Reflector antenna deformation compensation based on phased array feed

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***Abstract*—As human exploration of the universe advances, there is an increasing demand for spaceborne antennas with improved gain, frequency capabilities, and surface accuracy. This paper examines a 9-meter diameter spaceborne reflector antenna, characterized by a focal diameter ratio of 0.6 and operating at 31 GHz, utilizing a truss structure for precise modeling. The study compares the antenna gains achieved with Gaussian feed and phased array feed under varying reflector surface accuracies. At a panel accuracy of 2 millimeters, the Gaussian feed antenna experiences a 2.16 dB decrease in gain compared to an ideal reflector surface, while the phased array feed shows a smaller reduction of 1.55 dB, indicating superior performance with lower energy loss and higher antenna gain. Furthermore, the phased array feed exhibits a gain 1.14 dB higher than the Gaussian feed antenna under the same 2 millimeter panel accuracy condition. This research confirms the feasibility of using phased array feed for spaceborne reflector antennas to mitigate deformation losses. By accurately modeling the antenna's reflective surface, the study demonstrates that phased array feed, employing focal plane field analysis, effectively adapt to deformations of the reflector surface, thereby enhancing antenna performance in spaceborne applications.**

***Index Terms*—deformation compensation, focal plane field analysis, phased array feed, spaceborne reflector antennas**

I. Introduction

Since the dawn of the 21st century, human exploration of the universe has increasingly extended into deep space, leading to rapid advancements in observation methods and technologies. Spaceborne antennas [1] have become an essential tool for observing the cosmos and a prominent focus of satellite technology research. At specific operating frequencies, larger apertures on spaceborne reflector antennas yield higher gains, critical for capturing and observing faint electromagnetic signals from the cosmos. Although a larger diameter can significantly increase the gain, it also increases the antenna's requirements for surface accuracy. Deployable designs are often chosen for spaceborne antennas, exacerbating the challenge of reflective surface deformation. Such deformations directly cause antenna defocusing, thereby reducing both gain and efficiency.

The phased array feed [2] utilizes a small phased array antenna as the feed, which is placed near the focal plane of the reflector antenna, and uses the characteristics of the beam-forming network to realize the functions of beam assignment, beam scanning, and multi-beam. Focal plane field analysis [3] is a crucial method in feed design. Focal plane field analysis uses the reciprocity of electromagnetic field to analyze the field distribution generated by plane wave excitation in the focal plane after irradiating the reflected surface, so as to guide the feed design, which can effectively solve the feed design problems applied to complex microwave optical systems such as shaped beam antennas and beam waveguide antennas. In the face of the problem of defocusing caused by the deformation of the reflective surface, the characteristics of the phased array feed, combined with the focal plane field analysis method, can effectively compensate for the problem of antenna gain reduction caused by defocusing.

The structural design scheme of the space deployable antenna is the main factor affecting the deformation of the antenna of the spaceborne reflective surface, and different design structures will constitute different deformation surfaces. This paper models deformation surfaces of peripheral truss reflector antennas and conducts focal plane field analysis, while also comparing antenna gains under different feeds.

II. Data and methods

A. Deformation surface model

In order to study the compensation effect of the phased array feed on the deformation of the reflector antenna, it is necessary to accurately model the deformation surface [4]. In this paper, a rotating parabolic cable net antenna with an aperture of 9 meters and a focal length of 5.4 meters is taken as an example. The mesh division of the antenna is based on the Agrawal cable network generation method, which categorizes the mesh cable segments into primary, secondary, and tertiary cables. The primary cable nodes are positioned at equal intervals along the arc length of the parabola, while the secondary cable nodes connect pairs of primary cable nodes and divide their projected line segments equally. The cable network grid is divided into regular triangles within the antenna's optical aperture plane.

This method uses triangles to approximate the parabolic surface, resulting in a surface that deviates somewhat from the ideal parabolic shape. Further complex adjustments are necessary in practical engineering applications. To simplify the model, different offsets are added at the cable net nodes to test the ability of the phased array feed to compensate for the deformation of the antenna reflector under different plane accuracy. Fig 1 shows the z-error distribution of the entire parabola when a 2 mm random offset is added to the cable net node.

