FAST Illuminated Aperture Analysis Postprint

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Abstract

During observation, the 500-meter aperture spherical radio telescope transforms the shape of the illuminated region within the spherical reflector surface into a 300-meter aperture paraboloid, thereby implementing the prime focus antenna function of the telescope. The illuminated aperture of the telescope (the aperture of the spherical-to-paraboloid deformation) plays a decisive role in the observation performance of the telescope. For the potential performance enhancement and future development of the telescope, with the FAST telescope' s illuminated aperture at 300 meters and beyond, this paper conducts an analysis of the spherical-to-paraboloid deformation for different aperture paraboloids through calculations of deformation distances between paraboloids with various focal lengths and the reference spherical surface, and discusses the feasibility of increasing the illuminated aperture of the telescope. The selection of paraboloid focal length and focal ratio for increased-aperture paraboloid deformation is presented within the maximum travel range of the FAST reflector deformation actuators. The theoretical feasibility of the deformation is preliminarily demonstrated in terms of actuator travel. The relevant analysis is equally applicable to paraboloids of other apertures.

Full Text

Analysis of the Illuminated Aperture of FAST

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Abstract: The Five-hundred-meter Aperture Spherical radio Telescope (FAST) transforms the shape of its illuminated region from a spherical reflector into a 300 m aperture paraboloid during observations, thereby realizing the primary reflector antenna function. The illuminated aperture of the telescope—the aperture of the paraboloid transformed from the spherical surface—plays a decisive role in observational performance. To enhance the telescope' s potential performance and guide its future development, this study investigates the feasibility of enlarging the illuminated aperture by analyzing the shape-changing distances between paraboloids of different focal lengths and the reference spherical surface, for both the current 300 m aperture and larger apertures. We present the selection of focal lengths and focal ratios for enlarged-aperture paraboloids within the maximum travel range of FAST' s reflector actuators, thereby demonstrating the theoretical feasibility of such shape-changing from the perspective of actuator travel. This analysis is equally applicable to paraboloids of other apertures.

Keywords: Five-hundred-meter Aperture Spherical radio Telescope; active reflector; illuminated aperture; shape-changing distance

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As the world' s largest single-dish radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) achieves the highest observation sensitivity among existing radio telescopes due to its enormous reflector. The reflector is one of the telescope' s key components, with FAST' s reference state being a giant spherical cap of 300 m radius and 500 m opening diameter. The entire reflector is built within a karst depression in Guizhou, China. One of FAST' s main technological innovations is the application of active reflector technology, which enables the illuminated region of the spherical reflector to be actively controlled and transformed into a 300 m aperture paraboloid during observations. The paraboloid antenna collects radio waves from celestial bodies parallel to its axis and focuses them at the focal point, where they are received by the feed and receiver for subsequent processing. The paraboloid-shaped illuminated region moves within the spherical cap reflector, while the feed support system carries and drives the feed to move within the workspace, enabling observation of celestial objects at different positions and tracking of fixed targets. FAST officially began operations in January 2020. The structure of FAST' s active reflector is shown in Figure 1 [Figure 1: see original paper].

FAST' s active reflector system consists primarily of the ring beam, cable mesh, reflector panels, down-tie cables, and actuators. The cable mesh, which supports the reflector, is composed mainly of main cable units and main cable nodes. Reflector panel units are connected to the main cable nodes and laid on the cable mesh, with each main cable node connected to a ground-based actuator via a down-tie cable. The actuators are anchored to the ground and serve as the driving devices for reflector shape-changing. By controlling the piston rod length of the actuators, the relative positions of main cable nodes on the cable mesh are adjusted, enabling mesh deformation and consequently changing the shape of the reflector surface above it. FAST' s active reflector system has 2,225 main cable nodes and 2,225 corresponding actuators. The main components and equipment of FAST' s active reflector system are illustrated in Figure 2

[Figure 2: see original paper].

For FAST’ s reflector, the illuminated region departs from the spherical surface to form a paraboloid during observations. Since the illuminated region moves, different portions of the reflector transform between spherical and paraboloidal shapes. The aperture of the paraboloid antenna is crucial for further improving the telescope’ s observational performance. Therefore, exploring the feasibility of enlarging the paraboloid aperture under the current operating conditions of FAST’ s actuators is of practical significance for the telescope’ s future development and performance enhancement.

