Simulation of FAST Telescope EM Performance for both the axial and lateral Feed Defocusing

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Abstract Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single dish radio telescope in Guizhou province, Southwest China. The FAST feed cabin is supported and positioned by six steel cables. The deviation of the feed position and orientation would lead to the telescope efficiency loss. In this paper, a serial of EM simulations of FAST telescope with feed position and orientation offset were performed. The maximum gain of FAST telescope is about 82.3dBi and the sibelobe is -32dB to the main beam at 3GHz. The simulation results have shown that the telescope efficiency loss is more sensitive to the lateral feed deviation in comparison with the axial deviation. The telescope efficiency would decrease by 8.2% due to the FAST feed position deviation of 10mm rms when the observation frequency is 3GHz. The FAST feed deviation basically has no effect on the sidelobes and cross polarization characteristic according to the simulations.

Key words: techniques: FAST Telescope, Telescope efficiency, Feed position error

1 INTRODUCTION

Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single dish radio telescope in Guizhou province, Southwest China (Nan 2006). The main structure was completed in September 2016, and then the commissioning process and trial observation was started for about 3 years. The huge aperture led to the extremely high sensitivity to about 2000m²/k or more higher in L band, which is expected to be state of the art of radio astronomy observation in the next two decades. In order to achieve the high sensitivity, the feed need positioning on the focus precisely.

The illuminated aperture of the FAST telescope is 300m and the focal ratio is about 0.466 which means the feed need to located at ~140m above the main reflector. The feed cabin of the FAST telescope is about 13m in diameter and the weight is 30tons. So, there is no feasibility of building a rigid strut to supporting and positioning the feed cabin.

The FAST telescope innovatively uses six cables to supporting and positioning the feed cabin, each of which is about 600m long and 7 tons weight (Hans 2008). The cables are pulled down and back by the winches to parallel driving the feed cabin moving in a range of 206m and at a height of ~140m above the reflector. The six-cable driven parallel robot is a major innovation of large radio telescope, and greatly reduces the weight of the feed support system.
from tens of kilotons to dozens of tons. The six cables have less shielding effect on the reflector which has great benefit to further enhance the sensitivity of the telescope. At the same time, the cross-polarization mutual coupling and the standing wave caused by the multi reflection are also expected to be eliminated to achieving the broadband and high polarization purity observation.

However, it is found that the feed would have a deviation to the theoretical focus because of the measurement and control error during the observation (Sun 2014) (Yao 2017). The feed position and orientation deviation could affect the telescope efficiency.

2 THE TYPES OF FEED POSITION AND ORIENTATION ERROR

As a rigid body, the FAST feed have six degrees of freedom (DOFs) incuding of three translations: moving along X-axis (walking/surging), moving along Y-axis (strafing/swaying), moving along Z-axis (elevating/heaving) and three rotations: rotating along X-axis (yawing), rotating along Y-axis (pitching), rotating along Z-axis (rolling) (See Figure 1). Meanwhile, the FAST feed have three position errors and three rotation errors correspondently.

The feed moving left or right and forward or backward has the same effect on the telescope efficiency because they are both moving in the focal plane. For the rotation symmetry of the illuminated area and the feed, the swivels left or right (yawing) and tilts forward or backward (pitching) also have same effect. They are the angles to describe the feed orientation. And the rotation along the feed axial (rolling) has effect on the polarization observation but no effect on the telescope efficiency, so the feed rolling effect is not discussed here.

To simplify the effect of feed position and orientation error on the telescope efficiency, divide the feed position and orientation error into three types: feed position deviation in the focal plane, feed position deviation in the telescope axial direction and feed orientation deviation. For the feed position deviation in focal plane, the observation direction of the telescope would deviate from the telescope optical axis. So, the direction of telescope max gain would deviate from the expected radio source and the telescope efficiency would be decreased.

The feed position deviation in axial direction and the feed orientation deviation would change the phase and amplitude distribution of the electrical field on the illuminated aperture respectively. They would cause the telescope efficiency loss but have no effect on the telescope observation direction.
3 EM SIMULATION OF FAST TELESCOPE

The efficiency of radio telescope is the ratio of the effective collecting area to the geometry area. The effective collecting area is proportional to the max gain of the telescope. There are a lot of Electro-Magnetic(EM) simulation software to calculate the antenna radiated pattern (Huan 2003) (Khaikin 2006) (Pietro 2018). To perform the EM simulation of FAST telescope, the GRASP package was involved. In order to modelling the FAST telescope in GRASP, a 500m aperture spherical reflector with center hole of 300m (outer part) and a parabolic reflector with aperture of 300m (inner part) had been created. The FAST model and the radiation pattern with feed lateral offset of 10mm are shown in Figure 2. From the result, the maximum gain is about 78.3dBi and the HPBW (Half-Power Beam Width) is about 83arcsec at 3GHz. The sidelobes of FAST telescope is about -40dB to the main beam meanwhile the cross polar is about -60dB to the co-polar in the main beam.

