Single-Satellite Interference Source Locating Based on Four Co-efficiency Beam

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Abstract. With the previous method based on the signal strength of the three-beam interference source [1], after studying and deriving the antenna gain pointing model, this paper proposes a single-star interference source localization method based on the signal strength of the four-beam interference source. As for solving the nonlinear directional equations, this paper proposes an improved particle swarm optimization algorithm to obtain its numerical solution, which is compared with the previous ordinary particle swarm optimization algorithm [2]. Then, using the least square method, the multi-group data is used to determine the interference source with the smallest error. First orientation and then positioning. After the simulation test of the proposed positioning method, the feasibility of the algorithm for positioning is proved. The method proposed in this paper is compared with the previous positioning method to prove the robustness of the algorithm.

Keywords: Satellite communication · Interference source locating · Swarm optimization algorithm · Antenna gain pointing model

1 Introduction

Whether in daily life or in special activities such as wild patrols, military operations, earthquake relief, and other special activities, mobile communication systems are essential for communication. The satellite mobile communication system has the characteristics of wide coverage, good reliability and no geographical limitation, which makes up for the shortcomings of the ground mobile communication system and improves the robustness and reliability of the communication system [3]. Internationally, the development of satellite mobile communication systems is very rapid, a number of global or regional mobile communication systems including Iridium, Eurostar and international mobile communication satellite systems have been established. In personal communications, maritime transportation, satellite mobile communication systems are widely used

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and providing an effective means of communicating in all terrain conditions. With the continuous development of satellite communication technology, more and more spectrum resources are used, and the interference received by satellites is increasing [4]. In the military and civilian fields, the positioning of satellite interference sources has always been a hot issue. The single-satellite interference source of the geosynchronous orbit multi-beam satellite has a small Doppler shift due to its operation in the geosynchronous orbit, and can only be positioned by a single star, and the commonly used satellite positioning method cannot be used. The interference source localization method based on the signal strength of the interference source and the interference source localization method based on the movable spot beam obtain the incident direction of the interference source by establishing the relationship between the antenna gain and the interference source pointing direction. For the existing single-star interference source localization algorithm, the antenna pointing angle, satellite orbit height, signal source power and other data measured by the tracking telemetry system have different degrees of deviation [5], which influence the result of the pointing direction of interference source. At the same time, the particle swarm algorithm used in the positioning algorithm proposed by the predecessors tends to be unable to converge due to the random generation of the population position. The correct result cannot be obtained when calculating the incident direction of the interference source. This algorithm is designed for the geosynchronous orbit satellite mobile communication system. According to the limitations of the existing single-star interference source localization algorithm, a new interference source localization method is designed (Fig. 1).

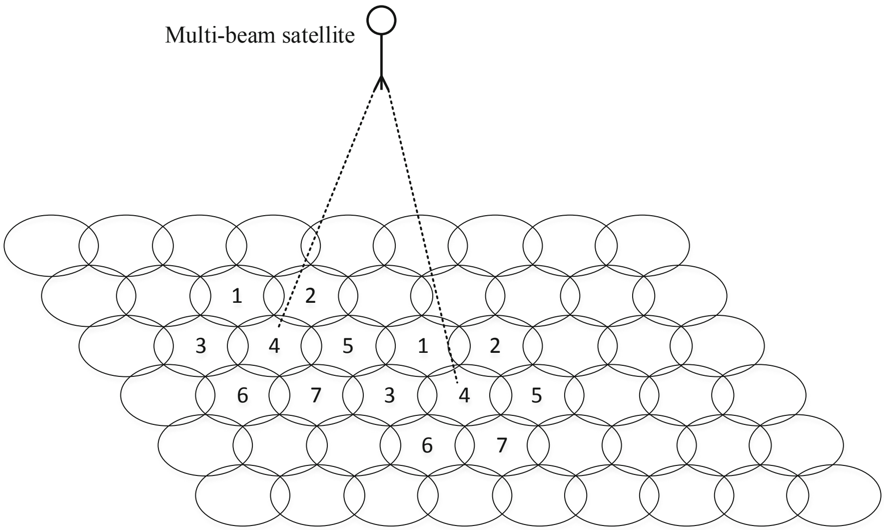

Fig. 1. Beam multiplexing schematic diagram

2 Previous Method

2.1 Antenna Gain Pointing Model

The antenna gain is the ratio of the power density of the signal generated by the actual antenna to the ideal radiating element at the same point in space under the condition of equal input power [6]. That is, it describes the ability of antenna radiating the input power directionally. Antenna gain is related to the angle $\boldsymbol{\theta}$ between the central axis of the antenna and the incident direction of the signal source (Fig. 2).