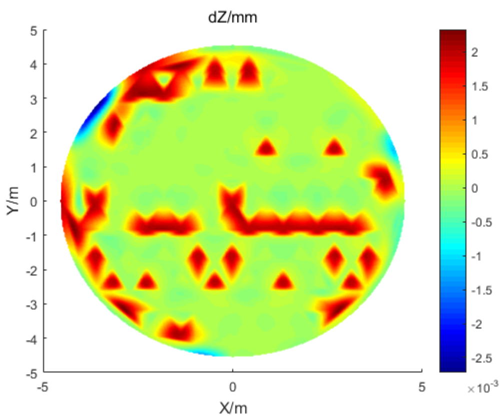

Fig. 1. z-error distribution of deformation surface

B. Focal plane field analysis

Focal plane field analysis is an essential technique for guiding feed design in complex microwave optical systems. This analysis, grounded in principles of physical optics and diffraction theory, evaluates the electromagnetic field distribution at the antenna's focal plane following reflection from the reflector, allowing for precise feed parameter determination.

For phased array feed, the distribution of the aperture field can be more freely altered. Let the aperture field of the feed be denoted as E_F, and the corresponding focal plane field distribution as E_R. The power transfer coefficient η can then be expressed as :

$$\eta = \frac{\left| \iint_s \left(\overrightarrow{E_F} \cdot \overrightarrow{E_R^*} \right) \right|^2}{\iint_s \left| \overrightarrow{E_F} \right|^2 dS \iint_s \left| \overrightarrow{E_R} \right|^2 dS} \tag{1}$$

From this formula, it is evident that when E_F and E_R are identical, the power transfer coefficient is 1. Thus, for receiving antennas, to achieve high antenna efficiency, the aperture field distribution of the feed should match the focal plane field. For transmitting antennas, the aperture field distribution of the feed needs to be conjugately matched to the focal plane field during reception.

When a plane wave irradiates an ideal parabola, the energy can be well focused near the focus, forming a symmetrical distribution, as shown in Fig 2. This concentrated and symmetrical energy distribution allows the general corrugated horn to achieve a high antenna efficiency. Consequently, low-cost corrugated horns offer an excellent cost-performance ratio under these ideal conditions, making them a popular choice for many applications.

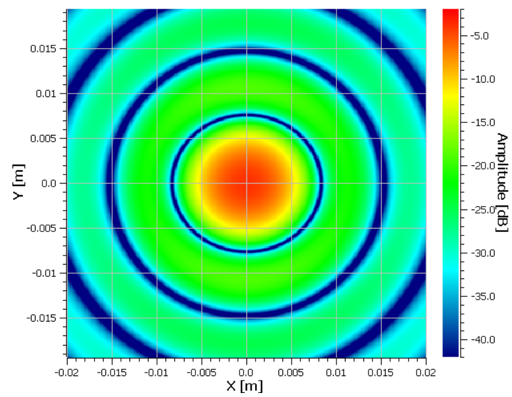

Fig. 2. focal plane field of paraboloid surface

However, when the reflective surface is deformed, the focal position of the parabola changes, resulting in the inability to accurately focus the energy to the original focal position, resulting in defocusing. The energy is no longer concentrated at one point, but distributed in the area near the focus, making the focal plane field no longer symmetrical, as shown in Fig 3. In this case, it is difficult for the traditional corrugated horn to effectively match the feed aperture field with the antenna focal plane field, and thus it is unable to maintain its original high efficiency.

In contrast, the phased array feed can flexibly adjust the phase and amplitude of each unit through its complex beamforming network, thereby realizing beamforming and directional control of the entire antenna array. This capability enables the phased array feed to dynamically adjust its output when the reflective surface is deformed, ensuring that the feed aperture field remains consistent with the deformed focal plane field. This not only compensates for the defocusing problem caused by the deformation of the reflective surface, but also improves the gain and efficiency of the antenna.

C. Phased array feed

Nowaday, phased array antenna not only to achieve electrical scanning, but also to achieve beamforming and multi-beam scanning, is a kind of comprehensive, to adapt to low profile, high gain, light weight and other requirements of the antenna. Phased array feed has higher design requirements than general phased array antennas. First, the use of phased array antennas as the feed directly limits its physical size, and too large phased array will block the reflector antenna and reduce the antenna efficiency. In addition, in order to achieve multi-beam, phased array feed is required to possess the characteristics of wide bandwidth and wide angles.

