A New Core Position Reconstruction Method Based on Ground-based Particle Detector Arrays (Postprint)

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Abstract

Core position reconstruction is a prerequisite and foundation for physics analysis in ground-based cosmic ray detection experiments. This paper proposes a novel core position reconstruction algorithm—the ellipse fitting method—based on the symmetry of extensive air showers and combined with detector characteristics, for reconstructing core positions from simulated data and comparing with the center-of-gravity method. For core-contained cosmic ray proton events with energies greater than 1 TeV, the core position resolution is less than 5 m, significantly superior to the center-of-gravity method; for events with energies greater than 1 TeV within 20 m of the array boundary, the core position resolution is less than 10 m, showing significant advantages over traditional methods. Since this method can reconstruct edge events and some out-of-core events while ensuring accuracy, it greatly increases the event utilization efficiency; for 1–10 PeV proton events, the detector array area utilization efficiency is increased by approximately a factor of two compared to the center-of-gravity method.

Full Text

Preamble

A New Core Position Reconstruction Method Based on Ground Particle Detector Array

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Abstract

Core position reconstruction is a prerequisite and foundation for physical analysis in ground-based cosmic ray detection experiments. Based on the symmetry of extensive air showers and the characteristics of detectors, this paper proposes a new core position reconstruction algorithm—the ellipse fitting method—for reconstructing core positions from simulated data and compares it with the center-of-gravity method. For in-core cosmic ray proton events with energies greater than 1 TeV, the core position resolution is less than 5 m, which is significantly better than the center-of-gravity method. For events with energies greater than 1 TeV within 20 m of the array boundary, the core position resolution is less than 10 m, showing significant advantages over traditional methods. Since this method can reconstruct edge events and some out-of-core events while ensuring accuracy, it greatly increases event utilization. For 1-10 PeV proton events, the detector array area utilization rate is approximately doubled compared to the center-of-gravity method.

Keywords: Cosmic rays; Extensive air shower; Event reconstruction; Symmetry; Water Cherenkov array

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The energy of cosmic rays spans more than ten orders of magnitude, and their flux spans more than thirty orders of magnitude. The energy spectrum approximately follows dN/dE E^{-γ}, where the spectral index γ is about 2.7 [1]. From the MeV to ~400 TeV energy range, the cosmic ray flux is relatively high and can be directly detected by satellites. For higher energy regions, the flux is too low, so cosmic rays are mainly detected indirectly through ground-based experiments [1,2]. The water Cherenkov detector is a type of ground-based cosmic ray detection technology with advantages such as all-weather operation and a wide field of view. It primarily reconstructs information about primary cosmic rays by measuring the extensive air showers produced when primary cosmic rays enter the atmosphere [1,30]. Several cosmic ray detection experiments, including HAWC in Mexico and LHAASO-WCDA in Daocheng, Sichuan, have adopted water Cherenkov detector technology.

Extensive Air Shower (EAS) [3,4] is a process in which high-energy primary cosmic rays interact with atmospheric components after entering the atmosphere, producing a large number of secondary particles through hadronic and electromagnetic cascades. Its physical characteristics are typically described by longitudinal development and lateral distribution. Commonly used models for describing longitudinal development include the Gaisser-Hillas function [27,31], Greisen function [28,31], and Gaussian-in-Age [29,31], all of which agree well with experimental measurements. The lateral distribution of EAS is usually described by the Lateral Distribution Function (LDF) and the Nishimura-Kamata-Greisen (NKG) function [3,5,16,31]. The LDF is a purely mathematically fitted empirical formula that simply describes the average distribution, and its parameters are not directly related to the physical characteristics of extensive air showers [4,8,16]. The NKG function is closer to the physical essence than LDF. On the one hand, the NKG function can reflect physical features such as the lateral distribution and longitudinal development of EAS. On the other hand, it fully considers the statistical fluctuations of EAS in the fitting process [3-5,31].

