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Research on the realization and application prospect of FAST active reflector shape adjustment technology

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Abstract: This paper studies the development of active reflector technology in radio astronomy and its market prospect. Firstly, the active reflector technology of FAST is introduced, and its potential in improving the sensitivity and resolution of radio telescopes is discussed. Then the specific application of active reflector technology in radio band celestial observation is analyzed in detail, including the advantages and challenges of beamforming, phase correction and interferometry. The prospects of active reflector technology in the market are further discussed, especially for potential applications in commercial radio astronomy and satellite communications. Finally, the future development direction and possible research directions of active reflector technology are prospected, and its importance and market demand in promoting the technical progress of radio astronomy and solving key scientific problems are emphasized.

1. Introduction

As an important field to explore the mysteries of the universe, radio astronomy has long relied on high sensitivity and superior spatial resolution to resolve the weak signals and detailed structures of celestial bodies. In recent years, with the technological progress of radio telescopes, active reflector technology, as a cutting-edge technology, has gradually become one of the key means to improve the performance of radio telescopes[1]. Active reflector technology can effectively compensate atmospheric disturbances and structural errors by dynamically adjusting the shape and position of the reflector, thus significantly improving the beamforming capability, phase correction accuracy and interferometry accuracy of the telescope. The purpose of this paper is to thoroughly explore the recent progress of active reflector technology in radio astronomy and its potential market prospects. First, we will introduce the active reflector technology of Five-hundred-meter Aperture Spherical radio Telescope (FAST) in detail and analyze its application potential in improving the sensitivity and resolution of the telescope[2]. Subsequently, we will explore the specific advantages and challenges of the active reflector technology in the observation of objects in the radio band, and analyze in depth its possible applications in commercial radio astronomy and satellite communications. Finally, we will look at the future direction of active reflector technology and explore the potential and challenges in driving technological progress in radio astronomy, solving key scientific problems, and meeting market needs[3]. Through this study, we aim to provide theoretical support and empirical analysis for the wide application of active reflector technology in the field of radio astronomy, and provide strong reference and guidance for the technical development and market landing of radio telescopes in the future.

2. Background analysis

According to the "China Reflector Antenna Market Analysis and Industry Survey Report 2024-2030" released by Booz Data, the industry will continue to develop in the next few years, and it is expected that the market size of China's reflector antenna will grow significantly by 2030. With the continuous progress of wireless communication technology, the demand for reflector antennas will continue to grow. Especially in spaceborne communication, 5G communication and other fields, reflector antennas will play an important role.

With the progress of science and technology and the increase of the demand for high-precision astronomical observation, the market demand for active reflector technology is large. For example, the FAST project itself represents a huge market demand, with its active reflector system consisting of 4,300 reflective panels and a complex cable network structure. All these require high-precision shape adjustment technology to ensure their performance [4]. At the same time, the research of reconfigurable intelligent reflective surface (RIS) technology for 6G mobile communication shows that adjusting and controlling the phase and amplitude of reflective surface is very important to achieve low energy consumption and high efficiency communication. The development of this technology provides a new solution for mobile communication and further promotes the demand for intelligent reflector regulation technology [5]. This technology is not limited to the above fields, but can also be applied to a variety of other scenarios, such as the service performance improvement of omnidirectional mobile antenna. This technology achieves precise control of reflected waves by controlling the tiny structure of the reflecting surface, so as to meet the requirements of different application scenarios.

According to the In-depth Evaluation and Investment Strategy Research Report on China's Reflector Antenna Market 2023-2029, China's reflector antenna market is developing rapidly and is expected to continue to maintain steady growth in the next few years. China's reflector antenna market has a high degree of concentration, with Antiraibo Technology Co., LTD., Xinhe Electronics (Shanghai) Co., LTD., Beijing Xingsheng Technology Co., LTD., Shenzhen Tianmagnetron Technology Co., LTD., and other enterprises occupying a dominant position in the market. However, the market competition is still fierce, and enterprises compete for more market share through technological innovation, product design and manufacturing, marketing strategy and other perspectives. Under the influence of the huge market size, the application demand of reflector antenna in satellite, radar, navigation and other fields is increasing day by day.

