Structural Shape-Preserving Design for the 70-Meter Antenna of China's First Mars Exploration Mission (Post-print)

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Date: 2023-10-17T00:00:00+00:00

Abstract

This paper presents a detailed account of the implementation methodology and key elements of the structural shape-preserving design for the 70 m antenna of the first Mars exploration mission: an umbrella-shaped support structure is employed to achieve equal-stiffness support for the reflector, thereby realizing uniform structural deformation and enhancing the fitting accuracy of the main reflector surface, which establishes a solid foundation for shape-preserving design; a three-degree-of-freedom adjustment mechanism is utilized to implement follow-up control of the sub-reflector surface, compensating for electrical performance degradation caused by optimal fitting of the main reflector surface and deformation of the sub-reflector support structure, thus providing robust assurance for shape-preserving design. The equal-stiffness design concept applied in this engineering project represents a rarely adopted design philosophy in China and holds reference significance for subsequent large-aperture antenna designs in the country. The three-degree-of-freedom adjustment mechanism can effectively compensate for electrical performance degradation resulting from deformation of the sub-reflector support structure and focal position adjustment after optimal fitting of the main reflector surface.

Full Text

Shape Preservation Design of the 70 m Antenna for China' s First Mars Exploration Mission

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Abstract

This paper presents the methodology and key elements of the structural shape preservation design for the 70 m antenna deployed in China' s first Mars exploration mission. The design employs an umbrella-shaped support structure to achieve uniform stiffness support for the reflector, which homogenizes structural deformation and improves the fitting accuracy of the main reflector, thereby establishing a solid foundation for shape preservation. A three-degree-of-freedom adjustment mechanism enables synchronized control of the secondary reflector to compensate for electrical performance degradation caused by both the best-fit adjustment of the main reflector and deformation of the secondary support structure, providing robust assurance for the shape preservation design. The equal stiffness design concept utilized in this project represents a novel approach rarely seen in domestic applications and holds significant reference value for future large-aperture antenna designs in China. The three-degree-of-freedom adjustment mechanism effectively compensates for electrical performance degradation resulting from secondary support structure deformation and focal position adjustments after main reflector best-fitting.

Keywords: shape preservation design; equal stiffness design; best-fitting technique; secondary surface follow-up control; large-aperture antenna

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1. Introduction

China' s first Mars exploration mission has been successfully completed. According to the implementation plan for the ground application system, a newly constructed 70 m fully steerable antenna was required to receive Mars remote sensing data. The mission also mandated that the antenna possess stepped satellite signal reception capability to enable measurement of reflector structural deformation. Due to the substantial distance between Mars and Earth—approximately three orders of magnitude greater than the Earth-Moon distance—the received signals are extremely weak. Consequently, the antenna must achieve high gain while simultaneously reducing sidelobe levels to improve the gain-to-noise temperature ratio.

From a structural design perspective, achieving high gain and low noise temperature necessitates improving reflector surface accuracy. For this S/X-band Earth-based antenna, the reflector error must be controlled within 0.9 mm (rms). However, the self-weight of large-aperture antennas, reaching thousands of tons (the telescope weighs 2.68×10^3 kg), makes it extremely challenging for structural engineers to control deformation precision at the millimeter or sub-millimeter level. The characteristic of large deformation under gravity has become a critical design challenge.

The concept of antenna shape preservation design was proposed to address this challenge. Early implementations involved fitting the deformed paraboloid to a new parabolic surface using best-fit techniques and moving the feed to the new focal point. This approach was primarily developed for single-reflector antennas. With the increasing adoption of dual-reflector antennas, the shape preservation concept has been extended and refined. This design philosophy offers a new direction for structural design and has been successfully implemented in numerous large-aperture telescopes worldwide, including the 100 m Effelsberg telescope and the 64 m Sardinia Radio Telescope (SRT) in Italy. Although domestic large-aperture antennas have attempted similar approaches, the results have been suboptimal.

For dual-reflector antennas, shape preservation design must address two critical aspects: first, employing best-fit techniques to improve main reflector accuracy, thereby mitigating performance degradation caused by massive deformation; and second, performing best-fit adjustment of the secondary reflector and repositioning it to the focal point of the best-fit parabolic main surface. For large-aperture antennas with stringent pointing requirements operating at high frequencies, two additional factors must be considered: (1) electrical performance degradation due to feed phase center errors caused by structural deformation, and (2) electrical performance impact from secondary reflector deformation. However, practical usage has verified that these two factors have negligible effect on antenna performance for this application. Therefore, the shape preservation design for the 70 m antenna focuses solely on main reflector best-fit and secondary reflector position adjustment.

2. Shape Preservation Design and Implementation of the 70 m Antenna

2.1 Main Reflector Best-Fit and Implementation The effectiveness of best-fit directly influences antenna surface accuracy. When main surface deformation is more uniform and continuous, the best-fit results improve significantly. The main reflector is supported by an axially symmetric structure, where the primary factor affecting deformation is the support configuration.

