OG.4.4.08

Correction of Air Shower Timing Using Shower Data

A.-M. Elo[1], H. Arvela[2]

[1] *Department of Physical Sciences, University of Oulu, FIN-90401 Oulu, Finland*

[2] *Laboratory of Electronics and Information Technology, University of Turku, FIN-20014 Turku, Finland*

Abstract

The azimuth distribution of air showers is not uniform if there is timing error in the measurement. The directions where the minimum and maximum are formed in the azimuth distribution reveal which detector is erroneous. The zenith angles also change so that their average value increases if there are timing errors.

We describe how to determine timing correction using observed shower data. We iteratively seek the correction value that minimises the average zenith angle, and thus yields a uniform azimuth distribution. As the result of this process, also the arrival direction distributions of air showers are obtained.

1 Introduction

The primary cosmic radiation is isotropic and therefore the arrival directions of extensive air showers should cover all directions in the sky uniformly. The arrival direction distributions are determined by using air shower array measurements performed on the ground. The isotropy of the primary radiation is retained in the azimuth distribution of arrival directions measured on the ground level. Atmospheric absorption, on the other hand, rapidly decreases the number of showers as the zenith angle increases. The increasing absorption more than compensates the effect of the growing solid angle of acceptance. Thus the arrival direction distributions measured underneath the atmosphere should obey the following dependencies (Sun, \& Winn, 1984):

$$(1) \quad \frac{dN}{d\theta} \propto \sin\theta \cos^n \theta \qquad\qquad \frac{dN}{d\psi} \propto constant \, .$$

Here the power n is experimentally found to be ~ 8-10. Deviations from these forms can be considered as signs of some faults in the experimental set-up.

2 Air shower direction determination

The simplest air shower array that can be used in determining the arrival direction distributions consists of three non-collinear detectors equipped with fast-timing measuring properties. The hit times of shower particles on the detectors are measured, usually relative to a certain fixed detector, or relative to the first reacting detector. The shower particles are assumed to form a plane, sweeping through the detectors at well-defined moments of time. The detector co-ordinates being known, it is then a straightforward mathematical problem to evaluate the direction of the normal of the shower plane, i.e. the direction of the shower axis.

The plane approximation is valid when the separations of the detectors are not very large, and when the shower core lands near the detectors. The particle density in the shower front should also be high enough. However, at lower densities or large distances the plane-approximation does not apply any more. In these cases there will be large fluctuations in the particle hit-times due to the longitudinal spread of particles across the thickness of the shower front, which is measured in metres, leading to timing fluctuations of nanoseconds. The shower particles also have lateral separations comparable to the dimensions of the detectors. This leads to fluctuations in the particle hit-positions as well. The consequences of these uncertainty factors have been studied by e.g. Linsley (1995). We have studied these effects quantitatively in the case of our small air shower array in Turku (Elo, \& Arvela, 1997).

All the above mentioned sources of inaccuracies in the direction determination are indigenous to air showers, and can therefore not be overcome but by applying the most sophisticated experimental or analytical techniques. Moreover, these are futile as long as there may be some unknown error sources present in the measurement system, causing systematic errors in the data. In paper OG 4.4.09 we have demonstrated how the shower arrival direction distributions can reveal some of these systematic error sources in the timing measurement. In this paper we describe how an adequate timing correction can be found.

3 Principle of timing correction

We have shown in paper OG.4.4.09 that an inappropriate delay or earliness of the signal from a Fast Timing detector (FT) is distinctly pronounced in the azimuth direction distribution deduced from a fairly modest amount of air showers (the size of our sample in the analysis was ~19,000 showers). If there is extra delay in the signal of one detector, the arrival directions shift ‘away from’ that particular detector. In the opposite case, if the signals arrive too early from one detector, the arrival directions of showers shift ‘towards’ that detector. This situation is illustrated in figures 1 and 2 in paper OG.4.4.09.

