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Method of Telemetry, Tracking and Control Monopulse System Simulation and Evaluation in Jamming

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Abstract

To evaluate the performance of spacecraft angle measurement in jamming, a method of TT&C (Telemetry, Tracking, and Control) monopulse system analysis is proposed in the condition that antenna keeps tracking the target. First, a geometric model of large aperture parabolic antenna is established, and the antenna patterns of sum, azimuth difference and elevation difference channel are derived through EM computation. Next, the positions and the simultaneous visibility of spacecraft and jammer are derived with orbit computation software. Then, formulae to calculate the positions of jammer in the antenna pattern, i.e. the angle of nutation and procession, are derived and used. Once again, according to the positions of spacecraft and jammer that relative to the ground station, the expressions to estimate the power of signal, internal noise, jamming are suggested, which are used to calculate the SNR and correlation coefficient. At last, the performance of the TT&C monopulse system of fix target and single observation is discussed. And the validity and feasibility of the method are verified with BD-2A as the target and X37-B as the Jammer. The proposed method realizes a kind of full path simulation which contains antenna pattern and its sidelobe, motion of target spacecraft and jammer, internal noise of receiver. It is more practical in engineering analysis.

Keywords: *Telemetry, Tracking and Control, Monopulse, Jamming, Antenna Pattern, Simulation*

1. Introduction

Monopule is one of the most important technical approaches that ensure the antenna point to correct direction and keep regular tracking, which is widely applied in the TT&C systems. Generally the complex monopulse ratio is adopted to express the performance of monopulse systems, of which the difference channel voltage is normalized by that of the sum channel. The statistical performance of monopulse in jamming or noise has been discussed in some literatures [1]. The research on the antenna of TT&C system is mainly about how to prevent the sidelobe tracking at present [2].And the performance is usually estimated with the link budget formulae assuming that the target locates in the mainlobe of the antenna pattern. The issues of anti-jamming have been discussed hardly.

When the performance angle measurement and tracking is evaluated, the factors such as the orbits of target and jammer, the offset angles from the Light of Sight (LoS), the powers of signal and jamming, the patterns of sum and different beamform, internal noise, etc., should be considered.

The limitations that calculate the loss induced by free space transmission with the height of orbits, the radiation powers of target spacecraft and jammer are as follow. (1)

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The visual angles of the target spacecraft and that of the Jammer are not considered. (2) The motion of target spacecraft makes its azimuth and elevation varies from time to time, so as to the jammer. Then the position of the jammer in the antenna pattern changes during the regular tracking, which results in the gain and phase of antenna change. (3) The difference between the effect of internal noise and that of the external jamming cannot be reflected. Thus, a method of TT&C monopulse system performance simulation in jamming is appealed, which can be used to analyze the performance of typical scene and form a distinct impression.

2. Method of Simulation and Analysis

2.1. Definition of Complex Monopulse Ratio

Without loss of generality, the amplitude comparison monopulse is discussed as an example, which is defined as the ratio of the voltage of the difference channel and that of the sum [1]

$$R = \mathrm{Re}\left\{ \frac{E\left[\Delta + n_{\Delta} + J_{\Delta}\right]}{E\left[\Sigma + n_{\Sigma} + J_{\Sigma}\right]} \right\} \tag{1}$$

Where, Δ is the amplitude of difference channel, Σ is that of the sum, n_{Σ} and n_{Δ} are internal noise of receiver, while J_{Σ} and J_{Δ} are the external jamming, respectively. $E[\cdot]$ denotes statistical expectation. Although the ration may be complex, the real part is used to represent angle error.

2.2. Method of Sum and Difference Antenna Pattern Achievement

A large aperture parabolic antenna pattern of TT&C system can be achieved through elevated yard. However, it has the shortcomings of longer test time, more workload, more difficult to obtain accurate 3D antenna pattern, and appropriate height and distance of mount [3]. With the development of electromagnetic computation techniques, the precision of antenna pattern has improved greatly, and can fulfil the demand of practical engineering.

The method to obtain the sum and the difference beamform pattern based on electromagnetic computation can be described as follow. First, construct the structure of paraboloid antenna and feed horns according to the physical and geometrical characteristics, and then acquire the antenna pattern of the sum beamform $G_{\Sigma}(\theta,\varphi)$, that of the azimuth $G_{A}(\theta,\varphi)$ and elevation $G_{E}(\theta,\varphi)$, the electronic field patterns which include the θ components θ $E_{\Sigma_{\theta}}(\theta,\varphi)$ and φ component $E_{\Sigma_{\varphi}}(\theta,\varphi)$ of sum beamform, and $E_{A_{\theta}}(\theta,\varphi)$, $E_{A_{\varphi}}(\theta,\varphi)$, $E_{E_{\theta}}(\theta,\varphi)$, $E_{E_{\varphi}}(\theta,\varphi)$ through numeric computation.

