Optimization Design for Panel Fitting of Reflector Antennas Based on Particle Swarm Optimization: Postprint

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Abstract

Taking a 40 m offset Cassegrain antenna as an example, different small panel fitting schemes are analyzed to investigate the relationship between panel design and surface accuracy, verifying that the surface accuracy of the reflector is proportional to the square of the circumferential and axial lengths of the panels. Simultaneously, simulation software is employed to validate different schemes, investigating the impact of panel size variations on antenna gain, and demonstrating that the ring spacing of small panels only affects the horizontal energy distribution, while the split width within the same ring determines the vertical energy distribution. The particle swarm algorithm is utilized to optimize the panel segmentation scheme to improve surface accuracy, thereby achieving the goal of reducing far-field sidelobes and RF interference. Simulation experiments were conducted on a 3 m panel scheme, verifying the reliability of this scheme, compensating for 3.6% of the energy loss in the central beam caused by surface variations, while effectively reducing the power of newly generated sidelobes by 1.15 dB, 0.77 dB, 0.52 dB, 1.02 dB, and 2.1 dB respectively.

Full Text

Preamble

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Optimized Design of Surface Antenna Plate Fitting Based on Particle Swarm Optimization

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Abstract

Taking a 40 m offset Cassegrain antenna as an example, this paper analyzes different small panel fitting schemes, investigates the relationship between panel design and surface accuracy, and verifies that the reflector surface accuracy is proportional to the square of both the circumferential and axial lengths of the panels. Simulation software is employed to validate various schemes and explore how small panel size variations affect antenna gain, demonstrating that small panel ring spacing influences only the horizontal energy distribution, while the segmentation width within each ring determines the vertical energy distribution. The particle swarm optimization algorithm is used to optimize the panel segmentation scheme to improve surface accuracy, thereby reducing far-field sidelobes and mitigating radio frequency interference. A simulation experiment conducted on a 3 m panel scheme verifies the reliability of this approach, compensating for 3.6% of the energy lost in the central beam due to surface deformation while effectively reducing newly generated sidelobe power by 1.15 dB, 0.77 dB, 0.52 dB, 1.02 dB, and 2.1 dB, respectively.

Keywords: surface antenna; small panel fitting; surface accuracy; large aperture antenna; optimization model

1. Introduction

Reflector antennas constitute a major branch of antenna design, offering advantages such as strong directionality and low manufacturing cost, leading to widespread application in satellite communications and radio telescopes. As technology advances, new explorations into deep space have imposed higher requirements on antenna sensitivity and resolution. For reflector antennas, increasing the aperture size is an effective approach to enhance sensitivity and resolution.

In practical engineering, large-aperture reflector antennas often require segmented manufacturing, where the number and types of panels directly affect construction costs. To reduce costs, small flat panels are frequently used to approximate the original curved reflector surface [1], introducing deviations from the ideal paraboloid from the initial design stage [2]. These deviations, commonly expressed as root-mean-square (RMS) values, are termed surface accuracy. Higher surface accuracy means the designed reflector more closely approximates the ideal paraboloid, but imposes stricter constraints on panel dimensions. Consequently, the variation in panel types and quantities, the impact of surface accuracy, and the ultimate effect on antenna electrical performance have become critical issues.

To better observe the 21 cm scattering radiation from neutral hydrogen hyperfine transitions at different redshifts, Brazil has led an international collaboration to design and construct the BINGO (Baryon acoustic oscillations for Integrated Neutral Gas Observations) radio telescope. BINGO employs neutral hydrogen intensity mapping technology to precisely measure baryon acoustic oscillations in the key redshift range (z = 0.13-0.45). Its primary objectives include investigating the nature of dark energy, testing the standard cosmological model, and accurately measuring key cosmological parameters. This radio telescope features a 40 m offset Cassegrain antenna [3] operating at 0.98-1.26 GHz. Using small panel fitting methods can effectively reduce construction costs. This paper models the reflector surface of the BINGO telescope, calculating variations in surface accuracy and antenna radiation patterns under different segmentation schemes.

