New Simple Method for Analysis of Extensive Air Showers

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Abstract

Cosmic rays have valuable information about universe surroundings us. Finding energy, mass and arrival direction of primary cosmic ray particle are the most important aspects of extensive air shower studies. In order to determine these parameters, arrival direction and core position of extensive air showers should be determined at first. In this article, a new method has been introduced that utilizes arrival time information of secondary particles of extensive air showers for finding their core location and correcting plane wave front approximation so that calculate the arrival direction of extensive air showers. This method does not need number sensitive detectors-detectors which are sensitive to the number of crossing particles- and consequently there is no need for lateral distribution models. This model has been developed by analysis of simulated events generated by CORSIKA package.

Key words: Cosmic ray, Extensive Air Shower
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1 Introduction

An Extensive Air Shower (EAS) is a large number of secondary particles originating from a high energy primary cosmic particle. A lot of efforts have been made for understanding the structure and development of extensive air showers. [1]. For accurate investigation of the EAS events we first have to know their direction and core position. The better the measurement of these parameters, the more precise exploring extensive air shower structures. Plane
Wave Front Approximation (PWFA)[2] is the simplest way for finding direction of EAS and spherical front approximation[3] is a complement approach of it for acquiring more accurate results. There are various methods for finding core location of extensive air showers such as: maximum likelihood method for large showers [4], fitting to the lateral density distribution function [5], and its modified form [6], and neural network method [7]. All these methods, use the particle density information without considering their Arrival Time Information (ATI).

Some attempts have been made to use mean arrival time and disk thickness as a measure of the shower core distance [8]. Measurement of the EAS disk structure was first attempted by Bassi, Clark and Rossi in 1953 [9] and continued later [10]. However, recently it has been shown that both mean arrival time and EAS front thickness in individual showers fluctuate strongly and cannot be a good measure of the distance from the EAS axis [11].

Although because of strong fluctuations we cannot use ATI as a measure of the distance from the core, at least we can use it to provide a statistical analysis about some of EAS features. In this paper ATI is used, in addition to the density information (we use density information only as a measure of distances of each two detectors, in order to find core position and correct determination of EAS direction). This method is a new and model independent (e.g. lateral density distribution function depends on the precision of Greisen function) approach which can be used as an alternative way for finding core locations of extensive air showers. Another feature of this method is its independence of number sensitive detectors (detectors which are sensitive to the number of crossing particles).

In order to examine the capability of the method, CORSIKA [12] package has been used. We have developed an algorithm using distances between two particles (the distance of two detectors which are triggered by the crossing particles, i.e. the ON detectors, in an array during an EAS event) for finding the nearest particles to the core among all EAS particles. In this algorithm, two common properties of EAS core have been considered: 1- Particle density in core neighborhood is more than the other regions; consequently, distance between two triggered detectors near the core is smaller than those of two triggered detectors far from the core. 2- Due to spherical front of EAS, in vertical EAS, secondary particles near the core region, reach ground level sooner than other particles. This feature will be valid for inclined showers by correction the inclination angle effects.

2 Physical Principles

For simplicity, we will be investigating vertical EAS events at first and then generalizing this method to inclined EASs.
A simple approximation method to find the core position is to calculate the center of mass of the ON detectors which is relatively a good approximation to find core of those EASs whose cores are very close to the center of an array. For enhancement of precision of this method we have introduced a procedure which improves the capability of the center of mass for finding core position even if the core position is far from the center of the array.

An important feature of EASs is their spherical front which is approximately a spherical cap. Therefore, particles in the core region reach ground level sooner than other particles. We can demonstrate this phenomenon by considering this fact that if we select randomly any two secondary particles of an EAS, we can see the first particle reaching ground level sooner, and on average is closer to the core position. Figure (1) shows that by increasing distance between two particles, the average distance of the first particle from the core increase slowly and the average distance of second particle from the core increases rapidly.