Ground-based cosmic ray detection experiments invert information such as core position, direction, and energy of events by detecting the density distribution of EAS secondary particles, including electrons (e+, e-), muons (-, +), and photons, as well as the arrival time of the shower front [5,6,9]. This process is called cosmic ray event reconstruction or EAS reconstruction, and core position reconstruction is an important component of EAS reconstruction. Commonly used core position reconstruction methods include the center-of-gravity method, tree analysis method, maximum likelihood method, and two-dimensional Gaussian fitting method, each with its own unique advantages and disadvantages [3,10,15,17]. The center-of-gravity and tree analysis methods have the advantage of small computational cost and save computing resources; their disadvantage is that they destroy the symmetry characteristics of events during reconstruction. The accuracy of core position reconstruction depends on the distance from the reconstructed core position to the detector center. The maximum likelihood method has high precision in core position reconstruction, but its accuracy also depends on the number of triggered detector units (Nhit). When Nhit is greater than 1000, its core position resolution is less than 2 meters, which is significantly improved compared to the former two methods. However, on the one hand, this method requires large computational resources, and on the other hand, its accuracy depends on many factors such as energy, direction, and Nhit. The two-dimensional Gaussian fitting method is a simple mathematical fitting approach that overcomes some disadvantages of the center-of-gravity and tree analysis methods. It works well for reconstructing events where the core position is inside the detector array (in-core events), but cannot accurately reconstruct events where the core position is outside the detector array [3,11,12,17]. Except for the maximum likelihood method, these reconstruction methods require screening conditions that discard large amounts of data, retaining only events with core positions in a small range near the array center. This sacrifices the effective area of the detector to ensure the reliability of reconstruction results, causing a waste of large amounts of observational data [5,10]. In addition, the low signal-to-noise ratio of water Cherenkov detector data is also a challenge for reconstruction. For example, the signal-to-noise ratio of LHAASO-WCDA observational data is about 70/218 before denoising, and about 22/70 after denoising using the traversal method. This means that for events triggering 70 detector units, about 22 channels of signals are noise, which brings great difficulties to accurate reconstruction, and the above methods can hardly handle the impact of noise well [10].

Based on the symmetry of extensive air showers and the physical characteristics of water Cherenkov detector arrays, this paper proposes a new core position reconstruction method—the ellipse fitting method. This method fully utilizes the symmetry of EAS to eliminate the impact of noise on core position reconstruction. Under the premise of meeting core position reconstruction accuracy, it can reconstruct events with core positions falling on the detector edge and out-of-core events, expanding the utilization rate of detector events.

1. Water Cherenkov Detector Technology

Water Cherenkov light detectors use pure water as the medium and collect Cherenkov photons produced by charged particles moving in water through photomultiplier tubes to measure extensive air showers. The unit detector construction and detection principle of water Cherenkov detector arrays adopted by various experiments are basically the same, though there are certain differences in various performance parameters and layout of detector units. LHAASO-WCDA is one of the most representative water Cherenkov detector arrays. When cosmic ray particles produce extensive air showers within the WCDA field of view, secondary particles will enter the pure water in the array and move at superluminal speed (speed of light in the medium) to excite Cherenkov light. The number of Cherenkov photoelectrons (NPE) collected by the photomultiplier tube (PMT) of each basic unit is proportional to the EAS secondary particle density at that location [32]. The trigger time of detector units can be accurate to the nanosecond level, and this data can be used to reconstruct information such as core position and direction [1,18,19]. Other experimental water Cherenkov detector arrays such as HAWC have different structures and layouts from LHAASO-WCDA, but their detection principles are basically the same [30].