2. Theoretical Basis

Variations in surface accuracy directly affect the optical path length of electromagnetic waves from the far field to the feed, consequently influencing the focal plane field distribution. Therefore, surface accuracy serves as a key design criterion, making accurate and rapid antenna modeling and surface accuracy calculation essential problems to address [4]. Current research on antenna modeling primarily focuses on measuring fabricated antennas and fitting surfaces using Coons patches [5] or least-squares methods [6].

This paper focuses on mathematically modeling surface errors in antenna design and conducting electrical performance simulations. This section introduces the computational methods and antenna electrical performance simulation approaches employed.

2.1 Calculation of Surface Accuracy for Arbitrary Polygons

Any polygon can be decomposed into multiple triangles, transforming the problem into selecting three points on the paraboloid, connecting them to form a plane, and calculating the deviation between this plane and the original paraboloid. To simplify calculations, we introduce global and local coordinate systems [7]. The global coordinate system is established with the paraboloid vertex as the origin, while the local coordinate system uses the fitted plane as its reference, requiring only the projection of the paraboloid onto the local coordinate system.

The local coordinate system can be obtained from the global coordinate system through translation and rotation. For any point P_1 in space, the coordinate transformation relationship is:

$$\mathbf{X}_B = \mathbf{R}_{BA} \cdot (\mathbf{X}_A - \mathbf{R}_B$$

where $\mathbf{R}_{BA} = (\hat{x}', \hat{y}', \hat{z}')$ represents the rotation matrix from global to local coordinates, composed of unit vectors of the local coordinate system expressed in global coordinates. With this transformation relationship established, substituting the paraboloid expression in the global coordinate system yields the functional relationship of the original surface in the local coordinate system, denoted as $f(x', y', z') = 0$. Similarly, the deformed surface expression is $g(x', y', z') = 0$. The domain of (x', y') is determined by the triangle' s position in the local coordinates, and the difference in distances to the $x'O'y'$ plane represents the error at that point.

Since all three vertices of the triangle lie on the paraboloid, the relationship between coordinates and focal length f can be obtained. Substituting these relationships further simplifies the calculations, yielding:

$$z - z_1 = \frac{2x_1(x - x_1) + 2y_1(y - y_1) + (x - x_1)^2 + (y - y_1)^2}{4f}$$

Using these equations, the error at any point can be expressed as $\Delta z' = z'_f - z'$. Through integration, the mean square error over the triangular region can be calculated as:

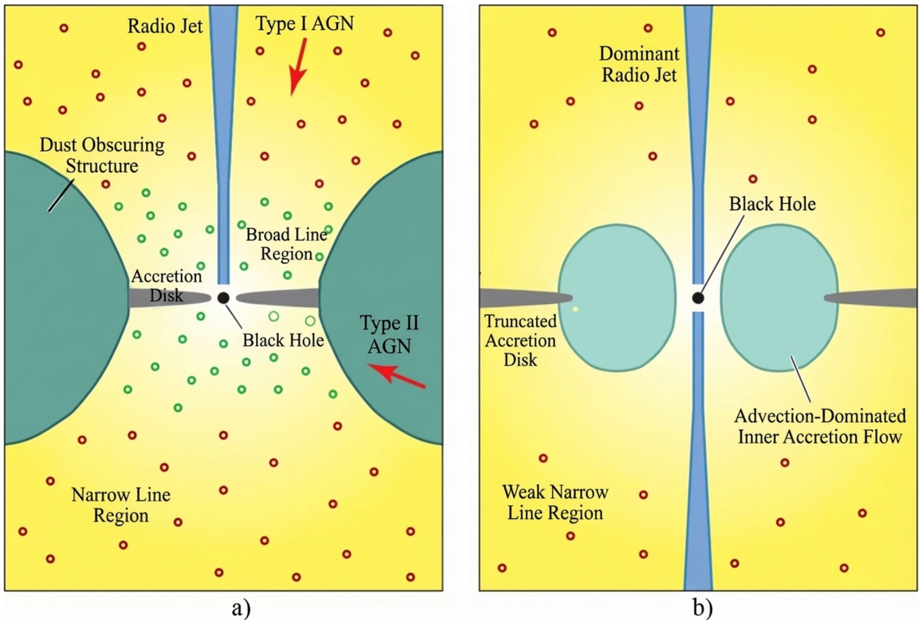
$$\text{MSE} = \frac{\iint (\Delta z')^2 dx' dy'}{\iint dx' dy'}$$

