A Wave Beam Interlocking Model and Simulation Based on Position Information Interaction

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Abstract. Aiming at the problem of wave beam interlock in directional antenna communication of aviation swarm, a mathematical model of wave beam interlock based on position information interaction is established. The core idea of this model is to transform the position information of the local machine and other machines into the wave beam direction of directional antenna through a series of coordinate transformations, so as to realize wave beam interlocking. This paper analyzes the source of the precision error of wave beam interlock in mathematical model, emphatically demonstrates the precision error of attitude measurement, and gives the error boundary conditions to maintain normal communication. Finally, the computer simulation of the mathematical model and error sources proves the validity of the mathematical model and the correctness of the error analysis. The model is simple, reliable and practical.

Keyword: Directional antenna pass, mathematical model, computer simulation.

1. Introduction

In aviation swarm communication, the narrow wave beam of directional antenna can produce the pattern characteristics with high gain and low sidelobe, which greatly improves the communication distance and anti-jamming ability, and effectively reduces the interception probability [1-2]. Although directional antenna has many advantages, the directivity of its wave beam signal also brings many difficulties to wireless network design. The biggest difference between directional communication and omni-directional communication is that directional communication requires antenna wave beam alignment, that is, wave beam interlocking, and communication can be achieved within a certain range of alignment accuracy, otherwise communication will fail [3]. At present, the research mainly focuses on the directional antenna communication in the static state [4]. With the development of 5G technology and the application of Massive MIMO technology, although there are some research results for mobile communication, the mobile terminal is an omni-directional antenna [5-8]. Literature [9] proposed an aperture alignment technology based on the main missile control, which is used in the missile-borne directional data link communication system. The model is mainly point-to-point communication. Literature [10] focuses on the networking protocol of UAV directional communication, and proposes a pure directional time division multiple access protocol, which does not involve the wave beam alignment mechanism of directional antenna. For aviation mobile communication, due to the three-dimensional mobility of communication nodes, higher requirements are put forward for wave beam interlocking, which leads to the failure of some directional communication algorithms. Therefore, we must first solve the problem of communication wave beam interlocking under the condition of high maneuvering narrow wave beam.

In this paper, the antenna pointing model of wave beam interlock and the accuracy error analysis of wave beam interlock in aviation cluster directional antenna communication are studied, and the effectiveness and feasibility of the proposed method are verified by computer simulation and experiment, which provides support for high-quality wireless communication of directional antenna.

2. Wave beam interlocking system model

The wave beam interlocking algorithm of aviation trunked directional communication adopts the wave beam interlocking algorithm based on location information interaction. On the aviation platform, it is assumed that space full coverage communication is completed through multiple directional antennas. When two nodes communicate bilaterally, the nodes participating in communication can be abstracted into a cuboid with sides of a, b and c. The center of each antenna is located at the center of six planes. Assuming that the center of the antenna plane of the data sender is D_1, this plane is called Plane A, the center of the antenna plane of the data receiver is D_2, and the corresponding plane is called Plane B.As shown in Figure 1, let the normal vector of the data receiver antenna plane be $\vec{r_1}$ and the normal vector of the data transmitter antenna plane be $\vec{r_2}$. The angle between normal vector $\vec{r_1}$ and vector $\overrightarrow{D_1D_2}$ is α_1, and the angle between normal vector $\vec{n_2}$ and vector $\overrightarrow{D_2D_1}$ is α_2.

If the actual coverage of antenna signal is a cone with half vertex angle of β_1 and the maximum deflection angle of the antenna plane is β_2, the coverage of antenna signal is a cone with half vertex angle of $\beta = \beta_1 + \beta_2$. To realize the data transmission between two antennas, the connection line $\overrightarrow{D_2D_1}$ must be located in a cone with D_2 as the vertex, $\vec{r_2}$ as the axis and half vertex angle of β, that is

