The Angular Reconstruction and Angular Resolution of Air Showers Detected at the Auger Observatory

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Abstract

The origin of the highest energy cosmic rays will be investigated by the Auger Observatory with unprecedented statistics. Searches will be made for point sources in the sky and for deviations from isotropy of the arrival direction. A detailed understanding of the detector properties is required in order to achieve the optimal angular reconstruction of the directions of the incoming cosmic rays. First results on the angular reconstruction and angular resolution of air showers detected by the Engineering Array are reported.

1. Introduction

The Auger Observatory is a 3000 km^2 array of 1600 Surface Detector (SD) tanks viewed by 24 Fluorescence Detector (FD) telescopes, currently under construction in Malargue, Argentina. It was designed to be fully efficient for showers of energy $\geq 10^{19}$ eV. A reduced portion of the Observatory, the Engineering Array (EA), was brought into operation in December 2001, and included 32 SD tanks placed at 10 km from 2 FD adjacent telescopes. A detailed description of the Auger Observatory can be found in [1]. In this paper, the angular reconstruction and angular resolution of air showers measured with the EA data is reported.

2. Angular Reconstruction with the Surface Detector

The shower direction is estimated with the ground array from the arrival times of the shower front at the different SD stations. The SD station coordinates x_i and y_i, which are known at the level of 1 m from the GPS positioning, and the shower front arrival time t_i, which is determined from the PMT FADC traces, are the basic quantities used for the angular reconstruction. The time difference Δt_i between the measured arrival time t_i at station i and the predicted arrival time for a given shower geometry can be written as:

$$\Delta t_i = t_i - \left(T_0 - \frac{u(x_i - x_{core}) + v(y_i - y_{core})}{c} \right), \tag{1}$$

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where T_0, $u = \sin\theta\cos\phi$ and $v = \sin\theta\sin\phi$ are the shower arrival time at ground and the shower direction cosines, respectively, and c is the velocity of light. The shower core position at ground, given by x_{core} and y_{core}, is determined by the barycenter of all triggered tank positions, weighted by the square root of their signals, with a typical accuracy of 150 m. In equation (1), the predicted arrival time is calculated assuming the simplest model of a shower front moving as a plane orthogonal to the shower direction. In this case, the core position does not affect the angular reconstruction fit. An additional term can be added in equation (1) to take into account the shower front curvature. The parameters T_0, θ and ϕ are extracted by minimizing $\chi^2 = \sum_i (\Delta t_i)^2/\sigma_{t_i}^2$, where σ_{t_i} is the uncertainty on the arrival time t_i. While conceptually simple, the angular fit is strongly based on the measurement of the arrival time t_i. The large sample of data collected with the Engineering Array has allowed detailed studies of the time measurement by the SD stations, and of its impact on the angular reconstruction of cosmic ray showers [2]. The time synchronization within a tank was checked by analysing the FADC traces of single muons, which are used for PMT calibration and show a clear signal with rise time of about 10 ns. The shifts in the signal peak time between the three PMTs were found to be less than 10 ns, to be compared with the FADC bin of 25 ns. The relative time synchronization of the EA tanks was estimated from the reconstructed showers. The time offset of a given tank i can be estimated from the difference between the measured arrival time t_i and the arrival time obtained by an angular reconstruction fit which makes use of all tanks in the event but tank i. The time offsets of each EA station, smaller than 100 ns in most cases, were determined from an iterative procedure. In order to have a reliable estimate of the error on the reconstructed shower direction on an event by event basis, the uncertainty on the arrival time σ_{t_i} must be properly parametrized. In fact, the accuracy of the shower front determination is expected to deteriorate for increasing distances from the shower core, due to the decrease in particle density and the flattening of the rise of the signal. A study of this effect was performed on the EA data set. In Fig. 1.a, σ_{t_i}, estimated from the time residuals of the shower fit, versus r is shown for events with $\geq$5 stations, after taking into account the uncertainty in the fit extrapolation. The σ_{t_i} was estimated to be 20 ns at the core, increasing to 50 ns at 1 km distance from the core. A parametrization of this effect has been included in the angular reconstruction fit.

3. Angular Reconstruction with the Fluorescence Detector

The Fluorescence Detector capability to measure air showers in their development through the atmosphere allows a 3-D reconstruction of the shower direction. The shower is observed as a sequence of triggered pixels with typical topology and time characteristics. The geometry of the triggered pixels can be used to determine the Shower Detector Plane (SDP), which is the plane defined