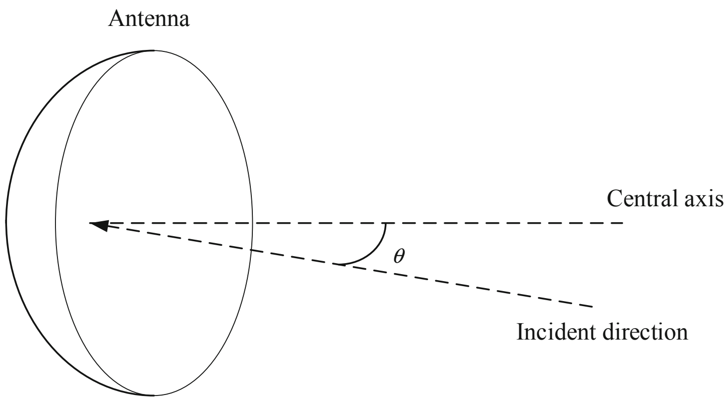

Fig. 2. The angle θ

The establishment of the spot beam radiation model can be approximated by a function provided by the literature [7], which relates the angle between the incident direction of the signal source and the central axis of the beam to the gain provided by the spot beam, and is represented by the following function:

$$G = G_0 * \left[\frac{J_1(u)}{2u} + 36 \frac{J_{3(u)}}{u^3} \right] \tag{1}$$

Where $\boldsymbol{G}$ represents the antenna gain, while $\boldsymbol{J}_1$ is the Bessel function of the first kind and order 1, and $\boldsymbol{J}_3$ is the Bessel function of the first kind and order 3. Independent variable $\boldsymbol{u}$ can be described as follows:

$$u = 2.07123 \sin(\theta) / \sin(\theta_{3dB}) \tag{2}$$

$\boldsymbol{\theta}$ is the angle between the incident direction of the signal source and the central axis of the beam and θ_{3dB} represents the half power lobe width:

$$\theta_{3dB} = 70 \cdot \frac{\lambda}{D} \tag{3}$$

$\boldsymbol{\lambda}$ is the wavelength of the Radiation signal, $\boldsymbol{D}$ represents the Antenna paraboloid diameter.

$\boldsymbol{G}_0$ can be obtained as follows:

$$G_0 = \frac{\pi^2 D\eta^2}{\lambda^2} \tag{4}$$

Where $\boldsymbol{\eta}$ is the antenna efficiency.

The incident direction of the interference source signal is represented by two angles. In order to derive the antenna gain pointing model, the angle between the incident direction and the center axis of the spot beam needs to be related to the incident direction of the signal source.

Through simple geometric derivation, following formula can be obtained:

$$\cos\theta = \frac{1}{2}\cos\varphi_0 \cdot \cos\varphi\left[\frac{1}{cos^2\varphi_0} + \frac{1}{cos^2\varphi} - (\tan\alpha_0 - \tan\alpha)^2 - (\tan\beta_0 - \tan\beta)^2\right] \tag{5}$$

$$\varphi_0 = arctan\sqrt{tan^2\alpha_0 + tan^2\beta_0} \tag{6}$$

$$\varphi = arctan\sqrt{tan^2\alpha + tan^2\beta} \tag{7}$$

Where the angle $\boldsymbol{\alpha}$ is the angle between the incident direction of the interference source signal in the direction parallel to the satellite's movement and the point right under the satellite. The angle $\boldsymbol{\beta}$ is the angle between the direction of the interference source signal in the direction perpendicular to the satellite's movement and the point right under the satellite. Also, $\boldsymbol{\alpha}_0$ and $\boldsymbol{\beta}_0$ are the angles of the central pointing direction of the beam. Using the above formula, the antenna gain pointing model can be obtained (Fig. 3).

