy of the surface detector is directly extracted from the data itself and on an event by event basis, and is given as a function of the number of stations triggered by the event and of the zenith angle of the shower. We compare the angular resolution of the surface detector obtained from hybrid events with the one obtained from the surface detector alone.

1. Introduction

To fulfill the goal of the Pierre Auger Observatory of determining the origin of the ultra high energy cosmic rays, their arrival direction must be obtained with optimal accuracy. This includes a precise measure of the angular resolution (\(\text{AR}\)), which we define as being the angular radius that contains 68\% of the showers coming from a given point source.

The Pierre Auger Observatory consists of two independent components: the surface detector (SD), which is comprised of 1600 water Cherenkov detectors distributed in a triangular grid with a separation of 1.5 km and covering an area of 3000 km\(^2\); and the fluorescence detector (FD), which is formed by 24 fluorescence telescopes located in 4 buildings overlooking the surface detector [1]. Hybrid events, i.e., events observed simultaneously by both components, have smaller reconstruction uncertainties than the events observed with only the surface component. On the other hand, the latter have much higher statistics than the former.

The angular resolution for hybrid events is determined from simulations, by computing the angle between the reconstructed shower direction and the true one, and \(V[\theta]\) and \(V[\phi]\) are the variances of \(\theta\) and \(\phi\) respectively. If \(\theta\) and \(\phi/\sin(\theta)\) have Gaussian distributions with variance \(\sigma^2\), then \(F(\eta) = \frac{1}{2} (V[\theta] + \sin^2(\theta) \ V[\phi])\) where \(\eta\) is the angle between the reconstructed shower direction and the true one, and \(V[\theta]\) and \(V[\phi]\) are the variances of \(\theta\) and \(\phi\) respectively. If \(\theta\) and \(\phi/\sin(\theta)\) have Gaussian distributions with variance \(\sigma^2\), then \(F(\eta) = \frac{1}{2} (V[\theta] + \sin^2(\theta) \ V[\phi])\).

The arrival direction of a SD event is determined by fitting the arrival time of the first particle in each station according to a shower front model. The accuracy achieved in the arrival direction depends on the clock precision of the detector and on the fluctuations in the arrival time of the first particle. The timing uncertainty is directly modeled from the data in each station [4] (section 3.1). The model is adjusted using pairs of adjacent stations located in the surface array. Then, it is validated by studying the \(\chi^2\) probability distribution for the geometrical reconstruction and by comparing two independent reconstructions of the same event (section 3.2). The angular resolution can therefore be estimated for the SD reconstruction on an event by event basis (section 3.3). Using the hybrid events, we are able to extract, for a subset of events, the angular resolution.
resolution of the surface detector and compare it
with the one obtained on an event by event basis
(section 4).

2. Angular resolution of hybrid events

The angular resolution for hybrid events is de-
termined from simulations, by computing the an-
gle ($\eta$) between the injected shower axis and the
reconstructed one. We simulated 5678 proton
showers with the Corsika 6.616 code [5] using
QGSJetII-03 [6] and FLUKA [7] codes for high
and low energy hadronic interaction models re-
spectively. The showers were simulated up to a
zenith angle ($\theta$) of 65°, with a distribution of
$\cos(\theta)\sin(\theta)$, an uniform distribution in the az-
imuth angle, and for various energies from 0.1
EeV to 10 EeV in steps of 0.25 in logarithmic
scale. For each shower we generated uniformly a
core position in a slice of 60° in front of one of the
fluorescence telescopes with a maximum distance
from the telescope increasing with the energy ac-
cording to the trigger efficiency [8]. Once the hy-
brid simulation was performed, we reconstructed
the simulated events with the same reconstruc-
tion chain used for data.

In figure 1 we show the angular resolution, de-
termined as the value where the cumulative distri-
bution function of $\eta(\theta)$ reaches 0.68, as a function
of the energy. As can be observed, the angular
resolution improves for larger energy showers. It
is worthwhile to remark that this behavior origi-
nates from the convolution of the dependence of
the angular resolution with the different geomet-
rical parameters. Also, it is important to check
these results using real data. For example, using
stereo events, which have fluorescence telescopes with triggered pixels in more than one building.

