Another approach for finding core locations of extensive air showers

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***Abstract*. In the high energy cosmic ray surface arrays, the primary energies are often determined by fitting the lateral distribution function to the distribution of detected secondary particles of extensive air showers. The accuracy of this model-dependent approach depends on the accuracy of the lateral distribution function and consequently can cause some difficulties. Here, we have presented a new model-independent method for finding core locations that uses two common principles of extensive air showers: the average distance between the secondary particles near the core location is smaller than in other regions. Also, the front of extensive air shower is thinner near the core and thicker in region far from the core.**

***Keywords*: Extensive Air Showers, Surface Arrays, Core Location**

I. Introduction

In order to reconstruct the properties of the primary cosmic ray, an accurate estimate of the shower core location is essential. The shower core position on the ground level is the point at which the primary would impact, if it traveled in a straight line through the atmosphere. The classic method for finding the core location of an Extensive Air Shower (EAS) is to fit the density of the secondary charged particles to a structure function called lateral distribution function. It has been customary to use a form like the NKG function for the lateral distribution function. The most common form is due to the Greisen [1], but its modified forms can be used as well [2]. However, from the literature it is clear that there is no agreement about the correct form of the lateral distribution function [3]. There are two solutions to handle this problem: either finding the more correct form of the lateral distribution function or discovering other methods for finding the shower parameters which are independent of the lateral distribution function.

In this article our purpose is to present a new model independent method for finding the core locations of EASs which does not depend on any lateral distribution function. Another feature of this method is direct use of the arrival time information of the secondary particles that are not directly used in the process of fitting lateral distribution function (except in determining the arrival direction of EASs).

Because of inaccuracies in finding the core locations of real EASs, we have used simulated EASs for comparison of this method with the Greisen function fitting method. To test our method, a full MC simulation for 90% proton and 10% alpha primaries (energy: 50TeV-5PeV, spectrum index: -2.7, azimuth angle: 0-360, zenith angle: 0-60) was done by using CORSIKA (QGSJET and GHEISHA for hadronic interactions)[4].

II. New Method for Finding the Core Location

In EASs the distance between each two particles near the core location is on average smaller than those of particles far from the core. The reasons behind this fact are that the density of particles per unit areas near the core location is higher (than other region) and the front of EAS is thinner near the core location [5]. Therefore if we had the distance between two particles, we would be able to estimate the average distances of the particles from the core location. If they are close to each other, they are averagely close to the shower axis. In particular for the vertical showers the first arriving particle is averagely closer to the axis of shower. The latter is due to the fact that the front of an EAS is not actually a plane and for the vertical showers, particles near the core region averagely reach ground level sooner.

Based on these facts, we introduce the following approach to find the core locations of EASs (For better understanding, at first EASs are assumed to be vertical): First, we calculate the 3-D distances between every couple of particles (see next section) and then choose the couple that its members have the smallest distance from each other. After finding the smallest couple, we define that particle of this couple, which has the smaller arrival time than the other one, as a near core particle.

In the second step, we eliminate the farthest particle from the chosen particle. We repeat this procedure until elimination of half of the particles and and remaining half of them. Then we can find the center of mass of the selected particles on the ground level which is a measure for finding the core location of the EAS.

In the real surface array every particle detector occasionally detects more than one particle. Another issue is that we can only find the distances between every two particles just on the ground level, not in the three dimensional space. So we should devise a procedure to generalize the previous method to their case.

In the vertical EASs, it is absolutely straightforward to find 3-D distance between two particles detected by two different detectors. We should only find their arrival time difference (assuming the speed of particles is the same as the speed of light, c, and their arrival direction is downward) in order to find their vertical distance. Then, by having horizontal distance between detectors on the ground level, 3-D distance between two particles can be easily found. With a simple time modification we can generalize this method to the inclined showers.

Every detector which has detected more particles is averagely closer to the core location. Therefore, probability of being closer to the core location for two triggered detectors is directly related to the number of detected particles in each detector and has inverse relation with the distance between two particles detected by them. So, if we divide the 3-D distances by the product of number of detected particles in each detector, it will be generalized to the case of detectors which have detected more than one particle.

