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Abstract

To solve the problem of time-consuming measurement and correction of large antennas' reflector deformation, a new microwave holography methodology based on a Phased Array Feed (PAF) is proposed. Starting from the known expression of receiving signals in microwave holography, the theory of PAF holography is derived through Geometrical Optics. Reflector deformation, as well as pointing deviation and subreflector offset, can be calculated out by applying the derived equations. A measurement and correction system based on PAF holography is depicted, and two kinds of measurement methods are illustrated. The proposed measurement methodology is verified by numerical simulation, and its measurement error is analyzed. The results indicate that our proposed methodology is feasible, especially for Cassegrain antennas.

Full Text

Preamble

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Abstract

To address the time-consuming nature of measuring and correcting reflector deformation in large antennas, we propose a novel microwave holography methodology based on a Phased Array Feed (PAF). Starting from the known expression for receiving signals in microwave holography, the theory of PAF holography is derived through Geometrical Optics. The derived equations enable calculation of reflector deformation, pointing deviation, and subreflector offset. We describe a measurement and correction system based on PAF holography and illustrate two measurement methods. The proposed methodology is verified through numerical simulation, and its measurement error is analyzed. The results demonstrate that our approach is feasible, particularly for Cassegrain antennas.

Key words: telescopes -methods: analytical -methods: numerical

1. Introduction

Large reflector antennas are essential tools for deep space exploration and radio astronomy research. To ensure optimal performance, it is necessary to regularly measure reflector surface accuracy and promptly correct any deformation. As the aperture diameter and operating frequency of reflector antennas continue to increase, their performance becomes increasingly affected by gravity, environmental wind loads, and solar irradiation, making measurement and correction of reflector deformation significantly more challenging. Consequently, controlling reflector antenna deformation during increases in aperture diameter and operating frequency has become a critical and active research topic.

Major large single-aperture antennas worldwide include the Sardinia 64 m Radio Telescope (SRT; Carretti et al. 2017), Tianma 65 m Telescope (Dong & Liu 2021), Jiamusi 66 m Radio Telescope (Yu et al. 2016), Wuqing 70 m Radio Telescope (WRT; Guo et al. 2021), Deep Space Station 14 (DSS-14) 70 m Radio Telescope (Imbriale & Hoppe 2000), Lovell 76 m Telescope (Morison 2007), Effelsberg 100 m Radio Telescope (Holst et al. 2014), Green Bank 100 m Telescope (GBT; Roshi et al. 2018), Arecibo 305 m Radio Telescope (Burnett et al. 2020), Five-hundred-meter Aperture Spherical radio Telescope (FAST; Tang 2015), and QiTai 110 m Radio Telescope (QTT, under construction) (Wang 2014), among others. To measure the reflector surface accuracy of these large radio telescopes, primary measurement methodologies including photogrammetry (Gale et al. 2016), laser scanning (Holst et al. 2017), and microwave holography (Serra et al. 2012) have been developed and successfully applied.

Among these methods, microwave holography is widely used (Rochblatt 1998; Hunter et al. 2011; Serra et al. 2012; Liu et al. 2016; Wang et al. 2017, 2019, 2022) due to its advantages of low cost, high precision, and short measurement time. Recent improvements have reduced measurement time to as little as 8 minutes (Dong & Liu 2021). Once reflector deformation is obtained, the adjustment value at each point on the reflector surface can be calculated, enabling correction through manual adjustment, actuators mounted on the antenna back frame, or using a deformable plate (Wang et al. 2013). These correction methods are essentially mechanical in nature. However, for large reflector antennas under certain operating conditions, mechanical adjustment methods are no longer feasible. For example, when the WRT operates at X-band in fresh gale conditions (force 8 wind), its signal-to-noise ratio (S/N) decreases by more than 6 dB and fluctuates violently—mechanical adjustment cannot keep pace with wind load variations. We have also measured the antenna G/T value (ratio of gain to noise temperature) at X-band during daylight and found it dropped by over 1.5 dB due to solar irradiation. At higher frequencies, such as Ka-band, the G/T value would drop by over 15 dB, resulting in very low antenna efficiency. In summary, traditional measurement and correction methods cannot achieve real-time measurement and correction of antenna deformation caused by wind and solar irradiation.