2.2 Panel Segmentation Scheme and Electrical Simulation

This experiment uses the BINGO telescope as a case study, focusing analysis solely on the main reflector. To reduce panel variety, a ring-based segmentation scheme is adopted where panels within each ring are identical. The projected length and width of small panels in the XOY plane are adjusted to vary the number of panel types and total quantity.

Figure 1

shows the vertex projections in the XOY plane for ring spacings of 2 m and 5 m with a panel width of 2 m. The reflector' s discrete point information is imported into the GRASP simulation software to construct the reflector surface using triangular planar configurations, as illustrated in Figure 2 [FIGURE:2]. During simulation, the feed and subreflector remain unchanged while only the main reflector shape is varied to investigate surface accuracy variations and far-field pattern changes under different schemes.



a) b)

Figure 1: Figure 1

2.3 Particle Swarm Optimization Algorithm

For reflector antennas using small panel fitting, overall panel surface accuracy correlates positively with antenna electrical performance—higher surface accuracy yields performance closer to the ideal surface and higher gain. Surface accuracy is directly influenced by the panel segmentation scheme. This paper first compares the electrical performance of different panel sizes, then performs fine adjustments after determining basic dimensions to compensate the segmented reflector and improve antenna gain.

Since panel shapes are interdependent during segmentation and the relationship between surface accuracy and sampling positions cannot be expressed by simple functions, this optimization problem can be abstracted as a multivariate function optimization problem. To address this, the particle swarm optimization algorithm [8] is introduced to find relatively optimal solutions through global and local search. Finally, electrical simulation of the reflector antenna verifies the feasibility of using particle swarm optimization to improve antenna gain.

3. Experimental Validation

The previous chapter introduced the antenna design methodology. This chapter adjusts small panel dimensions to calculate surface accuracy under various conditions and compares antenna electrical performance across different schemes.

3.1 Relationship Between Panel Size and Surface Accuracy

In engineering practice, engineers typically calculate surface accuracy using discretization methods—sampling points on panels according to certain rules and computing their distances to the ideal surface. However, this approach is limited by sampling method and density, requiring uniform and sufficiently dense points for accurate results. This paper employs coordinate transformation to preserve the functional relationship of the original surface coordinates, enabling more accurate and efficient calculations.

Initially, near-square rectangles are used for segmentation with equal ring spacing and width, gradually increasing both to study surface accuracy variations, as shown in Figure 3 [FIGURE:3]. As panel side length increases, the RMS error growth rate accelerates. To understand this trend, we calculated the slope variation rate shown in Figure 3b), revealing a quadratic relationship between panel surface accuracy and side length.

The first experiment used near-square panels where side length squared equals panel area, making surface accuracy linearly proportional to area for square panels. For rectangular panels with unequal sides, further experimental verification is needed. We separately varied ring spacing and width, observing surface accuracy changes shown in Figure 4 [FIGURE:4]. Both ring spacing and width exhibit quadratic relationships with surface accuracy. Denoting ring spacing as x and width as y, surface accuracy δ follows:

$$\delta = ax^2 + by^2$$

where a and b are constants related to the ideal reflector shape.

3.2 Relationship Between Segmentation Scheme and Radiation Pattern

The previous section analyzed the relationship between surface accuracy and panel segmentation, but surface accuracy and antenna electrical performance are not linearly related. Therefore, this section validates different segmentation schemes through simulation.