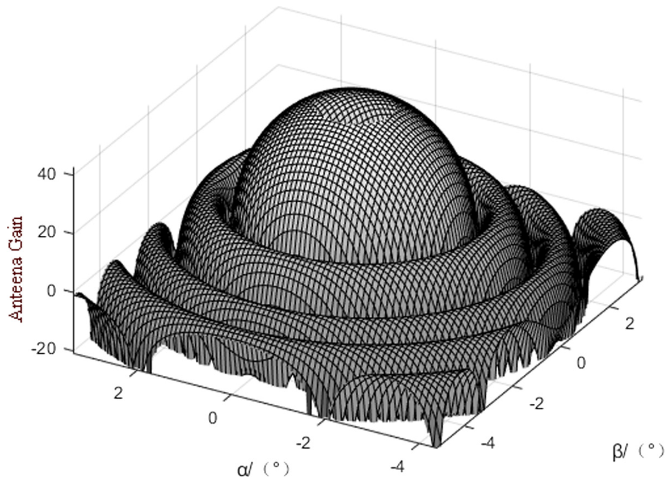

Fig. 3. Example of antenna gain pointing model

2.2 Orientation Equations

Assume that the closest three spot beams around the interference source: beam 1, beam 2 and beam 3 have received the interference source signal. When the interference source signal passes through the uplink, there will be free space transmission loss, atmospheric attenuation [8], multipath effect [9] and other losses. Set all losses on the uplink to $\boldsymbol{L}$, the signal transmission power of the interference source is set to $\boldsymbol{P_t}$, The antenna gain obtained by the interference source is set to $\boldsymbol{G_t}$, After the signal passes the uplink, the signal power received by the satellite is set to $\boldsymbol{P_{R1}}$, the pointing direction of beam 1 can be described as $(\boldsymbol{\alpha}_1, \boldsymbol{\beta}_1)$, while the incident direction of interference source is $(\boldsymbol{\alpha}, \boldsymbol{\beta})$.With the antenna gain pointing model, It can be obtained that the antenna gain obtained by the interference source in beam 1 is $\boldsymbol{G}_1(\boldsymbol{\alpha}, \boldsymbol{\beta})$, then we can get the following equation:

$$[P_{R1}] = [P_T] + [G_T] + [G_1(\alpha, \beta)] - [L] \tag{8}$$

For spot beam 2 and spot beam 3, we can also get the following equations:

$$\begin{cases} [P_{R2}] - [P_{R1}] = [G_2(\alpha, \beta)] - [G_1(\alpha, \beta)] \\ [P_{R3}] - [P_{R2}] = [G_3(\alpha, \beta)] - [G_2(\alpha, \beta)] \end{cases} \tag{9}$$

Using the particle swarm algorithm, we can solve equations and get $(\boldsymbol{\alpha}, \boldsymbol{\beta})$. When we have the incident direction, we can easily calculate the interference coordinate with the satellite ephemeris.

3 Ordinary Particle Swarm Optimization

The particle swarm optimization (PSO) algorithm is a global search algorithm that simulates the migration and aggregation behavior of bird populations in the foraging process in nature. The algorithm is based on mimicking the group behavior of birds in nature, and establishes an algorithm model similar to that on the computer, that is, the behavior of multiple birds looking for food [10].

At the beginning of the algorithm, the position of the particle is randomly initialized in the search space, and the speed of the particle is randomly initialized, that is, the particle can start from any position in the search space at any speed. Each particle has three positions, speed and fitness. Attribute, each particle searches in the search space by itself, and determines the location of an extremum based on the current fitness value of the particle, then determines the extremum position of the group by the optimal solution in all individual extremums, and in order to make the search direction Sex, the current velocity of each particle is determined by the previous velocity and extreme position. The current position of each particle is determined by the previous position and the current velocity. The fitness in the particle property is the position of the search space where the current particle is located. The coordinates are substituted into the nonlinear equations sought, and the closer the results are to the values, the lower the fitness [11].