The obvious correction method is to add or subtract an appropriate amount of time to or from the detected signal times of the erroneous FT detector. A coarse correction can first be found by trial, using corrections increasing with e.g. 2-3 ns intervals, and determining the average of the zenith angle, $<\theta>$, for each correction. This average $<\theta>$ will reach its minimum when the timing has no more error. Then the proximity of the minimum position is studied more carefully, with smaller steps, determining $<\theta>$ for each timing-correction Δt. Near the minimum the dependence of $<\theta>$ on Δt is approximately of second-order form:

(2) $$<\theta> = A + B\Delta t + C\Delta t^2 .$$

The timing correction Δt_{min} leading to the minimum value of the average zenith angle $<\theta>_{min}$ can then be taken as the final timing correction. The corresponding $<\theta>_{min}$ in then the average zenith angle of cosmic ray air showers detected with this particular instrument.

4 Effect of shower sample size on the determination of $<\theta>$

In determining $<\theta>_{min}$ care must be taken to keep the shower sample unchanged all the time. The timing shift makes some showers go down below the detection horizon and therefore they will be excluded from the analysis. At the same time other showers will rise above the horizon and will be accepted in the analysis. All these showers entering and exiting the analysis procedure have large zenith angles. To eliminate their impact on the value of $<\theta>$ a preliminary selection must be made, so that only showers with θ less than a fixed limit θ_{limit} are taken into the analysis. In our calculations the limiting value θ_{limit} = 45° was used.

Even with the preliminary selection some showers cross the chosen θ_{limit} causing some variation in the shower sample size as the timing correction Δt is varied. This causes variation in the average value $<\theta>$ and further corrections are required to eliminate this. This is essential as all these ‘crossing’ showers, again, have large θ and therefore they modify the average $<\theta>$. We made this correction so that we normalised the $<\theta>_i$ for each Δt_i to the average number of showers $<N>$ of the whole data set:

(3) $$<\theta>_i^{normalised} = \frac{\left[N_i \times <\theta>_i - (N_i - <N>) \times \theta_{limit}\right]}{<N>} .$$

The above normalisation means that if for a certain correction Δt_i the number of showers N_i is larger than the average shower sample size $<N>$, the contribution of the ‘excess’ showers to the average zenith angle is subtracted. It can be well assumed that these showers have zenith angles equal to θ_{limit}. If the number N_i of showers in the sample, on the other hand, is less than the average $<N>$, then the ‘missing’ number of showers with $\theta = \theta_{limit}$ is added in the evaluation of $<\theta>_i^{normalised}$.

An example of this correction procedure is illustrated in figure 1, where it is applied on the shower data measured with the air shower array in Turku.

