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LETTER

Phase measurement and adjustment of reflector antenna with beam waveguide feeds

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Abstract When reflector antennas with a beam waveguide feeding system are used in an array configuration, the transmission phase of each reflector antenna must be known and corrected. In this paper, we propose a method in which a reflector plate is placed in the center hole of the main reflector, the reflected phase at the primary radiator horn is measured, and half of the measured phase is used as the transmission phase of the beam waveguide feeding system. The proposed method was verified by calculation, measurement using a simple model with the same path length, and measurement using an actual reflector antenna, and its effectiveness was confirmed.

Keywords: reflector antenna, array configuration, beam waveguide feeds, transmission phase measurement
Classification: Satellite communications

1. Introduction

The site of the Deep Space Network (DSN) of the National Aeronautics and Space Administration (NASA) is located approximately 120 degrees apart on Earth at Goldstone, California; Madrid, Spain; and Canberra, Australia. Each of these sites consists of a Φ70 m antenna, a Φ34 m High Efficiency (HEF) antenna, and a Φ34 m Beam Wave Guide (BWG) antenna. To improve signal processing capability, a plan called the DSN Aperture Enhancement Project (DAEP) has been announced [1, 2] to eliminate the Φ70 m antenna and replace it with an array of four Φ34 m BWG antennas by 2025. The Φ34 m antenna is easy to maintain and can provide the same or better performance as the Φ70 m by arraying four units. Four antennas arrayed for reception and one antenna with 80 kW for transmission.

A beam waveguide feed system (BWG: Beam Wave-Guide) [3] is an antenna system in which radio waves are propagated from the primary radiator horn to the sub-reflectors with the beam focused by typically four reflectors. Since the antenna direction can be changed while the transmitter and receiver are fixed on the ground, this type of antenna is widely used for reflector antennas of medium size and larger. Strict phase adjustment is being considered by array signal processing in the receiving system, but when used as a transmitting antenna, the pass-through phase should be approximately adjusted.

In this paper, the authors describe a method for making the radiation phase of each antenna identical when configuring an array of reflector antennas with a beam waveguide feeding system [4, 5]. A reflector plate (center plate) is placed in the center hole in the center of the main reflector, and half of the reflection phase at the primary radiator horn is estimated as the one-way transmission phase. This estimated transmission phase is used to calibrate each antenna that composes the array.

Section 2 describes the method of measuring the transmission phase by the center plate, Section 3 shows the validation by calculated values, Section 4 demonstrates the measured values by the partial model, and Section 5 describes the results of the measurement using an actual antenna. Finally, Section 6 summarizes the conclusions.

2. Transmission phase estimation using center plate

In a beam waveguide feeding system (BWG), each reflector mirror is installed with a very long path length relative to the wavelength. Therefore, the propagation path length of the entire beam waveguide feeding system varies depending on the installation accuracy of the reflector mirrors, and the pass-through phase changes significantly. On the other hand, the installation accuracy does not affect the amplitude characteristics of the antenna. Since BWG antennas are generally used alone, there is no need to measure or adjust the transmission phase, and the installation accuracy is not required to be as accurate as adjusting the transmission phase for each antenna. The installation accuracy is on the order of millimeters, with a phase error of several tens of degrees, depending on the frequency band. It is impossible to improve the mechanical installation accuracy and make the transmission phase identical.

In this paper, we consider calibration by electrically measuring the transmission phase of each antenna that composes the array. While the radiation phase due to the installation accuracy of the main and sub reflectors can be estimated by external laser position measurement, the BWG is located inside cylindrical structures, making external position measurement difficult. As shown in Fig. 1, the BWG antenna has a small hole (center hole) in the center of the main reflector through which radio waves pass, and a reflector plate (center plate) is installed here. The reflection phase of radio waves emitted from the primary radiator horn, reflected by the center plate, and returned to the horn is measured. Since the reflection phase is affected by the round-trip path length, the one-way transmission phase can be estimated by half of the

