Application Research of Horn Array Multi-Beam Antenna in Reference Source System for Satellite Interference Location

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Abstract. The reference source system is a key factor to ensure the successful location of the satellite interference source. Currently, the traditional system used a mechanical rotating antenna which led to the disadvantages of slow rotation and high failure-rate, which seriously restricted the system’s positioning-timeliness and became its obvious weaknesses. In this paper, a multi-beam antenna scheme based on the horn array was proposed as a reference source for the satellite interference location, which was used as an alternative to the traditional reference source antenna. The new scheme has designed a small circularly polarized horn antenna as an element and proposed a multi-beamforming algorithm based on planar array. Moreover, the simulation analysis of horn antenna pattern, multi-beam forming algorithm and simulated satellite link cross-ambiguity calculation have been carried out respectively. Finally, cross-ambiguity calculation of the traditional reference source system has also been tested. The comparison between the results of computer simulation and the actual test results shows that the scheme is scientific and feasible, obviously superior to the traditional reference source system.

1. Introduction
Dual-satellite geolocation technology is most widely used in finding the interference source of satellite up-link station. In order to get more accurate positioning results, several known ground position of the uplink reference source signals should be transmitted for calibration ephemeris [1][2]. The reference source system generally uses a large caliber parabolic antenna, due to frequent use, that will inevitably lead to high mechanical failure, and if there are not enough number of normal working reference antennas, which can lead to positioning failure.

The reference source system is an important short board which plays an important role in restricting the performance of satellite geolocation system. At present, there is no open literature at home and abroad to put forward new ideas and new schemes for the next generation reference source system. The new reference source system proposed in this paper tries to overcome the defects of the traditional system and greatly improve the success rate and timeliness of satellite interference source localization.

2. How the reference source system works in dual-geolocation
The accuracy of the dual-satellite geolocation depends on the accuracy of the ephemeris of both satellites (main satellite and adjacent satellite), which is usually from forecast ephemeris in the foreign public website, in the case of actual interference geolocation[3]. Due to the insufficient accuracy, the direct use of public ephemeris will result in geolocation error of thousands of kilometers, leaving the
location results meaningless. Five different signals need to be transmitted up-to the satellite through five geographically dispersed reference source systems, which will be used to calibrate the ephemeris.

![Workflow diagram of reference source system based on parabolic antenna](image)

**Figure 1.** Workflow diagram of reference source system based on parabolic antenna

The reference signal is transmitted to the main satellite and "leaked" to the adjacent satellite respectively by the main lobe and side lobe through the transmitting antenna, as shown in figure 1. Then the same two signals are respectively received by different ground receiving antennas after transparent forwarding. By calculating the cross ambiguity function (CAF) of the two signals ($S_1(t)$ and $S_2(t)$), it is able to estimate the arrival time difference (DTO) of the two signals, and also their relative doppler frequency difference (DFO) due to the relative movement of the two satellites[4]. After successfully estimating parameters of the five reference signals, the ephemeris calibration algorithm can be used to precisely correct the ephemeris of the satellites, then get high-precise results of interference geolocation.

3. **Shortcomings in the traditional reference source system**

The current reference source system uses a parabolic reflector antenna, which has the advantage of high gain and affordable price. However it has some serious drawbacks as below:

- Mechanical rotation speed is slow and time-consuming, which causes that short-term interference signals can’t be located in time by the geolocation system.
- Long working time and frequent use of the reference source system can easily lead to mechanical failure.
- For the side lobe from transmitting antenna points to an adjacent satellite randomly, the side lobe pointing to the adjacent satellite may be just the zero point between the side lobes. In this case, it cannot work.

