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Study on the Optimal Working Paraboloid of FAST based on Reflector Adjustment

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Abstract

FAST is the world's largest radio telescope, which is of very high value in many fields and has now officially become one of the fifteen major projects of the Knowledge Innovation Project of the Chinese Academy of Sciences. However, to complete the astronomical observation, it is necessary to realize the accurate and reasonable control of the deformation process of the whole network of FAST active reflecting surface, which depends on the determination and realization of the ideal working paraboloid. To explore the mathematical model of the FAST radio telescope in some special cases, we set up the following cases: When the object to be observed is located at $\alpha=0^{\circ},\beta=90^{\circ}$ (α is azimuthal angle, β is elevation angle), we give a preliminary ideal paraboloid model based on the focal position and geometric relations. Subject to the radial expansion range of ±0.6m of the actuator, we calculate that to fit this paraboloid, there will be a part of the actuator expansion larger than 0.6m, even up to 0.6944m, which is beyond the range limit. Therefore, we consider the actual situation and condition constraints, take a very small step in MATLAB to traverse the two parameters of the paraboloid equation - f and h (f is the focal diameter ratio, h is the Z-axis intercept), and select the parameter value corresponding to the smallest actuator expansion and contraction, to obtain the actual fit of the ideal paraboloid model, the equation is: $z=\frac{x^2+y^2}{542.4}-300.37$. Finally, we analyze the model errors and strengths and weaknesses, evaluate them, and give corresponding improvement solutions for the weaknesses, and discuss the applicability of the model.

Keywords

Iterative Search; Single Objective Optimization; Discretization.

1. Introduction

The 500-meter Aperture Spherical Radio Telescope (FAST), one of the major national science and technology infrastructure projects, is the world's largest and most powerful single-antenna radio telescope in terms of aperture, which is of milestone importance for the development of radio astronomical observation and will essentially improve radio astronomical imaging capabilities.

FAST consists of the active reflector, the signal receiving system (feeder module) and the related control, measurement and support systems. The main reflecting surface can be adjusted in real time by setting a pull-down cable at each node of the main cable network and pulling the cable through the actuating device, so that the main reflecting surface forms an instantaneous paraboloid with an aperture of 300m in the direction of the object to be observed. Thus, the parallel electromagnetic waves from the target object are reflected and converged to the effective area of the feeder module at the focal point. Based on this analysis we will investigate the following question.

How to determine the ideal paraboloid model when the object to be observed is located at $\alpha = 0°, \beta = 90°$ (α is azimuthal angle and β is elevation angle), taking into account the reflecting panel adjustment factor.

2. Methodology

2.1 Problem Analysis

For the problem, first, since both spherical and parabolic surfaces have isotropic characteristics, and the parabolic surface formed by the translocation moves inside the sphere, the relative position relationship between the parabolic surface in different regions inside the sphere and the sphere remains unchanged, so when analyzing the deformation strategy, the problem can be simplified to two-dimensional space, using circular arcs instead of basic spherical surfaces and parabolas instead of parabolic surfaces. We use the relevant principles of geometric mathematics to derive a two-dimensional parabolic model based on the reflection law of the reflective panel and combined with the position of the focal feeder pod P. Then by symmetry, the parabola is rotated along the central axis for one week to obtain the preliminary ideal parabolic model of the paraboloid. At this point, the parallel electromagnetic waves from the observed object S can be fully converged to the focus P by the geometric relationship.

However, in the process of the specified tracking of the FAST reflecting surface, the stress of the main cable changes significantly, and in order to avoid the local relaxation of the main cable or its exceeding the limits of the stretching range due to excessive tension [1], the displacement of the nodes of the main cable should be within the range given in the title, and the closer to the preliminary paraboloid model, the better. After checking the corresponding literature, we define the distance from the reference state to the corresponding point of the working paraboloid in the radial direction as the radial expansion range. However, the nodes move from the reference state to the above ideal working state at a distance exceeding the stretching range, so the ideal working surface needs to be improved on this basis.

