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Analysis and Compensation of Subreflector Displacement for the Parabolic Antenna of a Radio Telescope

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Abstract—A subreflector system in the parabolic antenna of a 65 m radio telescope has been installed for compensating the gravitational deformation of the supporting frame in the antenna. This paper investigates the influence caused by the displacement of subreflector on the performance of the antenna and the corresponding compensation method. The investigation focuses on *Ku*-band frequencies and a new fitting formulation which is different from that of low-frequency bands is proposed to reduce the fitting error in the Y direction. In addition, the pointing deviation caused by the offset of the subreflector is analyzed and the model of pointing deflection caused by the displacement of subreflector is established, which can be used to improve the pointing accuracy. The model can determine the position and attitude of the subreflector with elevation and an extensive test shows that it can effectively improve the efficiency of the antenna at each elevation.

1. INTRODUCTION

A 65 m radio telescope in Shanghai, China is an advanced large-scale comprehensive movable radio telescope antenna system, which has the highest operating frequency and the largest number of bands in the world. It has been ranked the fourth in the world and the first in Asia, based on its overall performance. The antenna is equipped with eight frequency bands, i.e., L, S, C, X, Ku, K, Ka, Q, respectively, and covers almost 70 percent of the frequency range below 50 GHz. The main reflector diameter of the antenna is 65 meters and the subreflector is 6.5 meters. The subreflector weighs 1600 kg and it is connected to the main reflector by four trusses. In order to meet the working requirements in each band and compensate the changes of its performance caused by gravitational deformation or external factors, the Stewart parallel mechanism is installed between the subreflector and the trusses [1]. The six linear electro-mechanical actuators of the Stewart mechanism allow the subreflector to move in the space over the main reflector with a maximum extension range to compensate for the gravitational deformation of the main reflector and the structure of supporting the subreflector. To ensure that the antenna working in different positions and orientations can get the best observation efficiency, we can adjust the posture of the subreflector in a real-time mode according to the working status of the main reflector. The telescope takes a large Cassegrain configuration [2, 3]. In order to maintain the optimum parabolic shape, the block panel of the main reflector can conduct a wide adjustment range up to ± 15 mm and has a resolution of around 15 micrometer. This can reduce the deviation caused by the deformation of the supporting frame in a limited extent. In this paper, we study the impact of the displacement of subreflector on the performance of antenna and propose a compensation method by constructing a model which determines the position and attitude of the subreflector with elevation. Also, we investigate the effect of the movements of the subreflector in the pointing of the antenna. In the model, a new fitting formulation, which is different from the one in low-frequency bands, is proposed to fit the data and it can greatly reduce the fitting errors.

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2. GRAVITATIONAL INFLUENCE ON THE PERFORMANCE OF ANTENNA

If a telescope is much larger than the observing wavelength (e.g., $D > 10^4\lambda$), time-dependent mechanical distortions and uncorrected repeatable errors are likely to degrade its performance [4]. The 65 m radio telescope in Shanghai, China, is a giant antenna with the weight of about 2740 tons. The antenna will undergo a gravitational deformation with the change in elevation attitude in the working process and this deformation will worsen the precision of the reflector, resulting in the reduction of antenna's efficiency. The Gravitational deformation results in two changes, i.e., the surface shape of the main reflector, which varies along the elevation direction, and the alignment relationship between the main reflector and the subreflector, which also varies along the elevation direction. The second change is caused by the gravitational deformation of the supporting frame of the subreflector. At the moment the second is able to be compensated by adjusting the position and attitude of the subreflector and the first is able to be compensated by adjusting the panels of the main reflector. In addition, the position misalignment of the subreflector with the feed of the antenna due, for instance, to gravity will result in a loss in gain. Furthermore, the subreflector has a movement caused by the gravity and by the thermal deformation that produces shifts and tilts with respect to its ideal optical alignment. To ensure that the antenna of working in different positions and attitudes can get the best observation efficiency, the subreflector's rotation and translation can be remotely controlled by the active actuators of the subreflector so that the misalignment and defocus between the subreflector and main reflector can be compensated.