Therefore, we must consider electrical adjustment using a Phased Array Feed (PAF) for reflector deformation compensation. A significant benefit of electrical adjustment is its fast response. By electronically controlling the amplitude and phase excitation of each PAF feed element, we can accomplish deformation correction indirectly and instantaneously (Wang et al. 2013; Wu 2013). Rudge & Davies (1970) likely published the first analytical and quantitative study on using linear array feeds to instantaneously correct cylindrical reflectors with one-dimensional distortion profiles. Amitay & Zucker (1972) analyzed planar array feeds for compensating spherical reflectors, though their compensation procedure relied heavily on circular symmetry of the feed-plane field distribution. Blank & Imbriale (1988) proposed an algorithmic procedure for synthesizing planar array feeds for paraboloidal reflectors to simultaneously provide electronic correction of systematic reflector surface distortions and vernier electronic beamsteering capability. Their numerical results showed that with a one-ring (seven-element) array feed, 0.7 dB on-axis gain could be recovered from a 1 dB distortion loss compared to an optimal single feed. Rahmat-Samii (1990) conducted experimental studies using 16-element and 19-element array feeds for electrical compensation, with measured antenna patterns showing improved overall gain and reduced sidelobe levels after compensation.

These studies provide clear guidance on using properly excited array feeds to correct distorted antenna patterns caused by known reflector deformations, such as periodic and random surface distortions (Rudge & Davies 1970) and slowly-varying surface distortions (Rahmat-Samii 1990). However, none provides a formula for calculating antenna reflector deformation based on its focal field. This paper derives such a formula in Section 2.1. Furthermore, previous deformation correction methodologies are limited to electrical compensation alone, focusing on developing various array feed excitation methods to achieve higher on-axis gain or better beamsteering capability. This limits further antenna performance improvement because mechanical deformation remains. It is reasonable to combine electrical compensation and mechanical adjustment methods to enhance overall performance by establishing a feedback network where the current reflector deformation information is provided by an array feed. This concept is detailed in Section 2.3.

To date, PAF technology has been primarily used for neutral hydrogen intensity surveys (Li et al. 2021), pulsar observations (Deng et al. 2017), and space debris monitoring in Low Earth Orbit (LEO; Schirru et al. 2019). Chippendale et al. (2016) successfully deployed a PAF, shown in Figure 1(a), on the Parkes 64 m radio telescope and later on the Effelsberg 100 m telescope. The Parkes 64 m radio telescope with PAF mounted at the focus achieves aperture efficiencies ranging from 70% to 80%, which is very high. The Mk. II ASKAP PAF operates from 0.8 to 1.74 GHz and has made significant achievements in neutral hydrogen intensity surveys and pulsar observations (Deng et al. 2017; Li et al. 2021). The National Radio Astronomy Observatory (NRAO), Green Bank Observatory (GBO), and Brigham Young University (BYU) collaborated to design and produce a PAF for GBT containing 19 bipolar dipoles, shown in Figure 1(b). This PAF operates at 1.4 GHz and increases sky survey speed by 2.1 to 7 times (Roshi et al. 2018). Additionally, large reflector antennas including Australian Square Kilometer Array Pathfinder (ASKAP), Westerbork Synthesis Radio Telescope (WSRT), SRT, FAST, and QTT are already equipped with or plan to equip PAFs (Han & Zhong 2016; Beresford et al. 2017; Navarrini et al. 2019; Burnett et al. 2020; Pei et al. 2022; Van Cappellen et al. 2022).

Most PAFs mentioned above operate at L-band, a relatively low frequency. According to Ruze (1966), the impact of reflector deformation on antenna performance is relatively small at low frequencies, making electrical compensation unnecessary. However, as operating frequency increases, electrical compensation becomes essential. Unfortunately, producing PAFs for high frequencies is challenging, partly due to significant mutual coupling effects in tightly packed feed elements at high frequencies (Wu et al. 2013). Furthermore, considering that the main lobe becomes very narrow at high frequencies, and according to the reciprocity principle (Balanis 2005), slight deformation of the antenna' s pitch and azimuth motion supporting mechanism can cause the receiving signal convergence point to drift out of the receiving range, making electrical compensation alone insufficient to meet measurement and correction requirements. From this perspective, combining mechanical adjustment and electrical compensation methods for different types and magnitudes of antenna deformations is also reasonable to achieve optimal overall performance.