3. Angular resolution of the surface detec-
tor

3.1. Time variance model

The angular accuracy of the surface detector
events is driven by the precision in the measure-
ment of the arrival time of the shower front ($T_s$)
at each station [4]. The particle arrival time in
the shower front can be described as a Poisson
process over a time interval $T$. The arrival time
of the first particle ($T_1$) is used as the estimator
for the shower front arrival and its distribution function is given by:

$$f(T_1) = \frac{1}{\tau} e^{-\frac{T_1}{\tau}},$$

with $\tau = T/n$, where $n$ is the number of particles measured during the time $T$. Then, the variance of $T_1$ is $\tau^2$, but since we estimate the parameter $T$ from the data itself, it is modified to [4]:

$$V[T_1] = \left(\frac{T}{n}\right)^2 \frac{n-1}{n+1}.$$

The variance of $T_s$ in the SD stations is given by
the sum of the detector clock precision ($b^2$) and
of the variance of $T_1$. It then becomes:

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

where $T_{50}$ is the time interval that contains
the first 50% of the total signal as measured
by the photomultiplier FADC (flash analog-to-
digital converters) traces. The parameter $a$ is a

\(^2\)To calculate the number of particles $n$, we assumed that
the muons are the particles that contribute the most to
the time measurement and in average cross the detector
with the direction given by the zenith angle of the shower.
The number of particles is calculated as the ratio between
the total signal in the stations and the track length of the
particles.
scale factor, containing all the assumptions considered in the model and the treatment done to the FADC traces. The parameter $b$ should be given by the GPS clock accuracy (about 10 ns) and the FADC trace resolution ($25/\sqrt{12}$ ns), that is $b \approx 12$ ns. Both $a$ and $b$ are determined from the data.

A special sub-array of pairs of water Cherenkov detectors has been deployed as a part of the surface array. These are adjacent detectors located $\sim 11$ m apart, and therefore are sampling the same region of the shower front. To determine the parameters $a$ and $b$ we used all the events that pass our selection criteria [9] from April 2004 to the end of August 2008 with at least one pair in the event. There is total of 46416 events, which are used to fit these two parameters yielding:

$$a = 0.60 \pm 0.01,$$

$$b = (14.1 \pm 0.2) \text{ ns},$$

with a $\chi^2/ndof = 0.9992$. More details about the time variance model and the fitting procedure can be found in reference [4].

### 3.2. Validation of the time variance model

In this section, we show that the model correctly reproduces the uncertainties of the arrival time of the first particle in the stations.

We define the time difference $\Delta T = dT_1 - dT_2$, where $dT_1$ ($dT_2$) is the time residual of the first (second) twin station to the fitted shower front. If the time variance model describes correctly the measurement uncertainties, the distribution of $\Delta T/\sqrt{V[\Delta T]}$, where $V[\Delta T] = V[T_1] + V[T_2]$, should have unit variance. In figure 2 we show the RMS of the distribution of $\Delta T/\sqrt{V[\Delta T]}$ for the adjacent detectors as a function of $\cos(\theta)$ (top), the average signal in the adjacent detectors (middle), and the distance of the paired detectors to the core position (bottom). In all the cases, the RMS is almost constant and close to unity, which shows that the time variance model adequately reproduces the experimental data. It is worthwhile to notice that the time variance model does not explicitly depend on the distance of the station to the shower core. Despite this, the result shown in the bottom panel is satisfactory, with only a small tendency to overestimate the variance for detectors very near to the shower core.

We also studied the distribution of the $\chi^2$ probability of the geometrical reconstruction. In figure 3 (top) we show the distribution for the 308234 events passing our quality cuts [9] with 4 or more stations. This distribution is almost flat as it should be in the ideal case, despite the small peak at low values. This small peak could be due, for example, to some stations in the events that have low signal, causing a large $\chi^2$. But as is seen in figure 3 (bottom), the peak disappears for large multiplicity events (for 5 or more stations). For both cases, we only plot $\chi^2$ probabilities larger than 1% to avoid the large peak at zero corresponding to badly reconstructed events ($\sim 5\%$).

Also, we study the $\chi^2$ probability distribution for two zenith angle ranges, as shown in figure 4. The $\chi^2$ probability distribution is flat for both large and small zenith angles, which means that the model works for all angles without compensating one set from the other. This distribution shows that the variance model properly reproduces the uncertainties of the arrival time of the particles in the stations and allows us to determine the angular resolution from the uncertainties in the reconstruction data.