LHAASO-WCDA consists of 3 pools with 3120 unit detectors and subsequent functional systems for electronics, timing, data acquisition, trigger selection, data processing, and calibration. The unit detector (Fig. 1 [Figure 1: see original paper]) is a 5 m × 5 m water area with a depth of 4.4 m. Light-proof curtains separate two units, mainly to avoid crosstalk from signals of the same secondary particle, especially muon signals. WCDA uses 3120 large-size photomultiplier tubes (PMTs) placed at the bottom of each unit, facing upward for observation. In addition, 3120 small-size PMTs are placed in the pool next to the large-size PMTs to expand the dynamic range of shower particle number measurement, thereby enabling high-precision measurement of high-energy cosmic rays [1,18,19].

This paper will use the 150 m$×$150 m LHAASO-WCDA1 water Cherenkov detector array as an example to explain the physical ideas and algorithm design of core position reconstruction using the ellipse fitting method.

2. Ellipse Fitting Method

As shown in Fig. 1 (right), when an EAS enters the ground at a certain zenith angle, the EAS secondary particles arriving at the detector array plane are concentrated in a very thin front. The lateral distribution of secondary particles can be described by the NKG function [3-8,31]:

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In equation (1), Ne is the total number of particles in EAS, which mainly depends on the energy of the primary cosmic ray particle; rM is the Molière radius, which is related to the composition of the primary cosmic ray; s is a parameter describing the development stage of EAS, known as the age of EAS. When s=1, EAS reaches its maximum development, and it is a normalization coefficient. Equation (1) shows that for an EAS front with age s, the secondary particle density decreases with increasing distance r from the front. The larger the age, the slower the decrease, and the flatter the secondary particle density distribution function. When an EAS front with zenith angle ϕ approaches the detector array, it can be approximated that the secondary particle density change is negligible within the tens of nanoseconds when the front reaches the detector. Therefore, the secondary particle density reaching a detector unit at any position (x,y) is:

(x0,y0) is the core position on the ground plane, (,ϕ) is the direction of EAS, where is the azimuth angle and ϕ is the zenith angle, and (x,y) is the coordinate of a detector unit at any position on the plane. From the expression, it can be seen that it is related to the core position and direction of EAS, and its mathematical structure is very complex and inconvenient for analyzing its characteristics. To more intuitively understand the distribution of secondary particles in the shower front, numerical calculations were performed to obtain the distribution of secondary particles projected onto the ground for events with different zenith and azimuth angles, as shown in Fig. 2 [Figure 2: see original paper]. From Fig. 2, it can be seen that the EAS secondary particle density exhibits obvious symmetry. When the zenith angle is 0°, the secondary particle density contour lines are concentric circles. When the zenith angle is not zero, the contour lines are concentric ellipses, and the larger the zenith angle, the greater the eccentricity of the ellipses.

Therefore, a system of ellipse equations can be used to describe the secondary particle density contour lines:

$$1]cos)(sin)[(]sin)(cos)[(22002200 \quad nnnnnnbyyxxayyxx$$

where (x0,y0) is the common center of this series of ellipses, an and bn are the semi-major and semi-minor axes of the nth ellipse equation, is the azimuth angle of EAS, and the ratio of ellipse axes an/bn = f(ϕ,s) is a function of the EAS zenith angle ϕ and age s.

Fig. 2: The charged secondary particle density of EAS at different zenith angles calculated using the NKG function. The azimuth angles are all 45°, where the zenith angles of a, b, and c are 0°, 30°, and 45°, respectively. The color map shows the common logarithm of the secondary particle density, and d, e, and f show the contour line representations of a, b, and c, respectively.