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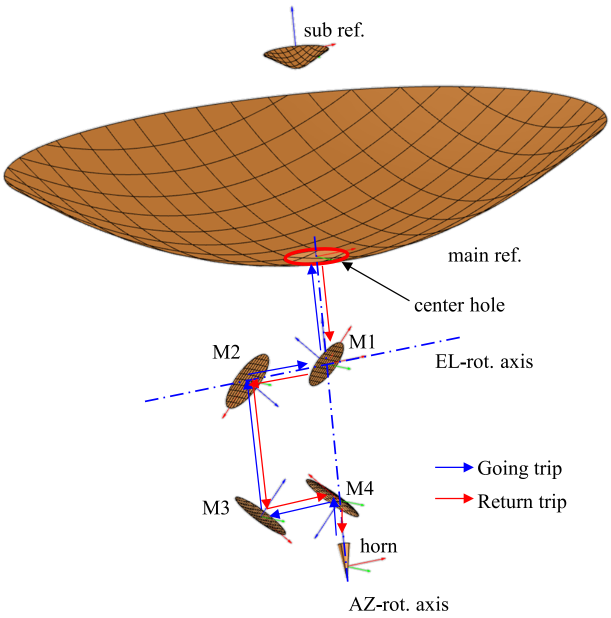


Fig. 1 Reflector antenna with beam waveguide feeds (BWG antenna).

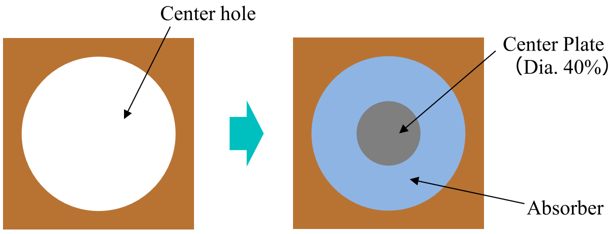


Fig. 2 Center plate (CP) installed in the center hole.

reflection phase. The accuracy of the center plate installation is directly related to the accuracy of the reflection phase. As shown in Fig. 2, the center plate is sized as a single plate that can be transported and installed (45% diameter of the hole), and an absorber is installed to remove the influence of the surrounding support structure. The absorber is assumed to be thin, and a reflection coefficient of -12 dB was set for the analysis, assuming that the amount of absorption is not sufficient.

3. Numerical verification

Using the *Coupling* function of TICRA's *Ticra Tools*, a simulation verification was performed. The analytical model and the coordinate system is shown in Fig. 3. The characteristics of the feeder circuit, which were not included in the analytical model, were added as S-parameters equivalent to the reflection characteristics of the feed circuit. The reflection characteristics of the feeder circuit were separated by applying a time gate in the FFT after calculating with a relative bandwidth of 10%.

Three cases with different phase shifts were assumed: case 1, M2 mirror shifted $+0.1\lambda$ in the x direction (path length decrease, positive phase shift); case 2, M1 mirror shifted $+0.1\lambda$ in the x direction (path length increase, negative phase shift); case 3, M1 mirror shifted $+0.1\lambda$ in the y direction (no path length change), phase (no path length change, no phase change) was calculated.