At present, the common commercial software of numeric electromagnetic computation includes HFSS, CST, FEKO, etc. FEKO integrates several numeric methods, such as the high order basis function MOM, and the high frequency methods, such as PO, GO, GTO, which lead to itself more suitable for the application of large electronic length computation, such as the large aperture antenna of TT&C system.

2.3. Method of Simultaneous Visibility Analysis

Regularly the LoS of ground station antenna points to the target spacecraft. When the target and the jammer are visible simultaneously, the monopulse system of TT&C would suffer interference. As we know, the orbit of spacecraft has the trait of period. Through the analysis of a certain duration orbit motion, the jammer can obtain the regular pattern about the simultaneous visibility and spatial location relative to the ground station. Then the orbit of the target spacecraft, the orbit or flight path of the jammer can be set according to the demand of simulation. Let T_{S_i} and T_{J_i} represent the visible time interval of the target and jammer, respectively. The common visible time interval is

$$T = \cup \left(T_{S_i} \cap T_{J_i} \right) \tag{2}$$

The azimuth A_T, A_J the evaluation E_T, E_J, and the distance ρ_T, ρ_J in the horizontal coordinate system can be obtain at the same time.

The aim of common visible time interval and the spatial position analysis is to calculate link power budget. Satellite Tools Kit (STK) permits antenna pattern, atmosphere model, rain attenuation to be loaded, configure the parameters of the transmitter and receiver. It can realize communication link analysis in the 3D simulation environment [4,[5]. However, the sum and difference antenna pattern cannot be loaded simultaneously in STK, *i.e.*, the signal and power of the sum and difference channel cannot be discussed directly. It can be used to carry out the simultaneous visibility, the positions of target spacecraft and jammer respectively.

2.4 Algorithm to Calculate Angles Position of Jammer in Antenna Coordinate System

The geometrical relationship of the target spacecraft, the jammer and the ground station can be shown in Figure 1, in which *O*-XYZ is the horizontal coordinate system of ground station, *O* is the phase center of the ground station antenna.

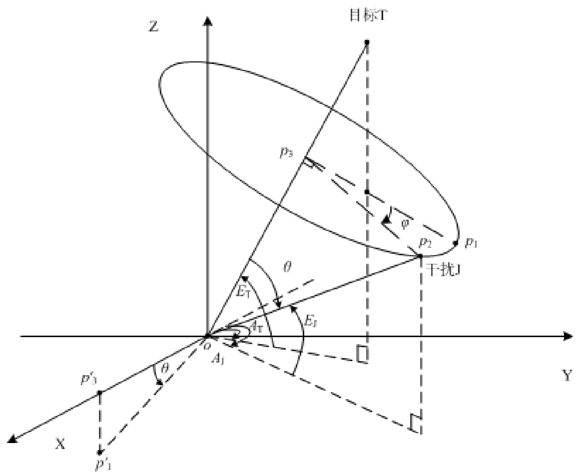

Figure 1. Position of Jammer in the Antenna Coordinate System

The distance of target ρ, azimuth A and elevation E corresponding to the time interval can be acquired through visibility analysis. Define the spatial vector $\rho = x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k}$ in the horizontal coordinate system, then

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\rho \cos E \cos A \\ \rho \cos E \sin A \\ \rho \sin E \end{bmatrix} \tag{3}$$

Assume the position vector of target spacecraft and jammer is ρ_T and ρ_J, respectively. The letter T in the subscript is used to represent the variable of target spacecraft, and J to jammer. According to equation (3), the coordinates of target spacecraft $[x_T, y_T, z_T]^T$ and jammer $[x_J, y_J, z_J]^T$ can be acquired. The angle between the vectors corresponds to the angle of nutation

$$\theta_0 = \cos^{-1}(\boldsymbol{\rho}_T, \boldsymbol{\rho}_J) = \cos^{-1}\left(\frac{\boldsymbol{\rho}_T \cdot \boldsymbol{\rho}_J}{|\boldsymbol{\rho}_T||\boldsymbol{\rho}_J|}\right) \tag{4}$$

Where φ is the dihedral angle of plane op_1p_2 and plane op_2p_3.