When the antenna is placed horizontally, the X-axis is parallel to the elevation axis of the antenna, Y-axis is parallel to the elevation gear plane (when the antenna is horizontally oriented, it is the direction of the gravity), and Z-axis is an outward direction along the focus. Also, α is the rotation angle around the X-axis and β is the rotation angle around the Y-axis. The displacement of Z-axis, Y-axis, as well as α of the subreflector will vary relatively large due to the gravitational deformation of the structure of supporting the subreflector, when the antenna is moving in its elevation range [5]. Figure 1 shows the change situation of the position and attitude of the subreflector with respect to the main reflector when the antenna moves in elevation from 90° to 40°. The subreflector behaves with the following characteristics: if the location center declines Δy, then the focus shortens Δz, and the tilt angle varies $\Delta\alpha$.

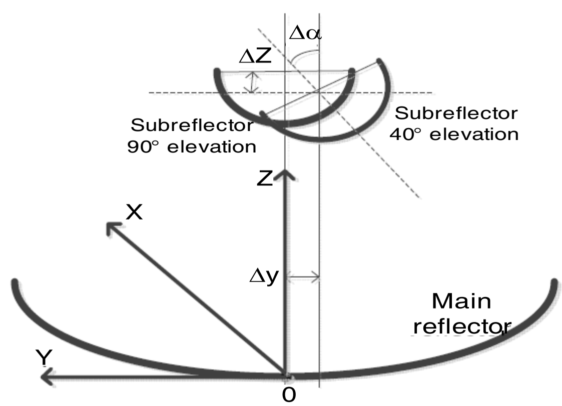

Figure 1. Posture change of the subreflector relative to the main surface caused by different elevations.

3. A SUBREFLECTOR MODEL AND POINTING ANALYSIS

The gravitational deformation of the radio telescope in all conditions is very large relative to small antennas. In order to ensure a good electrical property at various conditions, the subreflector should be adjusted appropriately. Large radio-telescope antennas are usually used to track celestial targets within a certain elevation range. In this process, the deformation of the main reflector caused by the gravity is a function of the pitch angle. The best match of the position of the corresponding subreflector is also relevant to the pitch angle. To have a good match between the main reflector and the subreflector and meet the required electrical performance in each pitch angle at the entire working zone, we should consider the range of the entire pitch angle. The fitting patterns of the measured data show that the offset in the X and Y directions will cause the deflection of the antenna's pointing while the amplitude fall of the main lobe is not obvious and the impact of the efficiency is not significant [6]. On the other hand, the offset in the Z direction will make the maximum value of the pattern decrease significantly. The effect on the antenna efficiency is remarkable, so the adjustment in the Z direction is particularly important for the antenna efficiency. In addition, due to the antenna's own symmetry, X axis and pitch axis are parallel each other, so the offset in the X direction is not very intense.

We can determine the scanning width and scanning period according to the working frequency band of the antenna. In this paper, the model is established in Ku band. Since the higher the frequency is, the narrower the beam is. To allow more scanning power, readings focus on the main lobe and a scanning width 0.1° ($\pm 0.05^\circ$) is selected. In order to make the scanning widths be consistent in the azimuth direction and elevation direction, the scanning width in the azimuth direction is $0.1^\circ/\cos(EL)$. The scanning periods in both directions are 30s. The power meter reads the power value twice per second.

When the antenna is tracking the target source scanning in the observation process, radio source with respect to the radio telescope in the elevation direction has a little movement. In addition, when the elevation angle is lower, due to atmospheric refraction, ground reflection, and other external factors, there is a big change in the noise of the scanning patterns at the same elevation. When calculating the Gaussian fitting peak, we need to cut the noise floor and align it, so that the peak can be obtained by Gaussian fitting. The multiple peak values obtained by Gaussian fitting at the same elevation and used to offset multiple displacements are fitted to a quadratic term so that the best offset of the subreflector can be determined.

