The Research of Actuators Distribution and Panels for Radio Telescope *

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Abstract Trying to achieve the best surface accuracy control with the fewest actuators, this article mainly studies the distribution of actuators and the method of panel design. The influence of the number of faulty actuators on the accuracy of the surface shape is demonstrated. And the method of triangle panel, node index and the fitting solution method of a single panel are also given. This method provides the reference for the design and realization of the active surface or the deformable sub-reflector for high performance large aperture radio telescopes.

Key words: radio telescope, triangle panel, method, design

1 INTRODUCTION

The active surface system can effectively eliminate the surface error that caused by gravitational or thermal deformation (WANG et al. 2019, DONG et al. 2018). Although it maintains the parabolic shape ideally, the number of the actuators is very large. Take the Tianma 65 meter antenna as an example, it is composed of 1104 actuators. The large number of actuators poses a great challenge to the reliability of the system. This paper studies the distribution of actuators, the influence of faulty actuators on the surface shape accuracy, as well as the panel design to reduce actuators. And the panel adjustment fitting model is given. This method is suitable for the top design of a radio telescope which equiped with active surface or deformable sub-reflector (WANG et al. 2020).

2 ACTUATORS DISTRIBUTION

Taking Tianma 65 meters as a reference, the active surface is designed with 1104 actuators’ positions. This paper simulates the optimal distribution of the actuators on the entire surface when the number of actuators is limited. It provides a basis for the subsequent development of using a smaller number of actuators to form an active surface or a deformable sub-reflector. The algorithm model for solving the optimal number and distribution of the actuators is given in Figure 1. Under normal circumstances,

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an aperture illumination distribution with a tapering of about 10 dB is usually applied for large radio telescopes. This is mainly to suppress sidelobe reception and reduce noise, but this will also cause some loss in gain. For deep-space data receiving large antennas, in order to maximize the gain, a uniform aperture distribution is used although the noise will increase (WANG et al. 2020).

![Diagram](image1.png)

**Fig. 1:** Optimized number of actuators and distribution model.

Figure 2 shows the 10 dB taper aperture illumination function and the Finite Element Method (FEM) simulation adjustment of each actuator over the entire range of elevation. The multiplication of the two data above is used as the weight function to make the decision of actuators’ arrangement and all actuators are prioritized. Figure 3 below shows the optimal placement of 400, 600 and 800 actuators respectively.

Table 1 shows the reduction of the aperture efficiency at each elevation under the compensation of different numbers of actuators, which was calculated by Lutz formula (Ruze 1966), as shown in the following formula 1. Where \(\lambda\) is the wavelength and \(\varepsilon\) (mm) represents surface accuracy of a parabolic antenna. The 57 degree elevation is the best position which is used as the normalized efficiency.

\[
\eta = \exp\left[-\left(\frac{4\pi\varepsilon}{\lambda}\right)^2\right]
\]  

(1)

Figure 4 shows the efficiency loss of the aperture surface efficiency at each elevation under the compensation of different numbers of actuators. It can be seen that when the number of actuators reaches more than 600, the gain loss in high and low elevation is already better than 80%. If the best efficiency is 60%, it can reach more than 48% at high and low elevation. It can be seen from Figure 3 that even the smallest distribution of 400 actuators presents a concentrated distribution of 6 large areas. This is advantageous for using the sub-reflector to compensate for the gravity deformation of the main surface. The diameter of the sub-reflector of Tianma 65 meters is 1/10 of the diameter of the main surface. It can be roughly estimated that the number of main surface actuators used is about 1/10 of the main surface. This means 80 actuators for sub-reflector compensation can almost achieve 90% performance of the 800 actuators on the main surface that mentioned above.