Define vector corresponding to p_1 is $\rho_1 = x_1\boldsymbol{i} + \boldsymbol{y}_1\boldsymbol{j} + \boldsymbol{z}_1\boldsymbol{k}$, the plane P1 forming from inter-section of line op_1 and line op_2 can be represented as follow

$$\boldsymbol{n}_1 \cdot \left[(\boldsymbol{\rho} - \boldsymbol{\rho}_T) \times (\boldsymbol{\rho}_T - \boldsymbol{\rho}_1)\right] = 0 \tag{5}$$

Where p_1 can be seen as the rotation of the coordinates $[x_3' \quad 0 \quad y_3']^T$ of p_1' . The procedure includes two steps. First, rotate right $\pi - A_T$ rad while maintaining Z axis unchanged; second, rotate left E_T rad while maintaining Y' axis unchanged

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \mathbf{R}_{Y'}(-E_T) \cdot \mathbf{R}_Z(\pi - A_T) \begin{bmatrix} x_1' \\ 0 \\ y_{1_1}' \end{bmatrix} \tag{6}$$

Where

$$x_1' = \|\boldsymbol{\rho}_T \cdot \boldsymbol{\rho}_J\| \tag{7}$$

$$y_1' = \left[|\boldsymbol{\rho}_J|^2 - (\boldsymbol{\rho}_J \cdot \boldsymbol{\rho}_1 / |\boldsymbol{\rho}_1|)^2\right]^{1/2} \tag{8}$$

The rotation matrix is defined as follow [6]

$$\mathbf{R}_Z(\pi - A_T) = \begin{bmatrix} -\cos A_T & \sin A_T & 0 \\ -\sin A_T & -\cos A_T & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$\mathbf{R}_{Y'}(-E_T) = \begin{bmatrix} \cos E_T & 0 & -\sin E_T \\ 0 & 1 & 0 \\ \sin E_T & 0 & \cos E_T \end{bmatrix} \tag{10}$$

The plane P2 is formed by the intersection of line op_2 and line op_3

$$\boldsymbol{n}_2 \cdot \left[(\boldsymbol{\rho} - \boldsymbol{\rho}_T) \times (\boldsymbol{\rho}_T - \boldsymbol{\rho}_J)\right] = 0 \tag{11}$$

According to the formula of dihedral angle calculation, the angle of precession of jammer in the coordinate system of the antenna pattern can be written as

$$\varphi_0 = \cos^{-1}(\boldsymbol{n}_1, \boldsymbol{n}_2) = \cos^{-1}\left(\frac{\boldsymbol{n}_1 \cdot \boldsymbol{n}_2}{|\boldsymbol{n}_1||\boldsymbol{n}_2|}\right) \tag{12}$$

2.5. Sum Channel SNR Calculation Algorithm

Generalized receiver noise includes broadband random jamming and internal noise. The jamming density that the ground receiver suffered corresponds to the radiation power of the target spacecraft, that of the jammer, antenna patterns, transmission path losses.

First, calculate the power of target signal and that of the jammer. The power received by the ground station is

$$P_r = P_t + G_t + G_r - L \tag{12}$$

Where P_t is transmit power, G_t is the power gain of the jammer transmit antenna. G_r is the power gain of the ground station antenna. L is the transmission path loss.

The path loss included loss of free space transmission, absorption of atmosphere, attenuation of rain and frog, where the loss of free space is the main factor. When high precision is not need, the path loss can be calculated with the free space loss only.

$$L = \left(4\pi lf / c_0\right)^2 \tag{13}$$

Where f is the operation frequency of the ground station, unit in Hz. l is the distance between the transmit antenna and that of the receiver, unit in m. c_0 is the velocity of light, 299792458m/s.

The received power of the target signal $P_{\Sigma,T}$, $P_{A,T}$, $P_{E,T}$, and the jamming power $P_{\Sigma,J}$, $P_{A,J}$, $P_{E,J}$.

Second, calculate the jamming power. Usually, the noise source of wireless receiver includes the internal noise n_{noise} (noise temperature represents as T_{noise}) such as antenna, RF components that links the antenna and LNA, etc., and the external noise n_{jam} (noise temperature represents as T_{jam}) introduced by space transmission path. Accurate noise temperature should be calculated using the method of system cascade connection[7]. Estimation in practice can consider three main components.

$$T_{noise} = T_{ant} + T_{line} + T_{lna} \tag{14}$$

Where T_{ant} is noise temperature of antenna, T_{line} is noise temperature of feed line, T_{lna} is noise temperature of LNA. As regard to monopulse system, sum and difference channel use the same feed source, T_{ant} of sum channel is equal to that of difference channel approximately. The corresponding parts of noise of two channels are correlated. However, since the different time delay between the channels, signal of sum channel to be process in the baseband tracking receiver is not correlate with that of difference channel. T_{line} and T_{lna} relate to the characteristics of each channel, and they are statistical independent. When the components of sum channel are well-consistent with that of the difference channel, the noise temperature can be set the same value.

Formula to calculate the noise power is

$$P_n = k_0 T_{noise} B_W \tag{15}$$

Where $k_0 = 1.38 \times 10^{-23}$ J/K; B_W is the receiver bandwidth of the ground station.