Assume in a D dimension search, there are n particles $\boldsymbol{X} = (\boldsymbol{X}_1, \boldsymbol{X}_2, \cdots, \boldsymbol{X_n})$, and initialization location of each particle is $\boldsymbol{X_i} = (\boldsymbol{X}_{i1}, \boldsymbol{X}_{i2}, \cdots, \boldsymbol{X_{iD}})^{\boldsymbol{T}}$, while the initialization speed is $\boldsymbol{V_i} = (\boldsymbol{V}_{i1}, \boldsymbol{V}_{i2}, \cdots, \boldsymbol{V_{iD}})^{\boldsymbol{T}}$. Initial individual extremum as $\boldsymbol{P_i} =$

$(\boldsymbol{P}_{i1}, \boldsymbol{P}_{i2}, \cdots, \boldsymbol{P}_{iD})^{\boldsymbol{T}}$, and population extremum as $\boldsymbol{P_g} = \left(\boldsymbol{P}_{g1}, \boldsymbol{P}_{g2}, \cdots, \boldsymbol{P}_{gD}\right)^{\boldsymbol{T}}$, we can use the following formula to update the speed and position of each particle.:

$$V_{id}^{k+1} = \omega \cdot V_{id}^{k} + c_1 \cdot r_1 \cdot \left(P_{id}^{k} - X_{id}^{k}\right) + c_2 \cdot r_2 \cdot \left(P_{gd}^{k} - X_{id}^{k}\right) \tag{10}$$

$$X_{id}^{k+1} = X_{id}^{k} + V_{id}^{k+1} \tag{11}$$

Where d represents the serial number of the coordinate dimension, i represents the serial number of particles, k means the number of iterations. $\mathbf{c}_1$ and $\mathbf{c}_2$ are Acceleration factors, $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are two random numbers within [0, 1]. These four coefficients are used to limit and control the position and velocity of the particles, preventing them from blindly searching. And $\boldsymbol{\omega}$ represents the linear decreasing inertia weight [12] (Fig. 4).