We are able to validate independently the time variance model by using the redundant informa-
For all the stations

For 5 or more stations

Figure 3. The $\chi^2$ probability distribution for all events (top) and for 5 or more stations (bottom). See text for details.

For 5 or more stations

Events with $\theta < 55^\circ$

Events with $\theta > 55^\circ$

Figure 4. The $\chi^2$ probability distribution for events with 5 or more stations and with zenith angle smaller (top) and higher (bottom) than 55°.

3.3. Angular resolution

Considering the quality of the time variance model for the measurement uncertainties, we can calculate directly the angular resolution on an event by event basis out of the minimization procedure. In figure 6, we show the angular resolution as a function of the zenith angle for various station multiplicities.

The angular resolution is about 2.2° in the worst case of vertical showers with only 3 stations hit. This value improves significantly for 4 and 5 stations. For 6 or more stations, which corresponds to events with energies above 10 EeV, the angular resolution is in all cases better than 1°. Above 60°, the event multiplicity increases rapidly with zenith angle, and only a few low energy events trigger only 3 stations, thus the accuracy decreases. Also, a hump appears around...
40°, more visible in the 3-fold case. This is due to the contribution of the uncertainties on the core position for events with lower energy (less than few EeV). In figure 7, we show the angular resolution as a function of the zenith angle for events with an energy above 3 EeV, which is the energy corresponding to a trigger efficiency greater than 99% [10]. In spite of the degradation of the statistics for 3-fold events, the hump disappears and the angular resolution gets better. For high multiplicity events, as it is expected, the angular resolution is not affected by the cut in energy. We want to remark that all uncertainties quoted in figures 6 and 7 are statistical only. We did not, at this stage, investigate possible biases or systematics in the determination of the arrival direction angles.

4. Angular resolution of the surface detector using hybrid events

Hybrid events that trigger 3 or more stations can be reconstructed using both the hybrid and the surface detector alone modes, giving two independent estimates of the geometry. The comparison of these estimates is therefore an additional independent check of the accuracy on the determination of the arrival direction of the cosmic rays. Therefore, we compute the angle (η) of those two estimates for different multiplicities and zenith angle ranges. Then, the angular resolution of the surface detector can be obtained as:

\[ AR_{SD} = \sqrt{AR_{\eta}^2 - AR_{hyb}^2} \]

where \(AR_{\eta}\) is the value of η for which the cumulative distribution function of η(θ) reaches 0.68 and \(AR_{hyb}\) is the angular resolution of hybrid events obtained from Monte Carlo simulations (shown in figure 1).

In figure 8 we show the angular resolution for the surface detector (\(AR_{SD}\)) using the hybrid reconstruction as a reference, as a function of the zenith angle (θ) for different numbers of stations in the event. This plot can be directly compared with the one in figure 6 despite the differences in the statistics. The values obtained in figure 8 are slightly higher than the ones obtained from the direct determination of the angular resolution on an event by event basis. This could be due to systematic uncertainties in the reconstructions. For the case of 3-fold events, this slight difference is not present and this could be due to the fact that the uncertainties seem to be overestimated (section 3.2).

5. Summary

We have determined the angular resolution for the hybrid events using Monte Carlo simulations and we found that for energies above 3 EeV it
Figure 8. Angular resolution for the surface detector events using the hybrid reconstruction as a reference, as a function of the zenith angle ($\theta$) and for different numbers of stations in the event. See text for more details.

is about $0.5^\circ$. For the surface detector, we determined the angular resolution from the data. This could be done thanks to the time variance model developed to describe the measurement uncertainties of the time arrival of the first particle in the surface stations. Using this model we obtain an optimal determination of the shower arrival direction and are able to extract the angular resolution of the surface detector on an event by event basis. We found the angular resolution to be better than $2.2^\circ$ for 3-fold events ($E < 4 \text{ EeV}$), about $1.5^\circ$ for 4-fold and 5-fold events ($3 \text{ EeV} < E < 10 \text{ EeV}$) and better than $1^\circ$ for higher multiplicity events ($E > 10 \text{ EeV}$).

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