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Monopulse Tracking Performance of a Satcom Antenna on a Moving Platform

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Abstract

A satellite communication (Satcom) antenna mounted on a moving platform provides a controlled heading that enables a geosynchronous satellite to communicate with the ground. A monopulse tracking method is effective for antenna control on a vehicle when it vibrates severely. However, this method has unexpected obstacles and its control performance is insufficient. To improve its control performance, the control command and monopulse error, the signal delay, and the radome effect are evaluated through tests. The authors then propose a method to transform the antenna error from 3D coordinates to 2D antenna coordinates. As a result, the antenna control performance is improved. As indicated in this study, examining antenna systems using the monopulse method on moving platforms is possible by understanding the antenna test process.

Key Words: Geosynchronous Satellites, Inertially Stabilized Platform, Monopulse Signal, Moving Platform, Radome, Satcom Antenna.

I. INTRODUCTION

The satellite communication (Satcom) antenna technology is applied to various systems to communicate with other systems that are distant. A message sent from a Satcom antenna goes through a geosynchronous satellite and is delivered to other antennas [1].

As geosynchronous satellites, which are used for this communication system, remain in the same location at geocentric earth-centered earth-fixed (ECEF) Cartesian coordinates, they appear to remain at one point in the sky. This kind of satellite moves around the Earth in an orbit that is farther away than those of other types of satellites. These two features make it easy for the Satcom antenna to connect with the satellite. As the antenna heads in one direction in the ECEF Cartesian coordinates, this antenna will communicate with the satellite regardless of time and space if the antenna does not move far away from its initial location. This characteristic enables the Satcom antenna technology to be simply applied to various types of moving vehicles, including those used in military applications [2].

To use the Satcom antenna technology on a moving platform, the inertially stabilized platform (ISP) techno-logy is usually applied to hold or control the line of sight (LOS) of the antenna relative to the satellite direction (Fig. 1). Several methods can be used to control the antenna. For an antenna on a stationary body, the step-tracking method is effective at finding the satellite direction by scanning the beacon level in the air and choosing the direction where the highest beacon level is scanned [3, 4].

The monopulse tracking method is preferred for controlling an antenna on a moving body. Monopulse measures the radiation direction in real time using a beam that is spread out across the centerline of the antenna. Therefore, the monopulse track-

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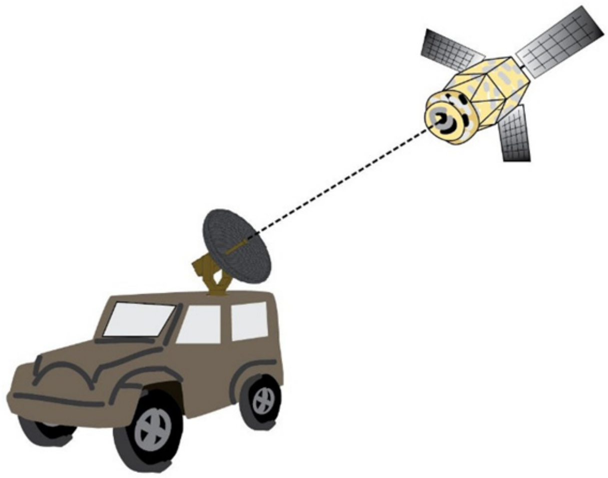

Fig. 1. Concept of the Satcom antenna control on a moving platform (This antenna uses ISP to hold the LOS stationary).

ing method is more effective on a moving body than the step tracking method, which requires sufficient time to scan the beacon level [5].

In this study, we seek to enhance the control performance of a Satcom antenna on a moving platform, such as a car, ship, or airplane. Wave motion can be imparted to these moving platforms or vibrated by external forces. As this research focuses on defense development for military purposes, most angles are normalized by multiplying them by an arbitrary number *K*, and several specific algorithms are not included.

II. Test Conditions

1. Antenna

The antenna pedestal structure used in this research consists of a two-axis gimbaled pedestal, with an azimuth axis and an elevation axis. Each axis is moved by a motor and a resolver [6]. The third motor is located behind the antenna aperture and rotates the feed antenna to adjust the angle to the monopulse signal, which exhibits linear polarization. As this axis is not used to control the LOS to the satellite, it is not considered in this research. A number of radio frequency-related components, such as a low noise amplifier, are placed at the back side of the antenna. As this moving platform has to change its direction freely, a slip-ring is used on the azimuth axis to rotate the axis beyond one revolution. The parabolic reflector is made from carbon composites, and the pedestals are fabricated from stainless steel.