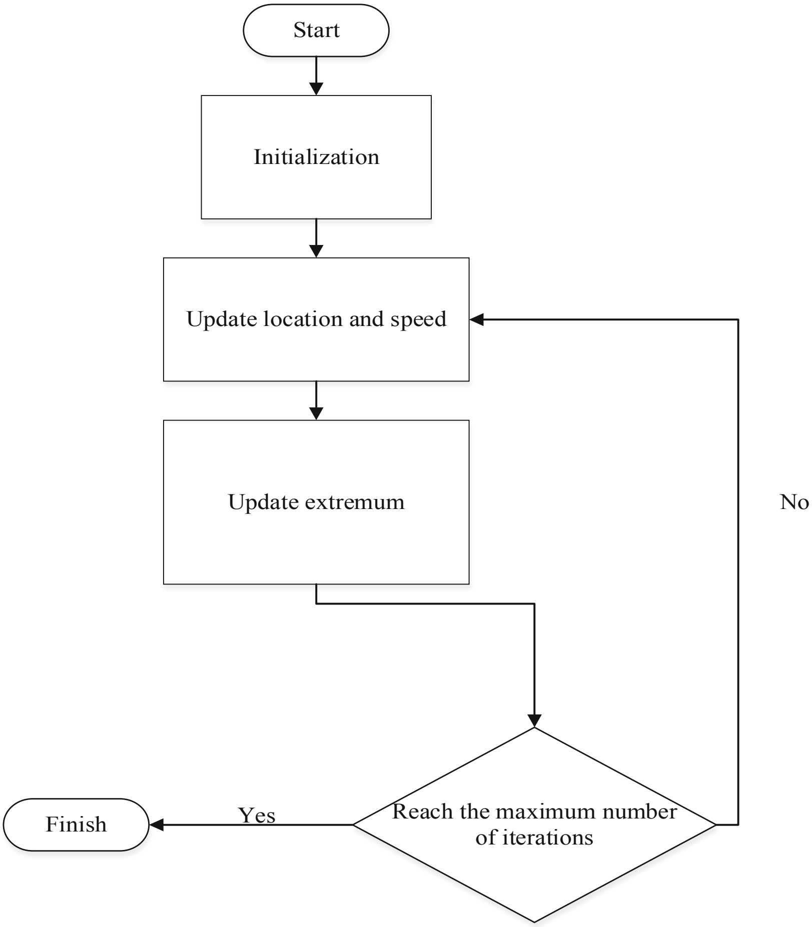

Fig. 4. Algorithm flow

4 New Method

4.1 Improvements to Orientation Methods

The method proposed by the predecessor to use the interference source signal strength received by the three spot beams interfered by the interference source and the antenna gain pointing model to establish the directional equations has good accuracy. However in the actual measurement process, because of the spot beam center pointing measured by the tracking telemetry earth station subsystem in the satellite communication system and the data of the interference source signal strength measured by the satellite side is deviated from the true value, at the time the satellite operates at a synchronization of about 35786 km from the ground, systematic error is inevitable, and the combination of measurement error and systematic error has a great influence on the accurate direction of the interference source. Therefore, it is possible to find the fourth spot beam closest to the interference source from outside the triangle to diminish the influence. The diamond region composed of two equilateral triangles can be used to study the location of the interference source (Fig. 5).

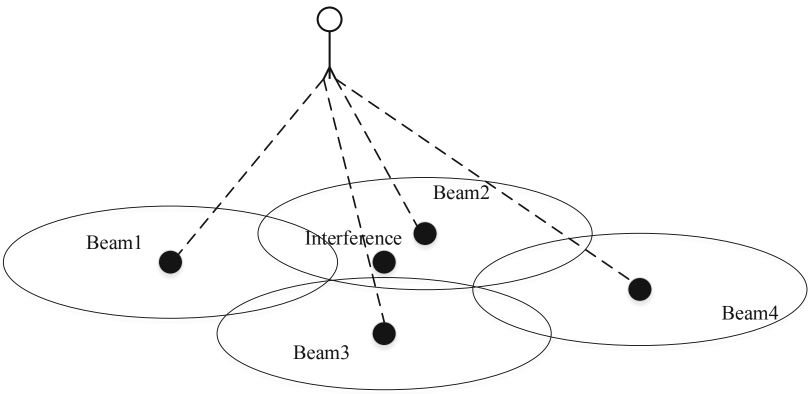

Fig. 5. Four beams around the interference source

Using this model, four sets of orientation equations established by three spot beams that are not identical can be obtained. If the four sets of orientation equations are treated as four independent orientation systems, which is equivalent to four measurements of the same physical quantity, this paper proposes to use the least squares method to process the data obtained. It is possible to obtain a result that is less affected by the error, reduce the influence of the error on the positioning, and enhance the robustness of the system.

It is assumed that the four spot beams around the interference source each receive different interference source signal strengths, and the incident directions of the four sets of interference source signals are calculated as (α_i, β_i), i = 1~4, Assuming that there are different degrees of deviation for the four sets of interference source points, after processing the four sets of data using the least squares method, the interference source direction with the degree of deviation between the minimum and the maximum can be obtained. Find a point that satisfies the following formula ($\boldsymbol{\alpha}$, $\boldsymbol{\beta}$):

$$\gamma_{min} = \sum_{i=1}^{4} \left[(\alpha_i - \alpha)^2 + (\beta_i - \beta)^2 \right] \tag{12}$$

This pointing direction is the most reliable value sought.

4.2 Improvements to the PSO Algorithm

As an advanced intelligent algorithm, the PSO algorithm has the characteristics of fast search speed and high efficiency, and the PSO algorithm is simple, which is very suitable for dealing with real value problems. However, the problem of the PSO algorithm is also very obvious. As shown in Fig. 6, the PSO search algorithm is performed 100 times, and there is a case where it does not converge and falls into local optimum.