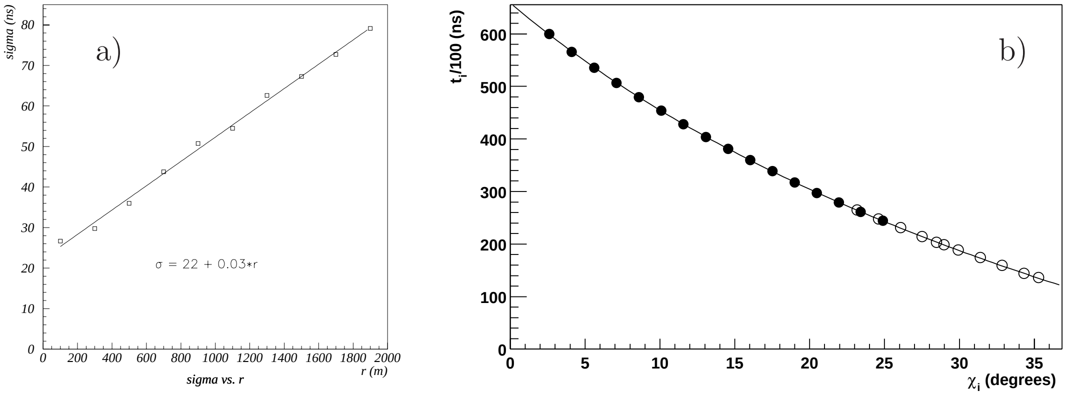

Fig. 1. a) The estimated σ_t versus the distance from the shower core for SD events with ≥ 5 stations; b) example of FD time versus angle fit, with open and closed dots corresponding to pixels of two different telescopes.

by the shower axis and the detector center. Each pixel corresponds to a direction $\overrightarrow{r_i}$ from the detector center to a point in the sky. Therefore, the SDP normal can be estimated by minimizing the quantity $\chi^2_{SDP} = \sum_i w_i \left(\overrightarrow{n}_{SDP} \cdot \overrightarrow{r_i}\right)^2$, where the signal measured in pixel i was used as weight w_i. The shower direction within the SDP can be estimated from the pixels time information. The expected time $t_{i,exp}$ of arrival of light at the pixel i is given by:

$$t_{i,exp} = t_0 + \frac{R_p}{c} tan\left(\frac{\chi_0 - \chi_i}{2}\right), \tag{2}$$

where χ_i is the direction of pixel i projected onto the SDP, χ_0 is the angle between the shower axis and the vector pointing from the shower ground arrival point and the detector, R_p is the shower distance of closest approach to the detector, and t_0 is the time at which the shower front reaches the position of closest approach. For each hit pixel i, the measured time of arrival of light, $t_{i,meas}$, is obtained from the FADC time centroid. A best fit to the three parameters χ_0, R_p and t_0 is performed by minimizing $\sum_i w_i(t_{i,exp} - t_{i,meas})^2$. The shower direction is then determined from the fitted values of $\overrightarrow{n}_{SDP}$ and χ_0. A precision of better than 0.1 degrees on the overall telescope alignment is expected from the telescopes mirrors and camera survey. An independent crosscheck was obtained by analysing the signal induced by stars passing through the pixels field of view. From the reconstruction of the star trajectory, a telescope pointing alignment of better than 0.1 degrees was found. The time synchronization between pixels of the same telescope was measured by illuminating all the PMTs at the same time with light pulses emitted from the centre of the mirror. From the analysis of the FADC traces, pixels relative time shifts were found to be less than 20 ns. The same method was applied to measure the synchronization between the two adjacent telescopes. A time shift of 40 ns was found. These time shifts should be compared with the

FADC bin of 100 ns. During the EA period, a roving laser was extensively used in order to check the FD performances. The laser was fired from different distances in the field, ranging from a few km to 26 km from the FD telescopes. The laser pulse light reaching the telescopes was effectively equivalent to a shower energy of about 10^{19} eV. Since the laser direction was precisely defined by aiming it at a bright star, a direct check of the angular reconstruction could be performed. The SDP fit procedure was found to be robust and reliable, with typical statistical errors smaller than 0.1 degrees for the SDP normal angles. The observed shifts with respect to the nominal angles estimated from the known laser geometry, smaller than 0.5 degrees in most cases, are compatible with the systematic uncertainty coming from the telescope and the laser direction alignment. In the time versus angle fit, the precision improves when the curvature of the function defined in equation (2) is larger. Due to this effect, the accuracy in the determination of χ_0 was found to vary between less than a degree to few degrees. R_p was reconstructed with a relative precision of better than 2%, with laser shots fired from distances of 16 and 26 km. The errors on the shower angles estimated from the fit procedure were found to be compatible with the residuals from the nominal geometry. An example of time fit for a candidate FD shower is shown in Fig. 1.b.

4. Conclusions

Detailed studies of basic detectors properties, in particular of the time measurement, and their influence on the angular reconstruction of air showers were performed on the data collected by the Engineering Array. Average errors $< \sigma_\theta > = 0.8$ and $< \sigma_\phi > = 1.1$ degrees on the shower angles were found from the angular reconstruction of EA events with ≥ 5 tanks triggered by the SD. An accuracy of the order of a degree was found when reconstructing laser shots of known direction with the FD. The angular resolution of the SD and FD is consistent with Monte Carlo expectations, and fulfills the physics requirements of the Observatory. The sample of hybrid events allowed cross-checks of the reconstruction, and demonstrated the superior accuracy which can be achieved when the information from both detectors is combined. Details of the hybrid analysis can be found in a separate contribution to this Conference [3].

5. References

1. Bluemer H. for the Pierre Auger Collaboration, Proceedings of this Conference
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