Once again, calculate the correlation coefficient of the sum and difference channel. Signals of each channel can be written as

$$r_\Sigma = s_{\Sigma,T} + n_\Sigma + J_\Sigma \tag{16a}$$

$$r_{\Delta A} = s_{\Delta A} + n_{\Delta A} + J_{\Delta A} \tag{16b}$$

$$r_{\Delta E} = s_{\Delta E} + n_{\Delta E} + J_{\Delta E} \tag{16c}$$

Where n_Σ , $n_{\Delta A}$ and $n_{\Delta E}$ are sum of internal noise of sum channel, azimuth difference channel and the elevation.

SJNR of sum channel signal is

$$\chi_\Sigma = P_{s,T} / \left(P_{s,J} + P_n\right) \tag{13}$$

Similarly, SNR of azimuth difference channel and that of elevation $\chi_{\Delta A}$ and $\chi_{\Delta E}$ can be derived.

Then covariance of azimuth channel and sum channel, elevation channel and sum channel can be written as follow, respectively.

$$C_{\Sigma,\Delta A} = E\left[J_\Sigma^* J_{\Delta A}\right] \tag{17a}$$

$$C_{\Sigma,\Delta E} = E\left[J_\Sigma^* J_{\Delta E}\right] \tag{17b}$$

For instance of the first term equation (17a)

$$\phi_{\Sigma,\mathrm{A}} \triangleq \arg\left(J_{\Sigma}\right) - \arg\left(J_{\Delta \mathrm{A}}\right) = \phi_{\Sigma,\mathrm{J}} - \phi_{\mathrm{A,J}} + \Delta\phi_{\mathrm{A},0} \tag{18}$$

Where $\phi_{\Sigma,\mathrm{A}}$ is the phase offset between antenna pattern of sum beam and that of difference beam， $\Delta\phi_{\mathrm{A},0}$ is the phase offset result from phase offset calibration. Since jammer usually locates in the antenna sidelobe of the receiver, the fluctuation of the offset is generally evident. $\phi_{\Sigma,\mathrm{J}}$ is the phase offset of jammer of the sum pattern, $\phi_{\mathrm{A,J}}$ is that of the azimuth difference pattern.

Since the initial phase of jamming of sum pattern is same to that of azimuth difference, and the phase offset is comparative tiny, $\phi_{\mathrm{A,J}}$ generally relates to the phase offsets that introduced by antenna pattern of sum beam and that of azimuth difference beam, so as to that of the elevation channel $\phi_{\mathrm{E,J}}$.

The method of phase offset calculation is given in the case of $\phi_{\Sigma,\mathrm{J}}$.

$$\phi_{\Sigma,\mathrm{J}} = \tan^{-1}\left\{\frac{\mathrm{Im}\left[E_{\Sigma_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Im}\left[E_{\Sigma_\varphi}\left(\theta_0,\varphi_0\right)\right]}{\mathrm{Re}\left[E_{\Sigma_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Re}\left[E_{\Sigma_\varphi}\left(\theta_0,\varphi_0\right)\right]}\right\} \tag{19a}$$

$$\phi_{\mathrm{A,J}} = \tan^{-1}\left\{\frac{\mathrm{Im}\left[E_{\mathrm{A}_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Im}\left[E_{\mathrm{A}_\varphi}\left(\theta_0,\varphi_0\right)\right]}{\mathrm{Re}\left[E_{\mathrm{A}_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Re}\left[E_{\mathrm{A}_\varphi}\left(\theta_0,\varphi_0\right)\right]}\right\} \tag{19b}$$

$$\phi_{\mathrm{E,J}} = \tan^{-1}\left\{\frac{\mathrm{Im}\left[E_{\mathrm{E}_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Im}\left[E_{\mathrm{E}_\varphi}\left(\theta_0,\varphi_0\right)\right]}{\mathrm{Re}\left[E_{\mathrm{E}_\theta}\left(\theta_0,\varphi_0\right)\right] + \mathrm{Re}\left[E_{\mathrm{E}_\varphi}\left(\theta_0,\varphi_0\right)\right]}\right\} \tag{19c}$$

From equation (18) and (19), there is

$$E\left[J_{\Sigma}^{*} J_{\Delta \mathrm{A}}\right] = \sqrt{P_{\Sigma,\mathrm{J}} \cdot P_{\mathrm{A,J}}}\, e^{-j\phi_{\Sigma,\mathrm{A}}} \tag{20a}$$

$$E\left[J_{\Sigma}^{*} J_{\Delta \mathrm{E}}\right] = \sqrt{P_{\Sigma,\mathrm{J}} \cdot P_{\mathrm{E,J}}}\, e^{-j\phi_{\Sigma,\mathrm{A}}} \tag{20b}$$

