



# A Correlation Analysis of Geomagnetic Field Characteristics in Geomagnetic Perceiving Navigation

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It is well-known that geomagnetic fields have multiple components or parameters, and that these geomagnetic parameters are related to each other. In this paper, a parameter selection method is proposed, and this paper mainly discusses the correlation of geomagnetic field parameters for geomagnetic navigation technology. For the correlation analysis between geomagnetic parameters, the similarity calculation of the correlation coefficient is firstly introduced for geomagnetic navigation technology, and the grouped results are obtained by data analysis. At the same time, the search algorithm (Hex-path algorithm) is used to verify the correlation analysis results. The results show the same convergent state for the approximate correlation coefficient. In other words, the simulation results are in agreement with the similarity calculation results.

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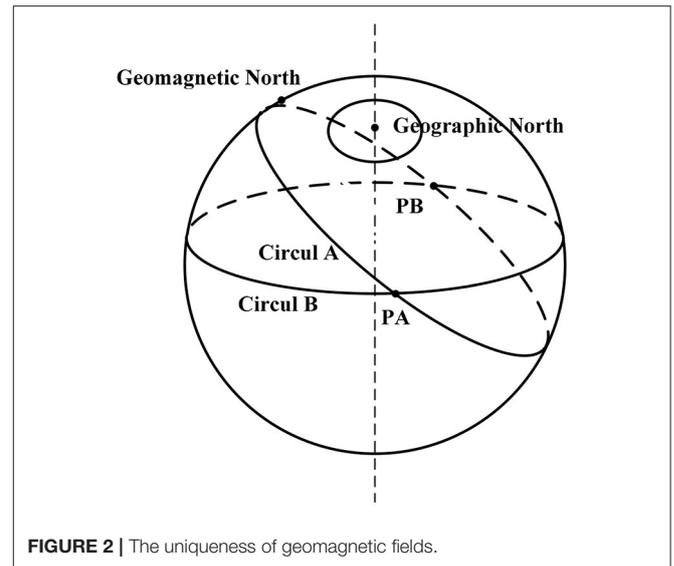
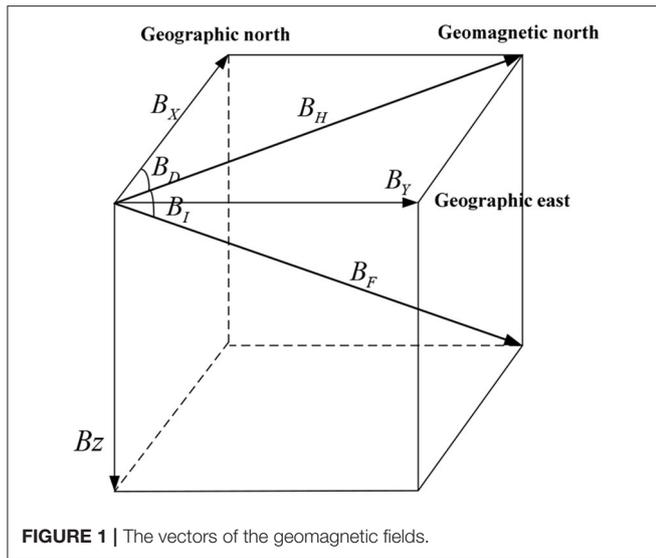
**Keywords:** animal geomagnetic perception, geomagnetic navigation, correlation analysis, hexpath algorithm, word magnetic model, world magnetic model

## INTRODUCTION

Lots of evidence has indicated that many kinds of animals can achieve long-distance and goal-oriented navigation without pinpoint accuracy (Walker et al., 2002). This is due to the existence of the 'geomagnetic sense' (Walker et al., 1997). Kramer states that animals could firstly determine their position relative to the goal and set the course for their goal by the Earth's geomagnetic field (Kramer, 1953). It is reported that pigeons and sea turtles can reach a destination by sensing geomagnetic information (Rodda, 1984; Dennis et al., 2007). These animals can locate homing and foraging areas depending on their perception of the geomagnetic field.

