An improved conical scanning tracking method in Satellite Communication Systems

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Abstract—Shipborne satellite earth stations will cause feed vibrations when the conical scanning frequency is too high under low dynamic conditions, which will cause large fluctuations in the received signal strength of the earth station in a relatively stationary environment. And too low conical scanning frequency will cause the earth station to lose the target satellite in a high dynamic environment. The tracking system adopts an adaptive speed regulation strategy and initial phase estimation algorithm, and adjusts the frequency of cone scanning in real time according to the motion attitude of the earth station measured by IMU, so that the earth station can adapt to different dynamic environments. In practical engineering, a Ku band tracking system of shipborne satellite earth station is designed and implemented based on FPGA. The actual test results show that the signal fluctuation of the improved cone scanning algorithm is about 2dbm lower than that of the cone scanning algorithm with a fixed frequency of 50Hz.

1. INTRODUCTION
Shipborne Satellite earth station can realize the communication of multimedia services such as voice, video and data without ground communication infrastructure, and provide reliable satellite communication services for military and civil fields. Its automatic tracking system can keep the earth station always pointing to the target satellite on the dynamic carrier, so as to achieve the purpose of satellite communication in the process of movement. The research of ball station tracking system has a good prospect[1],[2].

In the current research at home and abroad, there are three main tracking technologies for earth stations, monopulse tracking, step tracking and conical scanning tracking. The monopulse tracking has high precision and good real-time performance, which overcomes the influence of amplitude fluctuation of received signal on pointing error extraction. The earth station forms multiple beams in a single pulse time, compares and analyzes the echo signals of each beam, and determines its own pointing error[3],[4]. Step tracking is a tentative tracking method. The driving motor of the earth station controls its own azimuth or pitch direction to move a small angle. By comparing the received signal level before and after the movement, the next adjustment direction is determined, and the above actions are repeated continuously to ensure that it aims at the satellite with a certain accuracy[5]. Conical scanning tracking is to tilt and rotate the feed horn or sub reflector to make the beam conical. The pointing error
information of the earth station is included in the envelope of the received signal amplitude, and the target satellite is tracked by demodulation\cite{6},\cite{7}.

This paper proposes an improved conical scanning tracking method, which adopts an adaptive speed regulation strategy and an initial phase estimation algorithm to adjust the frequency of conical scanning in real time according to the movement attitude of the earth station measured by the inertial measurement unit (IMU), so that the earth station can adapt to the dynamic environment. Through the simulation analysis of the vibration offset of the secondary reflecting surface, the relationship between the distance from the main reflecting surface and the decrease of the gain is explained. In actual application, a set of Ku-band ship-borne satellite earth station tracking system is designed based on FPGA. The test results show that the performance of the improved conical scanning tracking method is better than the fixed frequency conical scanning tracking.

2. BASIC PRINCIPLES OF CONICAL SCANNING

The basic idea of conical scanning is to make the target deviate from the axis, the received signal strength is modulated by the feed rotation frequency, and the modulated signal is multiplied by the quadrature signal to demodulate the control signal proportional to the azimuth and pitch error. As shown in Figure 1, the target satellite position is at point T, the plane OTB is perpendicular to the central axis, point B is the direction of the maximum signal at a certain moment, $\varepsilon$ is the error angle of target deviation, $\theta$ is the angle between the central axis and the line of sight, $\delta$ is the fixed beam deflection angle, and R is the distance from the earth station to the target satellite.

Suppose the earth station pattern is denoted by $F$, then the signal strength received by the earth station is represented by equation (1), $K$ is the ratio constant.

$$U = K F(\theta) \frac{\epsilon}{\cos(2\pi f_0 t - \phi)}$$

(1)

In equation (1), $\epsilon$ is much smaller than $\delta$, $\phi = 2\pi f_0 t$, $f_0$ are the frequency of conical scanning, then $F(\theta)$ carries out Taylor series expansion at $\delta$, ignoring higher-order terms.

$$U = U_0 [1 + m \cos(2f_0 t - \phi_0)]$$

(2)

In equation (2), $U_0$ is the error-free received signal voltage amplitude when the earth station points to the target direction, and $m$ is the modulation index of the error signal. The receiver inputs the AC
component into the demodulator, multiplies it with the quadrature signal \( \cos(2\pi f_\omega t) \) and \( \sin(2\pi f_\omega t) \), and takes out the difference frequency component \( \epsilon_a \) and \( \epsilon_b \), which are given by

\[
\begin{align*}
\epsilon_a &= \epsilon \cos \phi_0 & (3) \\
\epsilon_b &= \epsilon \sin \phi_0 & (4)
\end{align*}
\]

In equation (3) and equation (4), \( \epsilon_a \), \( \epsilon_b \) are converted into the control quantity of the control motor, so that the earth station can track the target satellite in real time.