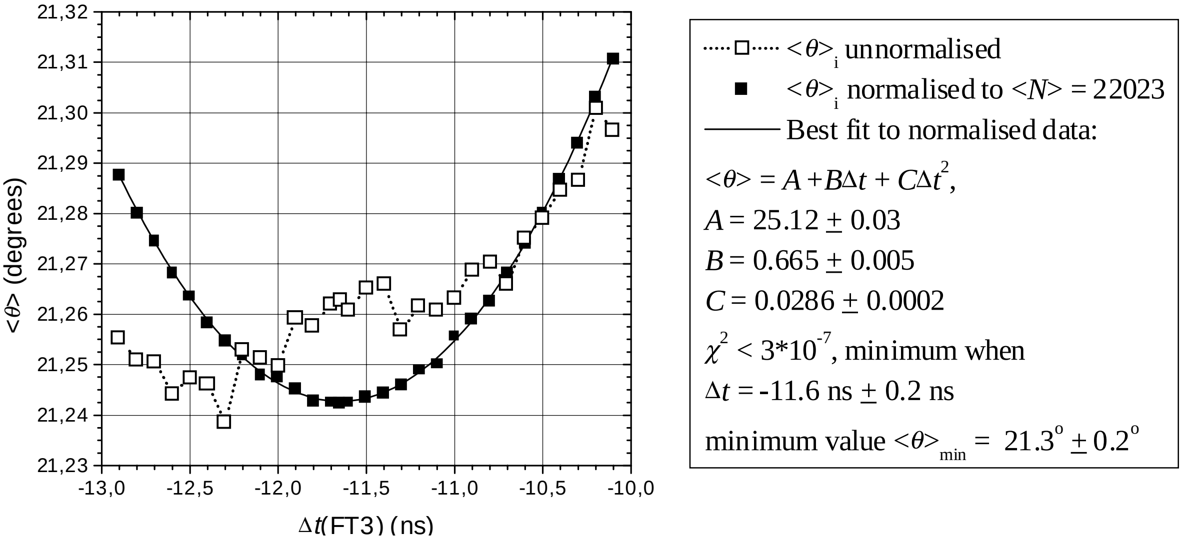

Figure 1: Average of the zenith angle $\langle\theta\rangle$ determined for a selection of showers with $\theta \leq 45°$ versus timing correction Δt. Note: the $\langle\theta\rangle_{min}$ is smaller than the average zenith angle for *all* showers.

5 Two erroneous timing signals

As we have shown in paper OG.4.4.09 in these proceedings, timing errors in more than one fast timing detector are also easily discovered by studying the azimuth distribution of air shower arrival directions. The correction of two timing errors involves now the minimisation of $\langle\theta\rangle$ with respect to two parameters: Δt^{FT1} and Δt^{FT2}. Instead of finding the minimum position of a parabola (2) it becomes necessary to search for the minimum of a two-dimensional surface. The amount of calculation is approximately quadrupled: instead of determining one parabola with say n trials for timing corrections, one needs to determine roughly m parabolas each with n corrections. However, the task is still quite manageable. All the other aspects concerning the analysis, discussed in the previous section apply here, too. An example of the $\langle\theta\rangle$-surface obtained in a double correction procedure is illustrated in figure 2. Here too the air shower data measured using our array in Turku was used. The surface does not look as smooth as the parabola in figure 1 because the vertical axis is only 0.06° high compared to 0.09° in figure 2.

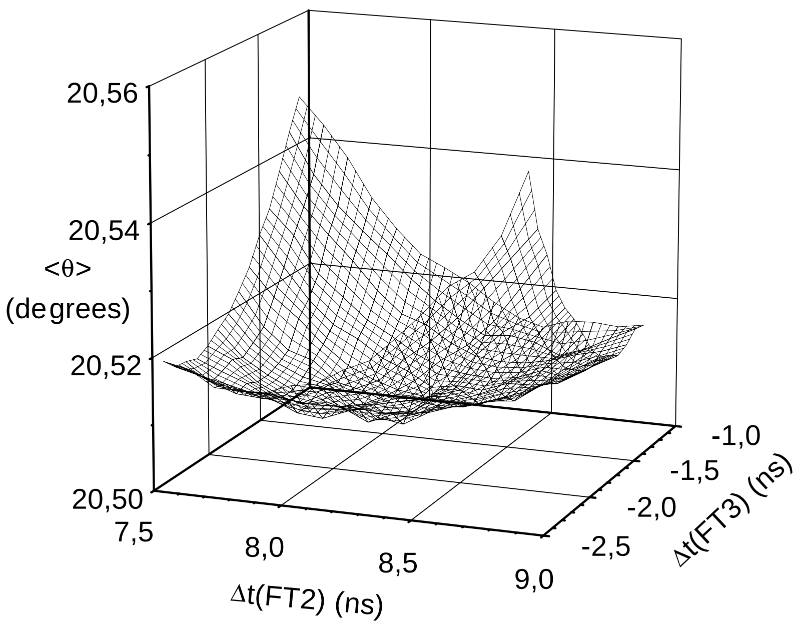

Figure 2: The average zenith angle $\langle\theta\rangle$ versus Δt^{FT1} and Δt^{FT2} for a selection of showers with $\theta \leq 45°$.

6 Validation of the correction

After finding the timing corrections yielding the minimum value of $<\theta>^{normalised}$ one needs to compute the azimuth distribution dN/dψ. For good timing corrections it should be very flat. In figure 3 we show the direction angle distributions of a set of real showers evaluated with proper timing corrections. From figure 3a all showers with $\theta < 27°$ are cut away in order to reduce the size of the plot file. These 15,669 showers are naturally included in figures 3b and 3c. The remaining spikes in the azimuth distribution at ~42° and ~223° are due to the timing measurement resolution (1 ns), which makes only discrete arrival directions detectable. Between the possible direction angles there are gaps of 'forbidden' arrival directions. The bins next to these gaps collect the showers that would fall into these gaps if the timing resolution were better. The allowed bins next to forbidden ones thus become pronounced in the azimuth distribution dN/dψ.