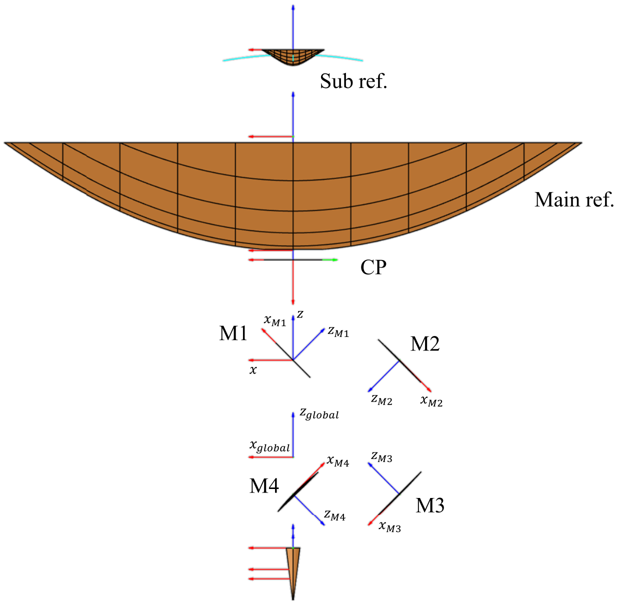
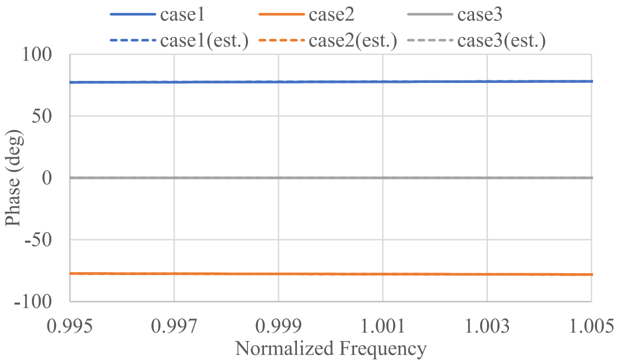
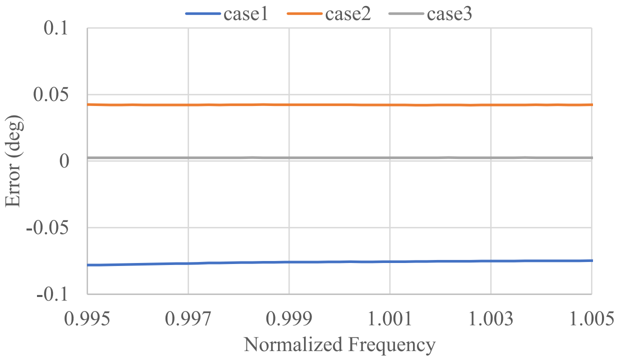


Fig. 3 Analytical model and coordinate systems of the BWG antenna.



(a) Calculated reflection phase with time-gate



(b) Calculated reflection phase error with time-gate

Fig. 4 Reflection phase characteristics of calculation.

Figure 4 shows the calculated phase difference from the reference model without the shift of the reflector mirror. Since the reflector mirror is intentionally shifted, the phase difference (amount of change) is known and is shown as "est" in Fig. 4 (a) with a dotted line. Figure 4 (b) shows the difference between the calculated and the assumed values as the phase error. The ripple is reduced by the time-gating process, and it can be confirmed that the phase difference can be estimated with an error of 0.1 deg or less in the calculated value.

Although detailed results are not presented in this paper, the following conclusions are obtained from the verification. The influence of absorbers around the center plate is sufficiently small and almost all power is reflected by the center plate. The effect of multiple reflections between the reflector mirrors is sufficiently small, and sufficient reflection phase measurement is possible if only the effect of reflections from the feed circuit is removed. The reflections of the feed circuit and the center plate are sufficiently far apart and can be sufficiently separated by time-gating. The frequency ratio bandwidth is set to 10% or more, the characteristics of the feed circuit can be removed, and the reflection phase (twice the passband phase) can be estimated with an accuracy of 0.1 deg or less.

4. Verification of measurement by simplified model

The actual measurements were verified on a simplified model with the same path length as the real antenna. The measurement system shown in Fig. 5 with facing horn reflectors was used. Although the number of reflector mirrors and their positions cannot be reproduced, a large amount of phase rotation ($300\lambda \times 360$ deg) was reproduced by making the round-trip distance the same as that of the real antenna. The position of the short end of the waveguide was varied by a known amount, and the phase amount change was compared between the estimated and measured values.

To achieve the highest possible time resolution (broadband measurement), measurements were taken over the entire bandwidth of the standard waveguide (45% relative bandwidth); the frequency interval was minimized by setting the maximum number of frequency points that could be set in the VNA (Vector Network Analyzer). The distance between the reflection point (short plate) and waveguide components with less favorable reflection characteristics (rectangle-to-circuler mode converter, coaxial waveguide transducers, etc.) was separated.

The gate width of the time-gating process must be set appropriately because if it is too narrow, necessary information is lost and the phase error becomes noticeably larger, and if it is too wide, the error becomes larger due to the influence of other reflected waves. In order to facilitate time-gate processing, the measurement system was adjusted so that the distance between reflection points is as large as possible. In the actual measurement, the reflection points are only the feeding circuit and the center plate, and the analysis confirmed that multiple reflections between the reflector mirrors can be ignored. The reflection points of the center plate and the feeding circuit are sufficiently far apart to not be a problem.

