Hybrid inversion method for equivalent electric charge of thunder cloud based on multi-station atmospheric electric field

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Abstract: This article proposes the hybrid method to inverse the equivalent electric charge of thunder cloud based on the data of multi-station atmospheric electric field. Firstly, the method combines the genetic algorithm (GA) and Newton method through the mosaic hybrid structure. In addition, the thunder cloud equivalent charge is inversed based on the forward modeling results by giving the parameters of the thunder cloud charge structure. Then an ideal model is built to examine the performance compared to the nonlinear least squares method. Finally, a typical thunderstorms process in Nanjing is analyzed by Genetic-Newton algorithm with the help of weather radar. The results show the proposed method has the strong global searching capability so that the problem of initial value selection can be solved effectively, as well as gets the better inversion results. Furthermore, the mosaic hybrid structure can absorb the advantages of two algorithms better, and the inversion position is consistent with the strongest radar echo. The inversion results find the upper negative charge is small and can be ignored, which means the triple-polarity charge structure is relatively scientific, which could give some references to the research like lightning forecasting, location tracking.

Key words: inversion of thunder cloud equivalent charge; atmospheric electric field; genetic algorithm; newton method

1 Introduction

The characteristics of lightning are closely associated with the charge structure of thunder cloud, which is usually the key point of the atmospheric electricity. In recent years, with the development of electronic information technology, the lightning disasters are increasing, and more and more scholars focus on this field. In addition, some researchers had uses the method of numerical simulation to analyze the charge structure [1-3]. Tan et al. [4] gave a relatively reliable model interpretation about thunder cloud and charge structure and the point distribution through the numerical simulation. Wan et al. [5] attempted to enhance the resolution by combining the surface detection data and numerical simulation. While the direct approach of researching thunder cloud charge structure is to observe the thunder cloud electric field and some type of hydrometeor particles, which is difficult to achieve under the current condition[6]. However, the method of applying the multi-station atmospheric electric field data for inversion is more practical. Therefore, Qie et al. [7,8] inversed the location and electrical discharge structure of charge source through selecting the cloud-to-ground flashes, and deduced the structure of lightning discharge can be represented by the triple-polarity charge structure. Zhang et al. [9] considered the phenomenon of thunderstorms ground electric field is caused by the actions of different charge region and analyzed a typical thunderstorms in Zhongchuan based on the observation of multi-station electric field.

As for the atmospheric electric field instrument, there is no doubt that the advantages of real time and large range can provide a great help to the lightning research. Traditionally, many researchers use the least square method (LSM) to inverse the amount of equivalent electric charge and position of thunder cloud, while the estimation of initial value is very essential and there is no effective solution. In other fields, some scholars chose the hybrid algorithm to improve the calculation accuracy [10-15]. However, there are just few studies on how to select the form of hybrid structure, and most of them tend to adopt the serial structure what takes the front result as other's initial value. What´s more, different structures usually have their own features and are just suitable for distinct problems, therefore, the choice is a key step for the hybrid inversion method.

Therefore, this article proposes a hybrid inversion method based on the genetic algorithm (GA) and Newton method, and chooses mosaic structure to enhance the inversion performance. In addition, a typical thunderstorms process in Nanjing is analyzed according to the observation of multi-station electric field, which is further compared with the radar echo.

2 Model assumption

The charge density distribution of isolated thunder cloud is related to the spatial location. Assuming that charge density is $\rho(x,y,z)$ [8] and evenly distributes in the horizontal direction, so the charge is just related with the vertical height. Moreover, the assumption involves the thunder cloud is divided into several regions with the same thickness in the vertical direction, and each region is consistent in horizontal direction as well as focus on one point. Therefore, the values of ground electric field are the result of the interaction of multiple charge areas.