4. **Horn array antenna**

The beam forming of the array antenna is achieved by the phase control of each element without mechanical movement, which keeps the horn antennas pointing to the satellite quickly and accurately. The use of array antenna for transmitting reference signals can completely avoid the disadvantages of traditional reference source due to mechanical rotation, as shown in figure 2. As mentioned above, the reference signals are invalid when the side lobe signal pointing to the adjacent satellite is too low or zero. However, the reference signal based on the horn antenna array can directly form two main beams with high gain when transmitting.
The array antenna with the same gain as the parabolic antenna requires thousands of antenna elements. And each element of phased-array antenna is equipped with a separate power amplifier unit and phase shifter, a large number of amplifiers and phase shifters will make the cost of the antenna array extremely expensive, thus lost its practical applicability[5][6]. If the gain of the antenna element is high, the number of antenna elements can be greatly reduced, thus reducing the cost of the antenna array. The gain of the horn antenna is proportional to the caliber, in order to avoid the phase ambiguity effect, the antenna element spacing should not exceed half a wavelength. This condition determines that the horn antenna diameter needs to be controlled in a certain range [7].

The horn array antenna is a rectangular array consisting of circular horn antennas. The array unit consists of an IF signal source, block up-converters (BUCs), phase shifters, and horn antennas. The phase shifter is a phase control unit, and the system configures the corresponding phase for each antenna element according to a specific multi-beam forming algorithm to realize multi-beam transmission of the antenna array. BUCs is the block up-converters which converts the IF signal to the RF signal and then amplifies the power, as shown in figure 3.

5. Beamforming algorithm
The beamforming algorithm at the receiver side is widely studied[8][9], unlike beamforming at the receiver side, the beamforming algorithm at the transmitter side does not amplify the noise, and the phase shift vector can be solved by using the least square method with some constraint conditions[10][11]. As shown in figure 4, the horn array antenna is a uniform planar array antenna and the spacing of the antenna array elements are λ/2, the origin of the axis is the reference point. Since the geostationary orbit satellites are mainly distributed along the azimuth plane, if the azimuth beam of the antenna array beam is too wide, it may interfere with the adjacent satellite, and the beam does not have the problem on the pitch surface. Thus the array is designed to have a number of elements in the azimuth direction greater than the number of elements in the pitch direction. Here, we assume the X-axis (in the azimuth plane) equidistant arrangement of 40 horn antennas, and the Y-axis (in the pitch plane) has 10 horn antennas.
Assuming that the array has \( N \) beams, then the \( i \)-th beam (\( 0 < i \leq N \), \( i \) is an integer), the angle between the beam and the \( Z \) axis is \( \theta_i \), and the angle between the projection of the beam on the \( X-Y \) plane and the \( X \) axis is \( \phi_i \).

The vector of the \( i \)-th beam along the \( X \)-axis array is then expressed as:

\[
a_i(\theta_i, \phi_i) = [1 \ e^{j2\pi \rho_i \sin(\theta_i) \sin(\phi_i)/d} \ \ldots \ e^{j2\pi \rho_i \sin((M_i+1)\theta_i) \sin(\phi_i)/d}]^T
\]

Similarly, the vector of the \( i \)-th beam along the \( Y \)-axis array is:

\[
a_i(\theta_i, \phi_i) = [1 \ e^{j2\pi \rho_i \sin(\theta_i) \cos(\phi_i)/d} \ \ldots \ e^{j2\pi \rho_i \sin((M_i+1)\theta_i) \cos(\phi_i)/d}]^T
\]

The symbol \( T \) means transpose. Where \( M_1=40 \), \( M_2=10 \). Then, the array steering vector of the \( i \)-th beam based on the rectangular array can be expressed as:

\[
a_i(\theta_i, \phi_i) = a_i(\theta_i, \phi_i) \otimes a_i(\theta_i, \phi_i)
\]

Where \( \otimes \) denotes the Kronecker product and equation (3) is equivalent to the straightening operation of the steering matrix of the array.