Traditional antenna structural design follows two approaches: (1) The reflector and mount are designed separately, with most loads transferred through the elevation mount directly to the bearings and azimuth frame, providing strong support stiffness. Minor loads pass through the large elevation arc to the second platform, but because this connection involves gear meshing, its support stiffness is relatively weak. To reduce reflector deformation, designers typically increase the connection area between reflector and mount—a "stiffer is better" philosophy that works for medium and small antennas but causes non-uniform deformation in large-aperture designs due to uneven support stiffness at the mount-reflector interface. (2) The reflector and mount are integrated using an umbrella-shaped support structure that evenly distributes forces from the elevation arc, counterweight, and mount across the reflector. This approach strengthens weak connections and weakens strong ones, achieving uniform support stiffness.

The umbrella support structure creates a sixteen-sided polygon that releases direct constraints between the elevation bearings and reflector, reducing uneven deformation effects from the elevation arc and counterweight. Sixteen support points uniformly distribute loads across the reflector backstructure. This equal stiffness design concept, rarely applied domestically for large antennas, significantly improves best-fit effectiveness.

[Figure 1: see original paper] shows the three-dimensional structure of the 70 m antenna elevation mount frame. Deformation cloud images of the reflector structure before and after equal stiffness design reveal that while maximum deformation values are similar, the non-uniformity at the outermost ring decreased from 6 mm to 1 mm. Before equal stiffness design, deformation exhibited radial distribution; afterward, it showed ship-shaped distribution with uniform deformation at the same radius, demonstrating substantially improved uniformity.

Despite achieving more uniform deformation through equal stiffness design, gravity inevitably causes overall displacement, rotation, and relative deformation between nodes, creating optical path differences that degrade antenna efficiency. Pre-adjustment techniques are therefore employed to improve accuracy across elevation angles. By extracting deformation data under both support conditions and applying best-fit techniques while accounting for assembly and measurement errors, the main reflector accuracy curves for the two support configurations were generated.

[Figure 4: see original paper] illustrates the 70 m antenna main surface accuracy variation with elevation angle. Under both support methods, accuracy trends with elevation angle are consistent, but equal stiffness design yields significant improvements: original surface accuracy improved from 25.7 mm (rms) to 18.6 mm (rms) after pre-adjustment and best-fit; with equal stiffness design, accuracy improved from 1.54 mm (rms) to 0.8 mm (rms). Following installation, photogrammetry measurements at multiple elevation angles achieved reflector accuracy better than 0.85 mm (rms) across the full elevation range, with 45° elevation reaching 0.35 mm (rms), meeting mission requirements. The successful application of equal stiffness design technology represents a domestic first and signifies that Chinese large-aperture antenna design capabilities are approaching international standards.

2.2 Secondary Reflector Position Adjustment and Implementation

After implementing equal stiffness design, main reflector best-fit effectiveness improved substantially, significantly enhancing main surface accuracy. Theoretically, to avoid efficiency and pointing performance degradation from main reflector best-fitting, the secondary reflector must shift from its theoretical position to align with the best-fit parabolic main surface focal point. Practically, this positional adjustment also compensates for secondary support structure deformation, bringing the antenna geometry closer to theoretical values for optimal performance.

To satisfy these requirements, we employ secondary surface follow-up control technology using a three-degree-of-freedom adjustment mechanism that actively adjusts the secondary reflector position as the antenna attitude changes, thereby optimizing performance.

[Figure 5: see original paper] shows the schematic diagram of the three-degree-of-freedom secondary surface adjustment mechanism. Implementation involves first calculating the secondary reflector's actual position and required theoretical position at different antenna attitudes from measurement data, then determining the adjustment required for the three-degree-of-freedom mechanism. Based on the actual coordinate motion functions in x, y, and z directions, built-in programs achieve automatic follow-up control.

Comparative measurements demonstrate the effectiveness: [Figure 6: see original paper] shows the measured X-band elevation pattern without secondary reflector follow-up, while [Figure 7: see original paper] shows the pattern with follow-up enabled. Although both patterns are similar, the follow-up-enabled version exhibits more regular characteristics, confirming significant performance improvement.

3. Conclusions

This paper introduced the principles and implementation methods for the 70 m antenna shape preservation design in China' s first Mars exploration mission, encompassing main reflector best-fitting and secondary reflector follow-up control. Following shape preservation design, antenna electrical performance improved substantially, with main reflector accuracy increasing from 25.7 mm (rms) to 0.8 mm (rms). Subsequent measurements confirmed actual main reflector accuracy better than 0.85 mm (rms) across all elevation angles, with pointing accuracy reaching 8.8 , fully meeting Mars exploration requirements.

Key conclusions: 1) The 70 m antenna main reflector design abandoned traditional rigid design principles, adopting an umbrella support structure to achieve equal stiffness design that homogenized reflector deformation and established a solid foundation for shape preservation. The three-degree-of-freedom adjustment mechanism enabled secondary reflector follow-up control, providing robust assurance for shape preservation design.

2) For the 70 m antenna operating at relatively low frequencies, secondary reflector deformation and feed phase center variation have negligible impact on performance when the secondary support structure maintains adequate stiffness. However, these factors require further investigation for higher-frequency large-aperture antennas.

The design methodology presented herein, rarely attempted in domestic antenna projects, provides valuable reference for future engineering applications requiring antenna shape preservation.

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Note: Figure translations are in progress. See original paper for figures.