Where E_k is the contribution of k_{th} charge region, and E_i is the observation value of i_{th} ground station. x and y are the center coordinates of equivalent point charge in each region, h and d are cloud-ground height and thickness of each layer respectively, x_i and y_i are the coordinates of each station. Obviously, the more regions thunder cloud stratifies, the more accurately calculation results reflect, meanwhile the corresponding amount of calculation will increase distinctly. If the number of thunder cloud layers is N, it has to get $N+4$ set of values including the unknown charge center position (x, y), h and d. So that the article preliminarily assumes the thunder cloud is divided into 4 constant-thickness layers shown in Figure 1.

$$E_i = \sum_1^n E_k = \sum_1^n \frac{Q_k(h + (k-1)d + \frac{d}{2})}{4\pi\varepsilon_0 [(x-x_i)^2 + (y-y_{i\ i})^2 + (h+(k-1)d + \frac{d}{2})^2]\frac{3}{2}} \tag{1}$$

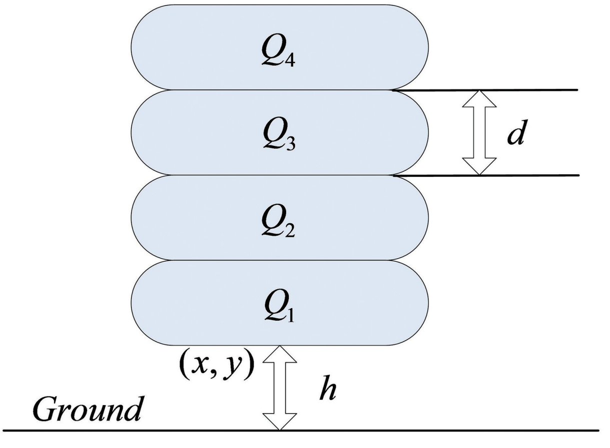

Fig. 1 The thunderstorms charge structure model

3 Genetic-Newton algorithm for the inversion of thunder cloud charge structure

Genetic algorithm[16] (GA) is a global optimal adaptive searching algorithm. However, GA can't timely get the feedback from network, and the speed of searching is slow, which means the algorithm needs more accurate solution and training time. However, Newton method [17] has the strong local searching ability and the mosaic hybrid structure can somehow improve the operation efficiency. Therefore, we combine GA and Newton method through the mosaic hybrid structure to enhance the inversion accuracy and speed.

3.1 Genetic algorithm

1) Coding mode

The parameters the inversion needs to optimize is relatively more, therefore we choose the method of the combination of binary and real coding. The binary encoding is convenient to encode and achieve the crossover and mutation, and the improved coding will distinctly help GA to improve the convergence speed and optimization precision.

2) Fitness function

Before the global searching, GA must determine the fitness function so as to ensure whether the individual species could continually exist according to the practical problem. The searching target of GA is to get the weight of each indicator when the sum of squared error in whole network is minimum, so the reciprocal of the error is selected to represent the fitness function:

$$F = \frac{1}{\frac{1}{l}\sum_{i=1}^{l}(T_i - S_i)^2} \quad (2)$$

Where l is the length of the data, T is the real value, S is the searching value.

3) Genetic operation

Genetic operations include selection, crossover and mutation [16]. The selection is in order to choose excellent individuals from the current group, and the stronger individual that has greater probability will be selected. In addition, the crossover is to create a new one, which inherits the features from the parents. In the end, the mutation is to change a particular binary code, so the new individual would have a greater fitness.

3.2 Newton method

Newton method [17] uses the derivative to ensure every step of the iteration is along the decreasing direction of the current function, which needs to set the right initial value that GA can provide to guarantee the algorithm has good convergence and speed. Therefore, assuming that $F=(f_1, f_2, \dots, f_D)$ is a function of $X=(x_1, x_2, \dots, x_D)$ and getting the iterative equation:

$$X^{(k+1)} = X^k - F'(X^{(k)})^{-1}F(X^{(k)}), k = 0,1,...D \quad (3)$$

Where $F'(X)^{-1}$ is the inverse matrix of F's Jacobian matrix:

$$F'(X) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_D} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_D} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_D}{\partial x_1} & \frac{\partial f_D}{\partial x_2} & \cdots & \frac{\partial f_D}{\partial x_D} \end{bmatrix} \quad (4)$$

3.3 The hybrid structure of Genetic-Newton algorithm

The mosaic structure [18] is widely used and can realize the bidirectional flow of information. After each global searching, it begins the local search based on the previous results and then feedbacks to the main algorithm, which is simpler and can give full play to the performance than serial structure, also lets the child algorithm can fully exchange information, so as to enhance the convergence precision.