From equation (17) to (20), complex correlation coefficient of sum channel and that of azimuth channel is

$$\rho_{\mathrm{A}} + j\zeta_{\mathrm{A}} = C_{\Sigma,\Delta \mathrm{A}} \Big/ \sqrt{\left(P_{\Sigma,\mathrm{J}} + P_{\Sigma,\mathrm{n}}\right)\cdot\left(P_{\Delta \mathrm{A,J}} + P_{\Delta \mathrm{A,n}}\right)} \tag{21a}$$

$$\rho_{\mathrm{E}} + j\zeta_{\mathrm{E}} = C_{\Sigma,\Delta \mathrm{E}} \Big/ \sqrt{\left(P_{\Sigma,\mathrm{J}} + P_{\Sigma,\mathrm{n}}\right)\cdot\left(P_{\Delta \mathrm{E,J}} + P_{\Delta \mathrm{E,n}}\right)} \tag{21b}$$

2.6. Method of Complex Monopulse Ratio Calculation

There is direct path between target and ground station. The signal can be modeled as fix target, and noise is AWGN. For the purpose of simple, the azimuth difference channel is set as an example. And the subscript A is omitted. Thus expect and variance of complex monopulse ratio estimation of single observation can be written as follow [10]

$$E = \hat{r} - \left(\hat{r} - \rho\frac{a}{b}\right)\frac{A_0}{P_D} \tag{22}$$

$$\begin{aligned}\sigma^2 = {} & \chi\nu^2\frac{A_1 + A_2}{P_D} - \nu^2\left(1 - \frac{A_0}{P_D}\right)^2 \\ & + \mu^2\frac{A_1}{P_D} + \chi\left(\zeta\frac{a}{b}\right)^2\frac{A_1 - A_2}{P_D}\end{aligned} \tag{23}$$

Where $\hat{r}$ the truth value of CMR of target spacecraft is, P_D is probability of detection of sum channel. The a of the azimuth channel is defined in equation (24a), and that of the elevation channel is defined in equation (24b).

$$a = \sqrt{\left(P_{\Delta A,J} + P_{\Delta A,n}\right)/2}\ ,\quad b = \sqrt{\left(P_{\Sigma,J} + P_{\Sigma,n}\right)/2} \quad \text{(for Azimuth)} \tag{24a}$$

$$a = \sqrt{\left(P_{\Delta E,J} + P_{\Delta E,n}\right)/2}\ ,\quad b = \sqrt{\left(P_{\Sigma,J} + P_{\Sigma,n}\right)/2} \quad \text{(for Elevation)} \tag{24b}$$

$$\nu = \hat{r} - \rho a/b \tag{24c}$$

$$\mu^2 = \left(a^2/b^2\right)\left(1 - \rho^2 - \zeta^2\right) \tag{24d}$$

$$A_0 \equiv e^{-\left(\ell_0 - \sqrt{\chi}\right)^2}\left[e^{-2\ell_0\sqrt{\chi}} I_0\left(2\ell_0\sqrt{\chi}\right)\right] \tag{25a}$$

$$\int_{\ell_0}^{\infty} e^{-\left(\ell - \sqrt{\chi}\right)^2} e^{-2\ell_0\sqrt{\chi}} I_0\left(2\ell_0\sqrt{\chi}\right)\frac{d\ell}{\ell} \tag{25b}$$

$$A_2 \equiv \int_{\ell_0}^{\infty} e^{-\left(\ell - \sqrt{\chi}\right)^2} e^{-2\ell_0\sqrt{\chi}} I_2\left(2\ell_0\sqrt{\chi}\right)\frac{d\ell}{\ell} \tag{25c}$$

$$P_D \equiv \int_{\ell_0}^{\infty} e^{-\left(\ell + \chi^2\right)} I_0\left(2\ell_0\sqrt{\chi}\right) 2\ell d\ell \tag{25d}$$

Numerical integral of P_D should be calculated with Marqum Q function. The statistical characteristics of CMR of multiple observations can be seen in reference [11].

In summary, the procedure to simulate the CMR of TT&C in jamming is illustrated as Figure 2.