$$< \vec{r_2}, \overrightarrow{D_2D_1} >= \alpha_2 \le \beta \tag{1}$$

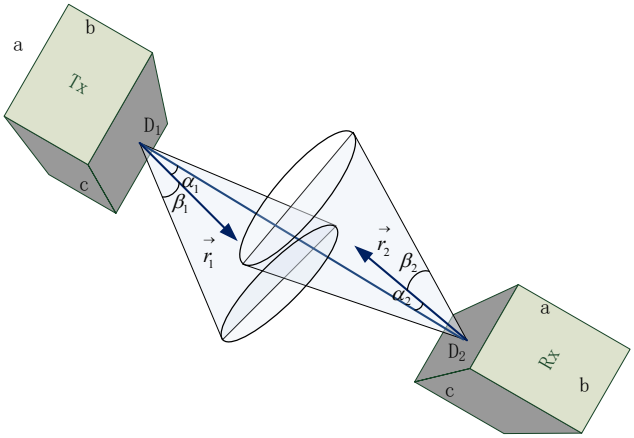


Figure 1. Schematic diagram of bilateral communication between two nodes of air platform

Similarly, the connection line $\overrightarrow{D_1D_2}$ must be located in a cone with D_1 as the vertex, $\vec{r_1}$ as the axis and half vertex angle of β, that is

$$< \vec{r_1}, \overrightarrow{D_1D_2} >= \alpha_1 \le \beta \tag{2}$$

In order to achieve better communication effect, the distance between the two antennas involved in communication should be less than a critical value R. If the distance is greater than R, it is considered that communication fails, so there are

$$\left|\overrightarrow{D_1D_2}\right| \le R \tag{3}$$

To sum up, equation (1), equation (2) and equation (3) constitute the necessary and sufficient conditions for data exchange between two antennas. According to the six parameters (position and attitude angle) of the aircraft participating in communication, the corresponding coordinates of the two antenna centers D_1 and D_2 and the normal vectors $\vec{r}_1$ and $\vec{r}_2$ of the antenna plane are calculated, further calculate the two included angles α_1, α_2 and the distance $\left|\overrightarrow{D_1D_2}\right|$, and determine whether the communication between two computers can be realized according to equations (1), (2) and (3). If there are multiple pairs of antennas that can communicate, they can be selected according to the principle of angle or distance priority.

The flow chart of the wave beam interlocking algorithm is shown in Figure 2. In the algorithm, four coordinate systems are defined to be transformed into roll, azimuth and pitch angle based on aperture coordinate system. The related coordinate systems include: aperture coordinate system (A system), airframe coordinate system (front, top, right, B system), local navigation coordinate system (N system), geocentric geodetic rectangular coordinate system (E system).

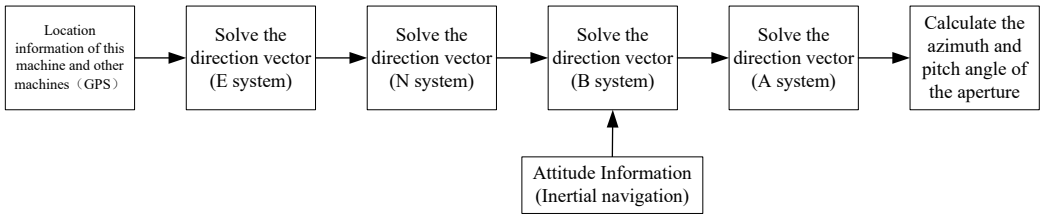


Figure 2. Flow chart of wave beam interlocking algorithm

Definition 1: The direction cosine matrix from aperture coordinate system to airframe coordinate system is $\boldsymbol{C}_a^b$, while the direction cosine matrix from airframe coordinate system to aperture coordinate system is $\boldsymbol{C}_b^a$. The directional cosine matrix is related to the actual installation position of the aperture. Assuming temporarily that the antenna axis is consistent with the direction of the aircraft head, then

$$\boldsymbol{C}_b^a = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}, \boldsymbol{C}_a^b = \boldsymbol{C}_b^{aT} \tag{4}$$

Definition: The direction cosine matrix from system B to system N is $\boldsymbol{C}_b^n$, while that from system N to system B is $\boldsymbol{C}_n^b$.The specific value of the direction cosine matrix is determined by the output of the inertial navigation system. Let the yaw angle, roll angle and pitch angle of the inertial navigation output be expressed as α, β and γ (in degrees) respectively, which are all Euler angles, then:

$$\boldsymbol{C}_n^b = \boldsymbol{C}_k^b \boldsymbol{C}_j^k \boldsymbol{C}_n^j \tag{5}$$