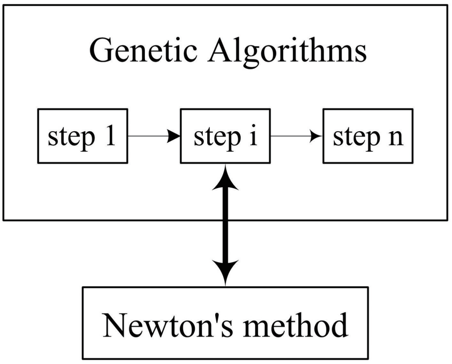

Fig. 2 The mosaic structure of the hybrid algorithm

3.4 Simulation

In order to verify the proposed method, this article firstly build an ideal model, which assumes that $Q_1=5C$, $Q_2=-25C$, $Q_3=12C$, $Q_4=-3C$, $x=0$, $y=0$, $h=2500m$, $d=1000m$ and accordingly gets the ground electric field values. The results are shown in Figure3, two groups of electric field values are selected as the detection value to examine the performance of the proposed algorithm, and establishing the objective function:

$$f(x,y,h,d,Q_1 \cdots Q_N) = \sum_{i=1}^{N} (E_{mi} - E_i)^2 \quad (5)$$

Where E_i is the electric field value of i_{th} station. Furthermore, the nonlinear least squares method is added to compare with Genetic-Newton algorithm and the results are listed in Table 1.

Obviously, the results of Genetic-Newton algorithm are closer to the real values compared with nonlinear least squares method. Especially for the space parameters, nonlinear least squares method has the serious deviation, which might be due to the selection of initial value that chooses the average of eight set of values. The results show Genetic-Newton algorithm has a better global searching capability, and the convergence process is shown in Figure 3. At first, the convergences of the two methods are both fast, but the convergence of Genetic-Newton algorithm is better in later and has a stronger local searching ability.

In addition, the serial structure is introduced to compare with the mosaic structure shown in Table 2, and the computing time of pure serial structure is obviously shorter than the mosaic structure, but the accuracy is far away from real values, therefore, which means theserial structure can´t incorporate the local search feature of Newton method into the main algorithm. Although the amount of calculation is increasing within acceptable range, but the mosaic structure can effectively reflect the two algorithms´ advantages better.

Table 1 Inversion results (Genetic-Newton algorithm/ Nonlinear least squares method)

Serial number	Inversion parameters							
	x/km	y/km	h/km	d/km	Q_1/C	Q_2/C	Q_3/C	Q_4/C
1	0.013/	0.020/	2.534	1.018/	5.034/	-25.409/	12.304/	-3.012/
	0.304	0.457	/2.798	1.307	7.210	-28.754	14.038	-4.891
2	0.011/	0.005/	2.561/	1.074/	5.104/	-25.218/	12.562/	-2.985/
	0.407	0.321	2.834	1.289	6.549	-27.693	14.343	-4.359

Table 2 Comparison of serial structure and mosaic structure

Structure Type	x/km	y/km	h/km	d/km	Q_1/C	Q_2/C	Q_3/C	Q_4/C	Time/min
Serial	0.154	0.143	2.682	1.309	8.431	-29.106	15.714	-1.452	6
Mosaic	0.013	0.020	2.534	1.018	5.034	-25.409	12.304	-3.012	15

