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Simulation of FAST 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 world's largest single dish radio telescope, which is located in Guizhou Province, in 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 loss in the telescope efficiency. In this paper, a series of electromagnetic (EM) simulations of the FAST facility with varying feed positions and orientation offsets was performed. The maximum gain of FAST is about 82.3 dBi and the sibelobe is –32 dB with respect to the main beam at 3 GHz. The simulation results have demonstrated that the telescope efficiency loss is more sensitive to the lateral feed deviation compared with the axial deviation. The telescope efficiency would decrease by 8.2% due to the FAST feed position deviation of 10 mm rms when the observing frequency is 3 GHz. 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 world's largest single dish radio telescope, which is located in Guizhou Province, in southwest China (Nan 2006). The main structure was completed in September 2016, and then the commissioning process and trial observations were conducted for about 3 yr. The huge aperture enables the extremely high sensitivity of about 2000 m^2 K^{-1} or more in L band. It is expected to be a state of the art facility for radio astronomy observation in the next two decades. In order to achieve such high sensitivity, the feed needs to be precisely positioned at the focus.

The illuminated aperture of FAST is 300 m and the focal ratio is about 0.466 which means the feed needs to located $\sim$140 m above the main reflector. The feed cabin of FAST is about 13 m in diameter and the weight is 30 tons, so there is no feasible way to build a rigid strut to support and position the feed cabin.

The FAST telescope innovatively implements six cables to support and position the feed cabin, each of which is about 600 m long and 7 tons in weight (Kärcher et al. 2008). The cables are pulled down and back by winches that move the feed cabin in a range of 206 m and at a height of $\sim$140 m above the reflector. The robot consisting of six cable drivers working in parallel is a major innovation in a 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 further enhances the sensitivity of the telescope. At the same time, the cross-polarization mutual coupling and standing wave caused by multiple reflections are also expected to be eliminated to achieving broadband and high polarization purity observations.

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

2 THE TYPES OF FEED POSITION AND ORIENTATION ERRORS

As a rigid body, the FAST feed has six degrees of freedom (DOFs) including three translations: moving along the X-axis (walking/surging), moving along the Y-axis (strafing/swaying) and moving along the Z-axis (elevat-

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ing/heaving), and three rotations: rotating along the X-axis (yawing), rotating along the Y-axis (pitching) and rotating along the Z-axis (rolling) (see Fig. 1). Meanwhile, the FAST feed has three corresponding position errors and three rotation errors.

The feed moving left or right and forward or backward has the same effect on the telescope efficiency because they are all moving in the focal plane. Due to the rotation symmetry of the illuminated area and the feed, the swivels left or right (yawing) and tilts forward or backward (pitching) also have the same effect. They are the angles to describe the feed orientation. Also, the rotation along the feed axis (rolling) has an 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, we 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 feed position deviation in the focal plane, the observation direction of the telescope would deviate from the telescope optical axis. So, the direction of maximum gain for the telescope would deviate from the expected radio source and the telescope efficiency would be decreased.

The feed position deviation in the 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 efficiency loss for the telescope but would have no effect on the direction of observation for the telescope.

3 EM SIMULATION FOR FAST

The efficiency of a radio telescope is defined as the ratio of the effective collecting area to the geometric area. The effective collecting area is proportional to the maximum gain of the telescope. There are a lot of electromagnetic (EM) simulation software packages that can calculate the radiation pattern for the antenna (Tran 2003; Khaikin & Lebedev 2006; Bolli et al. 2018). To perform the EM simulation for the FAST telescope, the GRASP package was applied. In order to model the FAST telescope in GRASP, a 500 m aperture spherical reflector with a central hole of 300 m (outer part) and a paraboloid reflector with aperture of 300 m (inner part) was simulated. The FAST model and the radiation pattern with feed lateral offset of 10 mm are displayed in Figure 2. From the result, the maximum gain is about 78.3 dBi and the half-power beam width (HPWB) is about 83 arcsec at 3 GHz. The sidelobes of FAST are about –40 dB with respect to the main beam while in the cross polar direction it is about –60 dB with respect to the co-polar direction in the main beam.

The frequency used in the simulation was 3 GHz, the highest operating frequency of FAST. Higher frequencies have a stronger influence on the the telescope efficiency as related to the feed position and orientation deviation. The simulation results and the efficiency loss are described in the three following subsections. It should be noted that the efficiency here is the ratio of telescope efficiency with respect to 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's far field pattern with feed offset for 0 mm, 10 mm, 20 mm, 30 mm and 40 mm in the focal plane are depicted in Figure 3. The direction of maximum gain offset with respect to the telescope axis for about 0.004 deg for every 10 mm of feed offset and the maximum gain decreases about 0.26 dB in the observation direction for 10 mm feed offset. The efficiency loss due to feed offset is provided in Table 1. The efficiency loss is about 6% for a 10 mm feed offset in the focal plane.