In order to obtain the exact number of optimized actuators, we propose to optimize the number on the basis of the above-mentioned optimal distribution of actuators. The basic criterion is the efficiency increasement caused by every 10 actuators and the minimum permitted efficiency. The efficiency
change rate at the lowest or highest elevation is most easily judged which we used as the basis. From Figure 4, we derive the relationship between the efficiency loss and the number of actuators at elevation of 17 degrees, as shown in Figure 5. And then derive the efficiency improvement caused by every 10 actuators, as shown in Figure 6. It shows that when the number of actuators is between 300 and 800, every additional 10 actuators can achieve more than 0.45% increment. The most efficiency number of actuators is about 550, every additional 10 actuators can improve the efficiency by about 0.7%. While at the number of 800, there is still an improvement about 0.45%. But after 900 actuators, the efficiency of each additional 10 actuators is less than 0.25%. It can be seen that if we take the 0.45% efficiency improvement for every 10 actuators as the threshold, we can get the optimal number of actuators about 800.

Fig. 2: Left: Aperture illumination function; Right: Compensation of 1104 actuators over entire elevation.

Fig. 3: Red circles mean the location of the actuators. Left: the optimal distribution of 400 actuators; middle: the optimal distribution of 600 actuators; Right: The final distribution of 800 actuators.
Table 1: The decrease of gain (efficiency) before and after compensation by different numbers of actuators.

<table>
<thead>
<tr>
<th>EL (°)</th>
<th>17</th>
<th>27</th>
<th>37</th>
<th>47</th>
<th>57</th>
<th>67</th>
<th>77</th>
<th>87</th>
<th>Number</th>
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<tr>
<td>Before</td>
<td>0.45</td>
<td>0.6</td>
<td>0.76</td>
<td>0.91</td>
<td>0.99</td>
<td>0.98</td>
<td>0.88</td>
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<tr>
<td></td>
<td>0.626</td>
<td>0.741</td>
<td>0.853</td>
<td>0.944</td>
<td>0.995</td>
<td>0.989</td>
<td>0.919</td>
<td>0.795</td>
<td>300</td>
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<td></td>
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<td>0.880</td>
<td>0.955</td>
<td>0.996</td>
<td>0.991</td>
<td>0.934</td>
<td>0.829</td>
<td>400</td>
</tr>
<tr>
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<td>0.741</td>
<td>0.830</td>
<td>0.907</td>
<td>0.966</td>
<td>0.997</td>
<td>0.993</td>
<td>0.947</td>
<td>0.860</td>
<td>500</td>
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<tr>
<td></td>
<td>0.809</td>
<td>0.877</td>
<td>0.934</td>
<td>0.976</td>
<td>0.998</td>
<td>0.995</td>
<td>0.960</td>
<td>0.890</td>
<td>600</td>
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<tr>
<td>After</td>
<td>0.881</td>
<td>0.927</td>
<td>0.961</td>
<td>0.985</td>
<td>0.999</td>
<td>0.996</td>
<td>0.973</td>
<td>0.923</td>
<td>700</td>
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<tr>
<td></td>
<td>0.937</td>
<td>0.964</td>
<td>0.981</td>
<td>0.993</td>
<td>0.999</td>
<td>1.0</td>
<td>0.982</td>
<td>0.942</td>
<td>800</td>
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<tr>
<td></td>
<td>0.965</td>
<td>0.983</td>
<td>0.992</td>
<td>0.996</td>
<td>1.0</td>
<td>0.998</td>
<td>0.987</td>
<td>0.956</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>0.984</td>
<td>0.995</td>
<td>0.997</td>
<td>0.998</td>
<td>1.0</td>
<td>0.999</td>
<td>0.990</td>
<td>0.965</td>
<td>1000</td>
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</table>

Fig. 4: The efficiency loss of the aperture surface efficiency at entire elevation under the compensation by different numbers of actuators.