1. Distance Analysis Between Reference Sphere and Paraboloid

The transformation of FAST’ s reflector between spherical and paraboloidal shapes necessitates distance analysis between the reference sphere and paraboloid as the foundation for reflector shape-changing. Figure 3 [Figure 3: see original paper] illustrates the relationship between the transformed paraboloid and the reference spherical surface.

Due to the symmetry of both spherical and paraboloidal surfaces, the transformed paraboloid moves within the spherical surface, maintaining a constant relative relationship with the sphere at different positions. In Figure 3, the solid line represents the reference spherical surface, while the dashed line represents the paraboloid formed through shape-changing from the sphere. Because of rotational symmetry, calculations involving the paraboloid and sphere can be performed in one dimension. With the sphere center as the coordinate origin, the general equations for the sphere and paraboloid are as follows:

Sphere equation: $x^2 + y^2 = R^2$
Paraboloid equation: $y = \frac{x^2}{4f} + c$

FAST’ s spherical reflector reference state features a sphere radius $R = 300$ m and opening diameter $D' = 500$ m, giving FAST an effective illuminated aperture of 300 m. The effective illuminated region is paraboloidal in shape, collecting parallel radio waves from celestial objects along the paraboloid axis and focusing them at the focal point to form a complete point image—constituting a prime focus system. The focal length and focal ratio of the paraboloid can be calculated, with the focal ratio F expressed as:

$$F = \frac{f}{D}$$

where f is the focal length from the focus to the paraboloid reflector, and D is the paraboloid aperture.

Within the 300 m aperture paraboloid range, the deviation of paraboloids with different focal lengths from the reference sphere can be calculated, as shown in Figure 4 [Figure 4: see original paper]. The horizontal axis represents the 300 m aperture paraboloid range, while the vertical axis shows the deviation between seven selected focal lengths (ranging from 136.56 m to 142.13 m) and the reference sphere. FAST' s illuminated region deviates from the spherical surface to form a paraboloid, meaning the surface moves either inward (closer to the sphere center) or outward (farther from the sphere center) relative to the reference sphere.

Figure 4 reveals that each paraboloid of a given focal length has a maximum deviation from the reference sphere, which reflects the maximum shape-changing travel required from the spherical to paraboloidal configuration. In FAST' s shape-changing system, the maximum actuator travel is approximately ±0.6 m. As shown in Figure 3, with the reference spherical surface as the initial position, the maximum travel in both directions—toward the sphere center (inward) and away from the sphere center (outward)—is about 0.6 m. The deviation values in Figure 4 are calculated relative to the spherical surface initial value, with outward deviation defined as positive. Thus, the maximum outward travel is +0.6 m, while the maximum inward travel is approximately −0.6 m. Figure 4 presents deviation profiles for paraboloids with maximum deviations of approximately +0.6 m, −0.6 m, ±0.8 m, ±1.0 m, and cases where the maximum deviations in both directions are approximately equal.

For a 300 m aperture paraboloid, when the focal length is approximately 138.33 m, the maximum deviations in both inward and outward directions from the reference sphere become essentially equal (as shown in Figure 4). With precise calculation, when the paraboloid focal length exceeds this value, the inward travel becomes dominant, while focal lengths smaller than this value result in dominant outward travel. Figure 4 demonstrates that for a fixed paraboloid aperture, as the focal length decreases, the overall paraboloid configuration shifts outward away from the sphere center. Conversely, for a given aperture, there exists one focal length where the maximum inward deviation is about 0.6 m, and another where the maximum outward deviation is also about 0.6 m. Between these two focal lengths, the deviation between paraboloid and sphere remains within ±0.6 m.

Through calculation, we can determine the focal lengths and focal ratios of transformed paraboloids within FAST' s actuator maximum travel range. For a 300 m aperture paraboloid, Figure 4 shows the deviations of two focal length paraboloids from the reference sphere within the current actuator travel range. This analysis demonstrates that when the paraboloid focal length falls within a certain range, the deviation from the sphere also falls within a specific range, meaning the shape-changing travel from sphere to paraboloid is constrained accordingly.