The NPE detected by each basic unit PMT of WCDA has a linear relationship with the secondary particle density at that location, so its NPE contour lines can be approximated as ellipses. Fitting the NPE contour lines with ellipse equations can yield a series of concentric ellipses. The common center of these ellipses is the core position of EAS. The ratio of the ellipse axes reflects the EAS zenith angle information, and the major axis of the ellipse reflects the EAS azimuth angle information. Fitting the series of NPE contour lines to reconstruct the core position has two advantages. On the one hand, for events where the core position is at the detector edge, causing severe destruction of EAS symmetry, the elliptical contour lines can be "completed" through local information (as shown in Fig. 3 [Figure 3: see original paper]), and the symmetry can be used to reconstruct an accurate core position. On the other hand, by utilizing the characteristic that all ellipses should be "concentric", data groups with low signal-to-noise ratio can be discarded, thereby achieving noise suppression. The specific algorithm flow is shown in Fig. 4 [Figure 4: see original paper]:

Step 1: Read the event to obtain the coordinates (xi,yi) of unit detectors useful for core position reconstruction.

Step 2: Sort the data in descending order according to NPE and divide the data into n groups.

Step 3: Fit n ellipse equations to obtain n (x0i,y0i).

Step 4: Calculate their average value.

Step 5: Determine whether it satisfies $$

$$ and if so, proceed to the next step. Otherwise, remove the point with the largest deviation and return to Step 4 until the condition is satisfied or n<3.

Step 6: Calculate the ratio NBN of the total NPE in the circular region within 30 m of the core position to the annular region between 30 and 40 m, and determine whether NBN is greater than NBNmin. If it is greater, output the result obtained in the previous step as the reconstructed core position. Otherwise, determine that the reconstruction has failed and do not include this event in the statistics.

Fig. 3: Schematic diagram of core position reconstruction by ellipse fitting method

Parameter Selection and Usage in This Method

1. **Point with maximum NPE.** For in-core events, the point with the maximum NPE cannot be used to fit the ellipse. This point is likely

located near the ellipse center.

2. **Number of data points used to fit ellipses in the ellipse system.** The farther the ellipse contour line is from the core position, the more detector units there are on that contour line. Therefore, the number of points used to fit an ellipse should be larger and theoretically proportional to the distance from the core position. Thus, we adopt a grouping method that increases linearly from inner to outer regions. The derivation above shows that fitting any ellipse on a plane requires at least 5 points, so each group of data is taken as 5n (n=1,2,3…), i.e., 5 points for the first group, 10 points for the second group, 15 points for the third group, and so on. From this, the relationship between the number of triggered detector units Nhit and the number of fitted ellipses n is:

$$), (00yxhitNnn\ \ 2)1(5$$

Fig. 4: Algorithm flow chart of ellipse fitting method

3. **decut.** The core of the ellipse fitting method is to fit the NPE contour lines with ellipse equations to obtain the ellipse center (x0,y0) as the core position of the cosmic ray event. Since all ellipse contour lines should be "concentric", theoretically only one contour line needs to be fitted to obtain the core position. However, to reduce statistical errors and improve the accuracy of core position reconstruction, it is necessary to make full use of the data to fit as many ellipses as possible. Due to physical fluctuations and differences in detector units, the fitted ellipse series center coordinates will have certain deviations. There are usually three situations: (1) The ellipse system center coordinates are distributed in a very small region, and the center of gravity of these points can be taken as the final reconstructed core position coordinates; (2) The ellipse system center coordinates are generally densely distributed with a few distant outliers. It is necessary to remove those distant coordinate values and take the center of gravity of the dense point group as the core position (as shown in Fig. 5 [Figure 5: see original paper]); (3) The ellipse system center coordinates are extremely discrete, and such events are treated as invalid events. decut is the standard used to quantitatively judge the degree of dispersion. Usually, the smaller the value of decut, the higher the core position accuracy. However, choosing too small a decut may discard some valid data and result in very low reconstruction efficiency. Through multiple attempts and comparisons, a value of 5 m was selected, which can balance core position accuracy and reconstruction efficiency. In situation (2) above, for low- and medium-energy events, the ellipse center coordinates fitted from small NPE data groups usually have large deviations from the core position. This is because the signal-to-noise ratio of detector units with relatively small NPE is low. For high-energy events, the ellipse center coordinates fitted from large NPE data groups have large

deviations from the core position, possibly because the photomultiplier tubes near the core position of high-energy events have already…

