

## A study of air shower core correction in the large ground array

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**Abstract:** Ultra high energy cosmic rays are detected via extensive air shower produced in the atmosphere which is measured by various techniques. In case of the geometric arrangement of the ground detectors, it is important to reconstruct the core location of the air shower, for accurate measurement of the energy of the primary cosmic ray particle. In this presentation, we report a new method to find the shower core position in a large-scale ground detector array.

**Keywords:** Cosmic Ray, Air shower core, Large Ground Array Experiment

## 1 Introduction

When a high energy cosmic ray particle enters the Earth's atmosphere, it collides with air molecules whereby generates a shower cascade with billions of secondary particles. They can be studied by indirect measurements with observation of the coincident signals in large arrays of particle detectors on the ground.[1]

Researchers in the large ground array experiments estimate the energy of the primary particles by detecting the secondary particles. The primary energy can be obtained from the following steps.

For example, in AGASA experiment, they use the fitting formulas adjusted to fit the Surface Detector(SD) data and Monte Carlo data.[4] Figure 1 shows a simulation event measured by the SD. The arrival time informations for describing the shower front curvature and the center of gravity (COG) point are used to obtain the shower core position.[5] The lateral energy distribution  $S(d)$ , where  $d$  is the distance from the shower axis, is fitted by the pre-determined function.[6] Then the primary energy is determined by the value of this function at a specified distance,  $S(\text{distance})$  and the zenith angle measured from the time information.

In this way, it is important to measure "Signal" and "distance" exactly. In this presentation, we follow above steps, but before using arrival time, we use relation between COG core and true core in a regular array to find shower core position accurately and to reduce the deviation of primary energy.

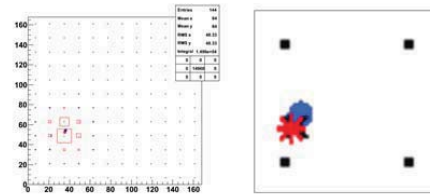


Figure 1: A sample of simulation event measured by SD

## 2 Preliminaries

### 2.1 Deviation of the core position

There are some steps for core estimation. The first step is the using COG. In Figure 1, black dots are detectors, blue circle is the true core position which was chosen randomly, and red star is the reconstructed core position determined by COG. Note the deviation between the blue circle and the red star. Such deviation of the reconstructed core position from the true one as shown on the figure is bound to happen because of grid-like detector array. In the following, we try to fix the core position as much as possible.

### 2.2 Monte-Carlo simulation

To give a correction to COG-core, we use the LDD data set which are generated using COSMOS[7] with following initial conditions.

Primary particle : proton  
Primary Energy :  $10^{18}, 10^{19}, 10^{20}$  eV

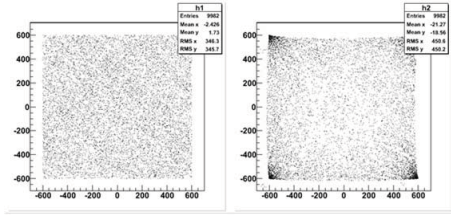


Figure 2: The true core distribution(left) and the COG-reconstructed core distribution(right)

Zenith angle : only the cases of zero zenith angle are shown.  
 Detector array : Squared grid  
 1 m.u : 87m[8]

Roughly, we used “muon density” for the detected signals without any detector simulation. And wild assumption is used such that particles can be detected when distance between detector and core is less than 2km.

We repeat similar studies many times with random choice of the core positions. The left-hand side of Figure 2 shows the distribution of true cores which were given randomly; The right-side of Figure 2 show the distribution of reconstructed core using COG. In the four corners, there are detectors.

The left side of Figure 4 show the relation between true core and reconstructed core position in units of meters. The Figure 5 corresponds to  $\Delta x$  (*i.e.* difference in the horizontal direction).

### 2.3 Relation between COG and true core

$$d_i = \sqrt{(x' - x_i^D)^2 + (y' - y_i^D)^2} \quad (1)$$

$$x'' = \frac{\sum_i f(d_i) x_i^D}{\sum_i f(d_i)} \quad (2)$$

$$y'' = \frac{\sum_i f(d_i) y_i^D}{\sum_i f(d_i)} \quad (3)$$

Equation 1,2 and 3 show the correlations between the COG-reconstructed core( $x'', y''$ ) and the true core( $x', y'$ ).  $f(d_i)$  is *LDF*. As can be seen on the equations, when primary energy is not known, it is not easy to go back to the true core from COG core, and dependence of both  $x''$  and  $y''$  for  $x'$  or  $y'$  is another problem. Therefore in this presentation, two sub-topics will be stated. One is about the correction using 2D fitting, and another one is the correction using the arbitrary energy.