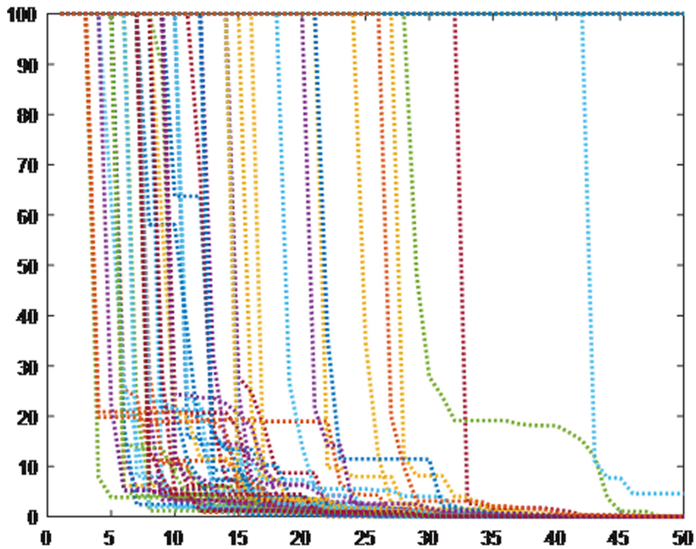

Fig. 6. Changes in fitness values during 100 searches

When the external fitness of the search space is set to a fixed value of 100, the algorithm cannot converge because the particle does not fall into the search space when the position is initialized. As the number of iterations increases, the fitness value does not change. In the figure, the value is 100. Straight line. In some cases, when the algorithm terminates, the particle still does not find the optimal solution, but falls into the local optimum. In most cases, the particle finds the optimal solution when the number of iterations is 45. In order to speed up the convergence, in order to speed up the convergence, the fitness function outside the search space is always taken to a larger value. When most of the particles are initialized outside the search space, it is easy to cause the generated particles to be global. The optimal solution is far away. In a limited number of iterations, it is easy to cause the convergence speed to be slow, or to fall into local optimum, or even to converge. That is to say, when the PSO algorithm cannot reach the vicinity of the optimal solution at the beginning of the iteration, we may not get the right answer.

Therefore, this paper proposes an improvement to the original PSO algorithm, changing the random initialization of the position of the particles to grid initialization, listing the center of the four spot beams on the ground, and meshing them to make the initial position of the particles. It is distributed in the search space, which can increase the probability that the particle will reach the optimal solution in the initial iteration, which is close to 100%, which improves the speed and reliability of the algorithm convergence.

The algorithm proposes to divide multiple grids in the diamond-shaped area, select multiple points in each grid randomly, and find the optimal solution grid by analyzing the fitness value of each point. Then the particle swarm algorithm is executed in the optimal solution grid.

5 Test Results and Comparison

5.1 Improved PSO Algorithm Testing

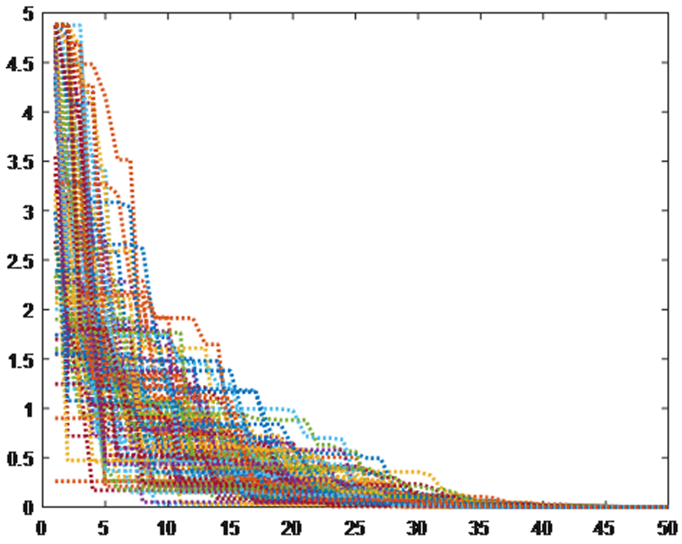

Fig. 7. Changes in fitness values during 100 searches

As shown in Fig. 6, in the search process of the original PSO algorithm, there is a non-convergence condition in which the fitness is always fixed, and there is also a case where the local optimal cannot reach the optimal solution. Although most of the search process converges, it has a large impact on the results when averaging.

In Fig. 7, the non-convergence disappears, and each search converges after 45 iterations, and the convergence speed is faster, improving the reliability of the previous algorithm.

It can be seen from the 100 average results in Table 1, the original algorithm is less reliable, and its correct orientation is (6°, 0.25°).

Table 1. Algorithm solution result.

Group	Solution result (average)
Improved algorithm	(6.000000624044548, 0.250000841961512)
Original algorithm (all)	(3.208875514278203, 0.142658280846434)
Original data (valid)	(6.000160308574986, 0.250032228895439)

5.2 Directional System Test

In this experiment, the results of the change when the center of the spot beam 1 is changed from 4° to 6° are simulated, and the changes obtained by the original method and the proposed method are compared (Figs. 8 and 9).