We classify antenna deformations into several categories in Table 1. Based on different structures, deformations can be divided into pointing deviation, servo tracking system error, main reflector deformation for single reflector antennas, or subreflector offset for Cassegrain antennas. Deformations can also be categorized as large or small, or as slowly changing/predictable versus rapidly changing. For example, deformation caused by antenna gravity is usually elevation-angle dependent, slowly changing, and predictable. In contrast, wind load-induced deformation generally changes rapidly and is difficult to measure and correct.

Through focal field analysis, we can obtain and identify deformation information from different antenna structures. This deformation information can then be fed back to the pitch and azimuth drive system, main reflector surface control system, subreflector control system, and electrical compensation system to ensure the antenna always operates in its optimal state. The measurement and correction methodology based on PAF is detailed in Section 2. Section 3 presents simulation of the Wuqing 70 m Radio Telescope’ s focal field based on reflector surface profile data from laser scanning and empirical equations, and applies PAF holography equations to recover the distorted reflector surface. Measurement error analysis is also presented in this section.

Methodology

The focal field contains significant information about the antenna, including pointing deviation, main reflector deformation, and subreflector offset. Several focal field analysis methods can be applied to determine deformation. For example, feed lateral defocusing theory (Zhan et al. 2010) can calculate antenna pointing deviation by extracting the position of maximum focal field amplitude on the focal plane. However, this method fails when the antenna reflector is distorted. Additionally, for Cassegrain reflector antennas, subreflector offset also influences the position of maximum focal field amplitude, making it impossible to individually identify pointing deviation, main reflector deformation, and subreflector offset based solely on feed lateral defocusing theory. An effective solution is to calculate the phase across the antenna aperture and perform a least squares fit for antenna deformation parameters according to Butler (2003). This requires studying how to obtain the antenna aperture field through focal field analysis. Padman (1995) and Rudge (1969) derived the relationship between focal field and aperture field for parabolic reflector antennas using Physical Optics (PO) and scalar diffraction theory. For electrically large antennas, Geometrical Optics (GO; Holt 1967; Smith & Stutzman 1989)—a ray-based model of light propagation—can also be used to analyze the focal field. In this paper, we start from microwave holography theory and utilize GO to derive a new main reflector deformation measurement method based on PAF, which we term PAF holography.

2.1. Theoretical Derivation of PAF Holography

A parabolic reflector antenna and its focal plane coordinate system are shown in Figure 2. In microwave holography theory, a parabolic reflector antenna' s far-field pattern is the integration of a function consisting of the induced current distributed across the parabolic surface, the wavenumber, focal length, paraboloid correction factor, and reflector surface deformation distribution (Rochblatt & Seidel 1992; Rochblatt et al. 1995). According to the reciprocity principle, for far-field single-carrier or narrowband on-axis incident signals, the receiving signal of a feed element (a single feed horn in microwave holography) placed at the focus can be expressed as (Rochblatt & Seidel 1992):

$$T(0,0) = \int_S J(x,y) e^{jkF[1-\cos\psi+\delta(x,y)]} \cos\psi \, dS \tag{1}$$

where $T(0,0)$ is the receiving signal at the focus $o(0,0)$; $J(x,y)$ designates the induced current distributed across the parabolic surface S; k stands for the wavenumber, i.e., $2\pi/\lambda$; λ is the wavelength; F is the focal length (or equivalent focal length for a Cassegrain reflector antenna); $\delta(x,y)$ is the reflector surface deformation distribution; and $\cos\psi$ is the paraboloid correction factor. It should be noted that the above and following equations in PAF holography are similar for Cassegrain reflector antennas using the concept of equivalent paraboloid (Rahmat-Samii 1984), i.e., replacing the focal length with the equivalent focal length.

If the feed element is not necessarily placed at the focus but at an arbitrary point P' on the focal plane, the receiving signal will be slightly different (Laviada Martinez et al. 2014). It is modified by adding a term to the integrand and can be expressed as:

$$T(\Delta x, \Delta y) = \int_S J(x,y) e^{jk[F(1-\cos\psi+\delta(x,y))+\Delta r]} \cos\psi \, dS \tag{2}$$

where $(\Delta x, \Delta y)$ are the x and y coordinate values of the arbitrary point P' on the focal plane; and Δr is the optical path difference, i.e., PP' in Figure 2.