### 3. DESIGN OF TRACKING SYSTEM

The shipborne satellite earth station is a parabolic antenna with a three-axis stable structure. The central processing unit chooses FPGA. For floating-point numbers, the calculation of trigonometric functions is far greater than that of single-chip computers of the same price, and it can add demodulation response. The logic structure function completed by FPGA in the earth station tracking system is shown in Figure 2. The functions completed by FPGA mainly include: RS232 serial communication, SPI protocol communication, AGC level preprocessing, antenna posture calculation, implementation of improved cone scanning algorithm, PID controller and motor drive module.

![Logic structure and function of FPGA](image)

#### 3.1. Initial phase estimation

Due to the influence of the structure of the hardware circuit and the processing speed of the receiver, it is inevitable that the initial phase lag between the acquisition signal strength and the demodulation process. When the hardware structure is determined, the conical scanning frequency is the main factor that affects the initial phase lag. The initial phase lag will cause a large deviation in the demodulation. Therefore, the initial phase estimation algorithm is designed. The schematic diagram of the algorithm is shown in Figure 3. The trajectory circle is the trajectory of the beam center of the earth station, and \( T \) is the tracking target direction. The points on the circle are separated by 45° and the radius is \( \epsilon \). Specific steps are as follows.

Step 1: Adjust the pointing of the earth station to find the target direction \( T \);

Step 2: Let \( X=A \), adjust the azimuth and pitch of the earth station, make the beam point to point \( X \), and obtain the demodulation error \( \epsilon_X = [\epsilon_{A_x}, \epsilon_{A_y}] \) of point \( X \) according to equation (2);

Step 3: Let \( X \) take the values \( B, C, D, E, F, G, H \) in turn, repeat step 2 to get \( \eta = [\epsilon_B, \epsilon_C, \ldots, \epsilon_H]^T \);
Step 4: Mark $\theta_n = \arctan(\eta_{1n}/\eta_n)$, $\theta_{2i} = [(i-1)\pi/4]$ then the initial phase estimation result this time is $\varphi_a = \sum(\theta_n - \theta_{2i})/8; (i=1,2,3...8)$

![Figure 3. Initial phase estimation](image)

Each conical scanning frequency can use the phase estimation algorithm to estimate the current phase error, that is, $f_{\alpha}$ and $\varphi_a$ have a one-to-one correspondence. The final pointing error is given by

$$\Delta_0 = \cos(\varphi_a + \varphi_a)$$  \hspace{1cm} (5)

$$\Delta_0 = \sin(\varphi_a + \varphi_a)$$  \hspace{1cm} (6)

Where $\varphi_a = \arccos(\varepsilon_a/\sqrt{\varepsilon_a^2 + \varepsilon_b^2})$.

3.2. Adaptive speed control strategy

Considering that the conical scanning frequency that is too high will cause the vibration of the secondary reflecting surface, and that the conical scanning frequency that is too low will cause the earth station to lose the target satellite, so the size of the conical scanning frequency should be selected according to the moving environment of the earth station.

Suppose the half-power beam $\theta_{0.5}$ of the earth station is $2.8^\circ$. The tracking accuracy using conical scanning is given by

$$\theta_{0.5} = 0.1\theta_{0.5} = 0.28^\circ$$  \hspace{1cm} (7)

Suppose the tracking accuracy of azimuth, pitch and roll are $\Delta_\alpha$, $\Delta_\beta$ and $\Delta_\gamma$, which is equivalent to considering the three-axis tracking accuracy, then

$$\Delta_0 = \left(\Delta_\alpha^2 + \Delta_\beta^2 + \Delta_\gamma^2\right)^{1/2}$$  \hspace{1cm} (8)

Therefore, the tracking accuracy of the three-axis should satisfy the following relationship

$$\Delta_\alpha = \Delta_\beta = \Delta_\gamma < \Delta_0/\sqrt{3} \approx 0.162^\circ$$  \hspace{1cm} (9)

The isolation of the gyroscope's stability loop is $L_1$, and the maximum carrier angular velocity is $v$, then the residual angle of the gyroscope's stability loop at time $t$ is given by

$$\bar{\xi}(t) = (vt)/10^{L_1/10}$$  \hspace{1cm} (10)

When using sub-reflector conical scanning tracking, the earth station can perform demodulation error pointing every other scanning period. If the demodulation is correct and the azimuth and pitch errors are completely eliminated, the following conditions should be met.

$$\bar{\xi}(t/f_\alpha) \leq \min(\Delta_\alpha, \Delta_\beta)$$  \hspace{1cm} (11)

Let $L_1 = 16dB, v = 100^\circ/s$, and put into equation (10) and equation (11), it can be given by

$$f_\alpha \geq v/6.449 \approx 15.5r/s$$  \hspace{1cm} (12)

According to equation (12), the conical scanning frequency can be obtained, and then considering the drift of the acceleration sensor, the gyroscope sensor, mechanical error, noise and other factors,
\( f_0 = k f_\text{ref} \) can be taken, and \( k \) takes a constant from 3 to 4. In order to reduce the vibration caused by the fixed scanning frequency, an adaptive speed regulation strategy is proposed. The specific steps are as follows:

Step 1: Under relatively static environment, calculate the initial phase deviation corresponding to the value of \( f_0 \) from 15Hz to 50Hz;

Step 2: In the case of automatic tracking, extract the angular velocity \( \omega \) of the azimuth and pitch measured by the IMU, and the angular acceleration \( a \);

Step 3: Calculate the current motion state \( \mathbf{v} = \omega + a \cdot t \);

Step 4: Compare \( v_a \) and \( v_b \), take \( \max(v_a, v_b) \) to calculate \( f_\text{ref} \);

Step 5: Adjust the conical scanning frequency according to \( f_\text{ref} \), and match the corresponding initial phase, then return to step 2, and continue adaptive speed regulation.