3.2 FAST Efficiency with Feed Offset in Axial Direction

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

3.3 FAST Efficiency with Feed Orientation Error

The simulation results of the FAST far field pattern with feed rotation for 0 deg, 1 deg, 2 deg, $\cdots$, 10 deg are shown in Figure 5. The direction of maximum gain is no offset and the maximum gain decrease is about 0.001 dB in the observation direction for 1 deg feed orientation error. The efficiency loss due to feed orientation error is written in Table 3.

The FAST feed orientation error could be less than 1 deg (Jiang et al. 2019). It could be concluded from the simulation results that the FAST telescope efficiency loss caused by the feed orientation error is less than 0.04%. Therefore, the efficiency loss due to feed orientation can be ignored.

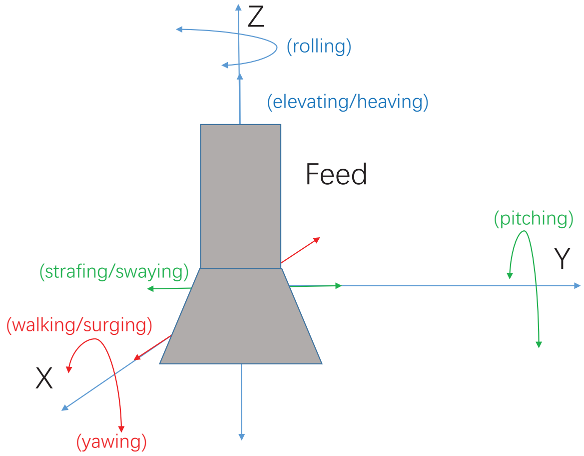

Fig. 1 The six DOFs of the feed: elevating/heaving, strafing/swaying, walking/surging, yawing, pitching and rolling.

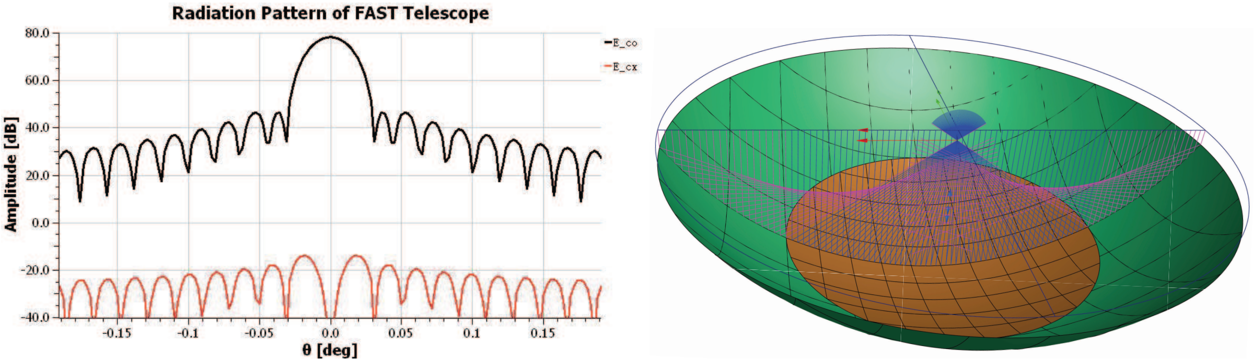

Fig. 2 The FAST model in GRASP (*right*) and the simulation result for 3 GHz (*left*).