Fig. 5: The relationship between the efficiency loss and the number of the actuators when El=17 degrees.
3 THE INFLUENCE OF FAULTY ACTUATOR ON SURFACE ACCURACY

Take the Shanghai Tianma 65 meter radio telescope as an example. There are 1008 panels and 1104 actuators. Under the condition that the illumination function respectively are evenly distributed and with a tapering of about 10 dB, we analyze the working mode of an actuator connected four panels’ corner. And we also suppose the accuracy of the main surface accuracy is 0.3 mm when there is no broken actuators. At the same time, assuming that the positioning standard deviation of a single faulty actuator is a random distribution of 5 mm, the simulation now randomly generates \( n (1 < n < 250) \) as the random faulty actuators, and the position error of the remaining \( 1104 - n \) actuators is 0.3 mm. The installation and distribution positions of the actuators on the Tianma 65 m aperture are shown in the Figure 7, which are also given as random positions. While considering the adjacent effect, in general, a faulty actuator will cause the error of the 4 panels to deteriorate. But if there are 2 actuators are broken and if the actuators are adjacent to each other. It will cause the accuracy of 6 panels to deteriorate instead of eight panels. Using the illumination function on the aperture and the panel area on each ring as the weighting factor, the adjustment errors of the actuators are multiplied by the weighting factor. And finally the standard deviation of 1104 data is counted as the \( n^{th} \) aperture deviation error. Repeatedly, after 250 times running we can get 250 aperture deviation. The result is as shown in Figure 8, where black means the aperture surface illumination is uniformly distributed, regardless of the area of each ring panel. Blue points means the illumination distribution is 10 dB taper, not counted the area weight of each ring panels. Red points represents illumination distribution is 10 dB taper and the panels’ area weight are all considered. It can be seen that in the case of uniform lighting distribution and a few faulty actuators at the beginning, the overall main surface statistical accuracy deteriorates rapidly. When there are ten dead actuators, the surface error has reached 0.5 mm. After the number has risen to fifty, as the probability of adjacent dead actuators increases, the deterioration speed begins to slow down. When considering the aperture illumination and the panels’ size in the different rings, this deterioration speed will be significantly reduced as shown in Figure 8 the blue and red distribution. But even so, when the number of dead actuators reaches 100, the total surface accuracy has reached 0.8 mm or more. In fact it has been unable to meet the needs of high-frequency K-band (22GHz) observation.
4 PANEL TYPING ANALYSIS

4.1 Triangular panel

The following is a quantitative analysis of different three-circle panels. Figure 9 shows the projection of the panels on the aperture surface. It mainly compares the number of panels in the case of triangular panel division and equiangular division when the area of the aperture and the number of panel rings are almost the same. The number of nodes is just the number of actuators in the active surface condition. In order to achieve the optimal surface accuracy, control and cost, the area of a single panel should be as small as possible, and the number of actuators should be as small as possible. Figure 10 shows a 60 degree sector, three traditional equiangular segmentation methods and triangular segmentation methods.
It can be seen from Table 2 below that the panel segmentation method of C has a maximum number of 60 panels and a single panel has the smallest area. The theoretical surface shape control accuracy will be the highest, but the number of nodes is also the highest which reached 73. The triangle division method has 54 panels, which is 6 less than C, and the number of nodes is only 37, half less than C. It can be seen that the advantage of triangular panel splicing is that it can effectively reduce the area of a single panel while sharply reducing the number of control nodes. This advantage becomes more obvious when the number of panel rings increases. In the traditional equiangular division method, the difference in area between the inner and outer single panel is generally large. It will not only cause uneven deformation of the inner and outer panels, but also will cause the outer edge of the backup frame to be too large and the stiffness of the outer rings will be deteriorated. Ultimately affect the panel adjustment accuracy. The analysis method of the triangular panel appeared in the initial design of LMT (Baars et al. 2018), while the practical application was carried out in the SKA intermediate frequency antenna (Dewdney et al. 2009).

Fig. 9: Left: Equilateral triangle panels are assembled into three circles, right: Panel circle dividing line

Fig. 10: 6 Equiangular parting A, B, C and regular triangular parting D
Table 2: Panel type.