Geomagnetic fields are a very important cue for navigation by these animals (Zhang et al., 2019). At any point on the Earth's surface, geomagnetic fields can be described as vectors in three-dimensional space (see **Figure 1**). It is fairly well-known that the fields are derived from sources in the core and crust of the Earth, and the total geomagnetic field vectors have seven components, which can be resolved into the north component  $B_X$ , the east component  $B_Y$ , the vertical component  $B_Z$ , the horizontal component  $B_H$ , the total intensity component  $B_F$ , the declination angle component  $B_D$ , and the inclination angle component  $B_I$ . Thus, geomagnetic fields can provide very stable information about a location which animals can use to navigate.

Geomagnetic navigation technology can provide a reliable navigation method by measuring geomagnetic fields for mobile robots, such as underwater vehicle navigation (AUV) (Kinsey et al., 2006) and unmanned aircraft (UA) (Yuan et al., 2011; Kebria et al., 2020). Conventional geomagnetic navigation methods mainly focus on geomagnetic matching algorithms, which mainly



include the Mean Absolute Difference algorithm (MAD) (Caifa et al., 2011), Mean Square Difference algorithm (MSD) (Rong, 2016), and Iterative Closest Contour Point algorithm (ICCP) (Lin et al., 2007; Xiao et al., 2019; Luo et al., 2021a). However, the conventional matching methods mainly depend on a priori geomagnetic map. There is a problem with the mentioned methods that the geomagnetic map needs to be drawn in advance (Ge and Zhou, 2007). To avoid any dependency on a priori geomagnetic map, the geomagnetic perceiving navigation method is proposed.

To satisfy the practical demand of geomagnetic navigation, the selection methods of characteristic components for geomagnetic matching were proposed based on statistical modeling (Qiao et al., 2007; Wei et al., 2010; Shang et al., 2019). The correlation research on the geomagnetic field parameters is indispensable for geomagnetic perceiving navigation, which introduced a new selection method for geomagnetic field parameters. We know that getting the right geomagnetic parameters affects the navigation result, and it is still important for navigational efficiency. This paper mainly discusses the correlation of geomagnetic field parameters for geomagnetic perceiving navigation technology.

In this paper, the similarity calculation based on the geomagnetic characteristics is a data association technology. For the correlation analysis between the geomagnetic parameters, the similarity calculation of the correlation coefficient is firstly introduced for geomagnetic perceiving navigation technology. Therefore, the correlation coefficient is calculated between the geomagnetic parameters, at the same time, the search algorithm (Hex-path algorithm) is used to verify the correlation analysis results. Simulation results of three cases are analyzed, and we can conclude that the same convergent state for the approximate correlation coefficient is apparent. In other words, the simulation results are in agreement with the similarity calculation results. In the future, we will focus on the research of geomagnetic perceiving navigation methods, and the present study is the

preliminary preparation and the theoretical foundation for the follow-up work.

The rest of this paper is structured as follows: in section Correlation analysis on geomagnetic field parameters, the correlation analysis on the geomagnetic field parameters is introduced, and the results are given. In section Problem formulation of geomagnetic perceiving navigation, the search problem of geomagnetic perceiving navigation is raised. Next, the Hex-path algorithm is adopted in section Algorithm verification. Then, the simulation is introduced in section Results. Finally, the conclusion is given in section Conclusion.

## CORRELATION ANALYSIS ON GEOMAGNETIC FIELD PARAMETERS

Geomagnetic fields can be divided into two categories: geomagnetic intensity and geomagnetic angle. The geomagnetic intensity is mainly composed of the total geomagnetic intensity ( $B_F$ ), the horizontal intensity ( $B_H$ ), the north component ( $B_X$ ), the east component ( $B_Y$ ), and the vertical component ( $B_Z$ ). The geomagnetic field angle is mainly composed of the geomagnetic declination angle  $B_D$  and the geomagnetic inclination angle ( $B_I$ ) (Zhao et al., 2014). Choosing suitable geomagnetic field parameters is the key to realizing geomagnetic perceiving navigation. Therefore, the selected geomagnetic parameters must have distinct statistical characteristics in the navigation area with high recognition and rich feature information.

If the Earth's geomagnetic field is an ideal magnetic dipole field, there will be two intersections PA and PB (see **Figure 2**) between the two geomagnetic contours in the whole Earth range, indicating that the geomagnetic components on these two points are the same (Jiang and Ran, 2011). It can be seen that only two geomagnetic characteristics fail to determine a unique geographical location on the Earth surface.