To establish the subreflector model in Ku band, we first fix the Y direction and X direction to their initial position and then offset the multiple displacements in the Z direction for the azimuth and elevation scanning to find the best offset in the Z direction in each elevation. After that, we offset the multiple displacements in the X and Y directions, respectively, by running the established Z-direction model. Thus, the X-direction and Y-direction models can also be built accurately in the high-frequency band. In the process of establishing the models at Ku band, the bandwidth of the detected signal is 1.5 GHz at the central frequency 13.5 GHz and a radio source 3C84 is selected. In order to reduce the influence of temperature and wind, we perform a test in the breeze in a clear night. An axial displacement of the focus is taken along the Z direction, which ideally coincides with the axis of paraboloid and hyperboloid. It can cause a change in the intensity of the detected signal and widen the beamwidth of the antenna. Therefore, the best axial focus is determined by measuring the intensity at different focus positions and at different elevations. The best Z-position offsets are achieved through solving the Gaussian amplitude determined by the least squares of fitting to the signal which are detected at different displacements in the Z direction. Then the maximum of the parabola is obtained by fitting the previously-solved amplitude values. Each series of data set consists of 5 or 6 different positions of the focus with a total displacement of two wavelengths. Table 1 shows the best Z-position offsets of the subreflector in every elevation and Figure 2 is the model in the Z direction. The error of fitting parameters under the root-mean-square (RMS) definition is very small. The more negative the value is, the smaller the distance between the main reflector and the subreflector is. According to this measurement, we can see that the total displacement of the focus from 5 to 90 degrees is about 30 mm, and this is probably due to the gravitational pull and the homologic design of the antenna in order to modify its shape of changing the focus position.

When building the models in the Y and X directions, we should make a real-time adjustment for the displacement of the subreflector in the Z direction in terms of the Z-direction model. Table 2 shows the best Y-position offsets of the subreflector in every elevation. Table 3 shows the best X-position offsets of the subreflector in every elevation. The data in Table 2 is fitted by Equation (1) and the results are shown in Figure 3. Equation (1) is the polynomial used to build the model in low frequencies for the telescope.

$$dy = p1 + p2 \times \cos(EL) \tag{1}$$

Using Equation (1) for the fitting model in the Y direction, we can obtain a RMS error of 3.42 and

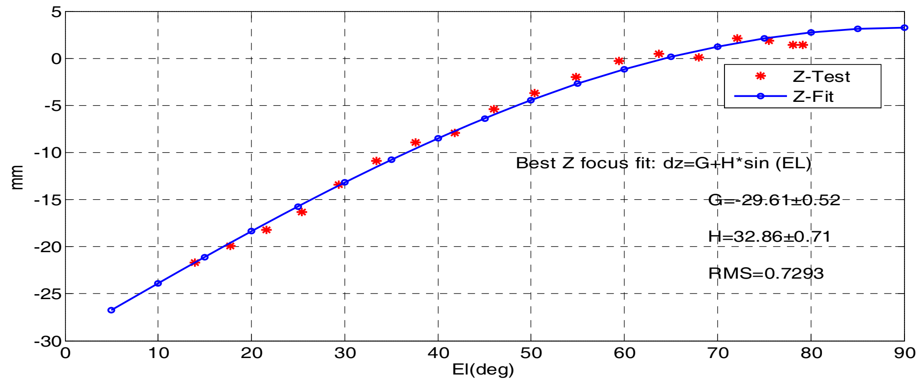

Figure 2. Model of subreflector's posture in the Z direction.

Table 1. The Best Z-position offsets of the subreflector in every elevation (Unit: mm).

EL (°)	13.9	17.7	21.6	25.4	29.4	33.4	37.4	41.8	46
Z (mm)	−21.7	−19.9	−18.2	−16.3	−13.4	−10.9	−8.9	−7.9	−5.4
EL (°)	50.4	54.8	59.4	63.7	68	72.1	75.5	78.1	79.1
Z (mm)	−3.7	−2	−0.3	0.5	0.1	2.1	1.9	1.4	1.4

Table 2. The best Y-position offsets of the subreflector in every elevation (Unit: mm).