The equation includes:

$$\boldsymbol{C}_n^j = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \boldsymbol{C}_j^k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \cos\beta \\ 0 & -\sin\beta & \cos\beta \end{bmatrix} \quad \boldsymbol{C}_k^b = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$\boldsymbol{C}_b^n = \left[\boldsymbol{C}_n^b\right]^T = \begin{bmatrix} \cos\beta\cos\alpha & -\cos\gamma\sin\alpha + \sin\gamma\sin\beta\cos\alpha & \sin\gamma\sin\alpha + \cos\gamma\sin\beta\cos\alpha \\ \cos\beta\sin\alpha & \cos\gamma\cos\alpha + \sin\gamma\sin\beta\sin\alpha & -\sin\gamma\cos\alpha + \cos\gamma\sin\beta\sin\alpha \\ -\sin\beta & \sin\gamma\cos\beta & \cos\gamma\cos\beta \end{bmatrix} \tag{6}$$

Definition: The direction cosine matrix from N to E is $\boldsymbol{C}_n^e$, while the direction cosine matrix from E to N is $\boldsymbol{C}_e^n$. The direction cosine matrix needs to be calculated according to the local GPS data (longitude and latitude). Definitions φ_{lo} and φ_{la} respectively represent the current longitude and latitude (in degrees) of the local computer, then

$$\boldsymbol{C}_e^n = \begin{bmatrix} -\sin\varphi_{lo} & \cos\varphi_{lo} & 0 \\ -\sin\varphi_{la}\cos\varphi_{lo} & -\sin\varphi_{la}\sin\varphi_{lo} & \cos\varphi_{la} \\ \cos\varphi_{la}\cos\varphi_{lo} & \cos\varphi_{la}\sin\varphi_{lo} & \sin\varphi_{la} \end{bmatrix} \tag{7}$$

$$\boldsymbol{C}_n^e = \left[\boldsymbol{C}_e^n\right]^{-1} = \left[\boldsymbol{C}_e^n\right]^T \tag{8}$$

GPS information is produced by geocentric geodetic rectangular coordinate system (E system). According to the GPS information of this machine and other machines, the processor first calculates the direction vector E based on the geocentric geodetic rectangular coordinate system, and then after three coordinate transformations, finally generates the direction vector A based on the aperture coordinate system. As shown in equation (9).

$$\boldsymbol{A} = \boldsymbol{C}_b^a \times \boldsymbol{C}_n^b \times \boldsymbol{C}_e^n \times \boldsymbol{E}^T \tag{9}$$

Finally, from the direction vector A, the azimuth angle of the aperture is ϕ (degree) and the pitch angle is θ (degree), and the control instruction is given to complete the wave beam mutual pointing. The calculation method of direction vector A in rectangular aperture coordinate system is as follows:

Assume that the direction finding results of other aircraft in the aperture sphere coordinate system are as follows: the azimuth angle is φ (degree), the pitch angle is θ (degree), and r is the distance between two aircraft. Then the direction vector of the target in the aperture rectangular coordinate system is [11]:

$$\boldsymbol{A} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r\sin\theta\cos\varphi \\ r\sin\theta\sin\varphi \\ r\cos\theta \end{bmatrix} \tag{10}$$

On the contrary, the direction vector (x , y , z) in the rectangular coordinate system corresponds to the representation in the polar coordinate system as follows:

$$\begin{aligned} \varphi &= \begin{cases} \arccos\left(\dfrac{x}{\sqrt{x^2+y^2}}\right), & y \geq 0 \\ 2\pi - \arccos\left(\dfrac{x}{\sqrt{x^2+y^2}}\right), & y < 0 \end{cases} \\ \theta &= \arcsin(\sqrt{x^2+y^2}) \end{aligned} \tag{11}$$

Ensure that the value ranges of φ and θ are [0 60。] respectively.] and [0 60。]. If x=y=0 in A, it is equivalent to that A coincides with the Z axis of the aperture rectangular coordinate system, then let $\varphi = 0^\circ$, $\theta = 0^\circ$.