Therefore, several geomagnetic characteristics are needed as geomagnetic parameters to ensure the unique position of the Earth surface.

The geomagnetic fields have seven parameters. There is a correlation between geomagnetic field parameters. In order to uniquely determine a position, we need to consider the independence of the three parameters from the seven vectors of the geomagnetic fields. Therefore, it is necessary to research the similarity degree of the seven vectors.

In essence, the similarity calculation based on the geomagnetic characteristics is a data association technology. The similarity between the geomagnetic characteristics mainly reflects the correlation of their variation characteristics. Therefore, the correlation coefficient is calculated by the similarity between multiple geomagnetic parameters, which are needed to take into account the global variation characteristics of the geomagnetic fields.

The data similarity calculation methods, which are commonly used in data association technology, mainly include the cosine similarity, the modified cosine similarity, and the correlation coefficient similarity (Saito et al., 1999; Luo et al., 2021b).

The three data similarity methods are followed as:

(i) The cosine similarity method can be described as:

$$r_{ij} = \cos(R_i, R_j) = \frac{\sum_{i \neq j, i, j=1}^n r_i r_j}{\sqrt{[\sum_{i=1}^n r_i^2] [\sum_{j=1}^n r_j^2]}} \quad (1)$$

where  $R_i$  and  $R_j$  are the vector-evaluated parameters, respectively.

(ii) The modified cosine similarity method can be described as:

$$r_{ij} = \text{Adjust cos}(R_i, R_j) = \frac{\sum_{i \neq j, i, j=1}^n (r_i - \bar{r})(r_j - \bar{r})}{\sqrt{[\sum_{i=1}^n (r_i - \bar{r})^2] [\sum_{j=1}^n (r_j - \bar{r})^2]}} \quad (2)$$

where  $\bar{r}$  is the evaluation value of the vector-evaluated parameters.

(iii) The correlation coefficient similarity method can be described as:

$$r_{ij} = \text{Adjust cos}(R_i, R_j) = \frac{\sum_{i \neq j, i, j=1}^n (r_i - \bar{r}_i)(r_j - \bar{r}_j)}{\sqrt{[\sum_{i=1}^n (r_i - \bar{r}_i)^2] [\sum_{j=1}^n (r_j - \bar{r}_j)^2]}} \quad (3)$$

where  $\bar{r}_i$  and  $\bar{r}_j$  are the evaluation values of the vector-evaluated parameters  $r_i$  and  $r_j$ , respectively.

For the correlation analysis between the geomagnetic characteristics, the similarity calculation method of the correlation coefficient is firstly adopted. This paper proposes a method to calculate the similarity between several parameters by

Euclidean distance. Therefore, the similarity calculation between geomagnetic characteristics can be expressed as follows:

$$r_{XY} = \frac{\sum_{i \neq j, i, j=1}^n (x_i - \bar{x})(y_j - \bar{y})}{\sqrt{[\sum_{i=1}^n (x_i - \bar{x})^2] [\sum_{j=1}^n (y_j - \bar{y})^2]}} \quad (4)$$

where  $X = (x_1, x_2, \dots, x_n)$  and  $Y = (y_1, y_2, \dots, y_n)$  are two parameter sequences,  $\bar{x}$  and  $\bar{y}$  are the evaluation values of the two parameter sequences, and  $r_{XY}$  is the correlation coefficient between two geomagnetic parameters,  $-1 \leq r_{XY} \leq 1$ .

According to the correlation coefficient calculation method of data association, the degree of correlation between parameters can be divided into the following categories (Kong et al., 2012; Hu et al., 2019, 2020; Wu et al., 2020; Luo et al., 2021c):

- (1) If  $r_{XY} < 0.3$ , the two parameters are irrelevant;
- (2) If  $-0.3 \leq r_{XY} < 0.5$ , the two parameters have a low degree of linear correlation;
- (3) If  $-0.5 \leq r_{XY} < 0.8$ , the two parameters are indicating significant linear correlation;
- (4) If  $0.8 \leq r_{XY}$ , the two parameters generally have highly linear correlation.