From the perspective of the astronomical telescope industry, active reflector technology has been applied to the FAST astronomical telescope project, which is a major national scientific and technological infrastructure project. This shows that the application of active reflector technology in high-end scientific research equipment has made remarkable progress, and with the continuous development of science and technology, its application in the future astronomical telescope industry will be more extensive [6].

Active reflector technology also shows great potential in the field of mobile communications. Especially with the research and development of 6G mobile communication technology, active reflector technology is considered as one of the key technologies to achieve more efficient and secure communication. In addition, combined with artificial intelligence (AI) technology, RIS technology will further boost its application in physical layer security technology.

Active reflector technology has shown strong market growth potential in a number of high-tech fields, but its development also needs to overcome some technical and market challenges. With the continuous advancement of technology and increasing market demand, the market prospect of active reflector technology is still very optimistic.

Although the reflector antenna technology is relatively mature, there are still some technical bottlenecks, such as signal coverage, gain and other limitations. The limitations of reflector antenna technology in signal coverage come from beam width, reflector accuracy and manufacturing process, band switching and operating frequency, and environmental factors. These factors jointly determine the coverage ability and performance of reflector antenna in practical applications.

The gain limitations of reflector antenna technology mainly come from surface accuracy and deformation, feed position errors, and challenges in high frequency applications. FAST active reflector shape adjustment can effectively improve these limitations and problems. In future research and development, innovative development can be achieved by using this technology to adjust the wireless environment, so as to further improve spectrum and energy efficiency. By improving the shape adjustment algorithm, the continuous displacement from the sphere to the paraboloid can be realized more effectively, thus improving the observation effect. For example, the establishment of an ideal parabolic distribution model and a reflective panel regulation model based on appropriate quantitative indicators can further optimize the regulation process.

Develop new materials and manufacturing techniques to reduce the impact of principle errors and gravity deformation. This can be achieved by adopting advanced manufacturing processes and material science research. In the field of intelligence research, artificial intelligence and machine learning techniques are used to optimize the performance of control systems. Through real-time data analysis and prediction, the shape and position of the reflecting surface can be adjusted more precisely. The active reflective surface technology will be combined with other technologies, such as 6G mobile communication technology, to study the reconfigurable intelligent reflective surface technology, so as to expand its application scope and improve the design. Finally, through practical application, the application possibility of active reflector technology in larger radio telescopes is explored.

3. Modeling and implementation

Our product is FAST active reflector shape adjustment technology, which is an advanced technology for adjusting the reflector panel of spherical radio telescope (FAST). It aims to optimize the reception effect of celestial electromagnetic waves by adjusting the shape of the reflector. FAST is currently the world's largest single-aperture and most sensitive radio telescope. The shape adjustment technology of its active reflection panel is to better adapt to different observation requirements, improve accuracy and resolution, so as to provide more valuable data for astronomy research. Through the shape adjustment of the active reflection surface, FAST Tianyan can better adapt to different observation requirements. Improve the accuracy and resolution, thus providing more valuable data for astronomy research.

FAST active reflector shape adjustment by controlling the shape change of the reflector, the accurate control of incident light is realized. Reflectors can flexibly adjust their curvature, surface structure and optical properties to match incident light of different modes and wavelengths, thus achieving flexible beam shaping in spatial frequency and direction [7]. This adjustment mechanism can be realized by digital signal processing and micro-operation execution system, which can complete shape adjustment in a short time, maintain stable shape within a small error range, adapt to different application requirements, and achieve low energy reflection by accurately controlling the shape of the reflection surface.

The active reflector system of FAST is one of its three independent innovations. Its core function is the active displacement of the reflector, that is, in the observation process, the reflector can realize the continuous displacement from sphere to parabolosphere. This modification capability enables FAST to adjust in real time according to the position of the object to be observed, thus forming a paraboloid suitable for signal collection. The forming of the working paraboloid of FAST requires extremely high accuracy, and its fitting root mean square error should be less than 5mm.