In Figure 4, the horizontal axis represents the 300 m aperture paraboloid range, and the vertical axis shows the deviation between paraboloid and sphere for different focal lengths. The figure indicates that for a focal length of 137.91 m, the maximum outward deviation is about 0.6 m, while for a focal length of 139.38 m, the maximum inward deviation is also about 0.6 m. Therefore, paraboloids with focal lengths between these two values deviate from the sphere by less than ±0.6 m. From Figure 4, we can determine the maximum deviation between paraboloid and reference sphere within this focal length range, as shown in Figure 5 [Figure 5: see original paper].

In Figure 5, the horizontal axis represents the focal length range from Figure 4, and the vertical axis shows the maximum deviation distance. To illustrate the travel limits, deviations in both inward and outward directions are shown as positive values. The figure shows that as the focal length increases, the maximum deviation distance first decreases to a certain value and then increases. Comparing with Figure 4, when the focal length is at the lower end, the outward maximum distance dominates; as the focal length increases, this outward maximum distance gradually decreases until the inward and outward maximum distances become approximately equal. With further focal length increase, the inward maximum distance becomes dominant and gradually increases until reaching the limit. This pattern aligns with the deviation changes shown in Figure 4 as focal length varies.

2. Analysis of Paraboloids with Apertures Larger Than 300 m

For paraboloids with apertures larger than 300 m, this study selects 305 m and 310 m for calculation and analysis. For a 305 m aperture paraboloid, Figure 6 Figure 6: see original paper shows the deviation between the paraboloid and reference sphere within FAST’ s current actuator travel range. The maximum deviation within this focal length range is shown in Figure 6(b). In Figure 6(a), the horizontal axis represents the 305 m aperture paraboloid range, and the vertical axis shows the deviation distance. The solid and dashed lines represent deviations for focal lengths of 137.62 m and 138.64 m, respectively. Figure 6(b) demonstrates that as focal length increases within this range, the maximum deviation transitions from outward-dominated to inward-dominated, following the same pattern observed for the 300 m aperture.

For a 310 m aperture paraboloid, Figure 7 Figure 7: see original paper shows the deviation within the actuator travel range, with the maximum deviation presented in Figure 7(b). In Figure 7(a), the solid and dashed lines represent deviations for focal lengths of 137.32 m and 137.85 m, respectively. Similarly, Figure 7(b) shows that the maximum deviation first decreases and then increases with focal length.

Based on these calculations and analyses, enlarging the illuminated aperture to 310 m is theoretically feasible from the perspective of actuator travel, with corresponding focal lengths and focal ratios selectable within a certain range. However, when the illuminated aperture increases, feed positioning and illumination must be matched to the paraboloid. FAST’ s feed support system, with its six-cable drive mechanism and AB axis mechanism, can achieve feed control and positioning. Compared with the 300 m aperture, the changes in feed position and illumination are relatively small for a 310 m aperture, making it easier to achieve matching with feed system components. During FAST reflector shape-changing, the current maximum actuator speed is approximately 1.6 mm/s. For a shape-changing adjustment of 0.6 m, the required time would be about 7 minutes at this speed.

Summary of Calculated Data

Table 1 summarizes the approximate focal lengths and focal ratios calculated for 300 m, 305 m, and 310 m aperture paraboloids within the maximum travel range of FAST' s current actuators.

Table 1. Main parameters of paraboloids of different apertures within actuator travel range

Aperture of the paraboloid (m)	Focal length of the paraboloid (m)	Focal ratio
300	137.91-139.38	0.4597-0.4646
305	137.62-138.64	0.4512-0.4546
310	137.32-137.85	0.4430-0.4447

4. Conclusion

When the paraboloid aperture and reference sphere dimensions are fixed, based on the fundamental relationship between paraboloid and sphere, calculations of paraboloid deviation from the sphere demonstrate that as the paraboloid focal length decreases, the overall configuration shifts outward away from the sphere center. Under the constraint of FAST' s actuator maximum travel range, shape-changing from the sphere to paraboloids of different apertures reveals that larger apertures correspond to smaller selectable focal length ranges, while smaller apertures allow larger focal length ranges. From the perspective of actuator travel, this study provides focal length and focal ratio values for 305 m and 310 m aperture paraboloids. Further investigation is needed regarding specific impacts on the telescope' s cable mesh and down-tie cables. The calculation method for paraboloid and reference sphere relationships is equally applicable to other aperture sizes.

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

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