According to the parameter values of the preliminary ideal paraboloid, we take the values in its vicinity and determine the appropriate step size to traverse in MATLAB, take the parameter corresponding to the shortest stretching distance within the specified range and bring it into the hypothetical equation to derive the ideal paraboloid model.

2.2 Model Assumptions

(1) Since the round hole does not affect the reflection, we ignores its effect.

(2) The thickness of the reflector plate is assumed to be negligible,since the emission source is far away from the working paraboloid, the signal can be assumed to propagate along a straight line.

(3) It is assumed that the nodal excess surface at the edge of the main cable network is smooth and well articulated when it overflows from the reference state to the working state within an aperture of 300m.

2.3 Description of symbols

Symbol	Description	Unit
α	Azimuth	degree
β	Elevation angle	degree
f	Focal-diameter ratio	—
k	Number of signal bars reflected to the feeder compartment	Article

h	Z-axis intercept of the parabolic equation	m

3. Experimental Settings

3.1 Preliminary Establishment of the Ideal Parabolic Model

According to the symmetry of the sphere and the paraboloid, the paraboloid formed by the dislocation moves inside the sphere, and the paraboloid in different regions inside the sphere remains the same relative to the sphere, so we simplify the problem to two-dimensional space, using circular arcs instead of the basic sphere and parabolas instead of the paraboloid. As shown in the figure 1, the problem is analyzed in the X-Y plane.

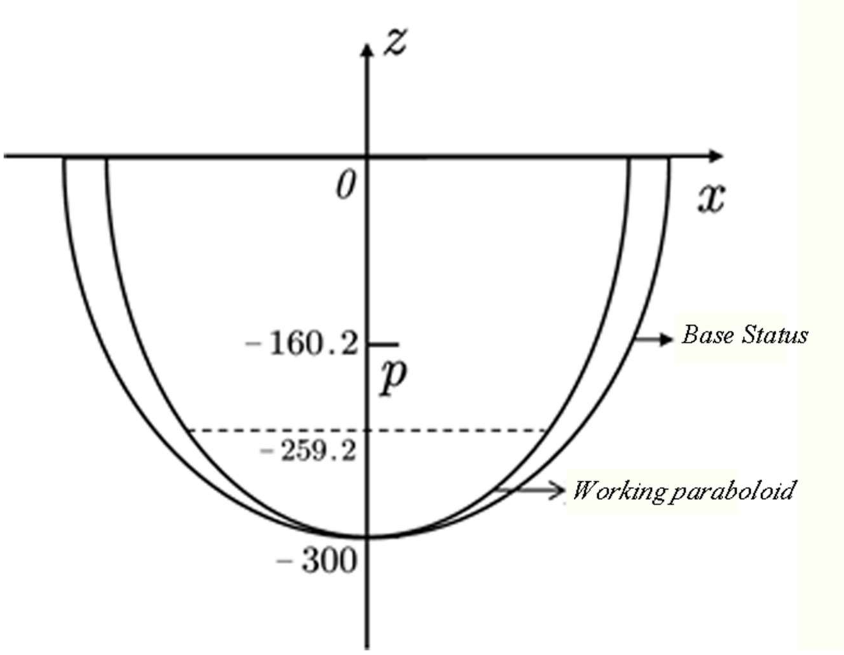

Figure 1. Two-dimensional diagram of the paraboloid

When the object to be observed is located at $\alpha=0^{\circ},\beta=90^{\circ}$, The feeder module P is located at the point $(0,-160.2)$, let the equation of the paraboloid be $z=\frac{x^2}{2p}-300$,the two-dimensional parabolic model is derived from $\frac{p}{2}=F=0.466R=139.8$,and two-dimensional parabolic model is:

$$z=\frac{x^2}{559.2}-300 \tag{1}$$

Rotate the plane along the z-axis for one week to obtain a three-dimensional preliminary ideal paraboloid model:

$$z=\frac{x^2+y^2}{559.2}-300 \tag{2}$$

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It is known from the geometrical relationship that the parallel electromagnetic waves emitted from the observing object S can converge to the focal point P when the active reflecting surface within the working range is almost completely fitted with the paraboloid.