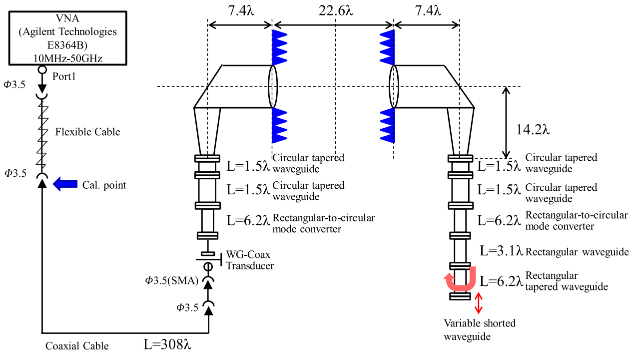
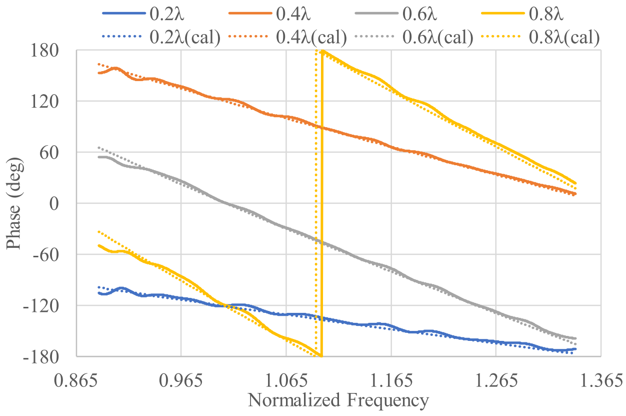


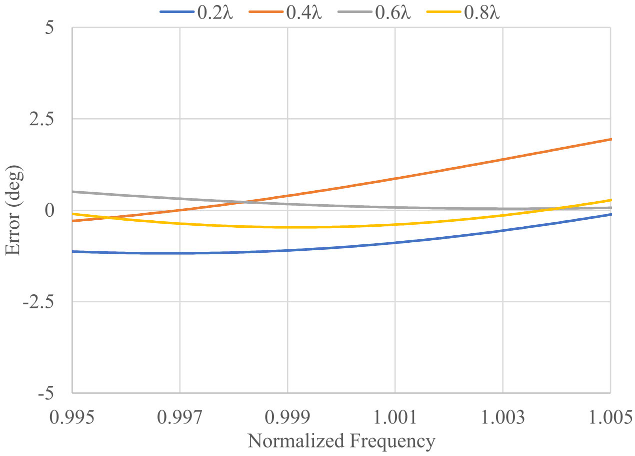
Fig. 5 Measurement system of simplified model.

Figure 6 (a) shows the results of the phase measurement. Only the reflections from the waveguide short are extracted by time-gating. The phase difference from the reference is shown when the short position is offset from the reference position. Note that "cal" is the amount of phase change estimated from the offset of the short position and calculated from the wavelength in the waveguide. Figure 6 (b) also shows the phase measurement error, and it was confirmed that a phase error of about 5 deg can be measured.

Although detailed results are not presented in this paper, the following conclusions are obtained from the verification. Bandwidth should be increased to the extent possible, and frequency intervals should be fine enough to avoid aliasing. The accuracy of the offset amount of the path length is directly related to the phase error, so the accuracy of the center plate installation should be high. If the distance between reflection points is close, it is difficult to separate reflections. In actual measurements, there are no reflection points other than the center plate and the feed circuit, and analysis has confirmed that multiple reflections by the reflector mirrors have no effect, so it should be possible to separate the reflected waves from the center plate and feeder circuit.



(a) Phase difference (whole band)



(b) Phase error (around center frequency)

Fig. 6 Calculated reflection characteristics.

5. Verification of actual measurement

The reflection phase measurement by the center plate has been verified and validated by calculated values and simplified measurement model. In this section, the first BWG antenna that comprising the array was manufactured and the phase measurement by the center plate was performed.