![Fig. 2 The FAST model in GRASP (right) and the simulation result of 3GHz(left).](image)

The frequency of simulation was 3GHz, the highest operation frequency of FAST telescope. For the higher the frequency, the more sensitive the telescope efficiency to the feed position and orientation deviation. The simulation results and the efficiency loss are given in the three following sections. It should be noted that the efficiency here is the ratio of telescope efficiency with feed position error to the telescope efficiency without feed position error.

3.1 FAST Efficiency with Feed Offset in Focal Plane

The simulation results of FAST telescope far field pattern with feed offset for 0mm, 10mm, 20mm, 30mm and 40mm in focal plane are shown in Figure 3. The direction of max gain offset to the telescope axis for about 0.004deg for every 10mm of feed offset and the max gain decreases about 0.26dB in the observation direction for 10mm feed offset. The efficiency loss due to feed offset is given in Table 1. The efficiency loss is about 6% for 10mm feed offset in focal plane.
Table 1 FAST Telescope Efficiency Loss with Feed Offset in Focal Plane.

<table>
<thead>
<tr>
<th>Feed Offset in Focal Plane (mm)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Gain (dBi)</td>
<td>78.279</td>
<td>78.012</td>
<td>77.198</td>
<td>75.786</td>
<td>73.673</td>
</tr>
<tr>
<td>Gain Loss (dB)</td>
<td>0</td>
<td>-0.26647</td>
<td>-1.0809</td>
<td>-2.4931</td>
<td>-4.6052</td>
</tr>
<tr>
<td>In Percentage</td>
<td>100</td>
<td>94.049</td>
<td>77.967</td>
<td>56.324</td>
<td>34.632</td>
</tr>
</tbody>
</table>

3.2 FAST Efficiency with Feed Offset in Axial Direction

The simulation results of FAST telescope far field pattern with feed offset for 0mm, 10mm, 20mm, 30mm and 40mm in axial direction are shown in Figure 4. The direction of max gain is no offset and the max gain decreases about 0.026dB for 10mm feed offset in axial direction. It is much less than the feed offset in focal plane. The efficiency loss due to feed offset is given in Table 2. The efficiency loss is about 0.6% for 10mm feed offset in telescope axial direction.

Fig. 3 FAST telescope pattern with feed offset in focal plane(left) and the detail of main beam(right).

Fig. 4 FAST telescope pattern with feed offset in axial direction(left) and the detail of main beam(right).
### Table 2  FAST Telescope Efficiency with Feed Offset in Axial Direction.

<table>
<thead>
<tr>
<th>Feed offset in focal plane (mm)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Gain (dBi)</td>
<td>78.279</td>
<td>78.252</td>
<td>78.173</td>
<td>78.04</td>
<td>77.853</td>
</tr>
<tr>
<td>Gain Loss (dB)</td>
<td>0</td>
<td>-0.026411</td>
<td>-0.10582</td>
<td>-0.23868</td>
<td>-0.42576</td>
</tr>
<tr>
<td>In Percentage</td>
<td>100</td>
<td>99.394</td>
<td>97.593</td>
<td>94.652</td>
<td>90.662</td>
</tr>
</tbody>
</table>

### 3.3 FAST Efficiency with Feed Orientation Error

The simulation results of FAST telescope far field pattern with feed rotation for 0deg, 1deg, 2deg, ..., 10deg are shown in Figure 5. The direction of max gain is no offset and the max gain decrease about 0.001dB in the observation direction for 1deg feed orientation error. The efficiency loss due to feed orientation error is given in Table 3. The FAST feed orientation error could be less than 1 deg (Jiang 2019). It could be concluded from the simulation results the FAST telescope efficiency loss caused by the feed orientation error is less than 0.04%. Therefor the efficiency loss due to feed orientation could be ignored.

From the EM simulation results, it is can be seen the telescope efficiency would be decreased by 6% when the feed position error is 10mm in the focal plane. In the direction of the telescope optical axis, the telescope efficiency loss is 5% when the feed deviation is 30mm. The ratio of sidelobe to the meanbeam basically keep constant while the feed defocuing and rotating within a small range. The cross polarization performance of the FAST telescope would not be downgrade by the feed defocuing.

In the real model, the feed position error would combine the two types of deviations, the efficiency loss would also a combination of the two types of errors. Consumption the statistics of the feed position error can be described by the Gaussian distribution function. So, the FAST

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**Fig. 5** FAST telescope pattern with feed orientation error(left) and the detail of main beam(right).