The optical path difference Δr in Equation (2) can be calculated as:

$$\Delta r = \sqrt{r^2 + \delta^2 - 2r\delta\cos\theta_{r\delta}} \tag{3}$$

where $\theta_{r\delta}$ is the angle $\angle PoP'$ in Figure 2. Since δ/r is very small, we can apply Taylor expansion to the square root, yielding the approximation:

$$\Delta r \approx -r\cos\theta_{r\delta} + \frac{\delta^2}{2r} \tag{4}$$

Equation (4) is derived under the condition that $\delta/r \ll 1$ and ignoring terms higher than $(\delta/r)^2$. By expanding $\cos(\psi + \Delta\psi)$ and considering that $\Delta\psi \approx \delta/r$, we obtain:

$$\Delta r \approx -\delta \sin\psi \cos(\phi - \phi') + \frac{\delta^2}{2r} \tag{5}$$

Substituting Equation (5) into (2), the receiving signal of any feed element placed on the focal plane can be approximately written as:

$$T(\Delta x, \Delta y) = \int_S J(x, y) e^{jk[F(1-\cos\psi+\delta(x,y))-\delta\sin\psi\cos(\phi-\phi')]} \cos\psi \, dS \tag{6}$$

Let $u = \sin\psi\cos\phi$ and $v = \sin\psi\sin\phi$. Equation (6) can be written as:

$$T(u, v) = \int_{-1}^{1}\int_{-1}^{1} J(l, m) e^{jk[F(1-\sqrt{1-l^2-m^2}+\delta(l,m))-\delta\sqrt{1-l^2-m^2}]} \, dl \, dm \tag{7}$$

After Fourier transform of $T(u, v)$, we obtain:

$$Q(l, m) = \mathscr{F}[T(u, v)] \tag{8}$$

where $\mathscr{F}$ designates the two-dimensional Fourier transform operator. Then by substituting $l = \sin\psi\cos\phi$ and $m = \sin\psi\sin\phi$ into Equation (8), we obtain:

$$Q(x, y) = J(x, y) e^{jkF[1-\cos\psi+\delta(x,y)]} \cos\psi \tag{9}$$

The phase distribution $\Phi(x, y)$ across the antenna aperture is then:

$$\Phi(x, y) = \text{Phase}\{\tilde{A}(x, y)\} = \text{Phase}\{jkF^2 Q(x, y)\} \tag{10}$$

where Phase$\{\cdot\}$ denotes phase calculation; and $\tilde{A}(x, y)$ is the aperture field. Combining Equations (7), (8), (9), and (10), we find that reflector surface deformation $\delta(x, y)$ of a parabolic reflector antenna can be calculated by:

$$\delta(x, y) = \frac{\Phi(x, y)}{kF} \tag{11}$$

Equation (11) is valid when there is no other deformation from the antenna' s pitch and azimuth drive mechanism, subreflector, etc.

The PAF holography equations from (1) to (11) work for both single reflector antennas and Cassegrain reflector antennas according to the equivalent paraboloid concept. As mentioned above, for Cassegrain reflector antennas, the focal length

F in these equations should be replaced by the equivalent focal length, which is the product of the focal length and the Cassegrain antenna magnification.

2.2. Identification of Pointing Deviation and Subreflector Offset

Equation (11) of PAF holography assumes no other deformation from the antenna’ s pitch and azimuth drive mechanism, subreflector, etc. However, deformation from these structures is inevitable and often causes two other important antenna structure parameters—pointing deviation and subreflector offset—that are not negligible. Considerable pointing deviation and subreflector offset can distinctly alter the focal field and the phase distribution across the antenna aperture. The solution is to identify the magnitude of pointing deviation and subreflector offset by generating a best-fit phase distribution across the aperture (Butler 2003). The residual aperture phase distribution can then be used to calculate the main reflector deformation.

The identification of pointing deviation and subreflector offset is also based on focal field data. Equations (8), (9), and (10) have derived the phase distribution across the antenna aperture. In reality, this is affected by pointing deviation, subreflector offset, and main reflector deformation, and can be expressed as:

$$\Phi(x,y) = \Phi_p(x,y) + \Phi_s(x,y) + \Phi_m(x,y) \tag{12}$$

where $\Phi_p(x,y)$, $\Phi_s(x,y)$, and $\Phi_m(x,y)$ are the aperture phase distributions affected by pointing deviation, subreflector offset, and main reflector deformation, respectively.