According to the distribution characteristics of geomagnetic parameters, the geomagnetic parameters  $B_X$ ,  $B_Y$ , and  $B_Z$  are different and independent from each other, so the correlation coefficient between the three parameters is 0 in theory.

If the correlation coefficient of any two geomagnetic parameters among the seven geomagnetic parameters is much larger than the correlation coefficient of the above three ( $r_{XY} \geq r_{B_X \leftrightarrow B_Y}$ ,  $r_{XY} \geq r_{B_X \leftrightarrow B_Z}$ ,  $r_{XY} \geq r_{B_Y \leftrightarrow B_Z}$ ), then the two parameters have high similarity, and these parameters with high correlation coefficients are usually grouped into a class.

The data analysis from the World Magnetic Model (WMM2015) (Russell, 2004; Chulliat et al., 2015; Hu et al., 2021) pointed out the correlation of geomagnetic components on the Earth surface. For simplification of data statistics, the seven geomagnetic characteristics in the northern hemisphere of the Earth are taken as examples. The northern hemisphere is divided into the first quadrant I and the second quadrant II (see **Figure 3**).

The correlation coefficient of any two geomagnetic parameters can be calculated from the World Magnetic Model database, and the results indicate that the seven parameters of the first and second quadrants of the northern hemisphere are divided into three groups as shown in **Table 1**.

In geomagnetic perceiving navigation, the greater the correlation coefficient value between geomagnetic parameters, the higher the degree of the linear correlation between the two parameters, which can be equated to one category. As for the selection of the geomagnetic parameters, it is advisable to choose one with a small correlation coefficient.

According to the above analysis, the correlation of the geomagnetic parameters should be considered when selecting the geomagnetic parameters for navigation search. In other words, the geomagnetic components should

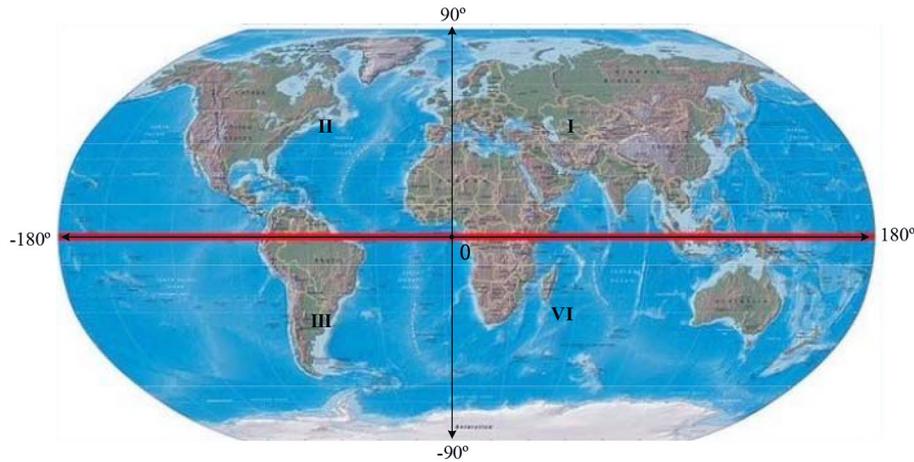


FIGURE 3 | The map of the Earth's magnetic field.

TABLE 1 | The correlation statistical results of geomagnetic parameters.

Components	Correlation	Value
$(B_X \ B_H)$	$r_{B_X \leftrightarrow B_H}$	0.9998
$(B_Y \ B_D)$	$r_{B_Y \leftrightarrow B_D}$	0.8365
$(B_Z \ B_I \ B_F)$	$r_{B_Z \leftrightarrow B_I}$ & $r_{B_Z \leftrightarrow B_F}$ & $r_{B_I \leftrightarrow B_F}$	0.9756 & 0.9666 & 0.8992

be selected from the three groups, respectively, such as  $(B_X \ B_Y \ B_Z)$ ,  $(B_H \ B_D \ B_I)$ ,  $(B_F \ B_D \ B_H)$ , etc.