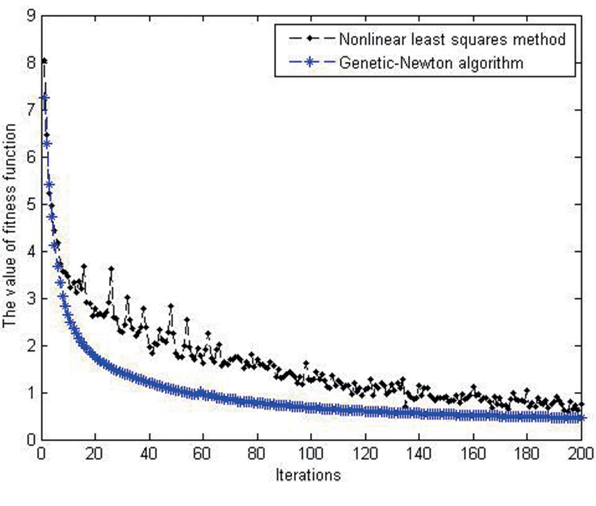

Fig. 3 Inversion convergence curves

4 Experiment

4.1 Data selection

In order to study thefeatures of thunderstorms lightning charge structure in eastern China, the experiment is conducted to analyze the variation of electric field and radar echo in the summer of 2010, Nanjing, and the instrument locations of observation area are shown in Figure 4. NUIST represents the station of Nanjing University of Information Science & Technology (32.11N, 118.71E), and the others are the abbreviation of stations. The observation area is relatively flat and the max elevation difference of stations is less than fifty meters. The geographical environment is conducive for multi-station observation. The diamond represents the location of the weather radar whose detection range is 230 km, which can cover Nanjing and surrounding areas, also observe the cloud top height, liquid water content and reflectivity data.

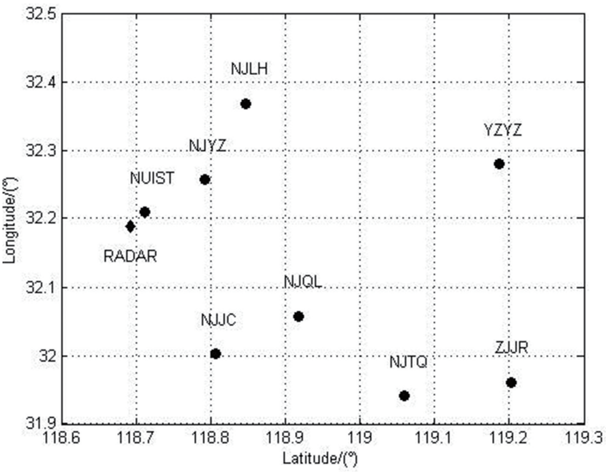

Fig. 4 The location of observation instrument

Considering the precipitation and the integrity of observation data during June to August 2010, this article selects electric field data on July 20, 2010. The curves represent the eight groups of electric field values are changing with time, which is shown in Figure 5. The polarity of ground electric field is influenced by the dominated charge of the thunder cloud, the distance of thunderstorms as well as the observation stations.

4.2 Data analysis and inversion results

In Figure 5, the process of thunderstorms can be divided into three stages. In NUIST station as an example, the first stage was from 12:30 to 12:40, the thunder cloud just came into the detection range and electric field curve gradually appeared to instable change with fluctuating. The second stage had many sharp oscillations. In addition, the progress of the charging and discharging in thunder cloud was remarkable and lightning activity was significant. Finally, in the third stage, the thunderstorm might dissipate or leave, and the electric field curve leveled off.