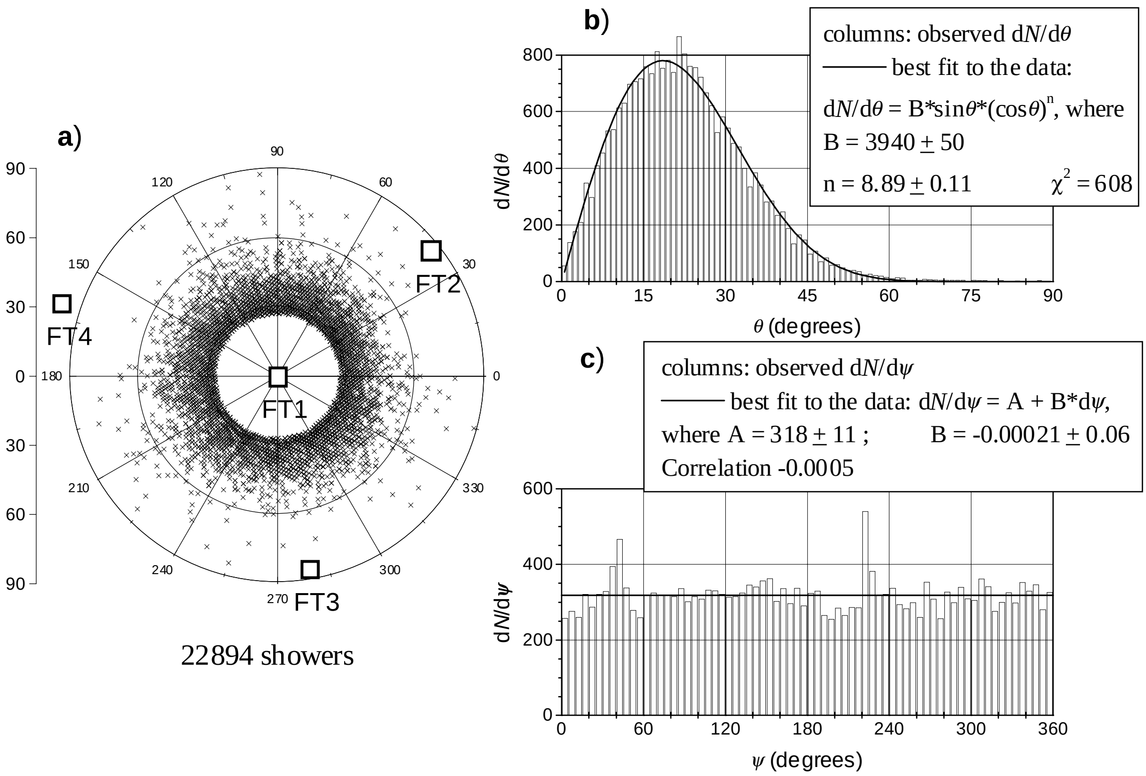

Figure 3: The effect of proper timing correction on the arrival direction distributions of a set of air showers. **a)** The (ψ,θ)-distribution; **b)** the dN/dθ-distribution; **c)** the dN/dψ-distribution.

7 Results and discussion

A method to correct air shower timing data is described. Finding the corrections also makes it easier to debug the experimental set-up. The average zenith angle of air showers is found to be 22.4° and the most probable angle is 18.5°. The power index in (1) for the zenith angle distribution is found to be 8.9 ± 0.2.

References

Elo, A.-M., \& Arvela, H., Proc. 25th ICRC (Durban, 1997), 7, 237

Elo, A.-M., \& Arvela, H., Proc. 26th ICRC (Salt Lake City, 1999), paper OG 4.4.09

Linsley, J., Proc. 24th ICRC (Roma, 1995), 1, 354

Sun, L., \& Winn, M. M. 1984, Nucl. Instr. Meth. in Phys. Res., 223, 173