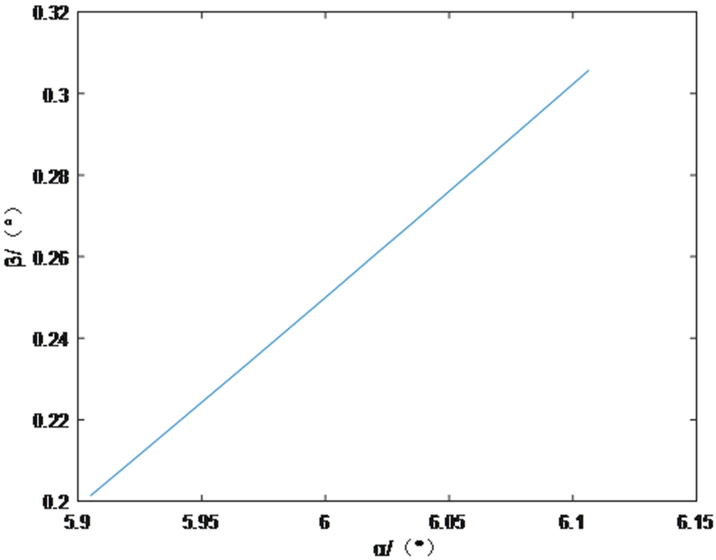

Fig. 8. Error curve when using the original three-beam method

As shown in the figure, the maximum error of the angle α is about 0.1° and the maximum angle error of β is about 0.003°, which is much better than the original method. And when the error is larger, since the satellite is in the GEO orbit, the 0.2° orientation error will produce an error of about one hundred kilometers. The curves in the previous two graphs are linked by 20 experimental results.

According to the experimental results, it is proved that the proposed method has better robustness and reliability than the original method in the presence of measurement deviation.

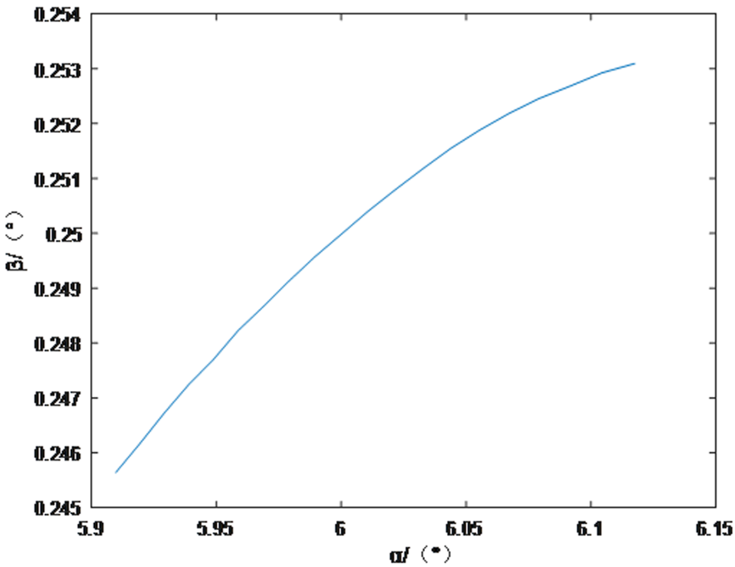

Fig. 9. Error curve when using the improved three-beam method

6 Conclusion

The existing synchronous multi-beam satellite interference source localization algorithm skillfully utilizes three spot beams that receive the interference source signal around the interference source to establish a link equation, and establishes an antenna gain pointing model to associate the interference source pointing with the antenna gain. The link equation is changed to an orientation equation, and it is solved by an efficient particle swarm optimization algorithm. Combined with the satellite operation data and the earth information, the position of the interference source can be accurately obtained under ideal conditions. However, the algorithm has deficiencies. In view of the limitations of existing algorithms, this paper proposes an improved algorithm, using four different sets of equations composed of four spot beams, and proposes an improved particle swarm optimization algorithm for solving the set of directional equations. When the particles are meshed and initialized, the reliability and convergence speed of the particles are improved. In the treatment of the four sets of interference source pointing data, this paper uses the least squares method to diminish the error influence.

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