III. Algorithm

Based on the mentioned principles we can introduce the following algorithm for finding core locations of EASs. First, we index triggered detectors based on their firing times (notice we are considering vertical showers now). For instance, the first triggered detector is no. 1; the second triggered detector is no. 2 and so on. Then, by having the coordinates of the ith and the jth detector on the ground level as (x_i, y_i) and (x_j, y_j) and their triggering times, we can calculate the distance between two detected particles by two detectors as: $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + c^2(t_i - t_j)^2}$ (actually this is the distance between the first particles detected by each detector). With having all distances between particles and the number of detected particles in each detector as n_i and n_j, we can construct the following matrix:

$$M = \begin{pmatrix} \times & m_{12} & m_{13} & \cdots & m_{1N} \\ \times & \times & m_{23} & \cdots & m_{2N} \\ \times & \times & \times & \cdots & m_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \times & \times & \times & \cdots & \times \end{pmatrix}$$

Where $m_{ij} = d_{ij}/(n_i n_j)$. Then we find the smallest element ($m_<$). Since the matrix M is symmetric we can just consider its upper half for our calculations. Assume that $m_< = m_{ij}$, thus we can consider the ith detector as one of the nearest detectors to the core of EAS (notice $i < j$). Now we can find one of the farthest detectors from the core by finding the biggest element of the ith row of matrix M, $m_>$. Assume $m_> = m_{ik}$, then the kth detector is one of the farthest detector from the core. Next, we eliminate the kth element by eliminating the kth row and column of the matrix M. Then, we eliminate the ith row and column of the matrix M. After this elimination cycle, two columns and rows will be removed from the Matrix M and the ith detector will be retained as a point close to the core.

Now we can determine the statistical importance of the ith detector. As we have seen in the last section, the probability of being closer to the core location for two triggered detector is directly related to the the number of detected particles in each detector and is inversely related to the distances of the first particles detected by each of them. It is logical to choose the smallest element of the ith row of the matrix M, $m_<$, as a weight for the ith detector. Therefore, we define $w_i = 1/m_< = n_i n_j / d_{ij}$.

With repetition of the mentioned procedure until removing all rows and columns of the Matrix M, half of the triggered detectors will be selected as the detectors near the core and half of them will be eliminated as detectors far from the core . We define the center of mass of selected detectors as: $x_{cm} = (\sum_i w_i x_i)/(\sum_i w_i)$, $y_{cm} = (\sum_i w_i y_i)/(\sum_i w_i)$. We will see that the center of mass is a good measure for the core location of an EAS.

We have discussed vertical showers and now we want to generalize this algorithm to the inclined EASs. In contrary to the vertical showers, in the inclined showers the nearest particles to the core do not reach ground level sooner than other particles. Hence, for making the arrival times a measure for defining remoteness and closeness of the particles from the core, we should modify arrival times. The coordinates of the particles on the ground level are x_i, y_i and z_i (the z components are 0). We transform the coordinates of the secondary particles to a new coordinate system with a $\acute{x}\acute{y}$ plane perpendicular to the arrival direction (shower axis) and a $\acute{z}$ axis anti-parallel to the arrival direction (shower axis). Assume that, θ is the zenith angle and ϕ is the azimuth angle of the EAS from the magnetic north. In the new coordinate system, the secondary particles have a z coordinate as: $z_i = -x_i \sin\theta \cos\phi - y_i \sin\theta \sin\phi$. Then, we modify particle arrival times as: $\acute{t} = t + z/c$. With performing these modifications, we define distances between particles as: $d_{ij} = \sqrt{(\acute{x}_i - \acute{x}_j)^2 + (\acute{y}_i - \acute{y}_j)^2 + c^2(\acute{t}_i - \acute{t}_j)^2}$ (notice all of coordinates are in the new system). Now we can find the M matrix and weights as before. Then we are able to find the center of mass in the ground level by these weights as before.