## PROBLEM FORMULATION OF GEOMAGNETIC PERCEIVING NAVIGATION

### Mathematical Model

Geomagnetic perceiving navigation is the search process of geomagnetic multi-parameters without a priori geomagnetic map. It indicates that an agent could only perceive the variation of the geomagnetic parameters to reach the destination by a geomagnetic sensor. The search behavior is the response to the geomagnetic environment stimuli, and its physical significance is that the geomagnetic multi-parameter could only determine geographic locations on the Earth (Liu et al., 2014). The process of geomagnetic perceiving navigation is the convergence process of the geomagnetic parameters from the start location to the target location. When the geomagnetic parameters converge to zero, it indicates that the agent has finished the navigation task. Therefore, the multi-objective convergence process can be considered as:

$$\begin{cases} \min F(k) = (f_1(B,k), f_2(B,k), \dots, f_n(B,k)) \\ \text{s.t.} : t_i = g_i(B, \theta^k) \leq \delta \end{cases} \quad (5)$$

where  $k$  is the number of iterations,  $F(\bullet)$  is the objective function,  $f(\bullet)$  is the sub-objective

function,  $\theta^k$  is the movement direction of an agent,  $g(\bullet)$  is the constraint condition, and  $\delta$  is a preset value.

### The Normalization of the Objective Function

The search process of geomagnetic perceiving navigation presents a posteriori and temporal characteristics, and the convergence of the geomagnetic multi-parameters has a strong incentive and a restriction relationship with the motion behavior of an agent. Considering that the above process is a multi-objective posterior search, the objective function needs to be established for the optimization. Based on the characteristics of geomagnetic fields, the sub-objective function of the geomagnetic parameter search is constructed as:

$$f_i(B,k) = [B_i(t) - B_i(k)]^2, 1 \leq i \leq 7 \quad (6)$$

where  $B_i(t)$  is the  $i$ th geomagnetic parameter of the target location and  $B_i(k)$  is the  $i$ th geomagnetic parameter of the current location. There are different magnitudes and units within the geomagnetic field parameters, the objective function should be normalized as:

$$F(k) = \frac{1}{N} \sum_{i=1}^7 \frac{f_i(B,k)}{f_i(B,0)} = \frac{1}{N} \sum_{i=1}^7 \frac{[B_i(t) - B_i(k)]^2}{[B_i(t) - B_i(0)]^2} \quad (7)$$

The purpose of the geomagnetic perceiving navigation is that the objective function could converge to the optimal value in the search process, which can be expressed as:

$$\|F(k) - F(k-1)\| \leq \varepsilon \quad (8)$$

where  $\varepsilon$  is a preset value.

Based on the above description, the geomagnetic perceiving navigation problem could be generalized as the multi-objective

posterior search problem, by calculating the objective function to find the optimal solution.

### ALGORITHM VERIFICATION

To analyze the correlation of the geomagnetic data, the Hex-path algorithm (Russell, 2004) will be adopted in the searching process of geomagnetic perceiving navigation. We know that the Hex-path algorithm has been used before, but only in odor source searching. The Hex-path odor searching algorithm could guide a mobile robot with a single gas sensor to search for an underground odor source. Here, the Hex-path algorithm is used

to guide toward the target of lower objective function. Although the Hex-path algorithm is applied in different fields, the essence is the same, which means are all based on a change in the objective function. The major difference between the two is the fact that the Hex-path odor searching algorithm is guided toward regions of higher objective function. The reason for using this algorithm is the fact that it is simple and easy to implement step-by-step.

The Hex-path algorithm is implemented in the following steps:

**Step 1: Heading initialization.** Randomly generate a number of  $N$  initial individuals in the heading space  $Q$ , which can be defined as  $Q = \{\theta_i | i = 1, 2, \dots, N\}$ .  $\theta_i$  can be expressed as:

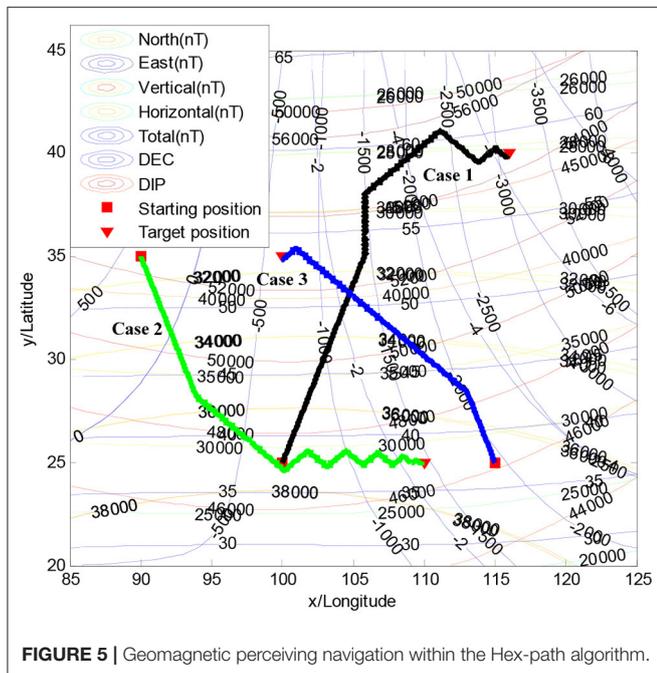
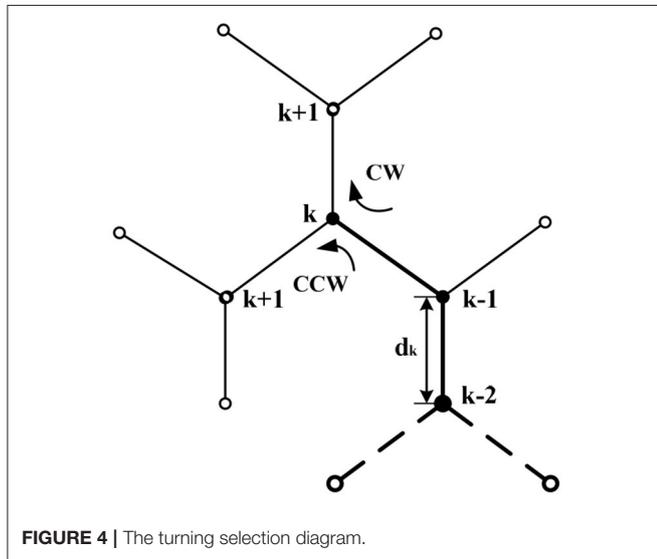
$$\theta_i = \Delta\theta \times j, j \in [1, m] \tag{9}$$

where  $m = \frac{2\pi}{\theta}$  and  $\Delta\theta$  is the sampling interval.

**Step 2: Heading selection.** Randomly select the sample  $\theta_i$ , and the probability of each selection is given by:

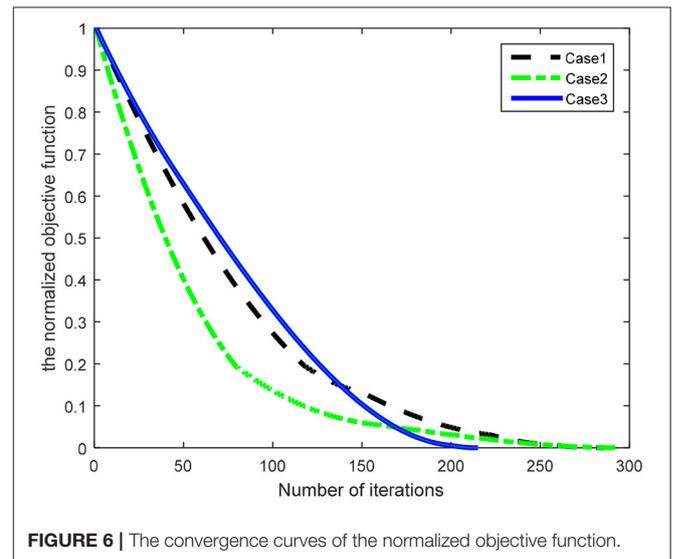
$$p(\theta_i) = \frac{1}{N} \tag{10}$$

**Step 3: Heading updating rule.** The objective function has been calculated at points  $(k - 2)$  and  $(k - 1)$ . If the objective function at  $(k - 1)$  decreases, it means that the target position is close to the right, and turning  $\Delta\theta$  to the clockwise (CW) direction could be performed. Otherwise, turning  $\Delta\theta$  to the counterclockwise



**TABLE 2 |** Setting navigation parameters.

No	Parameters	Size
1	$\Delta\theta$	60°
2	$\epsilon$	0.001
3	$\delta$	0.05
4	$d_k$	10 km



(CCW) direction could be performed. The heading updating rule is shown in **Figure 4**.

$$\begin{cases} \theta^{k+1} = \theta^k - \Delta\theta, \text{if } F(k-1) \leq F(k-2) \text{ and } d\theta < 0 \\ \theta^{k+1} = \theta^k + \Delta\theta, \text{if } F(k-1) > F(k-2) \text{ and } d\theta > 0 \end{cases} \quad (11)$$

where  $d\theta = \theta^k - \theta^{k-1}$ .