EL (°)	13.7	17.3	20.6	24.1	27.7	31.2	34.7	37.9
Y (mm)	33.4	33.5	29.5	28.8	25.2	25.6	21.5	17.2
EL (°)	43.4	47.6	51.9	56.3	60.9	65.3	69.5	78.9
Y (mm)	17.1	9.7	3.3	−1.2	−3.6	−7.2	−11.5	−11.8

Table 3. The best X-position offsets of the subreflector in every elevation (Unit: mm).

EL (°)	9.9	13.5	21.1	25.3	30.1	34.2	38.4	42.7
X (mm)	−0.45	−0.49	−0.50	−0.47	−0.51	−0.46	−0.49	−0.46
EL (°)	47.2	51.9	56	60.3	65.2	69.3	73.9	76.9
X (mm)	−0.50	−0.44	−0.51	−0.45	−0.43	0.45	−0.43	−0.48

the errors of fitting coefficients are 2.71 and 3.70, respectively. The maximum difference between the measured value and fitted value is 8.0 mm, which does not meet the requirement. To solve the problem, we propose to use the fitting tool "cftool" in MATLAB and adopt Equation (2) to refit the data in Table 2. The new results as shown in Figure 4 and the RMS error has been reduced to 1.70, while the errors of fitting coefficients are 0.62, 0.76, and 0.78, respectively, now. Compared to Equation (1), the fitting errors have been significantly decreased, leading to a great improvement on the accuracy of the Y-direction model. The Y position of the subreflector varies from 33 mm at the 14-degrees elevation to -12 mm at the 80-degrees elevation. This means that the subreflector apparently "falls" along the Y axis when the antenna is tilted towards the horizon and this is because the tetrapod support legs suffer from a gravitational flexure. The w in Equation (2) is the value that makes the fitting error minimum. Figure 5 is the X-direction model and it is also fitted with Fourier polynomials. The fitting curve in the X direction looks a straight line approximately and this is due to the symmetry of the antenna itself,

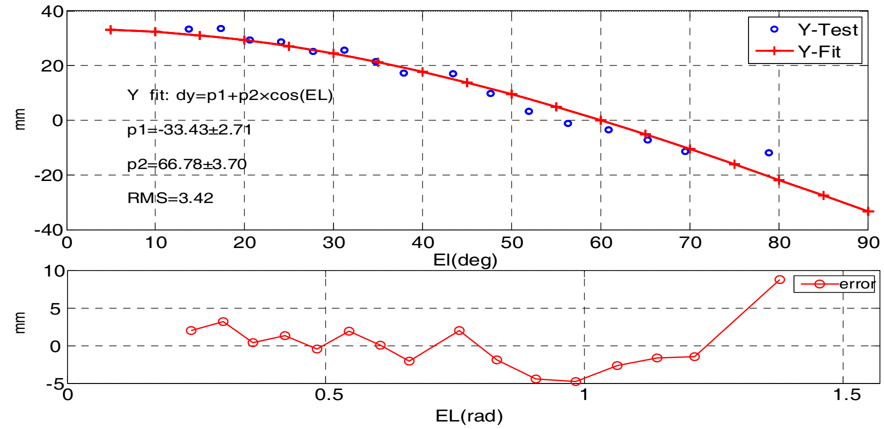

Figure 3. Model of subreflector's posture in the Z direction.

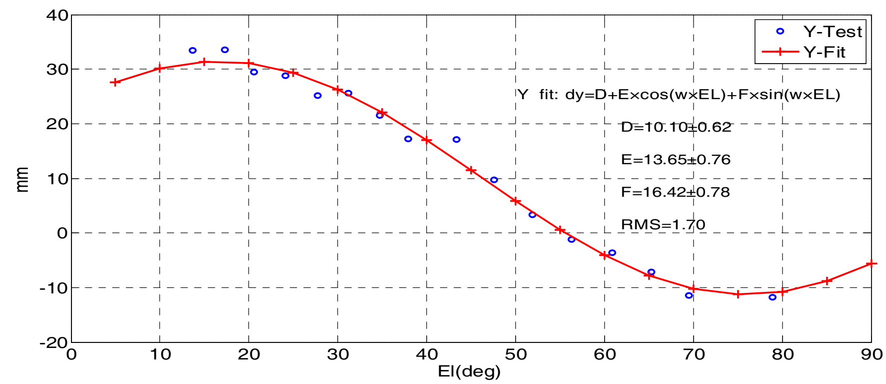

Figure 4. Model of subreflector's posture in the Y direction.