IV. Simulation

EAS Simulations have been performed for geographical longitude, latitude and altitude of $51E$, $35N$ and 1200 meters. The Earth Magnetic field has been assumed as $B_z = 38.4T$ and $B_x = 28.1T$ throughout the simulations. The detector array is a set

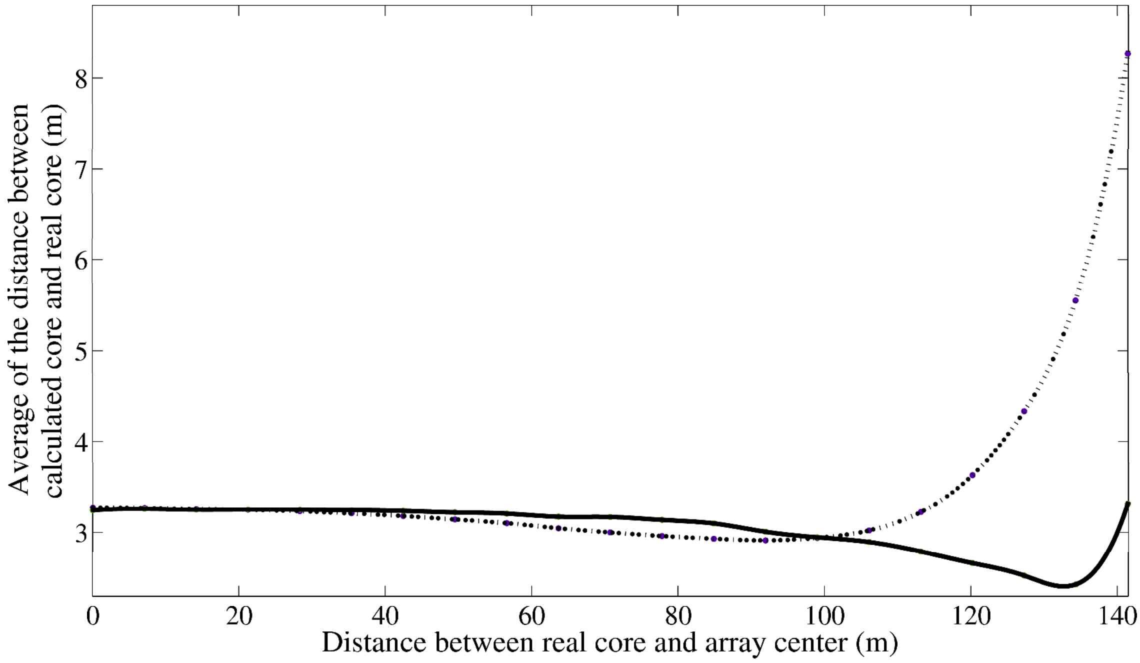

Fig. 1: Comparison of our method with the Greisen fitting method. The solid line belongs to the Greisen method and the dotted line displays the result of our method. The results up to the 110 m from the center of the array will be approximately the same as Greisen method.

of detectors with effective area of $1 \times 1m^2$ placed on a square network with a network constant of 5 meters on a total area of $200 \times 200m^2$ (41×41 detectors). The $1 \times 1m^2$ detectors will record the arrival time of the first crossing charged particles and the number of passing particles during an event. The coordinates of the detected particle will be referred to the coordinates of the center of the detector. The detection condition for an EAS is to fire at least 4% of all detectors in the array. The real core position is assumed to move on the array diagonal over a range of displacements between 0 in the center and $100\sqrt{2}$ in the corner of array. The results are obtained by an average over 10^4 EASs which satisfy the above conditions. If coordinates of the real core of the shower are (x_{rc}, y_{rc}), the distance between the real axis and the center of mass position will be: $r \cos\theta = \sqrt{(x_{cm} - x_{rc})^2 + (y_{cm} - y_{rc})^2} \cos\theta$.

V. Results

Figure 1 shows the results of our method and the prevalent Greisen function fitting method in the ideal conditions. The modified Greisen function has been used for fitting data of the array [2]. We assumed the EAS angle given by CORSIKA as the angle of EAS in our simulations and a 100% counting efficiency for both method. The non-linear Least Square method has been used for fitting data to the Greisen function. The dotted line in Figure 1 shows the result of our method in the ideal conditions. The solid line belongs to the results of fitting Greisen function. According to the figure 1, the accuracy of the methods is approximately the same up to 80% of the length of the array diameter. Although our method does not depend on the lateral distribution function, it has the same result as the Greisen function fitting method in accuracy region of our method.

VI. Conclusion

This paper presented a new method for finding core locations of EASs. The new approach is independent of lateral distribution function and indeed has the same results as other methods using it (at least up to 80% of the array length). In this method three dimensional distances between every two detected particles has been used in addition to the number of detected particles in every detector during an event. Then a statistical process has been used to eliminate some detectors, give weight to the remained detectors and find their center of mass that is a reliable measure for finding the core location.

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