Model	$10^{18}$	$10^{19}$	$10^{20}$
$10^{18}$	$-0.11 \pm 5.83$	$3.01 \pm 8.04$	$14.73 \pm 13.3$
$10^{19}$	<b><math>-3.77 \pm 9.23</math></b>	<b><math>0.08 \pm 5.56</math></b>	<b><math>11.95 \pm 11.53</math></b>
$10^{20}$	$-16.64 \pm 12.98$	$-12.81 \pm 10.48$	$0.11 \pm 8.08$

Table 1: Mean and standard deviation value in units of *permil* compared to the detector spacing of  $\Delta x$  after correction using each fitting model

## 3 Core Correction using relation between COG and true core

### 3.1 The correction using 2D fitting

Figure 4 show the distribution of  $\Delta x \equiv x' - x''$ , the difference in the  $x$  component between the true core ( $x'$ ) and the COG-reconstructed one ( $x''$ ). The left plot is the distribution of  $\Delta x$  at each position ( $x'', y''$ ). We see a clear pattern show up. We fit the  $\Delta x$  distribution using the following function:

$$f(x, y) = (a_5 x^5 + a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0) (b_4 y^4 + b_3 y^3 + b_2 y^2 + b_1 y + b_0) \quad (4)$$

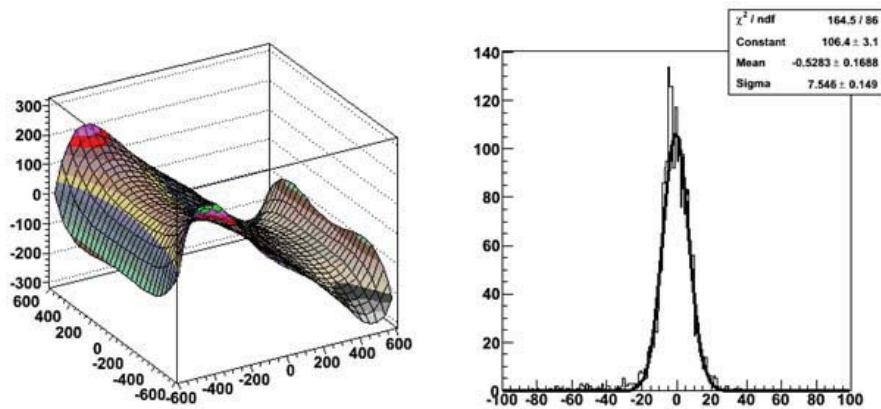
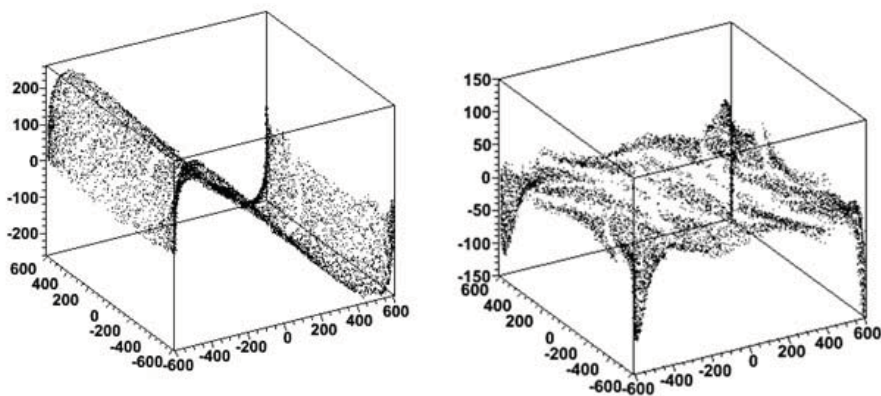
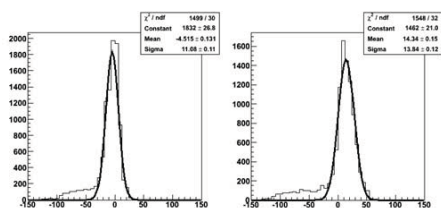
The left-hand side of Figure 3 is a graphical representation of the fitting function shown above. The right plot shows how well this functions describes  $\Delta x$  as it displays the difference between the measured  $\Delta x$  (Figure 4, Left) and fitted one (Figure 3, Left).

Figure 5 shows the deviation  $\Delta x$  between the corrected core obtained by the afore-mentioned fitting procedure and the true core. As can be seen on the right side of Figure 4, corrected results show large deviations from the true core around the four corners which correspond to the locations of the detector's. Otherwise, the deviation seems to be close to zero as is shown in the Figure 5

### 3.2 The correction using arbitrary energy

A problem with such a simple-minded correction is that the amount of correction actually depends on the assumption of the primary energy. For example, the two plots of  $\Delta x$  in Figure 6 show such a problem. The one on the left-hand side assumes, for correction function, a primary energy of  $10^{18}$  eV, while the right-hand side plot assumes  $10^{19}$  eV. As the simulated shower has a primary energy of  $10^{18}$  eV, obviously in the left-side plot we obtain more accurate shower core.