<table>
<thead>
<tr>
<th>Panel type</th>
<th>Number of panels</th>
<th>Number of nodes</th>
<th>Ratio of single panel area to equilateral triangle panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>55</td>
<td>$\sim 1.5$</td>
</tr>
<tr>
<td>B</td>
<td>42</td>
<td>55</td>
<td>Inner $\sim 1.5$</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>73</td>
<td>Inner $\sim 0.83$</td>
</tr>
<tr>
<td>D</td>
<td>54</td>
<td>37</td>
<td>1</td>
</tr>
</tbody>
</table>

4.2 Index of triangle panel

It can be seen from Table 2 above that the triangular panel type has a relatively large advantage for reducing the number of actuators. But after adopting this type of the panel, the indexing method of the panel and the node is more complicated than that of the trapezoidal panel. Here we need to discuss the indexing method of the nodes and the panels. The following Figure 11 is an example. The index law of panel number and node number is studied mainly based on the number of panels on each ring. Table 3 summarizes the index formula and calculation examples.

Fig. 11: Index of triangle panel.
4.3 The surface shape calculation for a single panel

For the panel installed on the antenna, we need to calculate the adjustment to maintain the overall approximation (shaping) parabola. And we also need to diagnose the internal deformation of the single panel. For the measurement and adjustment of the trapezoidal panel, the Y and X axis rotation (ie slope) $\alpha$ and $\beta$, in addition $l$ of the translation item are traditionally used (Rochblatt 1992). The core of this method is to use the panel as a rigid plane to solve, which is commonly used in engineering applications. Since the trapezoidal panel is supported by at least four points, internal deformation is inevitable. So the torsion term inside the panel can actually be added. The fitting model is different from the traditional rigid panel (Hoerner & Sebastian 1981). It can make the fitting error reduced and more in line with the actual situation of statically indeterminate installation of the panel. The following coordinate system can be used. When the Z-direction displacement of each point inside the panel is measured, the model can be used to perform the least square fitting of a single panel. The best adjustment of the four corners can be solved from the fitting. When the panel area is large, more adjustment points can be added, as shown in the left position in Figure 12. In this case, the model can increase the sum of the square term parameters of X and Y to make the fitting accuracy higher. Establish a complete single panel adjustment amount fitting model as shown in the following formula 2 (Lei 2000).

$$z(x, y) = l + \alpha x + \beta(y - \overline{y}) + \tau xy + \gamma x^2 + \lambda(y - \overline{y})^2$$  \hspace{0.5cm} (2)

Among them: $\overline{y}$ is the midpoint position of the Y-direction panel. This amount is subtracted to solve the coupling. Because if it is not subtracted, it will cause additional contributions to the panel in Z-direction. By comparing the solution results of many trapezoidal panels on Tianma 65 meters, the fitting error of a single panel is significantly reduced after the torsion term and the square term are used. The following Figure 13 shows the fitting comparison diagram of a panel. The left figure is the traditional rigid panel fitting method, and its fitting error (RMS) is 0.12 mm. The right figure is the fitting method using formula (2). The total error is 0.03 mm.

Compared with the trapezoid panel, in addition to the advantages mentioned above, a main disadvantage of the triangular panel is also obvious. Because triangular panel has fewer adjustment points, it can only do three point adjustment(X and Y slope item plus translation item). And it is not suitable for four parameter fitting surface (including XY cross fitting item) to obtain better adjustment. However, as long as the processing accuracy of the triangular single panel is guaranteed and the area is not large, the XY cross term is actually not large. When the area of the triangular panel increases, it can be appropriate to increase the adjustment point, as shown in the position on the right of Figure 12, which can achieve a method similar to equation (2) to improve the accuracy of the adjustment. In addition to giving the adjustment amount of the panel, this method can also accurately diagnose the deformation inside a single panel.
5 SUMMARY AND DISCUSSION

This article mainly studies the distribution method of actuators and the method of panel division. We tried to achieve the best surface accuracy control with the fewest actuators. By adopting the surface gravity FEM model and illumination design, the distribution of the actuators can be optimized. And then the triangular panel can effectively reduce the number of actuators. Then the influence of the number of faulty actuators on the surface shape accuracy is demonstrated. The uniformly illuminated antenna has the highest requirements for the reliability of the actuator. The paper presents the triangle panel and node index method as well as the fitting solution method of single panel. This method provides a reference for the design of active surfaces or deformable sub-reflectors for large radio telescopes.

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