**Table 3  FAST Telescope Efficiency with Feed Orientation Error.**

<table>
<thead>
<tr>
<th>Feed Orientation Error (deg)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Gain (dBi)</td>
<td>78.279</td>
<td>78.277</td>
<td>78.273</td>
<td>78.266</td>
<td>78.255</td>
<td>78.242</td>
<td>78.226</td>
<td>78.207</td>
<td>78.186</td>
<td>78.161</td>
<td>78.133</td>
</tr>
<tr>
<td>Gain Loss (dB)</td>
<td>0</td>
<td>-0.00145</td>
<td>-0.00580</td>
<td>-0.0130</td>
<td>-0.0232</td>
<td>-0.0362</td>
<td>-0.0523</td>
<td>-0.0712</td>
<td>-0.0932</td>
<td>-0.118</td>
<td>-0.146</td>
</tr>
</tbody>
</table>
telescope efficiency of the feed position error is
\[
\eta(\sigma, \delta) = \frac{\sum_{r=-3\sigma}^{3\sigma} \sum_{z=-3\delta}^{3\delta} G(r, z) \rho(r) \rho(z)}{G(0, 0) \sum_{r=-3\sigma}^{3\sigma} \sum_{z=-3\delta}^{3\delta} \rho(r) \rho(z)}
\] (1)

Where \(G(0, 0)\) is simulated FAST telescope gain with no feed position and orientation error; \(G(r, z)\) is the telescope gain with feed position error \(r\) in focal plane and \(z\) in optic axial direction; \(\rho(r)\) and \(\rho(z)\) is feed position error with standard Gaussian distribution
\[
\rho(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{r^2}{2\sigma^2}} \quad (2)
\]
and
\[
\rho(z) = \frac{1}{\sqrt{2\pi\delta^2}} e^{-\frac{z^2}{2\delta^2}} \quad (3)
\]

The integral interval \([-3\sigma, 3\sigma]\) and \([-3\delta, 3\delta]\) could cover the 99.7% of the whole probability. For each efficiency of the feed deviation \(\eta(\sigma, \delta)\), a number of EM simulations with the lateral and axial feed offset of \((-3\sigma, -3\delta), (-3\sigma, -2\delta), \cdots, (3\sigma, 3\delta)\) have been performed. Then, the \(G(r, z)\) in Formula 1 was derived from the EM simulation result. The calculation results of Formula 1 are shown in Table 4. It could be deduced from the calculation results that the telescope efficiency loss caused by the feed position error is dominated by the feed lateral deviation.

<table>
<thead>
<tr>
<th>Telescope Efficiency In Percentage</th>
<th>Feed deviation in focal plane (mm rms)</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>12</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed deviation in axial direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed deviation (mm rms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage</td>
<td></td>
<td>1</td>
<td>99.871</td>
<td>97.822</td>
<td>94.878</td>
<td>92.332</td>
<td>89.486</td>
</tr>
<tr>
<td>Feed deviation in focal plane</td>
<td></td>
<td>5</td>
<td>99.720</td>
<td>97.763</td>
<td>94.788</td>
<td>92.175</td>
<td>89.403</td>
</tr>
<tr>
<td>Feed deviation in axial direction</td>
<td></td>
<td>10</td>
<td>99.348</td>
<td>97.248</td>
<td>94.314</td>
<td>91.837</td>
<td>89.165</td>
</tr>
<tr>
<td>Feed deviation (mm rms)</td>
<td></td>
<td>15</td>
<td>98.649</td>
<td>96.6603</td>
<td>93.706</td>
<td>91.071</td>
<td>88.262</td>
</tr>
<tr>
<td>Feed deviation in focal plane</td>
<td></td>
<td>20</td>
<td>97.541</td>
<td>95.672</td>
<td>92.680</td>
<td>90.210</td>
<td>87.409</td>
</tr>
<tr>
<td>Feed deviation in axial direction</td>
<td></td>
<td>25</td>
<td>96.467</td>
<td>94.530</td>
<td>91.594</td>
<td>89.124</td>
<td>86.310</td>
</tr>
<tr>
<td>Feed deviation (mm rms)</td>
<td></td>
<td>30</td>
<td>94.920</td>
<td>93.029</td>
<td>90.243</td>
<td>87.831</td>
<td>84.986</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS AND DISCUSSION

As is shown in the simulation results, the feed position and orientation error would affect the FAST telescope efficiency. The FAST sidelobes and cross polarization basically keep the same shape while the feed defocusing in small range. The feed deviation in the focal plane is more crucial than the position error in optic axial direction and the feed orientation error. The telescope efficiency loss caused by the feed orientation error is less than 0.04% when the feed orientation error is 1deg.

In the case of the feed position error is 10mm rms in focal plane and 10mm rms in axial direction, the telescope efficiency could be decreased by 8.2% in 3GHz. The FAST telescope efficiency loss caused by the feed position error would be less than 4% in L band. In the near future, the FAST feed position error could be 5mm rms by upgrading the measurement and control equipments and techniques of the feed support system. The efficiency loss would be less than 2% in 3GHz and less than 1% in L band.

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