Next, we derive the influence of pointing deviation on the phase distribution across the antenna aperture $\Phi_p(x,y)$. Figure 3 shows the direction unit vector of the incident plane wave $I(\Delta l, \Delta m, \Delta n)$ slightly off-axis by a deviation of $\Delta l + \Delta m$. The angle between the x-axis and the projection $(O_{aI}a)$ of I on the aperture plane is ϕ_0. The red dashed line passing through coordinate origin O_a on the aperture plane is perpendicular to I and called the phase reference line. The phase of the aperture field at any point on this reference line is equal and set to zero. For an arbitrary point P_a on the aperture plane, we draw a line $P_{aP}f$ perpendicular to the phase reference line, where P_f is the foot point. Similar to time difference calculation in radio interferometry (Rogstad et al. 2003), the time difference between the incident plane wave arriving at P_a and P_f is τ, which can be calculated as:

$$\tau = -\frac{\Delta l x + \Delta m y}{c} \tag{13}$$

where c is the speed of light; and (x,y) are the x and y coordinate values of the arbitrary point P_a. Considering that $\Delta n = -\sqrt{1 - \Delta l^2 - \Delta m^2}$, $\cos\theta_0 = -\Delta m$, and $\sin\theta_0 = \Delta l$, we obtain:

$$\tau = -\frac{\Delta l x + \Delta m y}{c} \tag{14}$$

Then, the phase distribution across the antenna aperture can be expressed as:

$$\Phi_p(x, y) = 2\pi f \tau = k(\Delta l x + \Delta m y) \tag{15}$$

where f is the working frequency, i.e., c/λ; $k\Delta l x$; and $k\Delta m y$.

The subreflector offset consists of lateral displacement, axial displacement, and rotation. The influence of subreflector offset on the phase distribution across the antenna aperture $\Phi_s(x, y)$ has been given by Butler (2003):

$$\Phi_s(x, y) = k\,\big[\Delta x_s \sin\theta_p \cos\phi + \Delta y_s \sin\theta_p \sin\phi + \Delta z_s(1 + \cos\theta_p) + \Delta\alpha_x(C - A)\sin\theta_f \cos\phi + \Delta\alpha_y(C - A)\sin\theta \tag{16}$$

where θ_p is the angle between the optical axis and a ray from the feed to the subreflector; θ_f is the angle between the optical axis and a ray from the subreflector to the main reflector; $C - A$ is the distance from the primary focus to the subreflector surface along the optical axis; M is the antenna magnification; $(\Delta x_s, \Delta y_s)$ is the subreflector lateral displacement; Δz_s is the subreflector axial displacement; and $\Delta\alpha_x, \Delta\alpha_y$ are the subreflector rotation/tilt around the vertex.

For more details about Equation (16), please refer to Butler (2003). We can now eliminate or reduce the effects of pointing deviation and subreflector offset by calculating the phase across the antenna aperture and performing a least squares fit for the antenna deformation parameters. The residual vector is expressed as:

$$\mathbf{r} = \Phi(x, y) - \Phi_p(x, y) - \Phi_s(x, y) \tag{17}$$

where $\mathbf{p} = [\Delta l, \Delta m, \Delta x_s, \Delta y_s, \Delta z_s, \Delta\alpha_x, \Delta\alpha_y]^T$ is the vector of antenna deformation parameters. The least squares fit is performed by determining the values of $\Delta l, \Delta m, \Delta x_s, \Delta y_s, \Delta z_s, \Delta\alpha_x, \Delta\alpha_y$ that minimize $\|\mathbf{r}\|^2$. After the least squares fit, the residual phase distribution can substitute for $\Phi(x, y)$ in Equation (11) to calculate the reflector surface deformation.

2.3. Measurement and Correction System

We propose a deformation measurement and correction system for Cassegrain reflector antennas based on PAF holography, shown in Figure 4. For a single reflector antenna, the corresponding system is similar except that the subreflector system is absent. Focal field analysis is the core and fundamental component of the system. Mathematically, focal field analysis is performed by calculating the equations derived in Sections 2.1 and 2.2. The system contains two main procedures: the measurement procedure (denoted in light blue) and the correction procedure, which is accomplished through mechanical adjustment (denoted in light olive) and electrical compensation (denoted in light red).