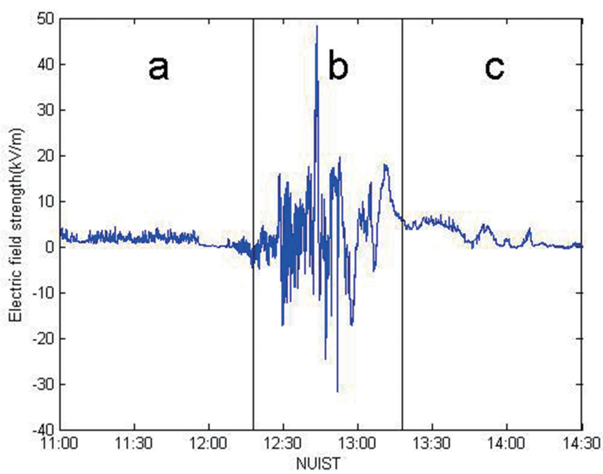

Fig. 6 The change of observed values in NUIST station

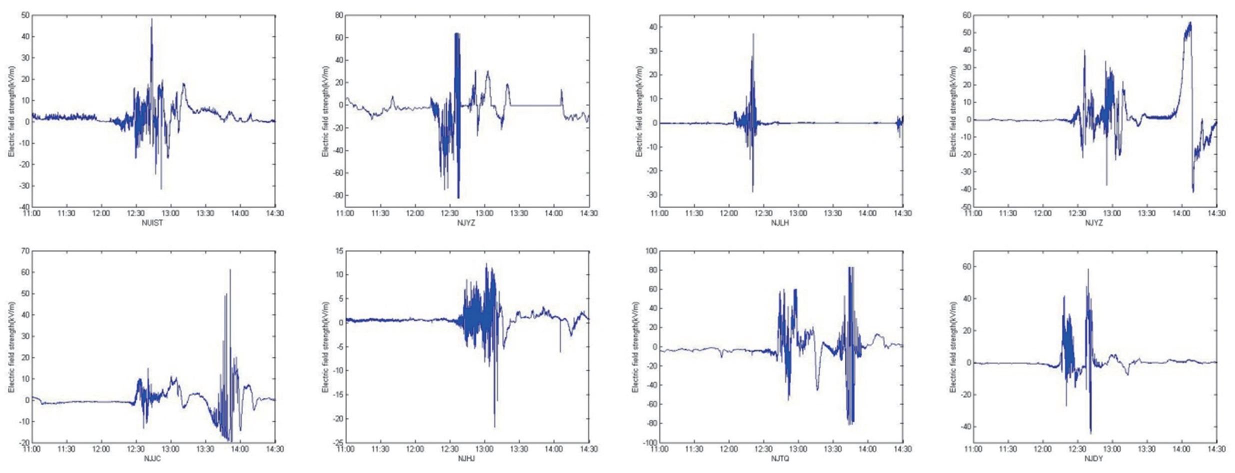

Fig. 5 The change of observed values in Nanjing on August 20, 2010

What´s more, when lightning is sharply changing, which could cause the electric field polarity reversal. Especially, the thunder cloud charge structure would be extremely complex within 1 minute after discharging. Therefore, more stable electric field values are chosen for inversion. Further, the interval time is set for 12minutes from 12:00 to 13:00 because the cycle time of weather radar is 6 minutes, and the inversion results are shown in Table 3 and Figure7.

Table 3 Inversion results

Time	Q_1 /C	Q_2 /C	Q_3 /C	Q_4 /C	h /km	d /km	*Longitude* /°	*Latitude* /°
12:00	4.6	-10.1	15.2	-1	1.4216	0.9471	118.51	32.22
12:12	4.9	-10.6	15.4	-1	1.4286	0.9441	118.72	32.22
12:24	6.2	-12.1	16.3	-1	1.4334	0.9321	118.74	32.18
12:36	6.9	-13.2	17.5	-1	1.4901	1.0601	118.91	32.22
13:48	5.7	-11.0	16.2	-1	1.4743	0.9126	119.02	32.30
13:00	3.8	-9.6	14.4	0	1.4447	0.9533	118.15	32.35

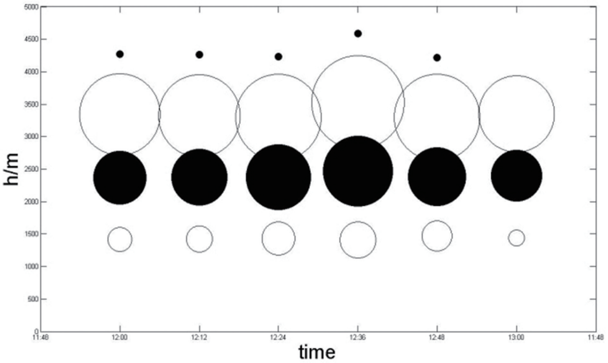

Fig. 7 The evolution of charge structure from 12:00 to 13:00, white circles represent positive charge region, black circlessignify negative charge regions, and the areas mean intensities of charge area

Figure 7 shows the positive charge area is always existing at the bottom of the thunder cloud. Main negative and positive charges are in the central area and the charge intensity changes significantly with time. The upper negative charge is so small that can be ignored. Furthermore, the inversion result and the observation of ground electric field show the thunder cloud has obviously hierarchical structure, which means Genetic-Newton algorithm can reflect the basic features of the thunder cloud and the triple-polarity charge structure is relatively scientific.

4.3 Comparisons with the radar echo

For the purpose of validating the charge structure has the practical value and rationality, the inversion center position of thunder cloud is analyzed with the help of the weather radar. Figure 8 shows the thunder cloud passed through the observation area from 12:00 to 13:00, which is exactly consistent with the inversion results.