To sum up, the steps of the wave beam interlocking algorithm based on position information are as follows:

Step 1. Convert the coordinates of A and B to E coordinate system;

Step 2. Taking machine A as the origin, converting the coordinates of machine B in E system to N coordinate system to obtain vector $\overrightarrow{ab}_n$;

Step 3. Convert vector $\overrightarrow{ab}_n$ to the fuselage coordinate system of A machine to obtain vector $\overrightarrow{ab}_b$;

Step 4. Channel selection: calculate the included angle between $\overrightarrow{ab_b}$ and the maximum gain direction G_i of each antenna respectively.

$$\alpha_i = \arccos\left(\frac{(\overrightarrow{ab_b}, G_i)}{\left\|\overrightarrow{ab_b}\right\|\|G_i\|}\right)$$

Find out the minimum included angle, and the corresponding aperture channel is the desired channel.

Step 5. Direction control: convert vector $\overrightarrow{ab_b}$ into aperture coordinate system to get $\overrightarrow{ab_a}$, and then get the azimuth φ, pitch angle θ and the distance r between the two machines.

3. Error analysis of wave beam interlocking accuracy

The error sources of wave beam interlock accuracy mainly include the following: errors caused by attitude measurement accuracy, errors caused by position accuracy, errors caused by aircraft attitude disturbance, errors caused by aperture wave beam mutual pointing accuracy, errors caused by aperture wave beam jump and antenna installation accuracy. For the above errors, this paper mainly analyzes the errors caused by attitude measurement accuracy.

Attitude measurement is mainly done by inertial navigation in aviation platform. The measured values of aircraft attitude are yaw angle $\hat{\alpha}$, pitch angle $\hat{\beta}$ and roll angle $\hat{\gamma}$ respectively, and the measurement errors are $\Delta\alpha$, $\Delta\beta$ and $\Delta\gamma$ respectively, so the true values of attitude parameters are $\alpha = \hat{\alpha} + \Delta\alpha$, $\beta = \hat{\beta} + \Delta\beta$ and $\gamma = \hat{\gamma} + \Delta\gamma$ respectively. Interlocking errors caused by attitude measurement accuracy occur during the conversion from N system to B system, as shown in Figure 3.

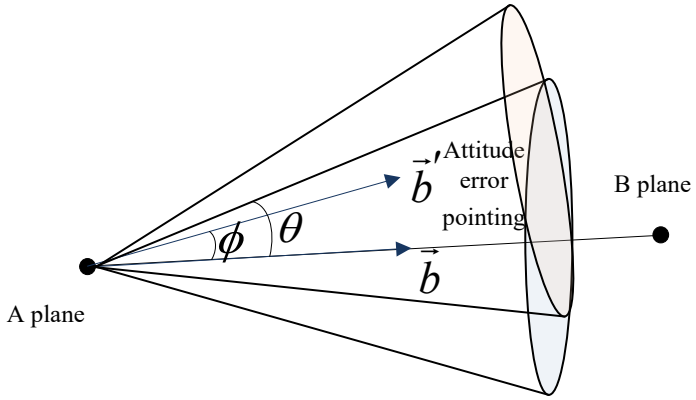


Figure 3. Analysis diagram of influence of aircraft attitude measurement error

In the analysis, it is assumed that the aircraft only has attitude measurement error and the aircraft is static. Aircraft A transmits a wave beam to aircraft B, and the antenna on aircraft A accurately points the wave beam center to aircraft B according to the measured aircraft attitude ($\hat{\alpha}, \hat{\beta}, \hat{\gamma}$), that is, the antenna wave beam center vector $\vec{b}'$ (which can be expressed as $[b_x, b_y, b_z]^T$ in the local coordinate system) is the unit vector from aircraft A to aircraft B. However, due to the measurement error, in fact, the difference between the real position vectors $AB = \vec{b}$, $\vec{b}'$ and $\vec{b}$ of the two machines is caused by the error ($\Delta\alpha, \Delta\beta, \Delta\gamma$). The relationship between $\vec{b}'$ and $\vec{b}$ can be obtained by the following coordinate system rotation operation:

(1) Firstly, the body coordinate system without attitude measurement error is rotated to coincide with the geographic coordinate system according to the precise attitude angle, and the vector $\vec{b}$ is rotated in the same way to obtain the vector $\vec{b}_0$, and the rotation matrix is recorded as R_1;

(2) Then, rotate the body coordinate system (which coincides with the geographic coordinate system) by the corresponding angle according to the attitude angle with error ($\Delta\alpha$,$\Delta\beta$,$\Delta\gamma$), and the vector $\vec{b}_0$ will rotate in the same way, thus obtaining the vector $\vec{b}'$, and the rotation matrix will be recorded as R_2 .