Here \( t \) is the interval between two speed adjustments, which is set to 1s.

4. SIMULATION AND TEST RESULT ANALYSIS

During conical scanning, vibration will cause the lateral (plane perpendicular to the target direction) of the sub-reflecting surface to shift the focal distance to a larger distance, which will affect the gain of the earth station, standing waves and other parameters[8].

Suppose the diameter of the parabolic surface of the earth station is \( D = 1 \text{m} \), the focal length is \( f = 0.42 \text{m} \), the working wavelength \( \lambda = 0.024 \text{m} \), the distance from a point on the parabolic surface to the normal is \( r \), and its azimuth angle is \( \chi \). Pattern function is given by

\[
F(r, \chi) = A(r, \chi)e^{i\phi(r, \chi)}
\]  

(13)

When the incident wave is uniform, then

\[
A(r, \chi) = 1
\]  

(14)

Suppose the phase difference caused by the sub-reflecting surface deviating from the focus is \( \Delta \phi(r, \chi) \), there is

\[
f(\theta, \phi) = \int_0^\theta \int_0^{2\pi} F(r, \chi) \exp\{-i[k \frac{2\pi}{\lambda} \sin(\theta) \cos(\phi - \chi) + \Delta \phi(r, \chi)]\} r dr d\chi
\]  

(15)

The phase difference laterally deviating from the focus is

\[
\Delta \phi_l(r, \chi) = \Delta \phi(r, \chi) \times \left[ 1 + \frac{\chi}{r} \cos(\chi) + \frac{\chi^2}{2r^2} r^3 \times \cos^3(\chi) + \frac{\chi^4}{6r^2} \right]
\]  

(16)

Let \( \Delta \phi(r, \chi) = \Delta \phi_l(r, \chi) \), substituting into equation (15), it can be obtained

\[
f_\text{l}(\theta, 0) = 2 \int_0^{\frac{\pi}{2}} J_0 \left( \frac{\chi^2}{r^2} \right) r \sin(\theta) - \frac{\chi^2 \delta \Delta \phi}{r^2 \delta^2} dr
\]  

(17)

Where \( k = \frac{2\pi}{\lambda} \). Equation (17) is the two-dimensional pattern of the direction of maximum gain. When \( \delta = 0.2, 4, 6, 8 \text{mm} \) is changed, the pattern of different lateral defocusing distances is obtained by simulation, as shown in Figure 4.
Figure 4. Simulation of lateral defocus

It can be seen from Figure 4 that the greater the vibration, the greater the offset distance of the pattern, and the left and right are no longer symmetrical. When $\delta_l = 2\text{mm}(4, 6, 8\text{mm})$, the parabolic optical axis deviates from the peak direction of the pattern by about $0.2^\circ(0.4^\circ, 0.65^\circ, 0.9^\circ)$. When $\theta = 0$, $P$ is used to represent the maximum receiving gain. The greater the vibration distance, the greater the drop in $P$. When $\delta_l = 2\text{mm}(4, 6, 8\text{mm})$, $P$ is reduced by $0.19\text{dB} (0.78, 1.78, 3.2\text{dB})$.

In order to verify the performance of the tracking system, a three-axis rocking table was used to test the ship-borne earth station. The azimuth, pitch and roll of the rocking table can achieve sinusoidal motion with amplitude less than 180 degrees and period greater than 1s.

At the test site Nanjing, the three-axis parameters of the swing table are all set to 5 degrees in amplitude and 8 seconds in period. The target satellite is CHINASAT 6A (Ku band). The received power of the beacon signal is represented by $P$. The test results are shown in Figure 5.

It can be seen from Figure 5 that the signal received power fluctuation of the improved cone scanning tracking system is about $1\text{dBm}$, and the signal receiving power fluctuation of the cone scanning tracking method with a fixed frequency of $50\text{Hz}$ is about $3\text{dBm}$. The improved tracking system reduces the signal fluctuation by about $2\text{dBm}$ in a low dynamic environment, and the signal quality is improved.

Figure 5. Received signal power of earth station
5. CONCLUSIONS
Although there are many ways to reduce vibration, it is undoubtedly an economical and simple method considering the software algorithm. The improved conical scanning tracking system proposed in this paper adopts the speed adaptive strategy and initial phase estimation algorithm. And through simulation and actual engineering tests, the improved cone scanning tracking system reduces the vibration caused by the fixed frequency cone scanning tracking system in a low dynamic environment, and improves the signal stability.

Acknowledgement
This work is supported by The National Natural Science Foundation of China (No. 91738201)

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