Through the dynamic adjustment strategy, the position of the reflector panel is constantly changed, so that the feed illumination part of the reflector can be adjusted into a high-precision rotating paraboloid in real time. This high-precision shape adjustment enables FAST to achieve multi-band observation using common point feeds. In the process of shape adjustment, FAST adopts a variety of optimization models and algorithms to determine the ideal paraboloid. These factors make the shape adjustment of active reflector of FAST have the characteristics of fast response and high controllability.

The active reflector of FAST consists of 6,670 steel cables woven into a cable net and suspended from a 500-meter diameter ring beam supported by 50 large steel columns. Under the cable network there are 2225 down cables, which are fixed to the ground actuator. The shape is adjusted by an electric field, and each cell adjusts its shape by an electric field. The ideal parabola optimization model determines the vertex stretching quantity, comprehensively considers the main cable node displacement and edge smoothness, the planning algorithm calculates the node target length, and the actuator stretching realizes the shape adjustment, as shown in Figure 1.

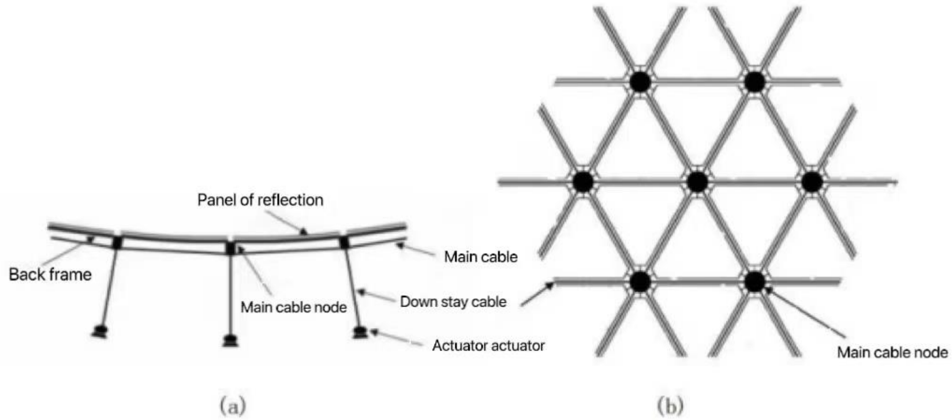

Figure 1: Schematic diagram of reflection panel, main cable network structure and its connection

FAST's 2,300 controllers, which control the movement of the reflector, operate on these calculations after receiving observation commands sent by the host computer. Each cable network node is connected with the foundation by the adjustment cable along the normal direction of the network surface. By changing the tension of the adjustment cable (adjustment force), the shape accuracy of the reflection surface can be adjusted to form a working paraboloid [8].

The FAST active reflector can be divided into two states: reference state and working state. In the reference state, the reflective surface is a sphere with a radius of about 300 meters and a diameter of 500 meters. In the working state, the reflector is partially adjusted to a working paraboloid with a 300 m diameter. FAST can adjust the reflection panel according to the position of the object to be observed, so as to form a paraboloid for effective signal collection. This flexible shape adjustment enables FAST to make efficient observations of different celestial bodies. The FAST active reflector shape adjustment technology achieves efficient and accurate shape adjustment through its unique cable network structure and electronic drive system, combined with optimization model and control algorithm, so as to meet the needs of different celestial observations.

The application of the ideal paraboloid optimization model in FAST technology is mainly reflected in the shape adjustment of the active reflector. By using the spatial geometry property of paraboloid, an ideal paraboloid optimization model is established to realize the optimal shape adjustment of the reflector panel, so as to improve the receiving effect of celestial electromagnetic waves. Specifically, the ideal paraboloidal optimization model is a univariate (z-coordinate of vertex position) nonlinear optimization model, whose optimization objective can be set according to actual needs, such as minimizing the average radial distance from the reference sphere. This model can ensure that the working paraboloidal surface is as close as possible to the ideal paraboloidal surface, so that the feed bin can receive the best effect of the reflected electromagnetic wave from the celestial body [9]. In addition, the shape of the reflective panel can be further optimized to make it closer to the ideal state by means of mechanism analysis, coordinate transformation and nonlinear least squares optimization. This optimization process usually needs to be carried out iteratively until convergence to ensure that the shape accuracy of the reflecting surface meets the requirements,as shown in Figure 2 [10].