In this study, the Vivaldi antenna array is chosen as the feed [5]. It achieves wide bandwidth characteristics by vertically expanding unit sizes while minimizing lateral dimensions

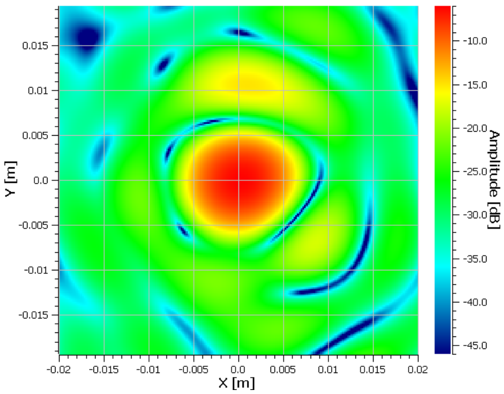

Fig. 3. focal plane field of deformation surface

through tight coupling. This configuration enables broadening of the antenna array's scanning angle. The specific structure, depicted in Fig 4, features a 9x10 Vivaldi antenna array with each unit having a 4 mm diameter. Fig 4(b) illustrates a single feed structure.

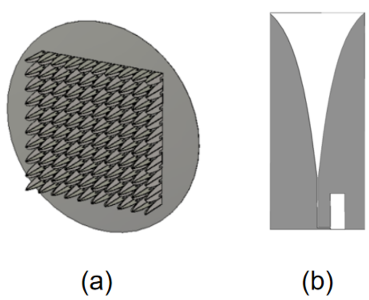

Fig. 4. phased array feed structure

III. Experiment and Results

In the previous discussion, we introduced the conjugate matching method and phased array feed. Phased array feed uses the conjugate matching method to adjust the phase and amplitude of each element, thereby compensating for surface deformations. However, due to physical size constraints of antenna elements, there is an upper limit on the density of phased array feed. Additionally, closely packed elements can lead to mutual coupling effects, deviating from theoretical expectations. In this experiment, we compared the gain achieved by Gaussian feed, phased array feed, and theoretical feed based on conjugate matching after illuminating deformed surfaces.

A. Antenna pattern of different feeds irradiating the reflective surface

In this experiment, the ideal reflective surface irradiated by the Gaussian feed is simulated firstly, and as the control group, the pattern is shown in Fig 5, and it can be seen that the gain of the antenna is 68.25dB under ideal conditions, and the pattern is symmetrically distributed. When the reflective surface is replaced with the deformation surface constructed in 2.1 and irradiated with a Gaussian feed again, the gain decreases to 66.09 dB, the side lobes increase, and the 90-degree side lobes increase more, which also corresponds to the constructed deformation surface, as shown in Fig 6.

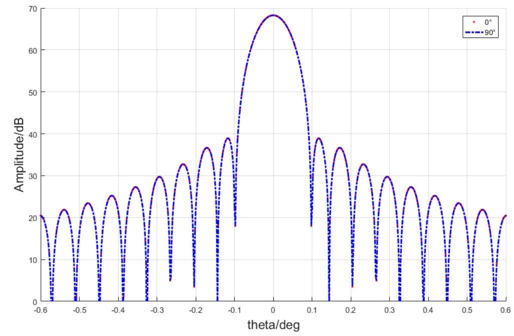

Fig. 5. paraboloid surface with gaussian feed

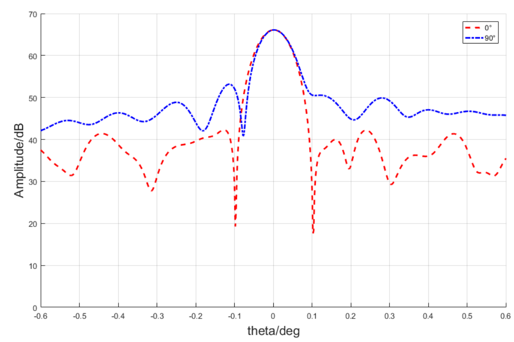

Fig. 6. deformation surface with gaussian feed

Next, the feed was replaced with the conjugate matching ideal feed and the Vivaldi array feed, with the ideal feed gain of 67.3 dB and the phased array feed gain of 67.23 dB. Comparing the pattern, the first sidelobe is higher than the Gaussian feed, while the far-field sidelobe is lower than the Gaussian feed, regardless of whether it is an ideal feed or a phased array feed, as shown in Fig 7 and Fig 8. It is proved that the energy of the reflective surface antenna can be concentrated in the center through the focal plane field analysis, and the antenna gain can be improved, so as to make up for the antenna gain loss caused by deformation.