In this research, two coordinates are set. The first one is the ground coordinate that is fixed on the ground under the antenna. It does not change even if the moving platform vibrates or if the antenna moves. Therefore, the LOS of the antenna on the ground coordinate is stationary because geosynchronous satellites remain unchangeable in terms of ECEF Cartesian coordinates. The second one is the antenna coordinate, which considered the center bottom of the antenna as the standard datum. The heading direction of the antenna can be represented on this coordinate using the azimuth and elevation gimbal angles.

In the ISP technology, a gimbal lock can occur when the LOS and the azimuth axis are driven into a parallel configuration. The gimbal lock effect means that the pedestals lose one degree of freedom of control. Fortunately, the moving platform on which this antenna is attached is expected to perform only in a designated area, and the gimbal lock effect is not considered.

2. Test Method

This research aims to stabilize the LOS of this antenna in a vibrating environment that imitates the platform's movement. A number of instruments are applied in this test.

A motion simulator is utilized to cause platform vibration. Fig. 2 illustrates the concept of this test. The antenna is fixed to a simulator, which generates a disturbance on the moving platform. This motion simulator can impart six axes of motion: roll, pitch, yaw, surge, sway, and heave. The test disturbance is calculated according to the test flight kinematic information. As the purpose of this test is to stabilize the LOS of the antenna, this antenna is tested only for the rotational axis.

The inertial navigation system (INS) is a sensor that can measure the motion and rotation of a moving object without external references using a combination of three gyro sensors and three accelerator sensors. For most moving platform systems, the platform's position information is delivered from the platform's main INS system to the control unit of the antenna. However, for this antenna test, another INS is mounted to measure disturbances of the motion simulator.

As the monopulse method is used to detect the satellite direction using specific signals sent by satellites, selecting the correct satellite with which to make the data link is important. For this test, a Korean geosynchronous satellite, which is a Ku-band

Fig. 2. Antenna on a six-axis motion simulator.

satellite that uses linear polarization, is applied.

This test is conducted inside a radome to protect the antenna from disturbances, such as wind, rain, and dust.

3. Performance

The antenna tracking test is conducted with the following prescribed conditions. The disturbance is a sine wave movement (17° 0.4 Hz) for the roll axis of the simulator. This wave is calculated using the real flight of an airplane, and the most severe expected external force is applied. Using the INS sensor and the monopulse signal, the control target angles of the azimuth and elevation motors are calculated on the basis of the antenna's position status.

Fig. 3 and Table 1 show the results of the monopulse tracking test. The black line is the control error, which indicates how well the antenna follows the target angle; the gray bold line indicates the monopulse error. For security purposes, the angles are multiplied by an arbitrary number *K*. The root mean square (RMS) and the peak angle of the error are provided in Table 1. The RMS of the monopulse error is 10 times higher than that of the control error. Therefore, the motors of the antenna pedestal follow the commanded angles well, but the LOS of the antenna does not head precisely for the satellite.

Section III describes the process to check for possible causes of instances in which the antenna cannot track the satellite accurately. Whether the command angles correspond with the direction of the satellite is not certain. The delay of the signal processing is then checked. The radome effect is also tested.

Table 1. Monopulse tracking test results (sine wave 17° 0.4 Hz)

	RMS (°)	Peak (°)
Control error	0.0786	0.2600
Monopulse error	0.7919	1.5559

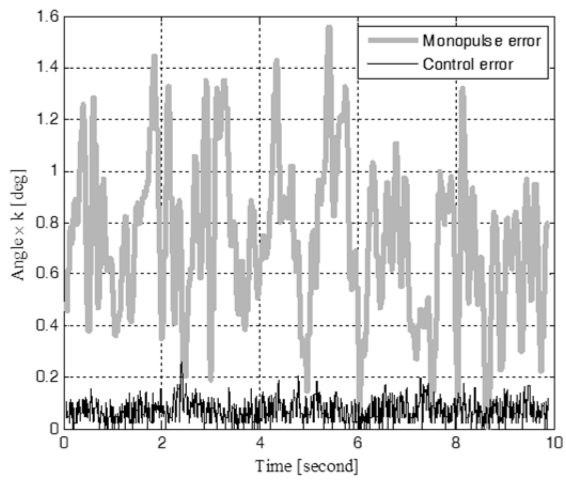

Fig. 3. Results of the monopulse tracking test: monopulse error and control error (sine wave disturbance 17° 0.4 Hz).