Each array element in the array has a corresponding phase shift for a certain wave direction, and the corresponding phase shift matrix is:

\[
W = \begin{bmatrix}
\beta_1 & \beta_{M+1} & \ldots & \beta_{(M+1)M+1} \\
\beta_2 & \beta_{M+2} & \ldots & \beta_{(M+1)M+2} \\
\vdots & \vdots & \ddots & \vdots \\
\beta_M & \beta_{2M} & \ldots & \beta_{3M}
\end{bmatrix}
\]

By the vectorizen calculation of matrix, then we have

\[
W = vec(W')
\]

When the product of the conjugate transpose of the steering vector \( a(\theta_i, \phi_i) \) and the array phase shift vector is 1, the array forms a main beam in direction \( a(\theta_i, \phi_i) \), otherwise, when the product is 0, the array forms null steering beams at the direction of \( a(\theta_i, \phi_i) \). \( H \) denotes conjugate transpose.

\[
a(\theta_i, \phi_i)^H W = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]
C and f denote the constraint matrix and the constraint response vector, respectively. And we can express the terms C and f as following:

\[ C = [a (\theta_1, \varphi_1) \ a (\theta_2, \varphi_2) \ a (\theta_3, \varphi_3) \ \cdots \ a (\theta_p, \varphi_p)] \]

\[ f = [1 \ 1 \ \cdots \ 1 \ 0 \ 0 \ \cdots \ 0] \]

(7)

In equation(7), the number of 1 in the constraint response vector f is the number of array beams and the number of 0 is the number of null steering beams formed by the array. Unlike the beamforming method at receiver side, the expression of W in the array that satisfies all the constraints is

\[ C^H \ast W = f \]

(8)

Therefore, the least squares solution for W in restricted all conditions is:

\[ W = (C \ast C^H)^{-1} \ast C \ast f \]

(9)

6. Computer simulation experiment

The simulation results are carried out in three steps: the first step is to calculate the gain pattern of the horn antenna. The second step is to make two beamforming of the antenna array according to the beamforming algorithm proposed above. The EIRP (Equivalent Isotropic Radiated Power) value range of two beams is calculated by combining the information obtained in the first two steps. In the third step, based on the EIRP values of the two beams, the two signals are transmitted through the satellite link, and the two signals are calculated by CAF calculation to verify the feasibility of the scheme.

6.1. Simulation experiment of the gain of horn antenna

Based on the avoidance of phase blurring, the aperture of the horn antenna is \( \lambda/2 \). The frequency is 6GHz, \( \lambda \) is 5cm, right circular circular polarization. The HFSS simulation shows that the gain of the antenna is shown in figure 5 and figure 6. Figure 7 shows the horn antenna model. The maximum gain of the antenna at 6GHz is 7dB on both E and H plane, gain range of 3dB beam is 4-7 dBi.
6.2. Simulation experiment of array antenna beamforming

Assume that the antenna is installed in Shenzhen, its pointing angles to the main satellite (China Sat 6B) and the adjacent satellite (Asian Sat 5) are respectively (22°, 49.2°) and (-13°, 53.6°) (the left side is the angle of azimuth, the right side is the angle of pitch).

According to the algorithm provided by formula (9), the array phase shift vector is calculated by Matlab, and corresponding phase configuration is carried out for each array unit. The two beam simulation results of the rectangular array are shown in figure 8, figure 9, figure 10.

The simulation result shows that each array processing gain of the two beams of the antenna is 26dB, the beam-steering angle to the adjacent satellite is (-13°, 53.6°), and the beam-steering angle to the main satellite is (22°, 49.2°). It meets the design requirements. Two beam azimuth 3dB beam width of the azimuth of the two beams are respectively 2.8° and 2.6°. The span between the satellites which cover China is generally greater than 3°. So the two main beams don't interfere with neighbor satellites.

6.3. Simulation of cross ambiguity function computing

The estimation of DTO and DFO of reference source is calculated by using CAF[12]:

$$A(\tau, f) = \int T s_1(t) s_2(t+\tau) e^{-j2\pi f} dt$$  (11)

S1(t) and S2(t) are the complex envelops of the two signals, \(\tau\) and \(f\) represent the time difference and frequency difference between the two signals, and \(T\) is the signal sampling time.

Simulation conditions: the signal transmission frequency is 6GHz, the bandwidth is 128kHz, and the EIRP of signals of the two channels transmitted through satellite link is from 30dBw to 43dBw. The Sampling bandwidth is 128KHz, the sampling time is 16s, the processing gain is 63dB.