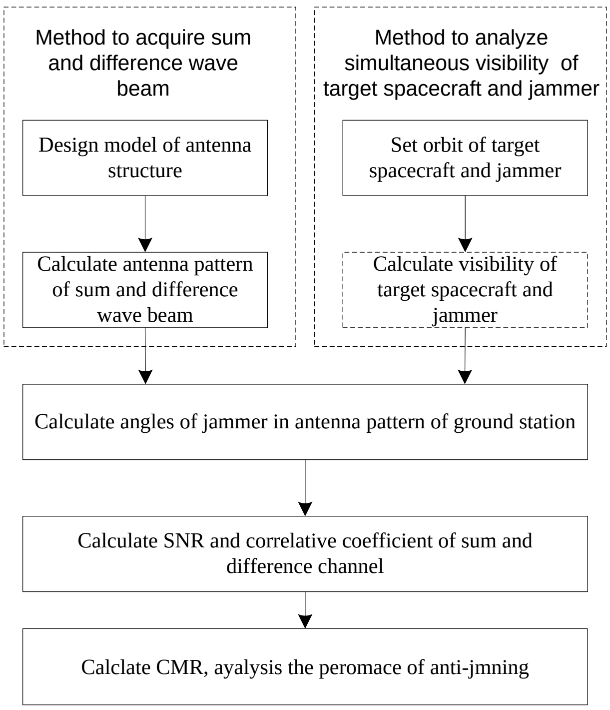

Figure 2. Procedure to Simulate the CMR of TT&C in Jamming

3. Analysis and Simulation

In order to obtain intense Jamming to Signal Ratio (JSR) for the ground tracking receiver, LEO satellite is selected as the jamming platform. The scene is set as below. A 12m diameter paraboloid antenna with four horn feed in the Sanya station is chosen. Set

BD-2A as the target spacecraft, and X-37B as the jammer. The method of complex monopulse ratio simulation and evaluation of TT&C in jamming is illustrated as follow.

Step 1, acquire the antenna patterns of the sum and the difference channel. According to the structure of practical TT&C equipment, the geometrical model is designed and imported into the simulation environment of FEKO, then configure the boundary condition and parameters of far field. The power gains of sum beamform, the azimuth difference, and the elevation difference are 43.1dB, -15.4dB, -10.6dB respectively. The corresponding CMRs of azimuth and elevation are 0.0012 and 0.0021. The radiation patterns are shown in Figure 3 – Figure 5.

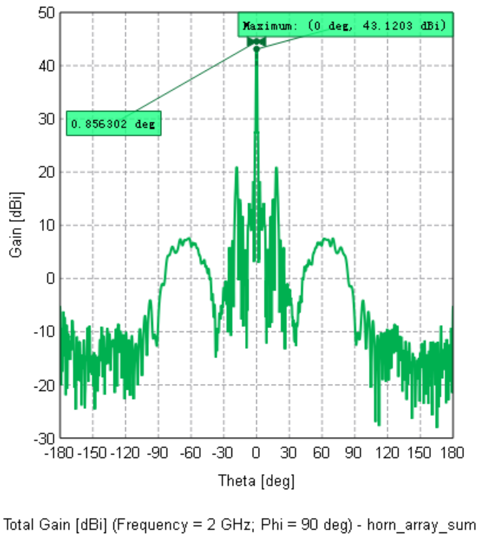

Figure 3. Radiation Pattern of Sum Beamform of 12m Diameter Antenna

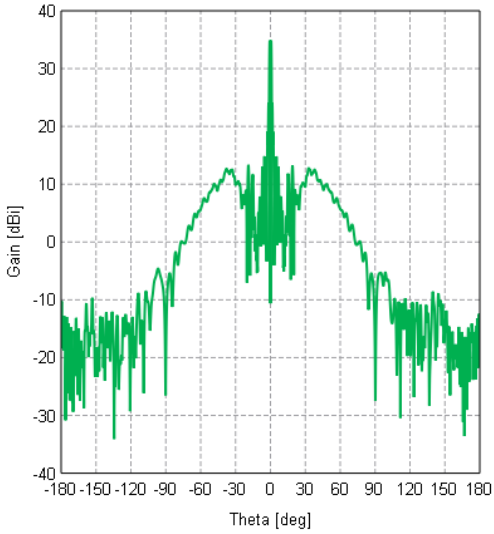

Figure 4. Radiation Pattern of Azimuth Difference Beamform of 12m Diameter Antenna

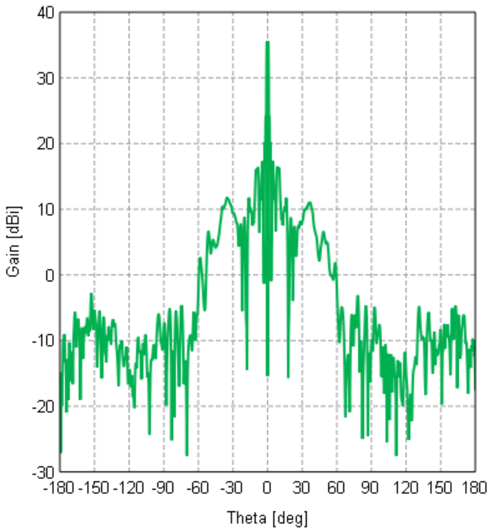

Figure 5. Radiation Pattern of Elevation Difference Beamform of 12m Diameter Antenna

Step 2, analyze of simultaneous visibility of target spacecraft and jammer. Set the orbit parameters of BD-2A and X-37B according to the two line ephemeris from online website [12]. Assume the geographic coordinates of Sanya station is longitude 109.505o, latitude 18.2431o, and altitude 0 m. Simulate the visibilities of the target spacecraft and the jammer during the time interval 0:00 ~ 24:00 at July 20, 2014, which is shown in Figure 6. It can be seen that there are 3 time intervals of simultaneous visibility. The azimuth A_T and A_J, elevation E_T and E_J, distance ρ_T and ρ_J are shown in Figure 6. To alleviate the computation burden, the data rate is set as once per second.