III. Cause Analysis

1. Command Angle and Monopulse Signal

To improve the control performance, a number of tests are conducted to confirm the critical factors affecting the control. The command angle is first tested. To check the command angle, the command angle and the monopulse angle are translated into direction angles on the ground coordinate. The monopulse angle is the sum of the motor angle feedback from the resolver and the monopulse error; this value is a direction heading for the satellite on the antenna coordinate measured by the monopulse system. By comparing the two angles on the ground coordinate, confirming which angle is wrong is possible. Given these two angles, the right angle must be unchangeable and the other is a variable that is considered a disturbance as the satellite is stationary.

In this comparison, the command angle and the monopulse angle are translated from the antenna coordinate to the ground coordinate. Using a trigonometric function, the vector for the LOS of the antenna on the antenna coordinate is written in terms of the azimuth and the elevation motor angles $\boldsymbol{\theta_{AZ}}$ and $\boldsymbol{\theta_{EL}}$, which are obtained from the monopulse tracking test.

$$\begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} = \begin{bmatrix} \cos\theta_{EL}\cos\theta_{AZ} \\ \cos\theta_{EL}\sin\theta_{AZ} \\ \sin\theta_{EL} \end{bmatrix}, \tag{1}$$

where the subscript l indicates that this vector is represented on the antenna coordinate. The subscript g indicates the global coordinate.

Using the inverse rotation matrix, which is a Euler matrix, about the X, Y, and Z axes, the vector in the ground coordinate can be calculated from the vector in the antenna coordinate as follows:

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = E_Z(\psi_1)^{-1}E_Y(\theta_1)^{-1}E_X(\varphi_1)^{-1}, \tag{2}$$

where the position angles on the stationary simulator ψ_1, θ_1, φ_1 are applied to the Euler matrix.

$$\begin{bmatrix} \theta_{AZ}^{ground} \\ \theta_{EL}^{ground} \end{bmatrix} = \begin{bmatrix} \tan^{-1}(x_g/y_g) \\ \tan^{-1}\left(z_g/\sqrt{x_g^2+y_g^2}\right) \end{bmatrix}. \tag{3}$$

From the vector on the ground coordinate, the motor angles of the antenna on the ground coordinate can be calculated using the reverse of (1).

$$\begin{bmatrix} \theta_{AZ\_error}^{ground} \\ \theta_{EL\_error}^{ground} \end{bmatrix} = \begin{bmatrix} \theta_{AZ}^{ground} \\ \theta_{EL}^{ground} \end{bmatrix} - \begin{bmatrix} \theta_{AZ}^{satellite} \\ \theta_{EL}^{satellite} \end{bmatrix}. \tag{4}$$

The precise ground angle cannot be revealed in this study because this antenna is developed for military purposes. The error against the theoretical satellite direction is plotted. The results are separated into the azimuth angle and the elevation angle, and the two graphs are synchronized based on time [7].

Fig. 4 shows how the monopulse angle and the command angle differ according to the actual direction. Although the gaps can change because of the disturbance from the simulator, the difference between the two angles is remarkable at the elevation angle. At the elevation angle, the variance of the monopulse error is two times more severe than that of the command angle. This graph indicates that the heading point of the input command angle is not the point where the satellite exists. The antenna cannot determine the heading of the satellite even if the motors follow the command angles. However, whether this is due to the command angle being miscalculated or not is not certain.

2. Monopulse Signal Delay

The previous test confirmed a gap between the satellite direction and the command angle. However, what degrades the antenna control performance remains unclear. To check for possible factors that can affect the control performance, a number of additional tests are conducted.

The phase difference between the command angle and the monopulse angle is about 0.4 second, as illustrated in Fig. 4. Therefore, the monopulse signal delay is considered to be an important factor affecting the antenna control. To determine the signal delay, the monopulse tracking test is conducted with a changed value of disturbance (sine wave 17° 0.01 Hz). The speed of the disturbance is only changed in comparison with the value in the previous test. Using a slowdown of the simulator movement, the effect of the signal delay can be minimized.

Fig. 5 shows the results of the monopulse tracking test on the

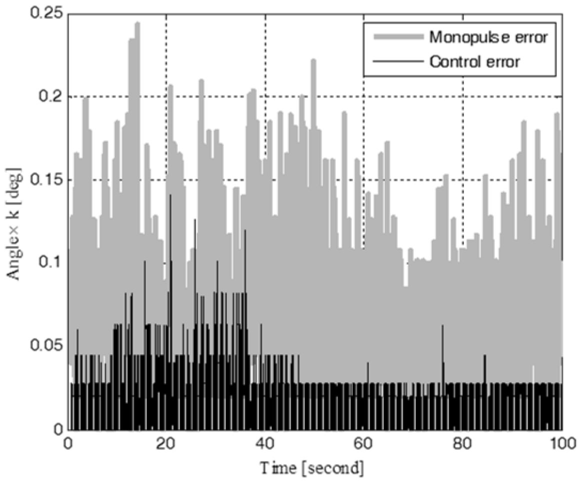

Fig. 5. Monopulse tracking test results: monopulse error and control error (sine wave disturbance 17° 0.01 Hz).