Since only one antenna was used, it was not possible to verify individual differences in radiation phase with other antennas, so the reflection phase was measured by changing the pointing direction of the main reflector using an antenna drive mechanism. Since the path length does not change with the pointing direction and the transmission phase does not depend on it, it was assumed that any change in the reflection phase at the horn would be limited to an error. However, as shown in Fig. 7, a large phase change of about 10 deg,pp actually occurred with AZ rotation, and we investigate the cause.

It was found that the cause was the coating paint on the surface of the reflector mirrors. In the case of normal incidence, no change occurs between TE and TM waves, but in the case of oblique incidence. It is known that the reflection phase differs between TE and TM waves due to the dielectric layer on the surface. The incident/outgoing angle to each reflector mirror is nearly 45 deg, and the effect is found to be significant. Since the polarization direction of this antenna is not controlled by rotation of the primary radiator, polarization rotation of the mirror incidence occurs depending on the antenna pointing direction. Therefore, the TE/TM component of the incident wave to each reflector mirror differs depending on the pointing direction, resulting in a reflection phase change with AZ rotation.

In the calculation model, each reflector mirror was loaded with a dielectric layer equivalent to the thickness of the coating film, and the reflection phase at the horn was calculated, confirming characteristics that agree with the measured values. Figure 7 shows the measured and calculated phase difference with AZ rotation, shown as relative values referenced to AZ = 270 deg. In the calculations, the coating thickness was measured by the eddy current method. Although the breakdown between the primer and topcoat layers is not known, the primer layer was set at the nominal value and the topcoat layer was set to match the total film thickness of the measured values. Catalog values were used for the dielectric constant of each material. As shown in Fig. 7, the agreement between the calculated and measured values was confirmed at EL = 90 deg and EL = 20 deg. Sufficient agreement between the calculated and measured values was confirmed, indicating that highly accurate measurements are possible with actual antennas.

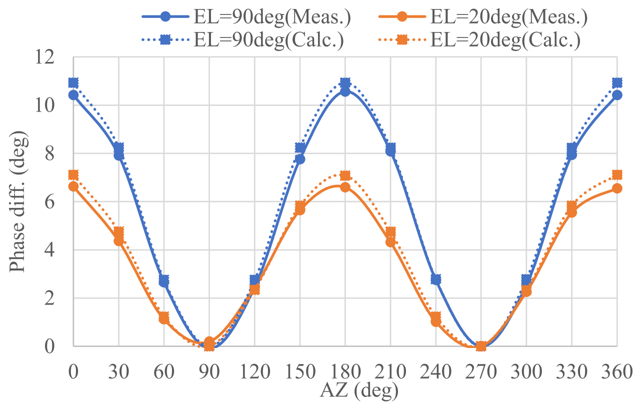


Fig. 7 Phase characteristics for AZ rotation.

6. Conclusion

We proposed a method to measure the transmission phase of a reflector antenna with a focused beam feeding system using a reflector plate (center plate) installed in the center hole. The phase of the reflected wave by the center plate at the primary radiator horn is measured, and half of it is estimated as the transmission phase.

The computational verification confirmed that the effects of absorbers around the center plate and multiple reflections between focusing reflectors can be neglected and that only the reflections of the feed circuit need to be separated. Simplified model measurements confirmed that the frequency bandwidth must be wide, the frequency spacing must be small, and the accuracy of the center plate installation must be improved. Furthermore, it was confirmed that the time-gate width must be appropriately set to separate the reflected waves by gating. Finally, the method was verified by manufacturing an actual antenna, and it was found that the reflection phase changed by about 10 deg,pp with AZ rotation. The cause of the phase change was confirmed to be the effect of the coating paint on the surface of the reflector mirror. The cause is that the ratio of TE/TM polarization components incident on each reflector mirror changes in response to the change in antenna pointing direction. We confirmed that the measured phase change was reproduced by measuring the film thickness and calculating the reflection phase. As a result, it was confirmed that the measurement can be performed with sufficiently high accuracy in the actual model.

The validity of this measurement and calibration method was confirmed through verification by calculation, actual measurement using a simplified model, and measurement using an actual antenna, respectively.

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