(1) The measurement procedure

The incident plane wave is reflected and converged by the reflector to reach the focal plane. Each feed element of the PAF receives a portion of the incident energy. After processing by the low noise amplifier (LNA), down converter (DC), and A/D converter, the receiving signal from each feed element is sent to the Field Programmable Gate Array (FPGA). In the FPGA, the focal field is first recovered using cubic spline interpolation based on the receiving signals. Then, by analyzing the amplitude and phase distribution of the focal field—i.e., calculating the equations derived in Sections 2.1 and 2.2—all antenna deformation parameters including main reflector deformation δ, pointing deviation $(\Delta l, \Delta m)$, and subreflector offset $(\Delta x_s, \Delta y_s, \Delta z_s, \Delta \alpha_x, \Delta \alpha_y)$ are obtained.

(2) The correction procedure

After focal field analysis, the pointing deviation $(\Delta l, \Delta m)$, main reflector deformation δ, and subreflector offset information $(\Delta x_s, \Delta y_s, \Delta z_s, \Delta \alpha_x, \Delta \alpha_y)$ are obtained and fed back to the pitch and azimuth drive system, main reflector surface control system, and subreflector control system to correct large or slowly changing deformations. For instance, based on this feedback, the pitch and azimuth drive system can eliminate pointing deviation by applying an adjustment of $(-\Delta l, -\Delta m)$ to the antenna pointing direction. Mechanical adjustment of main reflector deformation using actuators mounted on the antenna framework is described in Wang et al. (2017). Based on the subreflector offset information received, the subreflector control system can rotate and move the subreflector to its optimum posture and position. Next, weighted complex coefficients are generated for each feed element using the Conjugate Field Matching (CFM) method (Cherrette et al. 1989). After signal synthesis, residual or rapidly changing deformation is electrically compensated. Multiple FPGAs synthesize multi-beam data, which is transmitted to the GPU for further processing according to the antenna’ s actual observation needs.

Before focal field analysis in the measurement procedure, there are two primary methods to obtain the focal field of a Cassegrain reflector antenna using two types of focal plane arrays, shown in Figure 5. Both methods are also feasible for obtaining the focal field of a single reflector antenna.

(1) The static-type focal plane array

As shown in Figure 5(a), by pointing the antenna toward a known sky/artificial signal such as a geostationary satellite, radio source, or artificial beacon, the static-type focal plane array can obtain focal field data instantaneously, enabling real-time measurement. It should be noted that the element spacing in Figure 5(a) must meet sampling theorem requirements so that the focal field can be calculated immediately based on receiving signals from each feed element. Each feed element' s receiving signal should be cross-correlated with the receiving signal of the center feed element (the red one in Figure 5(a)) to reduce noise influence, especially when the sky/artificial signal is weak.

(2) The movable-type focal plane array

The focal field acquisition process in Figure 5(b) is slightly time-consuming because it requires scanning the focal plane while simultaneously tracking the radio source. Nonetheless, compared with far-field microwave holography, the time spent scanning the focal plane is much less. If feed elements are arranged as shown in Figure 5(b) and their supports are rigidly connected, a quick scanning motion of the feed elements—i.e., a full rotation of the supports around the center feed element (the red one in Figure 5(b))—will drive feed elements a1, b1, c2, d3, and e6 to accomplish focal plane scanning. It should be noted that in Figure 5(b), the position of feed elements on the element support should be adjustable so that engineers can change positions and feed element sizes according to actual observation needs. If the sky/artificial signal is a geostationary satellite or static artificial beacon, tracking motion is unnecessary due to the relatively stationary state of the antenna. Similarly, each feed element' s receiving signal in Figure 5(b) should be cross-correlated with the center feed element' s receiving signal to reduce noise influence, especially for weak signals.

Generally, the number of feed elements in a static-type focal plane array is far greater than in a movable-type array. The static-type array has the advantage of obtaining focal field data instantaneously, while the movable-type array inevitably requires time for mechanical scanning. One way to reduce scanning time is using more feed elements. For example, adding feed elements b3, c4, d1, and e2 on the opposite side of b1, c2, d3, and e6 respectively in Figure 5(b) would enable a half-rotation of the supports around the center feed element to accomplish focal plane scanning, cutting scanning time in half. Of course, more feed elements can be added, but this introduces mutual coupling problems, especially when element spacing is small. By appropriately designing feed element positions to scatter them individually, the mutual coupling effect in a movable-type focal plane array with relatively few feed elements can be reduced. When element spacing in a static-type focal plane array becomes very small, switching to a movable-type array can reduce mutual coupling effects. If a movable-type array has only one feed element, mutual coupling is eliminated, but scanning time increases significantly because the single element must perform both radial and circular movements to accomplish focal plane scanning. In summary, compared with far-field microwave holography where the entire antenna must perform radio source scanning motions (Wang et al. 2019), PAF holography measurement time can be much shorter using either movable-type or static-type focal plane arrays.