B. Deformation surfaces with different offsets

In the previous experiments, we verified that the phased array feed can compensate for the loss caused by the deformation of the reflector antenna to a certain extent. Further experiments compared the far-field gain of various feeds under different deformation conditions, and the specific data are listed in Table 1. Under non-deformation conditions, the gain of the phased array feed is still higher than that of the Gaussian feed, but the improvement is not significant. Therefore, in actual

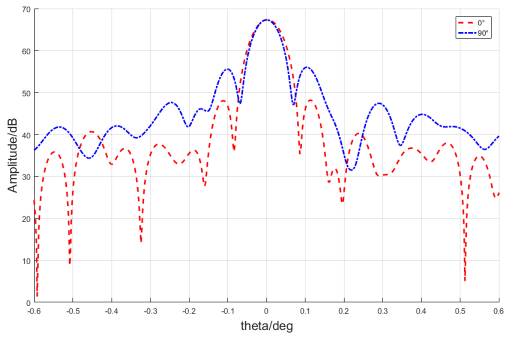

Fig. 7. deformation surface with conjugate field-matched beam

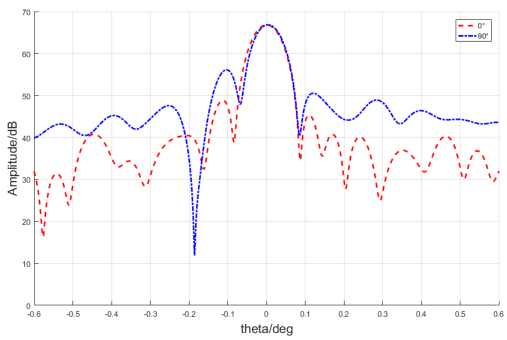

Fig. 8. deformation surface with phased array feed

engineering, considering the production cost, corrugated horns are usually selected as the feed.

However, as the deformation of the reflector gradually intensifies, the gain of the antenna decreases significantly faster. This is because that the deformation causes more changes in the propagation path of electromagnetic waves, which produces phase differences when reaching the focal plane, causing more energy loss. Specifically comparing the three feeds, when the deformation amount is 1mm, they decrease by 0.94dB, 0.72dB and 0.72dB respectively. This shows that the feed design based on focal plane analysis can more effectively adapt to the deformation of the reflector.

Nevertheless, when the deformation increases to 3 mm, which exceeds a quarter wavelength for 31 GHz electromagnetic waves, phased array feed based on focal plane analysis cannot effectively compensate for the antenna gain loss.

TABLE I
FAR-FIELD GAINS OF VARIOUS FEEDS

	0mm	1mm	2mm	3mm
Gaussian	*68.25*	*67.31*	*66.09*	*61.34*
conjugate matching	*68.87*	*68.15*	*67.3*	*64.92*
PAF	*68.78*	*68.04*	*67.23*	*64.78*

IV. Discussion and Conclusions

In recent years, phased array feed systems have rapidly advanced in beam synthesis and shaping capabilities. Small phased array antennas are applied to reflector antennas to achieve multi-beam synthesis and increase the speed of sky surveys. This paper studies the application of phased array feed in deformed reflector antennas. Through comparative experiments, its adaptability to deformed reflectors is verified, and the energy loss caused by the deformation of the reflector is reduced.

Taking a deployable space antenna with an aperture of 9 meters and a focal diameter ratio of 0.6 as an example, this paper compares the antenna gain and radiation pattern of Gaussian feed, ideal feed of conjugate matching method, and phased array feed under different surface accuracies. The ideal feed and phased array feed based on focal plane field analysis can focus energy on the center beam more effectively, and show good adaptability to the deformation of the reflector, reducing energy loss. However, these compensation capabilities are still limited, especially for severe deformations or deformations that cannot be accurately modeled, where improvements in antenna gain remain ineffective.

This study verifies that the feasibility of the application of phased array feed on spaceborne reflector antennas. Based on the known structural design, accurate modeling of the antenna reflector can effectively reduce the energy loss caused by the deformation of the reflector. This technology can also be used to improve operating frequency bands for large-aperture reflective surfaces without actuators, such as SKA.

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