Another feature of EASs is higher density of particles near the core region. The smaller distance of two particles from each other, their smaller distances from the core on average. We checked this feature for electrons and muons separately, and did not observe any distinguishable difference. Previous investigation shows that the arrival time difference between electrons and muons is negligible for distances less than 200 meters [13].

3 A Method for Finding Core Position

The density of secondary particles quickly decreases by increasing the distance of particles from the core region which is opposed to the slow increasing of the average arrival time of particles which is shown in figure (2). A rough investigation shows that random fluctuation of the density of the particles is very much less than their arrival time fluctuations (particularly far from the core).

Based on these facts, the following procedure for finding the core position is proposed as:

Particles (ON detectors) are indexed based on their arrival time (trigger time), the first arrived particle has the first index \(i = 1\) and so forth (We assume that every detector can just detect the first crossing particle and is unable to detect any other particle during an event). Figure (2) suggests that if \(i < j < k\) then \(\bar{r}_i < \bar{r}_j < \bar{r}_k\) (\(r_i\) is the distance of the first particle among \(i, j\) and \(k\) from the core and \(\bar{r}_i\) is its ensemble average). By this outcome and examining figure (1) this result can be achieved: \(d_{ij} < d_{ik}\) (where \(d_{ij} = |\vec{r}_i - \vec{r}_j|\)). If we want to find the nearest particle to the core, selecting the \(i\)th particle seems to be logical, but on the basis of the previous discussion the better choice will be obtained by the following procedure: Find the minimum value among \(d_{ij}, d_{ik}\) and \(d_{jk}\). Assume that the \(d_{jk}\) is the minimum value then \(j\) will probably be the nearest
particle to the core position (notice $j < k$).

3.1 SIMEFIC (SIEving MEthod for FInding Core) Algorithm

In this algorithm, off-core particles are eliminated and only nearby ones are selected (as a list). Let us assume that there are $N$ secondary particles (ON detectors) in an EAS event. Knowing the fact $t_1 < t_2 < \ldots < t_N$ ($P_1, P_2, \ldots, P_N$ are respective particles), we form a matrix $D_{N\times N}$, whose elements are $d_{ij}$ (distance between $P_i$ and $P_j$). In view of the fact that $D$ is symmetric, we just consider the upper triangle of the matrix (without principal diagonal elements).

\[
D = \begin{pmatrix}
\times & d_{12} & d_{13} & \cdots & d_{1N} \\
\times & \times & d_{23} & \cdots & d_{2N} \\
\times & \times & \times & \cdots & d_{3N} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\times & \times & \times & \cdots & \times 
\end{pmatrix}
\] (1)

We can find the smallest element ($d_<$) under two conditions:

1. If $d_{ij} = d_{kl}$, $i < k$ then $d_<= d_{ij}$.
2. If $d_{ij} = d_{ik}$, $j < k$ then $d_<= d_{ij}$.

Now we select the $i$th particle as the first particle of the list (because of its arrival time). Next in the $i$th row we find the biggest element ($d_>$) under the condition:

- If $d_{ij} = d_{ik}$, $j < k$ then $d_>= d_{ik}$.

We should now eliminate the $k$th particle as an off-core particle and then the $i$th and $k$th rows and columns of the matrix $D$. By repeating the same procedure for the new matrix ($D_{N-2\times N-2}$), we will reach a position in which half of the particles are retained and half of them are eliminated. Now, it is expected that the center of mass of the retained particles is a good measure of the core position.

Up to now our discussion was limited to the vertical EASs. Now the inclined EASs are also examined. In the case of examining inclined EASs, ATI of particles are used in addition to their distances from the core. Assume that the $\theta$ and $\phi$ are respectively the the zenith and the azimuth angles of arrival direction. The coordinates of the particles on the ground level are $x_i$, $y_i$ and $z_i = 0$. Now, the coordinates of the particles are transformed to a new coordinate system whose $x$ and $y$ axes are perpendicular to the arrival direction. To fulfill
this objective, we select an arbitrary point (e.g. center of mass of all particles) then the coordinates of the particles are rotated counterclockwise around the z axis through an angle $\phi$ and then the new coordinates are rotated clockwise around the $\hat{y}$ through an angle $\theta$. The z components in the new coordinate system are $z_i = -x_i \sin \theta \cos \phi - y_i \sin \theta \sin \phi$. Then ATI of particles are corrected by $\hat{t}_i = t_i + z_i/c$ ($c$ is the speed of light). Now the inclined showers are examined like the vertical ones. Notice because of the statistical nature of the procedure, the coordinates of the particles are not transformed to the new coordinate system.