3.1. Numerical Simulation

To verify the proposed PAF holography theory, we developed a MATLAB program based on the theory. The verification process is as follows: (1) Import an antenna's reflector surface profile obtained by traditional measurement methods (e.g., laser scanning) or empirical equations (Rahmat-Samii 1990) into electromagnetic simulation software (e.g., GRASP). The antenna' s focal field is simulated by exciting an incident planar electromagnetic wave whose propagation direction is exactly opposite to the antenna' s current pointing direction. (2) Export the antenna' s focal field data from the simulation and import it into MATLAB. Apply the PAF holography program to obtain the main reflector' s surface error cloud map. (3) Compare the main reflector' s surface error cloud maps obtained by traditional measurement methods and PAF holography. The more consistent the surface error cloud maps, the higher the accuracy of PAF holography.

We developed a structural model of WRT in GRASP with no pointing deviation or subreflector offset. Two surface profiles of the main reflector were generated using both laser scanning data from actual measurement (Fu et al. 2022) and empirical equations from Rahmat-Samii (1990). In this paper, we use SPLS to denote the main reflector surface profile obtained by laser scanning when WRT is at 90° elevation under solar irradiation, and SPEE to denote the profile generated by the following empirical equations (Rahmat-Samii 1990):

$$\begin{cases} x_P = r_P \cos\phi_P \\ y_P = r_P \sin\phi_P \\ z_P = \frac{r_P^2}{4F_{WRT}} + \delta_B \cos\left(\frac{2\pi r_P}{D_{WRT}}\right) \end{cases} \tag{18}$$

where (x_P, y_P, z_P) is the main reflector profile; F_{WRT} is the focal length; δ_B is the slowly varying main reflector deformation; D_{WRT} is the main reflector diameter; and r_P, ϕ_P are the polar radius and polar angle respectively of any point on the main reflector surface. Primary parameters of the Wuqing 70 m Radio Telescope are shown in Table 2.

Figure 6 shows the amplitude and phase distribution of the antenna focal field obtained in GRASP under the influence of SPLS and SPEE respectively. By applying the PAF holography program developed in MATLAB, the surface error cloud maps of WRT are obtained and shown in Figure 7. The far-field patterns of WRT under SPLS and SPEE are also simulated. Then, by applying far-field microwave holography equations (Rochblatt & Seidel 1992), two additional surface error cloud maps based on microwave holography are obtained and displayed in Figure 7. To reduce simulation time, the working frequency is set to 8 GHz. There are 129×129 sampling points in the $1.4\,\mathrm{m} \times 1.4\,\mathrm{m}$ sampling range in PAF holography, meaning the sampling interval is about 0.011 m, i.e., 0.29 times the wavelength. In far-field microwave holography, the number of sampling points is also 129×129, and the sampling range is $0.016\,\mathrm{rad} \times 0.016\,\mathrm{rad}$.

Figures 7(a), (b), and (c) depict the surface error cloud maps of WRT with distorted reflector SPLS obtained by laser scanning, microwave holography, and PAF holography respectively. The corresponding calculated RMS errors of reflector deformation are 1.351 mm, 1.716 mm, and 1.268 mm. The outer parts—especially the right side, lower right corner, left side, and upper right corner—of these three surface error cloud maps show good consistency. The inner parts also show good consistency except for the upper right section where steep-varying deformation occurs. This steep-varying deformation at the upper right of the reflector' s inner part is due to occlusion during laser scanning (Fu et al. 2022). Both microwave holography and PAF holography are not adept at measuring steep-varying deformation because it causes multiple reflections in local areas, heavily scattering the far-field amplitude distribution and, consequently, the focal field amplitude distribution, as shown in Figure 6(a). There is a clear difference between Figures 6(a) and (c); the latter is simulated under conditions where deformation is slowly varying across the entire distorted reflector.

Figures 7(d), (e), and (f) are surface error cloud maps of WRT with distorted reflector SPEE obtained by empirical equations (Equation 18), microwave holography, and PAF holography respectively. The corresponding calculated RMS errors of reflector deformation are 1.366 mm, 1.168 mm, and 1.166 mm. These three surface error cloud maps show good consistency, indicating that PAF holography theory is feasible. There is an RMS gap between Figures 7(f) and (d) because the sampling range of the focal field—the space domain of the 2D Fourier transform in our PAF holography simulation—is limited, not covering the entire focal field. A similar RMS gap occurs when comparing Figures 7(e) and (d) for analogous reasons: in microwave holography, the far-field sampling range is also limited, not covering the entire far-field.