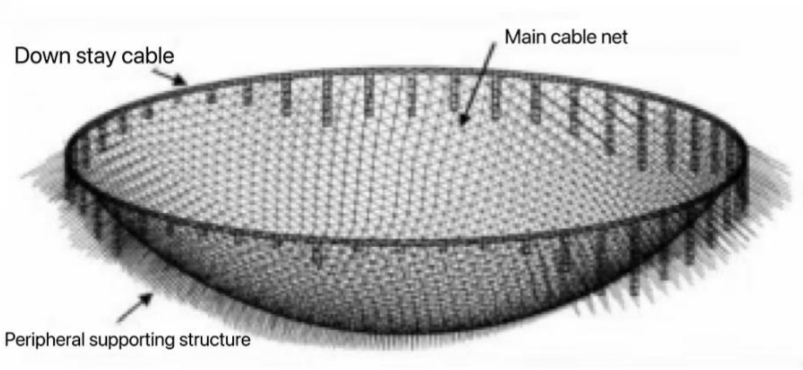

Figure 2: Schematic diagram of FAST structure

Table 1: Algorithm and steps

Algorithm 1: Binary search algorithm
1. Select the boundary value. Firstly, according to the problem setting and the actual situation, 100 and 400 are selected as the left and right endpoints of the binary search interval.
2. Take the midpoint coordinate of the bisection search interval into the gradient function of the formula, and calculate the gradient value corresponding to the point.
3. If the gradient value is much larger than 0, set the right endpoint of the binary search interval to the current midpoint and return line 2.
4. If the gradient value is much less than 0, set the left endpoint of the binary search interval to the current midpoint and return line 2.
5. If the absolute value of the gradient value is less than the machine precision value epsilon, the midpoint is the minimum point to be solved, and the program ends.

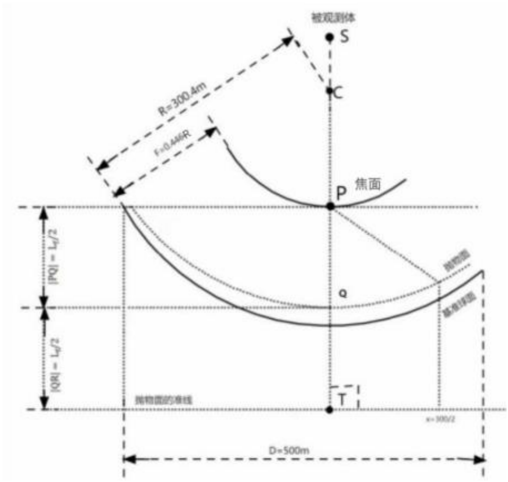

Figure 3: Schematic diagram of FAST profile

As shown in Table 1 and Figure 3, based on Algorithm 1, the profile view 4 of the ideal paraboloid and the radial height difference between the ideal paraboloid and the reference sphere are given by programming the solution in MATLAB, as shown in Figure 4.