4. **Standard deviation of x0i and y0i.** The standard deviation of x0i and y0i is used as a judgment parameter to determine the dispersion degree of this series of ellipse centers. If its standard deviation is large (as in situations (2) and (3) above), it indicates that some data groups contain almost no core position information. These NPE are mainly caused by noise, so this data is treated as noise and removed. Conversely, concentrated ellipse center coordinates indicate that the corresponding data has a low noise ratio, and their contribution to the core position coordinates is retained. Fig. 5 shows the coordinates of each ellipse center reconstructed from grouped data for an event. Finally, only the dense points within the red box are retained and averaged as the final core position reconstruction result.

Fig. 5: The center of each ellipse and the real core position reconstructed by the ellipse fitting method, where the blue “+” is the center of the ellipse reconstructed from each group of data, and the red ”*” is the real core position.

5. **NBN and NBNmin.** After obtaining the average value of the ellipse center coordinates ($_0$, $_0$) that meet the dispersion requirements, it is also necessary to use the ratio NBN = N10/N20 of the total NPE in the 10 m circle and the 10-20 m ring near this point to determine whether the NPE distribution around this point conforms to the NPE distribution characteristics near the core position. NBN > NBNmin indicates that the reconstructed core position error is less than 10 m, and the calculation result can be taken as the final reconstructed core position. The value of NBNmin can be obtained through numerical estimation and data statistics. When it is necessary to reconstruct out-of-core events near the array boundary, considering that N10 may be 0, NBN = N20/N30 or NBN = N30/N40 can also be used to achieve the same judgment effect, although the fluctuation becomes larger and the accuracy becomes worse. These can only judge whether the reconstructed core position error is below 20 m or 30 m, respectively.

3. Reconstruction Results of the Ellipse Fitting Method

Monte Carlo simulation is an important means to study cosmic ray physics. This paper uses extensive air showers simulated by Corsika and detector response simulated by Geant4 to verify the actual effect of core position reconstruction using the ellipse fitting method. Proton events with energies from 10 TeV to 10 PeV are selected, with zenith angles of 0-40° following a $\cos^2$ distribution and azimuth angles of 0-360° following a uniform distribution.

The detector references LHAASO-WCDA1, with all parameters consistent. In the coordinate system, the detector array area is (-75 m<x<75 m, -75 m<y<75 m). Noise of 60 kHz is added to the data, and after denoising using the traversal method with a 200 ns time window, the signal-to-noise ratio is about 70/22.

Both the center-of-gravity method and the ellipse fitting method are used to reconstruct events and compare their reconstruction accuracy and event utilization rate. First, it is necessary to verify the reconstruction capability of this algorithm for events with core positions at the edge of the detector array. Proton events with energies of 10-100 TeV and true core positions (xct,yct) located outside the detector array and close to the boundary (75 m<x<85 m, -75 m<y<75 m) are selected for core position reconstruction. The results are shown in Fig. 6 [Figure 6: see original paper]. From the figure, it can be seen that the distribution of reconstructed core positions is basically consistent with the true core positions. From the right figure, it can be seen that the deviation of most reconstructed core positions dr = √((xct-xtr)^2 + (yct-ytr)^2) is less than 10 m. Taking the 68% value of dr as the resolution gives approximately 9.6 meters.

Fig. 6: Real core position and reconstruction core position distribution (left), reconstruction core position deviation statistics (right)

To quantitatively describe the accuracy of core position reconstruction using this method and the utilization rate of the detector area, 4000 proton events each with energies of 1-10 TeV, 10-100 TeV, 100-1000 TeV, and 1-10 PeV are selected. The true core positions are uniformly distributed in the region (-150 m<x<150 m, -150 m<y<150 m). Both the center-of-gravity method and the ellipse fitting method are used to reconstruct the core positions. Since the true core positions are uniformly distributed in a 300 m\$×300*mregion*, *whilethedetectorarrayareais*150*m*×\$150 m, the ratio of the number of successfully reconstructed events to the number of events with core positions within the detector array is taken as the detector area utilization rate = [corrupted formula]. The 68% value of the dr distribution is taken as the core position reconstruction resolution. The results are shown in Fig. 7 [Figure 7: see original paper].