On the other hand, when our detectors are sensitive to the number of the crossing particles, the algorithm changes as follows:

Another matrix $N$ is formed whose elements are $n_{ij} = n_i + n_j$ ($n_i$ is the number of the detected particles by $i$th detector) in correspondence with $d_{ij}$ element in $D$. Now we first impose maximum $n_{ij}$ condition, then other conditions for finding nearby particles. Assume that $n_{ij}$ has been selected and $n_i < n_j$, then $j$ is a nearby particle. If $n_i = n_j$ ATI will be a determining factor.

The precision of final results of SIMEFIC algorithm is very tied to the precision of arrival direction (ATI of particles has a lot of fluctuation and if the arrival direction fluctuation is added to them, the uncertainty increases greatly). Hence, we must find arrival direction with high precision. There are a variety of methods for correction of arrival direction such as: sphere front approximation, use hybrid detectors and so on. Now an alternative method is introduced that can be used in parallel to the other methods. Assume that we have a $\{P_i\}$ set (secondary particles or ON detectors). By using the SIMEFIC algorithm $\{\hat{P}_i\}$ set is found. Number of $\{\hat{P}_i\}$ members is half of the first one. Now using PWFA for the $\{\hat{P}_i\}$ set, arrival direction with a rather high precision can be found. The reason for better approximation of this technique in comparison with the PWFA for the set $\{P_i\}$ is that ATI has less fluctuation in near core region than in far region from the core. The front of an EAS is also smoother in near core region than far region. In view of these facts the SIMEFIC method presents a better approximation in contrast to the PWFA for all of the particles. Now we propose a refinement to the SIMEFIC method: first finding arrival direction by $\{\hat{P}_i\}$ set, then using this arrival direction as an input parameter for SIMEFIC algorithm. Again, by using SIMEFIC algorithm for the primary set, $\{P_i\}$ another set $\{\hat{P}_i\}$, will be reached. From now on we just use $\{\hat{P}_i\}$ as the output of the SIMEFIC.

4 Simulations with CORSIKA

The geographical coordinates of Alborz observatory Location (in city of Tehran) has been imposed in EAS simulations ($35^\circ N$, $51^\circ E$ and 1200 meters over sea level). Geomagnetic field components of Tehran are $B_x = 28.1 \mu T$ $B_z =$
38.4\mu T. For simulation of low-energy hadron interactions, GHEISHA \cite{18} package and for High energy cases QGSJET01 package have been used. Zenith angles of particles were chosen between 0° and 60°. The compositions of particles have been 90\% protons and 10\% helium nuclei. Primary particle energy ranges are between 100 Tev and 5 Pev.

The assumed array is a square detector array with an area of 200 × 200\,m² composed of 1 × 1\,m² detectors on a lattice with a 5-meter lattice constant. Since arrays around the world are chiefly made up of scintillator detectors with high efficiency, they are not sensitive to the position of the secondary crossing particles and we cannot exactly realize how many particles have passed through them. Therefore, the following assumptions have been applied for the simulation:

1. When the first particle crosses an area of 1×1\,m², the detector is triggered.
2. The next particles which cross through this hypothetical detector (second, third particles and etc.) are not taken into account.
3. The coordinates of the triggered particles are assigned to the hypothetical detector (area of 1 × 1\,m²) center.

The center of mass of the ON detectors will be as follows: $x_{CM} = 1/N \sum x_i$, $y_{CM} = 1/N \sum y_i$. If the coordinates of the EAS real core are denoted by $(x_{rc}, y_{rc})$, the distance of the real core and the center of mass will be $r = \sqrt{(x_{CM} - x_{rc})^2 + (y_{CM} - y_{rc})^2}$.