Following the previous section’ s setup, we compare the electrical performance of different square panel sizes, extracting horizontal radiation patterns after reflection from different surfaces. Multiple sidelobes with significantly increased gain are observed, termed “bulges.” Their positions and impact on the main beam are recorded in Table 1 . Figure 5 [FIGURE:5] shows the co-polarized radiation pattern, clearly illustrating that as panel side length increases, sidelobe bulges appear with varying severity, and their quantity is proportional to the rectangular side length.

Table 1 reveals that the first bulge position moves closer to the beam center as panel size increases. When panel side length reaches 5 m, this sidelappears within 3°, severely impacting target detection accuracy. At the beam center, gain degradation occurs more rapidly than surface accuracy deterioration.

Similarly, vertical radiation patterns (Figure 6 [FIGURE:6]) show noticeable bulges only when panel side length exceeds 3 m, with positions consistent with the horizontal direction. This confirms that panel segmentation causes gain variations at different angles, related to square panel side length.

To further investigate segmentation shape effects on antenna gain, we separately varied panel length and width for electrical simulation comparison. Since patterns change minimally for panel side lengths under 1 m, we fixed one dimension at 1 m while varying the other. When only ring spacing is changed, vertical patterns show negligible variation while horizontal patterns exhibit bulges proportional to ring spacing, as shown in Figure 7 [FIGURE:7]. When only panel width is changed, horizontal gain remains essentially unchanged while only vertical energy distribution is affected, as shown in Figure 8 [FIGURE:8].

Comprehensive results indicate that ring spacing primarily affects horizontal radiation, while width changes mainly influence vertical radiation. From an electromagnetic wave propagation perspective, increasing spacing enlarges phase variations in reflected waves, and after vector superposition, energy concentrates at corresponding angles, creating bulges.

These experiments demonstrate that surface accuracy affects overall antenna electrical performance, but not through simple linear relationships. Panel design directly impacts energy distribution in different directions. The 3 m × 3 m panel segmentation scheme exhibits prominent sidelobes with slight central beam degradation, providing a good basis for optimization studies. Fixing panel width at 3 m for the 40 m aperture antenna yields 14 rings. Without changing the ring count, adjusting inter-ring distances improves gain and reduces sidelobes.

With multiple ring spacing variables exhibiting non-linear effects on surface accuracy, traditional optimization methods cannot efficiently find optimal solutions. Particle swarm optimization combines global and local search to find optimal points without excessive constraints, making it suitable for improving panel segmentation schemes. The optimized radiation pattern is shown in Figure 9 [FIGURE:9].

Results show the central beam improves by 5×10^{-4} dB, compensating for 3.6% of the energy lost from the 0.0139 dB degradation. Meanwhile, bulges on both sides decrease significantly by 1.15 dB, 0.77 dB, 0.52 dB, 1.02 dB, and 2.1 dB. Sidelobe correction improves with distance from the central beam. Different observation targets have varying sidelobe requirements [9]. Before optimization, the first bulge amplitude exceeded the first sidelobe, potentially causing false targets. After optimization, this bulge falls below the first sidelobe, more than 30 dB below the central beam, reducing observation error rates.

4. Conclusion and Outlook

This paper analyzes different panel sizes using the BINGO project' s 40 m offset antenna as an example, calculating surface accuracy under various dimensions and demonstrating that surface accuracy is proportional to the square of panel side lengths. Simulations in GRASP for different reflectors show that increasing panel sizes introduces high-gain sidelobes of varying degrees. Further investigation reveals that horizontal gain variations are primarily affected by circumferential panel length changes—when ring spacing increases, generated sidelobes gradually approach the central beam with increasing gain. At 5 m ring spacing, sidelobes increase by 30 dB. Similarly, with fixed ring spacing, panel width changes only affect vertical energy distribution, though less significantly than ring spacing changes, which is also related to the offset feed and feed polarization direction.

This paper provides in-depth analysis of reflector design for large-aperture antennas, summarizing how segmentation design affects surface accuracy and energy distribution. Using flat panels to approximate curved surfaces creates phase variations in reflected electromagnetic waves, causing interference and generating sidelobes. Finally, global optimization algorithms fine-tune segmentation schemes to effectively reduce sidelobes and improve central beam gain.

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