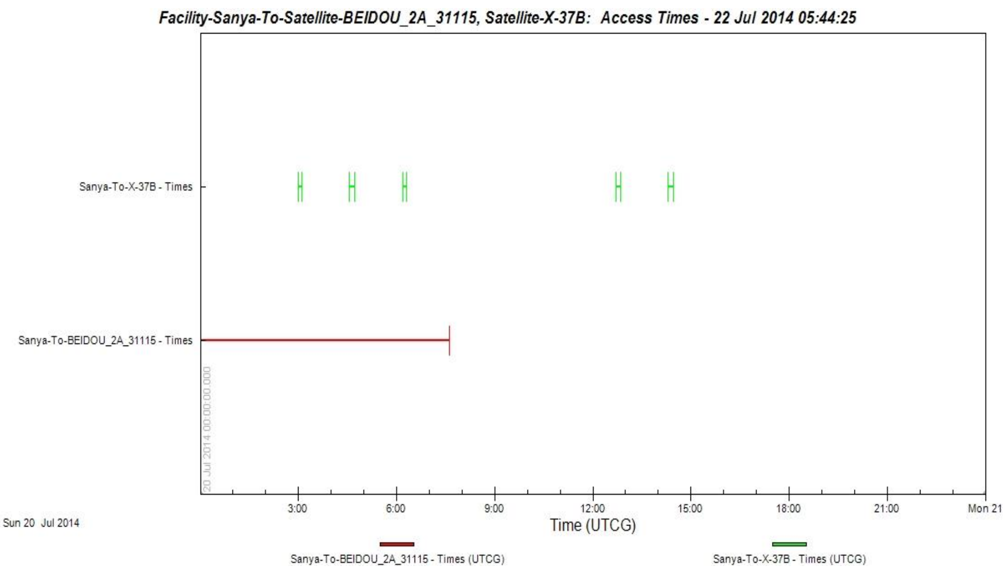

Figure 6. Visibility of Target Spacecraft and Jammer

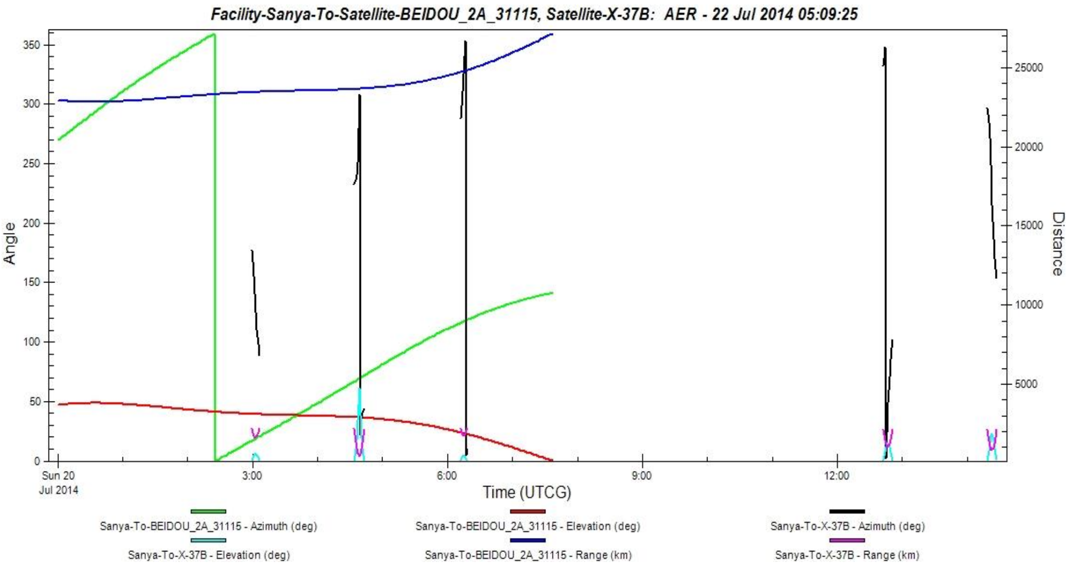

Figure 7. Azimuth Elevation and Distance of Target Spacecraft and Jammer

Step 3, calculate the angles of nutation and precession. Based on the position of the jammer that relates to the target spacecraft, carry out the angles of nutation θ and precession φ . To reduce the length of the article, only the first interval of visibility is exemplified in Table 1.