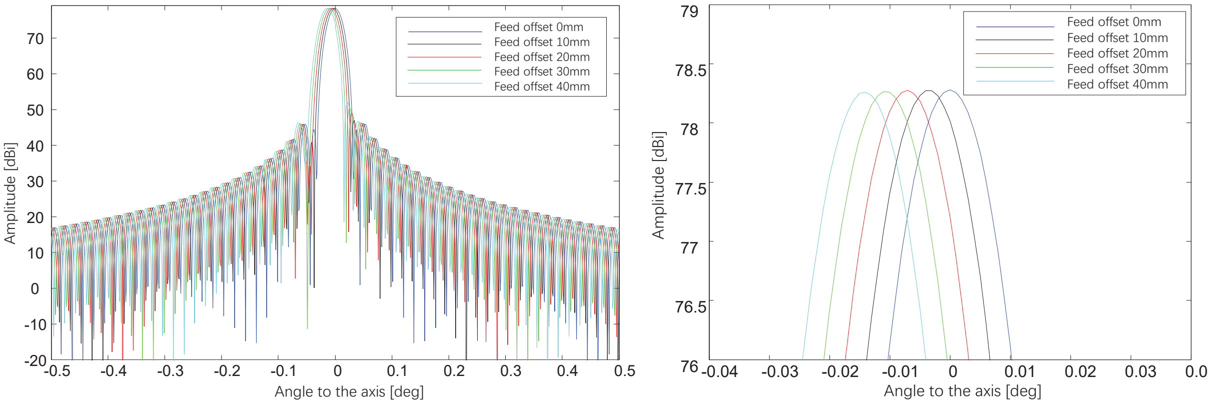

Fig. 3 FAST telescope pattern with feed offset in the focal plane (*left*) and details of the main beam (*right*).

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

In the real model, the feed position error would combine the two types of deviations, and the efficiency loss would also be a combination of the two types of errors. Statistics of the feed position error can be described by a Gaussian distribution function. So, FAST's efficiency for the feed position error is

$$\eta(\sigma,\delta)=\frac{\sum_{r=-3\sigma}^{3\sigma}\sum_{z=-3\delta}^{3\delta}G(r,z)\rho(r)\rho(z)}{G(0,0)\sum_{r=-3\sigma}^{3\sigma}\sum_{z=-3\delta}^{3\delta}\rho(r)\rho(z)}\,, \tag{1}$$

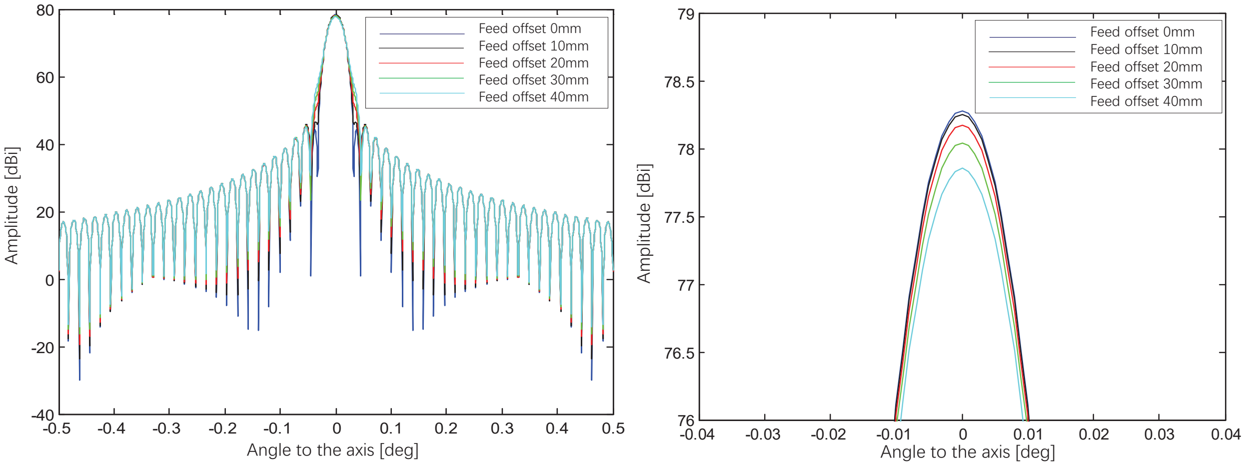

Fig. 4 FAST telescope pattern with feed offset in the axial direction (*left*) and the details of the main beam (*right*).