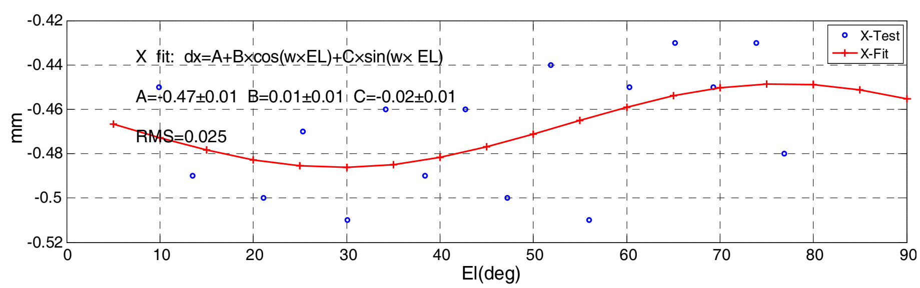

Figure 5. Model of subreflector's posture in the X direction.

while its offset in the X direction is not dramatic. Although the difference between the test and the fitting curve looks large, we can see that it is only about 0.5 mm. In the process of observation, the supporting frame of the subreflector could sway due to the wind and this will produce some errors in the observed data. Usually, the above difference is acceptable for a large antenna.

$$dy = a + b \times \cos(w \times EL) + c \times \sin(w \times EL) \tag{2}$$

The change trend between the measured model curve and the model curve of finite element simulation which the antenna design manufacturer provided is consistent. However, the measured data shows that the actual position and attitude of the subreflector are more severe than those of finite element simulation. Equations (3), (4), (5) are the used subreflector models for the telescope at Ku

band [7]. In the equations, the constant terms represent a zero drift in the subreflector and the cosine terms represent a compensation for the gravitational deformation of antenna. Also, the sine terms can be interpreted as the sagging effect on the edge of the main reflector which is caused by the gravity when the antenna is at a higher angle of elevation where the main reflector may produce a larger parabolic opening. This deformation tends to cause the shift of focus. The effect in the azimuth is not considered because the gravitational deformation of the antenna mainly occurs in the elevation angle.

$$dX = -0.47 + 0.01 \times \cos(3.797 \times EL) - 0.02 \times \sin(3.797 \times EL) \quad (3)$$
$$dY = 10.10 + 13.65 \times \cos(3.032 \times EL) + 16.42 \times \sin(3.032 \times EL) \quad (4)$$
$$dZ = -29.61 + 32.86 \times \sin(EL) \quad (5)$$

Figures 6 and 7 show the comparison of the subreflector models at X, Ku, and Ka bands, in the Z and Y directions, respectively. It can be found that there is a very small difference between different bands in the Y-direction model, while the Z-direction model presents a constant shift. This is because the position of receivers for each band in the focus direction has a deviation and it does not result in a significant difference between different bands, except a constant shift, in the Z-direction model.

The analysis for the measured scanning data in the azimuth and elevation offset of the subreflector shows that the offset in the Y direction can lead to the asymmetry of the pattern and an elevation-pointing offset. The offset in the X direction can also lead to the asymmetry of the pattern but generate an azimuth-pointing offset. Theoretically, the offset of the subreflector in the Z direction does not cause a pointing deviation. The test is carried out at the elevation of 52 degrees. Table 4 shows the pointing influence by the subreflector offset in the Z direction and it can be seen that the pointing influence is negligible.