From Fig. 7, it can be seen that for proton events in all energy ranges, the core position reconstruction accuracy of the ellipse fitting method is better than that of the center-of-gravity method, and the ellipse fitting method can significantly improve the utilization rate of the detector array, with the improvement becoming more significant as the energy increases. For 1-10 TeV events, the detector area utilization rate of the ellipse fitting method is slightly less than 1, which means that only a few events with core positions at the detector edge are poorly reconstructed. The area utilization rate increases with energy. For 1-10 PeV events, the area utilization rate is greater than 1.3, which means that about 30% of events located outside the detector array have core position reconstructions that meet accuracy requirements. The phenomenon in the left figure that the core position reconstruction resolution of the ellipse fitting method increases with energy is not as expected. This is caused by the inclusion of a large number of out-of-core events in the statistics, which leads to an increase in area utilization. This can be confirmed by the core position resolution after normalizing the area utilization rate.

Fig. 7: Ellipse fitting method and center of gravity method core position recon-

struction resolution (left) and detector array area utilization (right)

The reconstruction resolutions of the ellipse method and the center-of-gravity method when the area utilization rate is 0.67 for each energy range are shown in Fig. 8 [Figure 8: see original paper]. Under the same reconstruction efficiency, the core position resolution of the ellipse fitting method is significantly better than that of the center-of-gravity method. Moreover, the core position resolution of both methods decreases with increasing energy. However, since the ellipse fitting method itself can eliminate most noise interference, its reconstruction accuracy does not change significantly with energy.

Fig. 8: Reconstruction resolution of core positions for each energy segment when the area utilization ratio is 0.69

4. Conclusions and Outlook

Through verification with Monte Carlo simulation data, the ellipse fitting method has obvious advantages over the center-of-gravity method. The advantages of the ellipse fitting method are mainly reflected in two aspects. First, it fully considers the symmetry characteristics of EAS, and uses this symmetry to accurately reconstruct events at the edge of the detector array and even outside the detector region. Second, it effectively eliminates the impact of noise on core position reconstruction through a grouped reconstruction approach, thereby significantly improving the accuracy of core position reconstruction. Based on the reconstruction results from simulated data of the 150 m$×$150 m WCDA-I, the core position reconstruction accuracy for in-core events using the ellipse fitting method can reach below 5 meters. The resolution in each energy range is less than 50% of that of the center-of-gravity method, showing a significant improvement in reconstruction accuracy compared to the center-of-gravity method. On the other hand, it can solve the problem that the center-of-gravity method cannot accurately reconstruct the core positions of events at the edge of the detector array. The area utilization rate for reconstructing low-energy events is about 40% higher than that of the center-of-gravity method, while for high-energy events, the area utilization rate is nearly twice that of the center-of-gravity method. Both the core position reconstruction accuracy and the detector array area utilization rate are significantly improved compared to the center-of-gravity method.

The noise suppression capability of the ellipse fitting method stems from the fact that the NPE signals triggered by EAS secondary particles have contour lines that are a series of concentric ellipses, while noise signals are uniformly distributed. Based on this principle, a denoising algorithm can be designed to achieve deep denoising using core position information on the basis of traversal method denoising. In addition, it was found that the arrival time of secondary particles at the shower front is also symmetrically distributed about the shower core. Based on this characteristic, the direction can be reconstructed through zoning to avoid problems caused by dependence on cone correction parameters, and the direction information can be used to achieve further deep denoising.

Subsequent research will mainly proceed along this direction.

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