Now the SIMEFIC method is used to find EAS core (instead of the center of mass of all particles) and once again we measure the real core distance from the EAS center. The results are shown in figure (3). It is clear that by increasing the distance of the real core from the center of the array (we consider the center of the array as the point (0, 0), the real core in this figure is on the diagonal line on the points (10i, 10i), and i ranges from 1 to 10) the center of mass of all the ON detectors is precise only for those EASs whose core are near the central part of the array and by increasing the distance of EAS core from the center of the array, the error increases gradually. But in the SIMEFIC method the precision even up to 50\% of the length of the array is approximately the same. 3000 EASs have been averaged for each step. Acceptance condition for EASs is triggering at least 4\% of detectors of the array by secondary particles. For example, in figure (4) an EAS with core on point (−80, −80) is shown. In this figure, detectors accepted by SIMEFIC method are shown by the bold circles and the omitted ones by the empty circles. It is clear that although the shower real core is near the edges of the array, this algorithm has approximately chosen proper detectors. Although some of the detectors which are far from the core and near each other, have not been chosen (the omission of these detectors is the most important effect of using temporal information). This method is precise up to the point that almost half of the detected particles are symmetrically spread around the core.
In figure (5) spatial angle between the EAS primary direction and the direction which has been found by the SIMEFIC method and PWFA have been shown. It is clear that SIMEFIC approximation has approved PWFA significantly.

Now assume that detectors are also sensitive to the number of crossing particles too. Figure 6 also shows SIMEFIC results for number sensitive detectors.

5 Conclusion

In this investigation we have developed a simple method for finding the position of the EAS core and the proper correction of the PWFA for finding the EAS direction. In addition to the information of the secondary particles positions on the ground level ATI is also used. This method is based on measuring the distances between pairs of particles, choosing particles with the minimum distance and arrival time, omitting particles with the maximum distance (from the core) and arrival time and using center of mass of chosen particles for finding core location of EAS.

The essence and scheme of the method envisioned by scrutinization of vertical showers have been formulated for inclined showers. An operational algorithm has been developed and tested on $3 \times 10^5$ simulated EAS events generated by CORSIKA package. The analysis technique proposed here is adequate for simple EAS arrays without number sensitive detectors and has been generalized for arrays with number sensitive detectors.

The results of applying the method on the simulated events show that, the EAS core location is improved to about the distance between the array’s adjacent detectors for an EAS whose core falls within central detectors of the array. Furthermore, by using the PWFA for the ON detectors selected by this method, the spatial angular resolution of the primary direction is improved significantly compared with the case of using PWFA to all ON detectors of the array during an event (figure (5)).

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Fig. 1. Average distance of the first particle (lower curve) and the second particle (upper curve) from the core versus their distance from each other for electrons (black curve) and muons (grey curve) (The results has been reached by additional 10,000 vertical single energy (100 TeV) showers generated by CORSIKA. The low energy hadronic model is FLUKA [14,15] and the high energy hadronic model is QGSJETII [16,17]. Other characteristics are described in section 4).
Fig. 2. The average of the arrival times of the particles versus distance from the core for the same showers which have used in figure (1).
Fig. 3. Comparison of the center of mass of all particles (upper curve) and those which have been selected by SIMEFIC (lower curve).
Fig. 4. The ON detectors which are accepted by SIMEFIC method are shown by the bold circles and the omitted ones by the empty circles. The position of the real core and the center of the array have been shown. The zenith and azimuth angles of the shower are $29.5^\circ$ and $329.5^\circ$ respectively, and its energy is 157.5 TeV.
Fig. 5. The angle between the EAS primary direction and the direction which has been found by the SIMEFIC algorithm (lower curve) and also PWFA (upper curve) versus distance of the real core from array center.
Fig. 6. The center of mass of all particles (upper curve) and those which have been selected by SIMEFIC algorithm (lower curve) for number sensitive detectors.