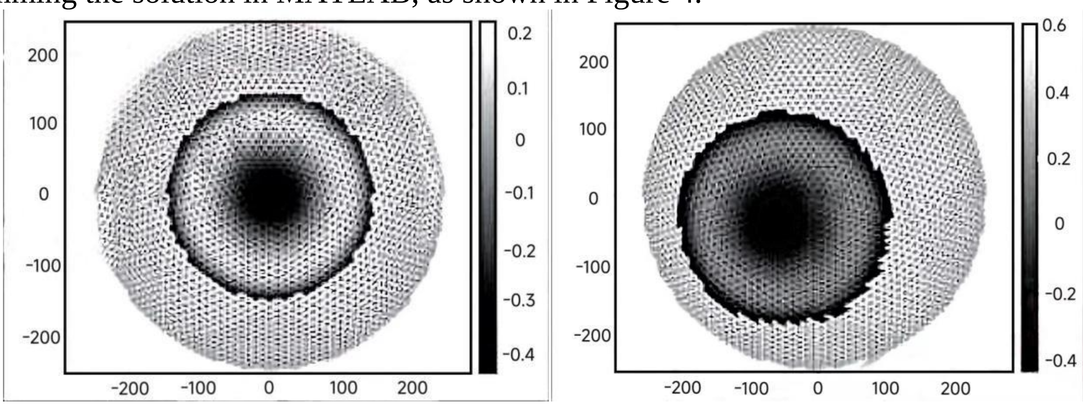

Figure 4: Optimal parabolas for FAST 2D and 3D profiles

The final result solves the focal length L of the ideal paraboloid, the exact value of is 280.854, and the minimum value of the integral of the square error on the aperture is$10.112, \mathrm{L} = 280.854, \mathrm{R} = 300.4, \mathrm{F} = 0.466\mathrm{R}$.

Ideal paraboloid solution:

According to the conclusion of rotation matrix and graph transformation in model preparation, the ideal paraboloidal surface S solved is:

$$S(x, y, z) = 0.001780x^2 + 0.001780y^2 - z - 300.884 = 0 \tag{1}$$

Then the rotated paraboloid S is:

$$S(x, y, z) = So\varphi - {}^{1}(x, y, z) = 0 \tag{2}$$

Namely:

$$s(x, y, z) = 0.16418x + 0.1228y + 0.97876z - 0.0017797(0.59895x - 0.80078y)^2 - 0.0017797(0.78377x + 0.58623y - 0.20503z)^2 + 300.88 = 0 \tag{3}$$

Since the ideal paraboloidal vertex is $(0,0,-300.884)$, after the rotational coordinate transformation of φ, the first step is obtained:

The vertex coordinates of the paraboloid are $((\mathrm{R} - {}^{1}\mathrm{RZ}^{1}(0,0,-300.884)\mathrm{T})$, and are:

$$(-49.3194, -36.8890, -294.0187) \quad (4)$$

Therefore, the obtained results are consistent with the subject setting:

The ideal paraboloid model for the shape adjustment of the active reflector of FAST telescope is established based on analytical geometry theory. Specifically, using conditions such as the coordinates of the intersection point, the length of the focal length and the direction of the focal length, the researchers have developed three strategies: the standard formulation, the downward partial formulation, and the consulting formulation to establish the equations for the ideal paraboloid. These equations can make the reflector as close to the ideal paraboloidal shape as possible after adjustment, so as to optimize the reflection effect of celestial electromagnetic waves and make them better captured by receiving equipment. The advantage of this approach is that it provides a systematic way to predict and adjust the shape of the reflecting surface. It is verified by simulation that the transition between the ideal paraboloid and the reference sphere is relatively smooth, which means that the shape change of the reflector can be effectively controlled while maintaining the stability and reliability of the system.

4. Conclusion

This paper systematically discusses the recent progress of active reflector technology in radio astronomy and its potential market prospects. Based on the analysis of existing research and practical application cases, we can draw the following conclusions:

First of all, active reflector technology has significant potential in improving the performance of radio telescopes. By dynamically adjusting the shape and position of the reflector, atmospheric disturbances and structural errors can be effectively compensated, so as to improve the sensitivity, resolution and beamforming ability of the telescope. Secondly, the active reflector technology is not only suitable for large ground-based radio telescopes such as FAST, but also expected to be widely used in satellite and space radio astronomy. With the further maturity and commercialization of the technology, it is expected that the active reflector technology will become one of the key technologies in radio astronomy in the next few years. In addition, although active reflector technology faces challenges in the application process, such as the improvement of control accuracy and cost management, these challenges can be effectively solved with the continuous development and improvement of related technologies. Finally, looking into the future, this text suggest further strengthening international cooperation to promote the research and application of active reflector technology, in order to open up a broader prospect for the scientific research, technological innovation and market application of radio astronomy.

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