Table 2. Monopulse tracking test results (sine wave 17° 0.01 Hz)

	RMS (°)	Peak (°)
Control error	0.0197	0.1414
Monopulse error	0.0828	0.2433

17° 0.01 Hz sine wave disturbance. The RMS and the peak of the error are provided in Table 2. In comparison with the previous test, a control error that has four times better RMS and two times better peak error is found. In addition, a nine times better RMS error and a six times better peak error are found for the monopulse error. Greater improvement is achieved for the monopulse error than for the control error.

These results imply that the time delay of the monopulse signal processing can be regarded as one of the important aspects that degrade the antenna control performance.

To obtain an accurate analysis, the angles are translated to ground coordinates in the same way as in the previous test. Fig. 6 shows the results of the angle translation. As shown in this graph, the command angle and the monopulse angle are headed toward the same direction as in the previous test. That is, the command angle is accurately headed for the satellite direction. However, even though the monopulse error decreases, the heading direction of the antenna changes with the movement of the motion simulator.

3. Radome

According to the previous test results, the LOS of the antenna is not constant with the movement of the simulator. As the satellite is located far from the Earth, the LOS of the antenna must be constant regardless of the position of the antenna. For this reason, the radome is unlikely to be the source of the variable LOS of the antenna.

A radome is used to protect the antenna from external im-

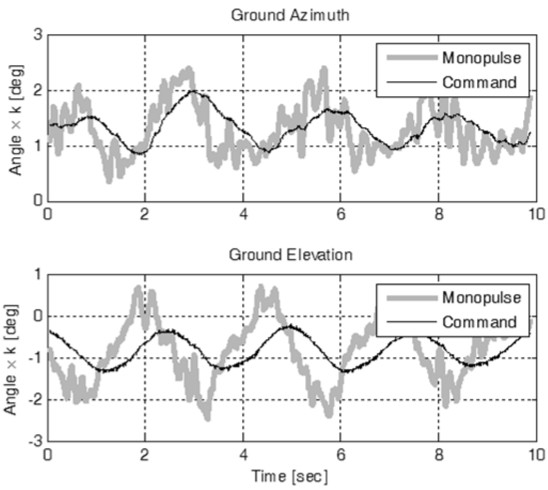

Fig. 4. Monopulse tracking test results for the ground coordinate (sine wave 17° 0.4 Hz).

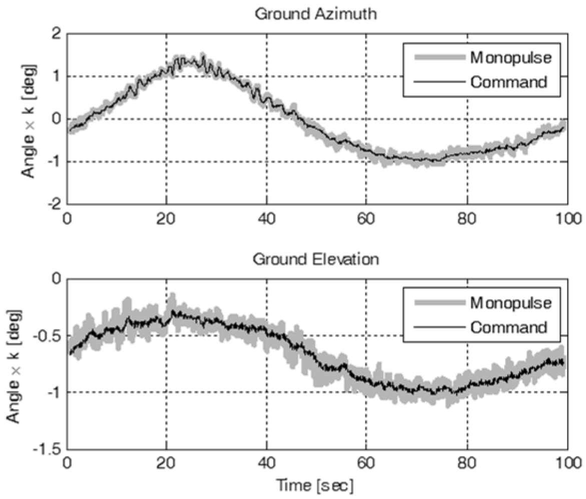

Fig. 6. Results of the stabilization test for disturbance (sine wave 17° 0.01 Hz).

pacts that can affect the antenna control, make the heading direction inaccurate, and lower the antenna communication ability. However, a radome can attenuate, depolarize, and distort the antenna wave, which can all degrade the antenna pattern. Fig. 7 shows the LOS distortion problems that can result from using a radome. The Satcom antenna's LOS follows the dotted line, but the signal LOS changes to a solid line after going through the antenna radome [8]. The Satcom antenna is usually located on the topside of the moving platform and is covered by the radome. The body of the moving platform is designed to consider the aerodynamics and weight balance of the vehicle. For this reason, the shape of the radome is not simple and modeling the radome is complicated when attempting to compensate for the bending of the antenna signal.