Figure 9 shows the difference in the center position between the strong echo and the inversion. Clearly, the inversion results and the strongest echo are basically consistent, which means the proposed method has the great reference value like the thunderstorms forecasting and location tracking.

5 Conclusion

This article uses the data of ground electric field to study the features of charge structure inversion of thunder cloud, and further proposes an inversion method based on genetic algorithm and Newton method. Assuming that the spherically symmetric multilayer model is feasible, the simulation shows Genetic-Newton algorithm can enhance the evolution speed and accuracy by taking advantages of the global optimization ability of genetic algorithm and local searching ability of Newton method. In addition, with the help of weather radar, the proposed method

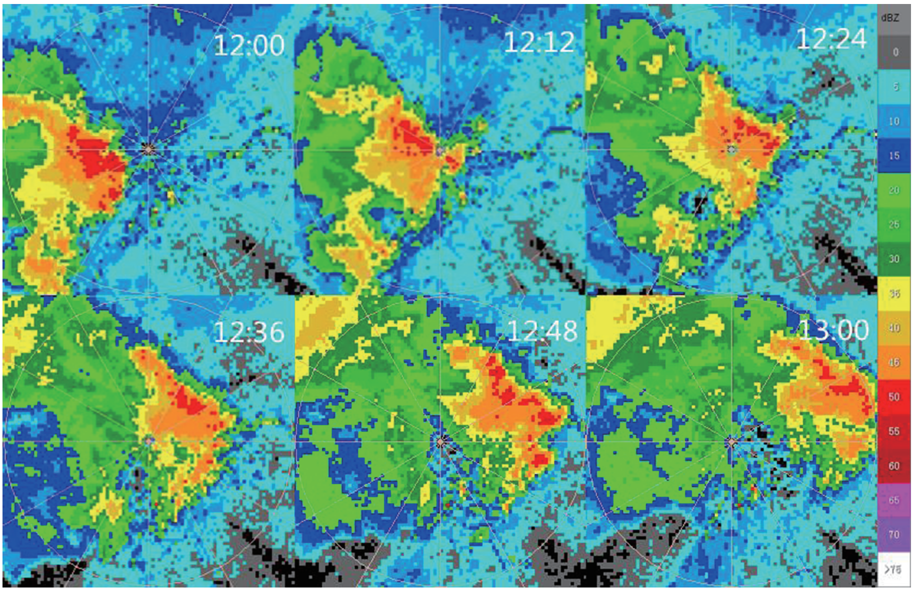

Fig. 8 The radar echo from 12:00 to 13:00

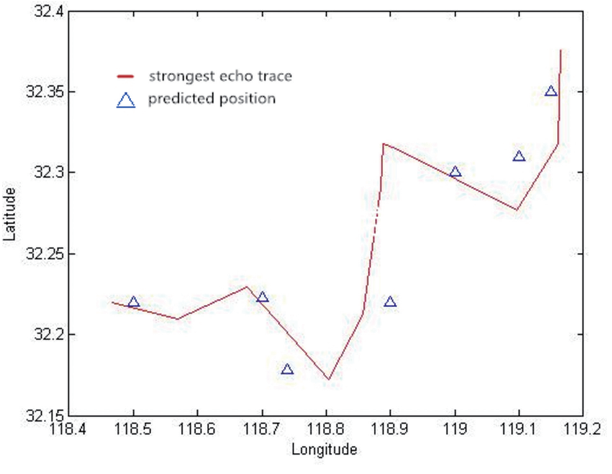

Fig. 9 The strongest radar echo traces and the invention location of thunder cloud

is applied to inverse and analyze a typical process of thunderstorms in Nanjing, and the result shows that Genetic-Newton algorithm can effectively get the global optimal values and the location of the thunder cloud, which proves the triple-polarity charge structure is still relatively simplified and scientific. As for the inversion, eight atmospheric electric field instruments are used to ensure the validity, and the next work is to consider more about the influence of geographical environment. On the other hand, the increase of the layer number of charge might help to understand the more complex process of thunderstorms, so as to achieve the regional independent lightning forecasting.

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