**Step 4: Terminate condition.** If the search algorithm meets the termination condition (12), the search algorithm will terminate; otherwise go to step (3) above.

$$\begin{cases} \|F(k) - F(k-1)\| \leq \varepsilon \\ \mathbf{0} \leq \mathbf{g}_i(\mathbf{B}, \theta^k) \leq \delta \end{cases} \quad (12)$$

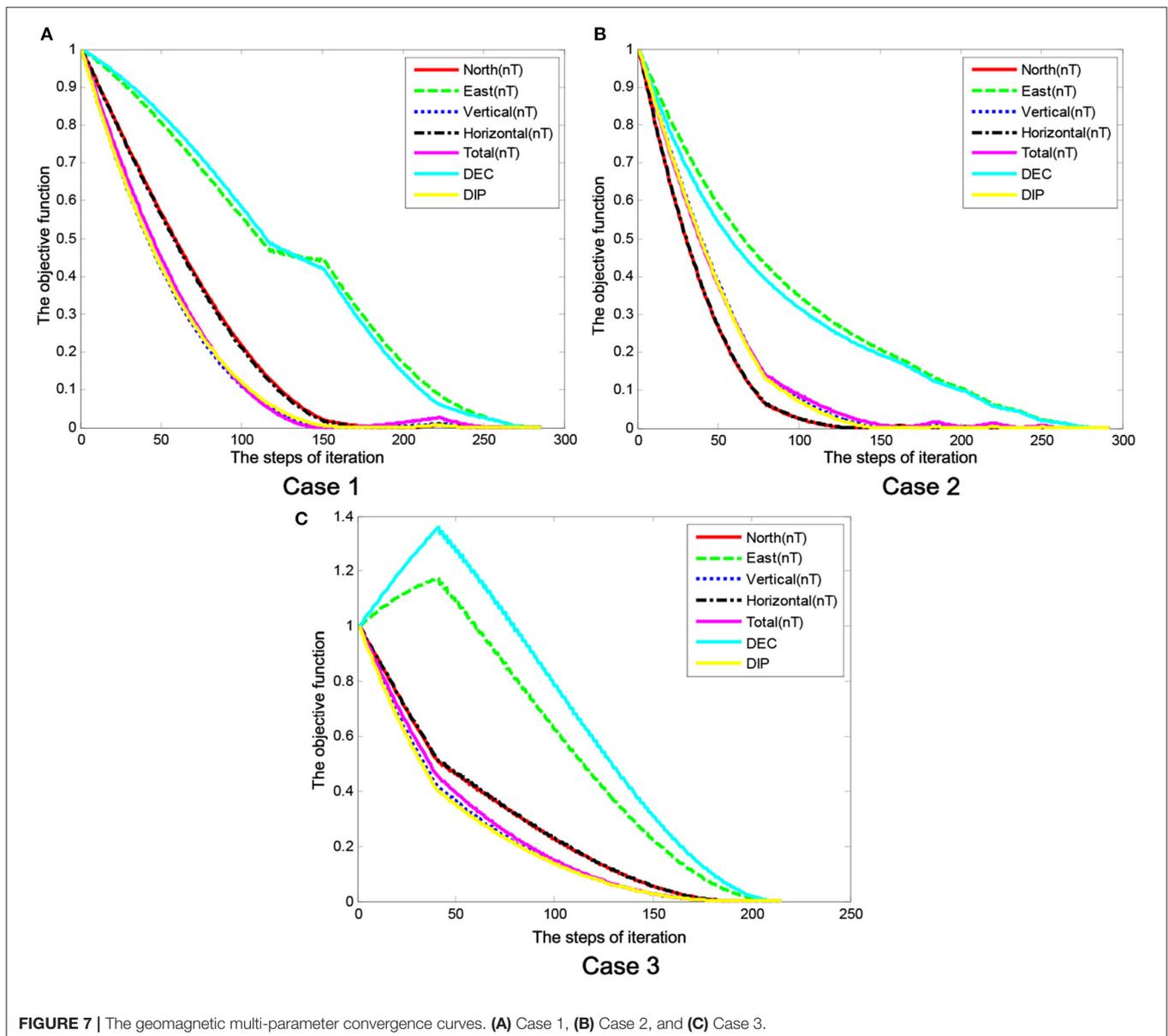
## RESULTS

To show the correlation of geomagnetic field characteristics, numerical simulations are implemented.

### Simulation Setup

The World Magnetic Model (WMM2015) is used to provide real-time geomagnetic data. Simulations have been carried out based on the seven physical fields.

In simulations, we choose a rectangular area from 20° north latitude and 85° west longitude (20N, 85W) to 45° north latitude and 125° west longitude (45N, 125W). In this scenario, the starting position is the red square “□,” and the target position is the red triangle “▽,” which are depicted in **Figure 5**. The simulation parameter are listed in **Table 2**.



## Simulation Results

To demonstrate the effectiveness of the Hex-path algorithm, several simulation results are given in this paper. As presented in **Figure 5**, three different starting positions and target positions are randomly selected.

**Figure 5** illustrates the searching trajectory of the Hex-path algorithm, where the heading is updated continuously depending on the objective function at  $k$  and  $k - 1$ . The searching results of the Hex-path algorithm present a good global search capability.

**Figure 6** illustrates the convergence property of the normalized objective function in three cases, from which we can see that the number of iterations is 286, 292, and 215 for the Hex-path algorithm, respectively. The results show that the Hex-path algorithm could converge to a stable state.

The similarity in the number patterns of the normalized objective function shows the robustness of the Hex-path algorithm mentioned above. **Figure 6** illustrates the steady states of the seven geomagnetic parameters.

## Analysis of the Results

**Figure 7** shows the convergence property of the geomagnetic multi-parameter, wherein **Figure 7A** represents the above Case 1, **Figure 7B** represents the above Case 2, and **Figure 7C** represents the above Case 3. The convergence curves of the sub-objective function show a significant difference between the multi-parameters.