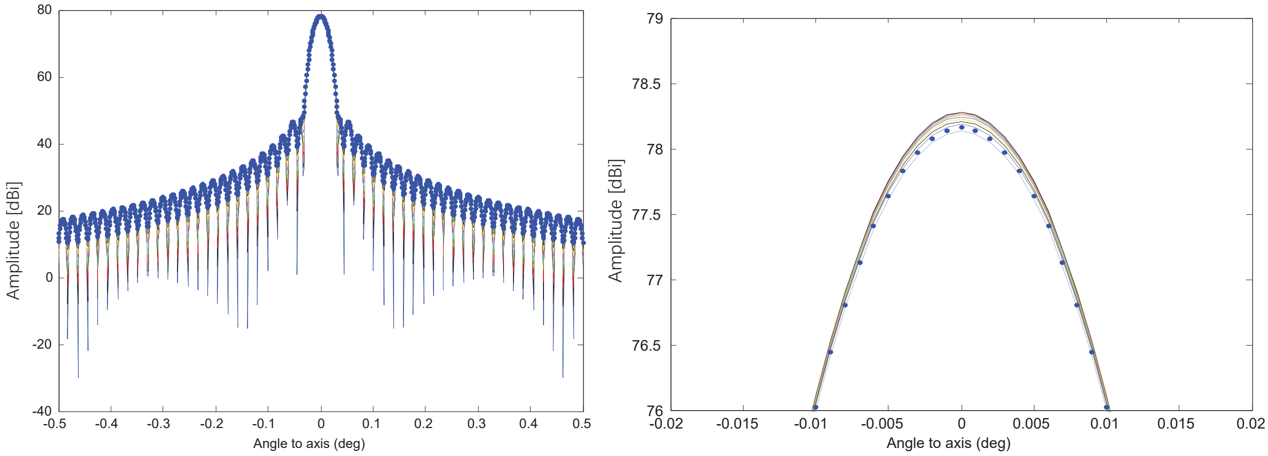

Fig. 5 FAST telescope pattern with feed orientation error (*left*) and the details of the main beam (*right*).

Table 1 FAST Efficiency Loss with Feed Offset in Focal Plane

Feed Offset in Focal Plane (mm)	0	10	20	30	40
Max Gain (dBi)	78.279	78.012	77.198	75.786	73.673
Gain Loss (dB)	0	–0.26647	–1.0809	–2.4931	–4.6052
In Percentage	100	94.049	77.967	56.324	34.632

Table 2 FAST Telescope Efficiency with Feed Offset in Axial Direction

Feed offset in focal plane (mm)	0	10	20	30	40
Max Gain (dBi)	78.279	78.252	78.173	78.04	77.853
Gain Loss (dB)	0	–0.026411	–0.10582	–0.23868	–0.42576
In Percentage	100	99.394	97.593	94.652	90.662

Table 3 FAST Telescope Efficiency with Feed Orientation Error

Feed Orientation Error (deg)	0	1	2	3	4	5	6	7	8	9	10
Max Gain (dBi)	78.279	78.277	78.273	78.266	78.255	78.242	78.226	78.207	78.186	78.161	78.133
Gain Loss (dB)	0	–0.00145	–0.00580	–0.0130	–0.0232	–0.0362	–0.0523	–0.0712	–0.0932	–0.118	–0.146
In Percentage	100	99.967	99.867	99.700	99.467	99.168	98.803	98.373	97.878	97.318	96.695

Table 4 FAST Efficiency Related to No Feed Position Error

Telescope Efficiency In Percentage		Feed deviation in focal plane (mm rms)					
		1	5	8	10	12	15
Feed deviation in axial direction (mm rms)	1	99.871	97.822	94.878	92.332	89.486	84.907
	5	99.720	97.763	94.788	92.175	89.403	84.721
	10	99.348	97.248	94.314	91.837	88.916	84.411
	15	98.649	96.6603	93.706	91.071	88.262	83.768
	20	97.541	95.672	92.680	90.210	87.409	82.853
	25	96.467	94.530	91.594	89.124	86.310	81.876
	30	94.920	93.029	90.243	87.831	84.986	80.637

where $G(0,0)$ is FAST's simulated gain with no feed position or orientation error; $G(r,z)$ is the telescope gain with feed position error r in the focal plane and z is the optical axis direction; $\rho(r)$ and $\rho(z)$ are feed position errors with standard Gaussian distributions

$$\rho(r)=\frac{1}{\sqrt{(2\pi\sigma^2)}}e^{-\frac{r^2}{2\sigma^2}} \tag{2}$$

and

$$\rho(z)=\frac{1}{\sqrt{(2\pi\delta^2)}}e^{-\frac{z^2}{2\delta^2}}. \tag{3}$$

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

4 CONCLUSIONS AND DISCUSSION

As demonstrated in the simulation results, the feed position and orientation errors would affect FAST's efficiency. The FAST sidelobes and cross polarization basically keep the same shape while the feed defocuses in a small range. The feed deviation in the focal plane is more crucial than the position error in the optical 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 1 deg.

In case the feed position error is 10 mm root mean square (rms) in the focal plane and 10 mm rms in the axial direction, the telescope efficiency could be decreased by 8.2% at 3 GHz. FAST's 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 5 mm rms by upgrading the measurement and control equipments and techniques for the feed support system. The efficiency loss would be less than 2% at 3 GHz and less than 1% in L band.

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