So there is

$$\vec{b}' = R_1 R_2 \vec{b} = R_{\text{rot}} \vec{b} \tag{12}$$

It can be seen from Figure 3 that in order to ensure that airplane B is covered in the wave beam of airplane A, the included angle between $\vec{b}'$ and $\vec{b}$ must be less than or equal to the wave beam angle ϕ, that is

$$\phi = \arccos\left(\vec{b}^{\,\mathrm{T}} R_{\text{rot}}^{\mathrm{T}} \vec{b}\right) \le \theta \tag{13}$$

4. Simulation analysis

The attitude measurement accuracy of GPS integrated inertial navigation system is as follows: heading angle error $\Delta\alpha \in [-0.15^\circ, 0.15^\circ]$, pitch angle error $\Delta\beta \in [-0.08^\circ, 0.08^\circ]$ and roll angle $\Delta\gamma \in [-0.08^\circ, 0.08^\circ]$; wave beam width index is $\theta = 6^\circ$. Assuming that wave beam edge attenuation is not considered, the system can communicate normally when the mutual pointing error of two-way antennas is $\phi < \theta$ .The maximum communication distance is 80km. The influence of the measurement accuracy error on the wave beam pointing is obtained from equation (13) by matlab simulation as shown in Figure 4.

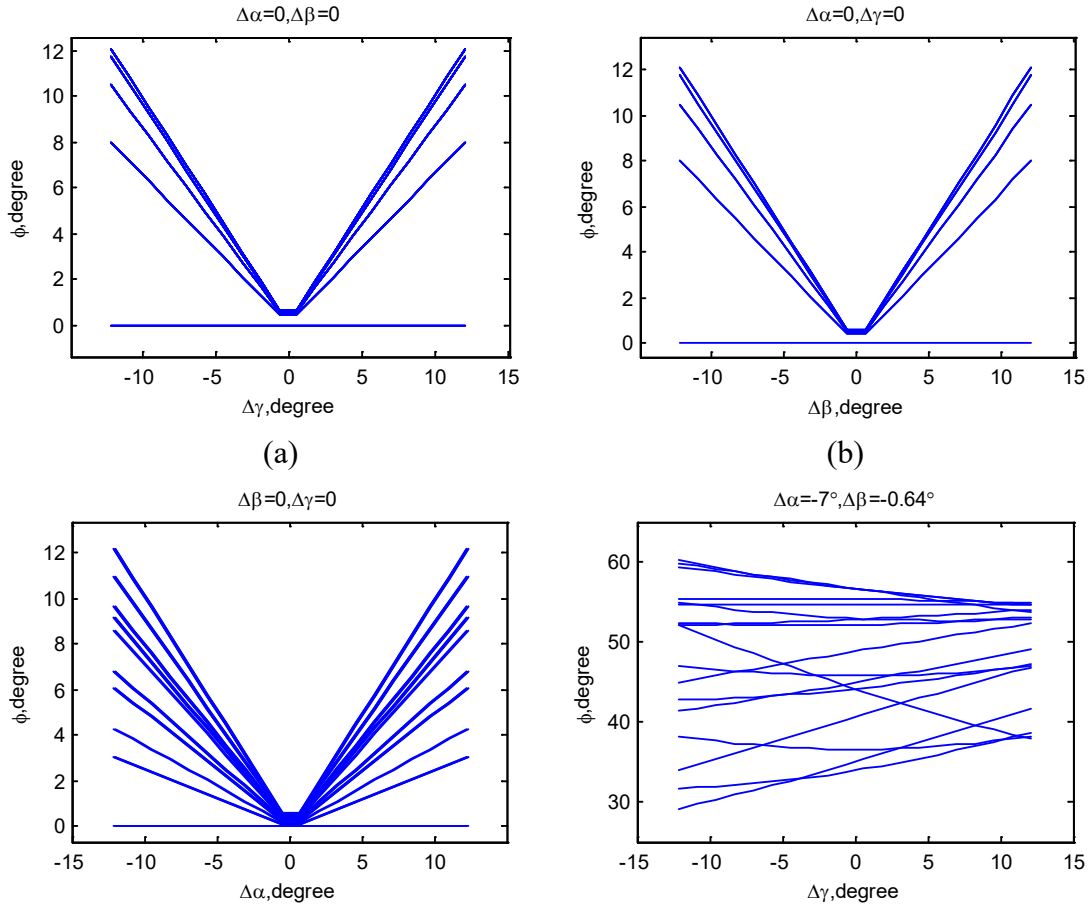


Figure 4. Influence of attitude measurement accuracy error on wave beam pointing error