However, in the actual operation of the main cable nodes, the expansion and contraction range of each node is limited, and the expansion and contraction range in the radial direction needs to be controlled to ensure the stable operation of the main cable network, so the maximum displacement from the base state to the working state nodes needs to be calculated.

After checking the related literature, we found that the node displacement can be replaced by its radial distance from the reference state to the working state. Therefore, in order to judge whether the preliminary ideal parabolic model can be realized, We take $z=kx(k<0)$ in the two-dimensional plane, find the intersection points with the circle (base state) and the parabola (working state) respectively, and calculate the distance d between the intersection points.

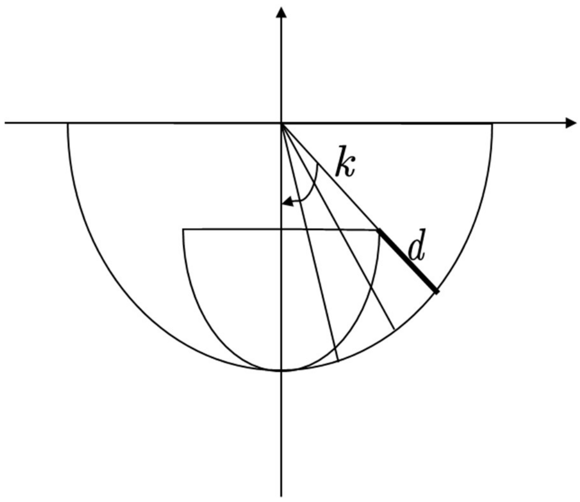

Figure 2. Schematic diagram of radial distance calculation

We first search for the approximate range of k in MATLAB in steps of -1, then reduce the step size to -0.01 and traverse k to obtain: When $k\in[-3.376,-2.186]$, the distance d exceeds the stretching limit of 0.6, up to a maximum of about 0.6944. Therefore, the initial ideal parabolic model cannot be realized within the specified stretching range, and the model needs to be corrected and made as close as possible to the new model.

3.2 Ideal Parabolic Model

Consider introducing a model $z=\frac{x^2}{2p}-h$, referring to the relevant literature ,we use the focal diameter ratio f to solve the problem. According to $f=\frac{p}{2R}$,we can get $z=\frac{x^2}{4Rf}-h$, bringing in $R=300$ has:

$$z=\frac{x^2}{1200f}-h \tag{3}$$

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Considering that the direct treatment of the reference state as a circle will produce a large error, we introduce the idea of discretization to verify the hypothesis. The paraboloid is expanded as shown in the figure below, and can be viewed as a regular hexagon consisting of a square triangle with the side lengths scaled up by a certain percentage

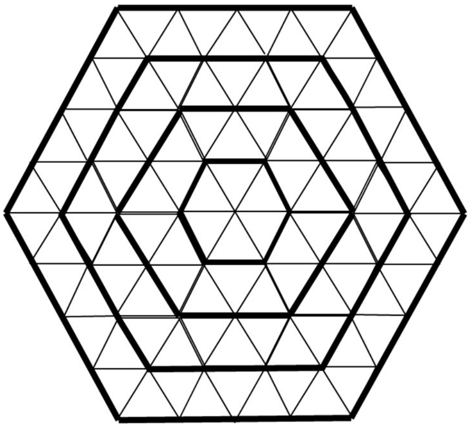

Figure 3. Paraboloidal expansion diagram

Considering that there are about 4300 reflective panels in total, it is known by mathematical induction that it has $N=12n-6$ panels in each circle. Using the equivariant series summation formula, we get $\frac{(6+12n-6)}{2}=4300$, the solution is $n=26.77$, rounded to n=27. i.e. as shown in the figure .4,when $\phi=90^{\circ}$, the right half of the paraboloid can be discretized into 27 line segments.