Although the use of a radome brings these problems, the antenna nonetheless must be protected by the radome on the platform. Distortion of the antenna signal occurs regardless of how precisely the radome is designed. Another solution is to try to improve the performance of the antenna control. Although distortion exists, the control error is sufficiently low that the antenna's control performance can be improved by decreasing the monopulse signal delay.

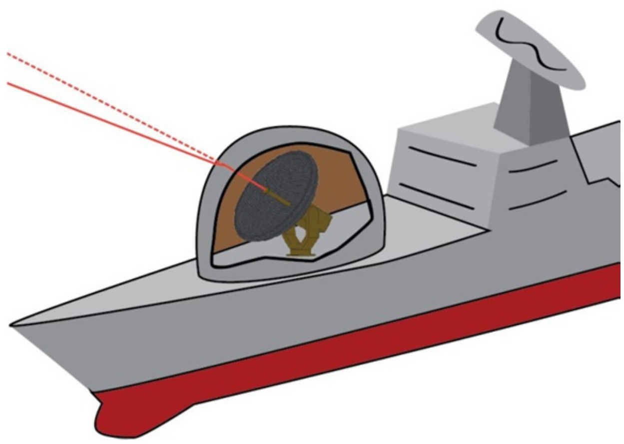

Fig. 7. Effect of radome on the LOS of antenna.

Table 3. Monopulse tracking test results (sine wave 17° 0.4 Hz with the changed monopulse signal filter)

	RMS (°)	Peak (°)
Control error	0.0389	0.1826
Monopulse error	0.1486	0.2236

Monopulse signals are used to detect the direction of a satellite. When using such signals, a filter is essential because monopulse signals are noisy and unclear. To clarify the monopulse signal, a finite impulse response (FIR) filter is applied for system robustness, which is the most important factor in defense applications. The FIR filter incurs no feedback from output to input and is stable because all the poles lie in the origin. However, this filter requires more taps than the infinite impulse response (IIR) filter. This requirement increases the filter processing time and causes the monopulse signal to have a long delay [9].

To decrease this delay, the filter is changed from an FIR to an IIR. The IIR filter incurs feedback from output to input but requires fewer taps to obtain the step-up and step-down responses. Therefore, the sensing delay can be decreased by changing the filter. The robustness of the filter is compensated for by the software setup. The specific filter algorithm is not revealed in this study for security reasons of defense development.

IV. Improved Performance

Fig. 8 presents the results of the monopulse tracking test for a 17° 0.4 Hz sine wave disturbance with the changed monopulse

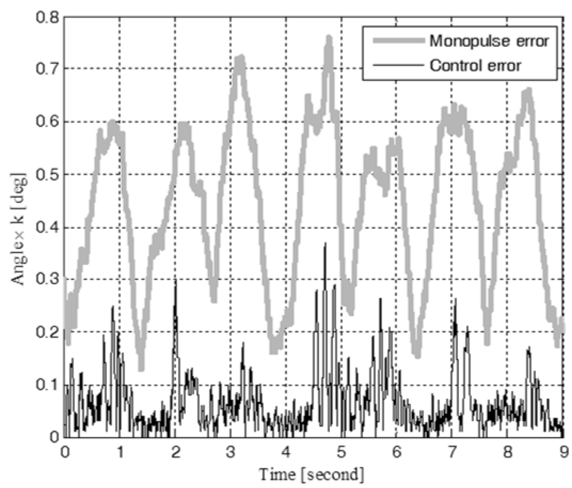

Fig. 8. Monopulse tracking test results of the monopulse error and control error (sine wave disturbance 17° 0.4 Hz and changed monopulse signal filter).

signal filter. The RMS and peak error are shown in Table 3. The control error is similar to that in the test using the previous filter. However, the monopulse error is 2.5 times smaller than the RMS and a 3.5 times lower peak error is found. These results confirm that the antenna using the new monopulse signal processing filter can track the satellite more accurately than the antenna with the previous filter.

Ⅴ. CONCLUSION

A Satcom antenna on a moving platform points to a geosynchronous satellite and communicates through it. Moving platforms are subject to vibration by external disturbances when they move. According to the disturbance data of the platform, an antenna control test is conducted for the disturbances. A way to change the antenna heading error from ground coordinates to antenna coordinates is suggested through the test. Accordingly, delay is decreased and the performance of the antenna control is enhanced by changing the monopulse signal processing. The antenna shows 2.5 times better control performance than before. Overall, this study provides a better understanding of monopulse antenna systems on the move.

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