Obtain the ephemeris of the main satellite and the adjacent satellite at a certain moment through STK software. The two main beam signals are transmitted up-to the two satellites and received by the ground station, then the related peak of two signals are computed by Matlab.

The actual test is known: when the EIRP value of the antenna is 35dBw with bandwidth 128kHz, then the carrier-to-noise ratio (CNR) of the signal after forwarding on the transponder is 0dB.
The EIRP of the satellite beam is 31dBw, 35dBw, 39dBw, 43Bw (the bandwidth is 128KHz, the same below), the range of the EIRP of the adjacent satellite beam is from 30dBw to 43dBw, and the step is 1dBW. The simulation results are shown in figure 11. It shows that when the two signals take the minimum value, the EIRP value of the main satellite is 31dBw (CNR = -4dB), the EIRP value of the adjacent satellite is 30dBw (CNR = -5dB), the CAF correlation peak is 49 dB, and it beyond the available threshold(20dB) of 29dB. When the two signals take the max value, the EIRP value of the main satellite is 43dBw (CNR = 8dB), the EIRP value of the adjacent satellite is 43dBw (CNR = 8dB), the cross ambiguity function correlation peak is 57dB, and it beyond the available threshold of 37dB. Within the range of the EIRP value, the CAF correlation peak of the two signals can be significantly beyond the threshold. And it fully meets the positioning requirements.

Figure 11. Cross ambiguity function computing result

6.4. Actual test of conventional reference source
Here are the actual test conditions of conventional parabolic reference source antenna. The gain of antenna is 40dB. The range of the transmitter power amplifier output is between 1 and 13 dBi, and the EIRP output of the main satellite ranges from 40dBW to 53dBW. The transmitting bandwidth is 128kHz. The test results are shown in table 1.

Table 1. The experimental results of traditional reference source antenna

| Processing Gain (dB) | EIRP of Main Sat (dBw) | The Peak of CAF (dB) |
|----------------------|------------------------|---------------------|
| 63                   | 40                     | 0                   |
| 63                   | 43                     | 0                   |
| 63                   | 46                     | 20.8                |
| 63                   | 49                     | 22.1                |
| 63                   | 53                     | 26.8                |

In the test, the CAF confidence threshold is set to 20 dB. The peak values will be displayed if they are higher than 20 dB, while those lower than the threshold will be displayed as 0, which are determined not trustable. As shown as the results, only when the radiated power of the main beam from the parabolic reference source antenna reaches 46 dBW(CNR=9dB), which is 16 dBW higher than the minimum EIRP of the array antenna, the correlation peak above the threshold can be extracted.

6.5. Comparison of the experiment results
It can be concluded by comparing the test results of two kinds of the reference source antennas:
Under the premise that the EIRP value is much smaller than that of the parabolic reference source, the CAF SNR of the horn antenna array reference source is significantly larger than that of the traditional reference source, that means the confidence of the parameter unbiased estimator is higher.

The horn array antenna still has a large CAF SNR which is much larger than the threshold, when the two beam EIRP values are less than 35 dBW(CNR<0 dB, and in this case, the reference signal does not adversely affect the normal operation of the transponder). The parabolic reference source however requires the CNR of the main satellite larger than 9 dB to get a trusted correlation peak.

7. Conclusion
When the horn array antenna is used to the reference source system of satellite interference source, it has the advantages of high reliability of parameter estimation and can reduce the time of satellite interference source localization by more than 5 times, which can improve the positioning timeliness. And it can greatly improve the satellite interference system on the short-term interference source. It is the feasible option for next generation of reference source system, and has a huge application prospects.

Due to the limitation of the wavelength which is less than half the wavelength, the horn antenna gain is small, that the array number still has a large scale, the next work will consider the use of non-uniform horn array, increase the horn spacing. Use a larger caliber horn antenna to reduce the number of array elements and their associated BUCs to further reduce array costs.

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