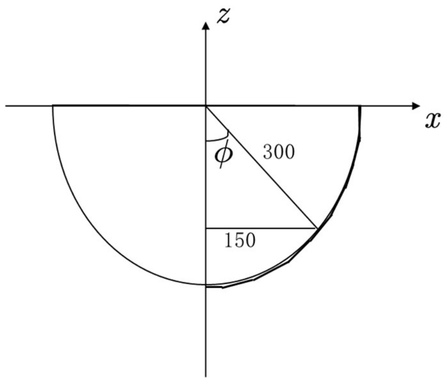

Figure 4. Parabolic dispersion schematic

From geometrical mathematics, it follows that the working paraboloid corresponds to the $\phi=30^{\circ}$, According to the ratio relationship, the triangular panel of the working paraboloid can be discrete to each node according to a certain distance. Therefore, the nodes of the panel of the corresponding profile can be found in Annex I in accordance with the law of equipartition to sit marked as the initial state of the nodes and brought into SPSS for fitting to obtain the curve expressions still as: $x^2+z^2=300^2$. This further validates the assumption that the reference state is spherical. Then, repeat the steps in 3.1 above to find the most desirable a and b , taking $k\in[-57.3(-\tan 89^{\circ}),\ -\sqrt{3}(-\tan 30^{\circ})]$, take a step size of $0.02(\tan 1^{\circ})$, Parallel standing (3) equation:

$$\begin{cases} z = kx \\ z = \dfrac{x^2}{1200f} - h \\ x^2 + z^2 = 300^2 \end{cases} \tag{4}$$

Find the expression for the nodal scalar containing f、h, i.e., d. Then combining the parameter data of the preliminary ideal parabolic model, we take $f \in [0.47, 0.455]$ in MATLAB, and set step lengths as 0.001; $h \in [300.2, 300.5]$,and set the step lengths as 0.01 to traverse. Find the time when $f = 0.452$、$h = 300.37$, d_{min} =0.37. Therefore, the ideal parabolic model at this point is the equation of this parabola after winding around the z-axis, which is:

$$z = \frac{x^2 + y^2}{542.4} - 300.37 \tag{5}$$

4. Conclusion and Analysis

4.1 Accuracy Analysis

When we consider the radial displacement of the actuator to meet the constraint of ±0.6m, the initial state is the position of the point on the standard sphere of 300m radius, while the actual reflective surface is not a regular smooth sphere, but consists of individual triangular reflective sheets. Therefore, the coordinates of each discrete point in the 300-meter-aperture illumination area are used as the initial state, which theoretically has a smaller error, and the obtained f, h parameters are closer to the ideal paraboloid.

4.2 Advantages of the Model

The actual active reflective surface is composed of several triangular reflective surfaces, we treat the surfaces composed of discrete planes as smooth parabolic and spherical surfaces, and simplify the calculation by symmetry to two-dimensional planes before rotating to get the final model, effectively reducing the workload and improving efficiency.

When calculating the nodal expansion, we introduced the idea of discretization to bring the points on the model to the corresponding nodes accurately into the calculation, which minimizes the error.

4.3 Disadvantages of the Model

When calculating the node stretching volume, the radial variation distance is used instead of the stretching volume. Although the model is effectively simplified to a certain extent, the magnitude of its variation in space in the longitudinal and latitudinal directions is ignored, which may lead to a small gap in the calculated ideal paraboloid.

When searching for the ideal paraboloid near the initial ideal paraboloid, the range and step size of the traversal may be too small.

4.4 Model Improvement

Extension of the model:

For disadvantage 1, its changes in the meridional and latitudinal directions can be considered comprehensively, and it is known from the relevant literature [2] that when changing from a spherical surface to an instantaneous paraboloid, the nodes produce displacements in the radial and meridional directions, and the latitudinal direction only has a change in the cable length within the stress reserve, and no latitudinal displacement occurs, and the ideal paraboloid can be further optimized according to the above conditions.

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For disadvantage 2, the larger intervals near the optimal paraboloid parameters can be traversed in larger steps first, and the intervals and step lengths can be gradually reduced in the range of smaller stretch. However, the step size should not be too small, otherwise it will lead to larger time and space complexity and longer program running time.

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