As can be seen in **Figure 7**, the variation rules of the geomagnetic multi-parameters reflect the correlation on the geomagnetic field parameters, where the north geomagnetic field component  $B_X$  and the horizontal magnetic field component  $B_H$  show the same convergent state of change, the east geomagnetic field component  $B_Y$  and the declination angle  $B_D$  show the same convergent state of change, and the vertical geomagnetic field component  $B_Z$ , the inclination angle  $B_I$ , and the total intensity  $B_F$  show the same convergent state of change. Meanwhile, the same results can be seen in **Table 1**.

From the above analyses, we clearly see that the Hex-path algorithm ensures the desired target position depends on geomagnetic environment stimuli during the training iteration, and the learning task of each iteration also depends on those of the completed ones. The similarity in the number patterns of the objective function shows the consistency of the convergence trend on the correlation analysis results mentioned above.

## CONCLUSION

This paper discusses the correlation of geomagnetic field parameters, and the simulations show the same results as

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in **Table 1**. The results show the same convergent state for the approximate correlation coefficient. In other words, the approximate correlation coefficient between the geomagnetic parameters can be regarded as one class. The correlation study on geomagnetic field parameters is crucially important for geomagnetic navigation technology and introducing the selection and application of geomagnetic field parameters.

In the future, we will focus on the research of geomagnetic perceiving navigation methods, but the study of the correlation of geomagnetic field parameters is very necessary for geomagnetic perceiving navigation technology. We know that getting the right geomagnetic parameters might affect the navigation result, and it is still important for navigational efficiency. Therefore, this paper mainly discusses the correlation of geomagnetic field parameters for geomagnetic perceiving navigation technology. The present study is the preliminary preparation and the theoretical foundation for the follow-up work.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

HL, JQ, XJ, and YN designed and established the theoretical model. HL wrote the paper and performed the experiments. JQ provided some ideas to improve and perfect the paper. YN analyzed the data. XJ reviewed and edited the manuscript. All authors read and approved the manuscript.

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