3.2. Error Analysis

PAF holography measurement results inevitably contain some error due to the approximation in Equation (4) of Section 2.1. The corresponding phase error can be simulated. Here, we consider a parabolic reflector antenna with a 70 m aperture diameter operating at 26 GHz. Since the reflector surface is circularly symmetric, we can examine the one-dimensional case. The approximation in Equation (4) can be performed through linear fitting by the least squares method. Let the approximated path difference from linear fitting be Δr_a; then the corresponding phase truncation error $\Delta\Phi_{ra-r}$ can be calculated as:

$$\Delta\Phi_{ra-r} = \frac{2\pi f_w}{c}(\Delta r_a - \Delta r) \tag{19}$$

The phase truncation error $\Delta\Phi_{ra-r}$ and the corresponding real phase difference $\Delta\Phi_r$ (i.e., the optical path difference Δr in Equation (3) divided by $c/(2\pi f_w)$) are calculated and depicted in Figure 8. The two simulation variables are the ratio of focal length (or equivalent focal length) to aperture diameter (f/d in the legend), and the distance (δ in the legend) between the feed element and the antenna' s focus (or secondary focus). r_f designates the radius of the first dark ring of the focal field of an undistorted reflector antenna, calculated by (Yang 1993):

$$r_f = \frac{1.22\lambda F}{D\cos(\theta_0/2)} \tag{20}$$

where θ_0 is the half-angle subtended by the subreflector at the feed for a Cassegrain reflector antenna or the half-angle subtended by the aperture at the feed for a single reflector antenna. θ_0 and the f/d ratio are negatively correlated, thus r_f and f/d ratio are positively correlated.

The phase difference curves in Figure 8(a) imply that for reflector antennas with a large f/d ratio, the real phase difference is almost a straight line. Comparing phase truncation errors for $f/d = 1.2$ and $f/d = 2.4$ in Figure 8(b), we conclude that for both Cassegrain and single reflector antennas with larger f/d ratios, the approximation in Equation (4) of Section 2.1 is more reasonable. However, when the feed element is too far from the focus (i.e., δ is too large), as shown by the magenta dashed curve ($f/d = 1.2, \delta = 2r_f$) in Figure 8(b), the phase truncation error becomes significant and the approximation is no longer accurate. Interestingly, doubling the f/d ratio makes the distance between the feed element and focus have very little influence on phase truncation error, as evidenced by the overlapping curves in Figure 8(b). For single reflector antennas, PAF holography must be conducted with a smaller PAF due to their smaller f/d ratio. Fortunately, the focal field energy of single reflector antennas is more concentrated compared to Cassegrain antennas (Yang 1993), making PAF holography with a small PAF feasible. Additionally, if the deformation of a single or Cassegrain reflector antenna is very large, its focal field energy will be severely scattered, resulting in inaccurate measurements near the reflector edge. Thus, PAF holography results need to be corrected according to actual conditions.

4. Conclusion and Prospect

This paper derived the theory of PAF holography and established a new deformation measurement and correction system for large reflector antennas based on PAF holography. The system can measure and correct main reflector surface deformation for both single reflector and Cassegrain antennas. Using a static-type PAF enables real-time measurement of surface accuracy and real-time correction of deformation caused by wind load, solar irradiation, or antenna gravity.

The proposed measurement methodology was verified through numerical simulation, and its measurement error was analyzed. Simulation results show good consistency between the proposed PAF holography method and traditional measurement methods, demonstrating that PAF holography theory is feasible. Correction through electrical compensation can be easily accomplished using the commonly employed Conjugate Field Matching (CFM) method. The key is determining the appropriate array layout, number of feed elements, and element spacing. The performance of PAFs with different numbers of elements and element spacing is investigated in a separate paper to be published later.

In future research, a small-size PAF will be designed, manufactured, tested, and optimized. To conduct experiments, other WRT systems such as the antenna receiving system and data processing terminal for PAF must also be developed. After optimization, we will deploy the small-size PAF on the secondary focal feed of WRT and conduct PAF holography and electrical compensation experiments to further verify the proposed measurement and correction methodology.

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