Figure. 4(a) shows the relationship between ϕ and $\Delta\gamma$ when $\Delta\alpha = 0$, $\Delta\beta = 0$, $\vec{b}$ is different. The straight line with constant 0 in the figure proves that $\Delta\gamma$ has no effect on ϕ when $\vec{b}$ is parallel to the X axis. (b) It represents the relationship between ϕ and $\Delta\beta$ when $\Delta\alpha = 0$, $\Delta\gamma = 0$, $\vec{b}$ is different. The straight line with constant 0 in the figure proves that $\Delta\beta$ has no effect on ϕ when $\vec{b}$ is parallel to the Y axis. (c) It represents the relationship between ϕ and $\Delta\alpha$ when $\Delta\beta = 0$, $\Delta\gamma = 0$, $\vec{b}$ is different. The straight line with constant 0 verifies that $\Delta\alpha$ has no effect on ϕ when $\vec{b}$ is parallel to Z axis. Simulation results show that the interlocking pointing error ϕ is not only related to ($\Delta\alpha, \Delta\beta, \Delta\gamma$), but also related to $\vec{b}$. When $\Delta\alpha$, $\Delta\beta$ and $\Delta\gamma$ are not zero, the relationship between ϕ and $\Delta\alpha$, $\Delta\beta$ and $\Delta\gamma$ becomes very complicated, as shown in Figure 4(d).

Table 1 shows the influence of $\Delta\gamma$ on wave beam pointing error in four states of $\Delta\alpha$ and $\Delta\beta$ respectively. Simulation analysis shows that when the yaw angle error $\Delta\alpha$=-0.15°, the pitch angle error $\Delta\beta$=-0.08° and the roll angle error $\Delta\gamma$=-0.08°, the maximum antenna wave beam center error angle $\phi_{max} = 0.1837^0$ can be obtained. It is proved that the inertial navigation attitude measurement accuracy has little influence on the antenna beam pointing error when it is high enough.

Table 1. Influence of Inertial Navigation Attitude Measurement Accuracy Error on wave beam Pointing (unit: °)

$\Delta\alpha$ = -0.15°	$\Delta\gamma$	-0.08°	-0.07°	-0.06°	-0.05°	-0.04°	-0.03°
$\Delta\beta$=-0.08°	ϕ_{max}	0.1837656°	0.1796353°	0.1768667°	0.1746606°	0.1728600°	0.1714775°
$\Delta\alpha$ = -0.15°	$\Delta\gamma$	0.02°	0.03°	0.04°	0.05°	0.06°	0.07°
$\Delta\beta$=-0.05°	ϕ_{max}	0.1584060°	0.1604402°	0.1629093°	0.1657937°	0.1690723°	0.1730726°
$\Delta\alpha$ = 0.05°	$\Delta\gamma$	-0.03°	-0.02°	-0.01°	0°	0.01°	0.02°
$\Delta\beta$=0.06°	ϕ_{max}	0.0829847°	0.0785614°	0.0781024°	0.0781024°	0.0781024°	0.0781024°
$\Delta\alpha$ = 0.15°	$\Delta\gamma$	0.03°	0.04°	0.05°	0.06°	0.07°	0.08°
$\Delta\beta$=0.08	ϕ_{max}	0.1714620°	0.1728415°	0.1746406°	0.1768468°	0.1795978°	0.1837237°

5. Conclusions

This paper mainly studies the wave beam interlocking algorithm of directional antenna, the accuracy error analysis and simulation of wave beam interlocking, etc. Firstly, the principle of wave beam interlocking based on position information interaction is introduced. The factors causing the error of wave beam interlocking accuracy are analyzed, and the influence of the error of attitude measurement accuracy on wave beam pointing is emphatically analyzed, which lays a good foundation for realizing high-quality wireless communication of directional antenna. Computer simulation proves that the method proposed in this paper has high application value.

Acknowledgments

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