In Table 1 we show the mean and the standard deviation values of  $\Delta x$ . Each column corresponds to a shower with a primary energy of  $10^{18}$ ,  $10^{19}$ ,  $10^{20}$  eV, respectively (left to right). Each row corresponds to the assumed energy which was used for finding the correction formula. The smallest mean deviations and  $\sigma$ 's are obtained in the diagonal, *i.e.*

Figure 3: The fitting function of  $\Delta x$  distribution(left) and fitting result(right)Figure 4:  $\Delta x$  distribution at each COG position. The left plot is for the COG core, and the right one is for the corrected coreFigure 6:  $\Delta x$  after correction using fitting model which is obtained from  $10^{19}$  eV.  $10^{18}$  eV(left) and  $10^{19}$  eV(right) cases.

where the actual value and the assumed value of the primary energy match. This shows that it is crucial to have a “correct guess” of the primary energy. The question then is how. We try to estimate the primary energy for the  $10^{19}$  eV shower (bold-text data in the middle line of Table 1). To estimate the primary energy, We use the corrected core

and the Linsley formula[9] which is expressed as the Equation 4.

$$f(x) = Ax^{-1.2}(1+x)^{p_1}(1+(x/15))^{p_2} \\ (1+(x/30))^{p_3}(1+(x/60))^{p_4} \quad (5)$$

Figure 7 compares the deviation for various cases: (red) COG-reconstructed core, (blue) corrected core. The simulated primary energy is  $10^{19}$  eV and the assumed energy for correction is also the same. The  $x$  axis is estimated energy divided by the original primary energy, thus  $x = 1$  corresponds to a perfect estimation of the primary energy. It is obvious that the corrected core (blue) has better behavior than the COG-reconstruction (red).

But if we assume wrong value for primary energy, the correction will not be perfect. Table 2 shows the cases with  $10^{18}$  eV and  $10^{20}$  eV, which are corrected using fitting model obtained from  $10^{19}$  eV primary energy, respectively. The correction result of Table 2 shows the corrected ones are better than uncorrected ones.

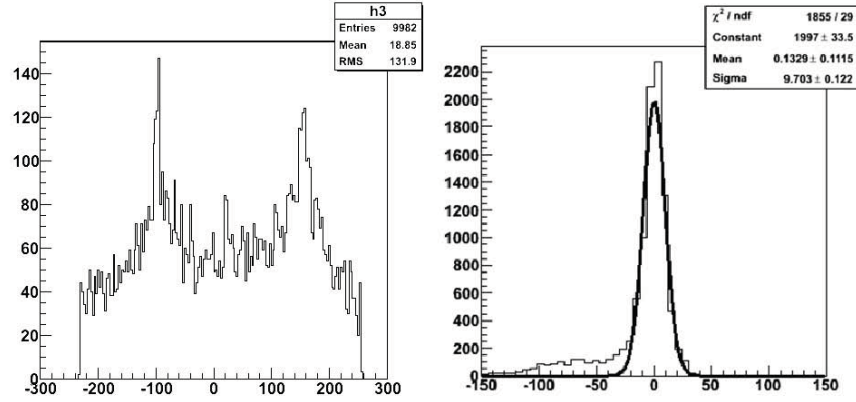


Figure 5:  $\Delta x$  distribution. The left plot is for the COG core, and the right one is for the corrected core

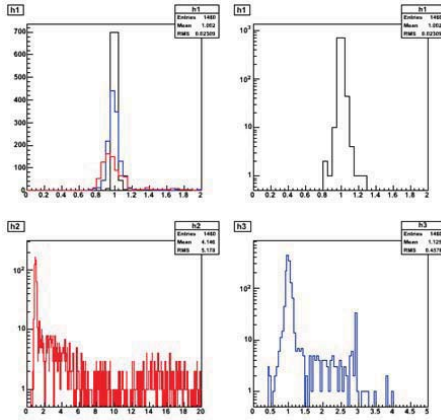


Figure 7: The distribution of estimated energy/original primary energy

## 4 Summary

When ultra high energy cosmic rays are detected via the geometric arrangement of the ground detectors, it is important to reconstruct the core location of the air shower, for accurate measurement of the energy of the primary cosmic ray particle. We study air shower production and detection with Monte-Carlo simulation with ground detector array set-up to find a new method to correct the shower core

Core	$10^{18}$	$10^{19}$	$10^{20}$
True	0.09	0.03	0.02
Corrected	<b>0.28</b>	<b>0.40</b>	<b>0.47</b>
COG	0.75	0.66	0.72

Table 2: The RMS value of  $\log_2$ (estimated energy/original primary energy)

position in a large-scale ground detector array.

Using correlation between COG and true core, we could get corrected core. Assuming arrival direction is already known, even though primary energy is unknown, core can be corrected using 2D fitting. If, in addition to a simple geometric correction as shown in this presentation, we also use the information about arrival time, a better correction may be made possible. Research of dependence on zenith angle will be studied. We expect that this study contribute to reduce the deviation of estimated primary energy.

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