Table 1. The Simulation Data of Angle in the First Visible Time Interval

No.	Angle of nutation θ_0 (deg)	Angle of precession φ_0 (deg)	Distance of target (km)	Distance of jammer (km)
1	137.0285	4.3452	23449.5100	2200.6936
2	130.5523	9.0628	23452.1783	1925.7740
3	121.7708	16.4417	23454.7992	1704.6205
4	110.6807	28.3418	23457.3732	1567.6574
5	98.2965	50.5082	23459.9010	1538.3782
6	86.6165	78.3196	23462.3831	1622.9349
7	77.2597	77.7350	23464.8204	1805.2564
8	70.6102	90.4415	23467.2135	2059.0360

Step 4, calculate SJNR of the sum channel, which of the azimuth (elevation) difference channel, and the corresponding correlative coefficients. Assume the noise temperature of sum channel equals to 180K, and that of the difference channel equals to 180K also. Set the transmit power of the target spacecraft and the jammer are both 10W, the gain of the transmit antenna are 1, the operation frequency are 2250MHz, B_w equals to 2 kHz. The results of signal and the jammer through numerical computation can be seen in Table 2.

Table 2. SJNR and Phase Offset of the First Visible Interval (SJNR unit: dB)

No.	sum	azimuth		elevation	
	SJNR	SJNR	correlation coefficient	SJNR	correlation coefficient
1	38.3	-2.4	-0.08-0.31j	-4.2	-0.17-0.33j
2	31.8	-6.8	-0.78+0.27j	-8.2	0.59-0.62j
3	33.0	-2.7	-0.42+0.51j	-1.1	0.58-0.07j
4	34.9	-3.3	-0.56-0.28j	-2.8	-0.57-0.27j
5	31.3	-1.1	-0.02+0.56j	-5.3	0.62-0.52j
6	29.3	-1.5	-0.53+0.31j	-3.0	-0.69-0.34j
7	32.6	-17.1	0.81-0.33j	-9.2	-0.73+0.42j
8	32.0	-7.9	0.62+0.57j	-13.9	-0.32-0.83j

Step 5, Let the threshold of signal detection equal -20dBW/Hz, calculate complex monopulse ratio in the case of the first visible time interval. The result is shown in Table 3.

Table 3. CMR of the First Visible Time Interval

No.	azimuth		elevation	
	expectation	variance	expectation	variance
1	0.0012	0.00016	0.0021	0.00018
2	0.0012	0.00150	0.0021	0.00173
3	0.0012	0.00032	0.0021	0.00030
4	0.0012	0.00035	0.0021	0.00036
5	0.0012	0.00017	0.0021	0.00043
6	0.0012	0.00023	0.0021	0.00036
7	0.0012	0.02157	0.0021	0.01727
8	0.0012	0.00200	0.0021	0.00363

From Table 2 and Table 3, it should be found that the variance of angle error estimation is relating to the SJNR of difference. The lower the SJNR, the more evident the variance. As for the seventh data in the tables, the variance increases obviously with the SJNR decrease. Since the power of jamming is set equal to that of the target in this procedure, the result will deteriorate in practical jamming scene.

In the simulation, the internal noise of each channel of the ground station is -173dBw. The received power of jamming is about -134dBW. So the jamming signal becomes the main part. Since jammer usually locates in the sidelobe of the radiation pattern, the fluctuation of the lobe results in the rapid change of the jamming power, i.e., the SJNR in NOT relatively stable. It should be considered while processing the signal of monopulse system.

The jamming of difference channel may be intense than the sum channel. It is thought that the accuracy is in proportion to twice of SJNR in sum channel in general. However, it is shown that the performance of monopulse system relates to the SJNR of difference channel more intensely in the jamming environment.

4. Conclusion

The method of TT&C monopulse system for performance evaluation in random jamming is proposed. The narrow bandwidth jamming and the pulse jamming can removed using various methods of jamming reduction, or transform to broadband random noise with the techniques of spread spectrum, and converted to SNR or SJR in the end. Thus, the methods such as sum and difference antenna pattern achievement, simultaneous visibility analysis, angles position of jammer in antenna coordinate system calculation, sum channel SNR calculation, and complex monopulse ratio calculation can be used to deal with narrow bandwidth jamming and the pulse jamming. As for the spread spectrum TT&C system, jamming can be converting to broadband random noise, the methods proposed here can be applied for jamming rejection. The corresponding methods and thinking also can be use to emulate TT&C monopulse system, simulate target angle tracking system and train the operators.

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