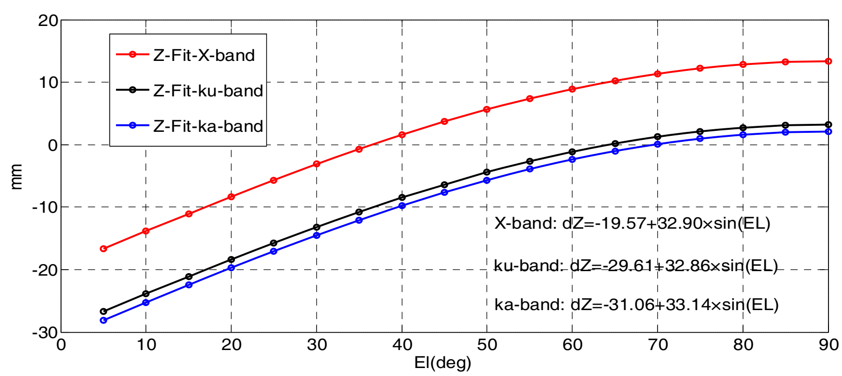

Figure 6. Model of subreflector's posture in the Z direction.

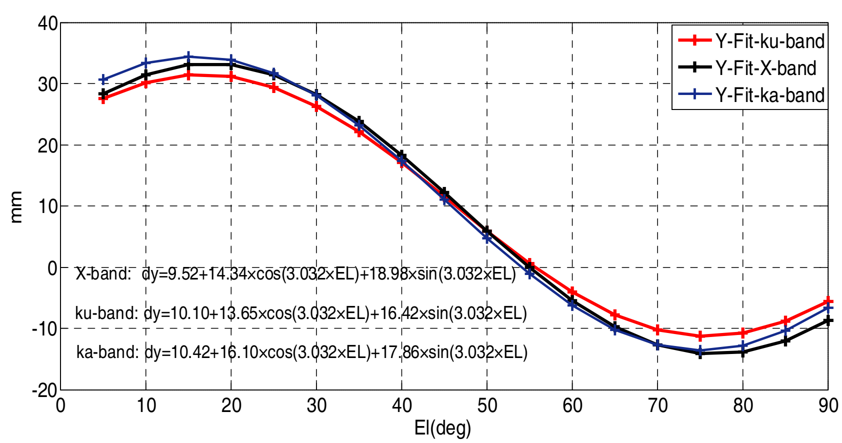

Figure 7. Model of subreflector's posture in the Y direction.

Table 4. Pointing deviation caused by subreflector offset in the Z direction (unit: arcsec).

Z (mm)	-14	-9	-4	1	6	11
dEL	-5.1	-4.6	2.1	-3.9	-5.6	-6.5
dAZcosEL	6.1	5.3	5.4	2.6	7.2	7.9

As seen from the adjustment model of the subreflector, the adjustment range in the Y direction is relatively large and it could cause an elevation deviation. Therefore, in the adjustment process for the subreflector, we need to compensate for the pointing deviation caused by the subreflector offset. Equation (6) is the pointing compensation formulation in the elevation while Equation (7) is the one in the azimuth.

$$\Delta EL = \Omega_Y \Delta Y \tag{6}$$

$$\Delta AZ = \Omega_X \Delta X \tag{7}$$

where Ω_Y (unit: arcsec/mm) indicates the pointing deviation value of elevation due to a unit displacement in the Y direction and Ω_X (unit: arcsec/mm) denotes the pointing deviation value of azimuth due to a unit displacement in the X direction. In order to measure the parameters Ω_Y and Ω_X, we let the subreflector offset multiple displacements in the X and Y directions and then scan the target source in the azimuth and elevation. After that, a Gaussian fitting for the power reading is performed to determine the pointing deviation. Finally, the average pointing deviation caused by the unit displacement of the subreflector is calculated. Surprisingly, we notice that the two coefficients are not approximately constant values and they are related to the elevation angle of the antenna. Figures 8 and 9 respectively show the measured values of Ω_Y and Ω_X related to the elevation angle of the antenna. The numerical difference of Ω_Y between the high-elevation and low-elevation angles is 1.5 mm. However, the adjustment range of the subreflector model in the Y direction is about 40 mm. Note that Ω_Y is a fixed value derived for a simulation experiment in advance and this will lead to an elevation-pointing error of 60 arcsecs. Equations (8) and (9) show the pointing-deviation value caused by a unit displacement of the subreflector in the Y and X directions, respectively.

$$\Omega_Y = 3.02 + 1.52 \times \cos(EL) + 2.95 \times \sin(EL) \tag{8}$$

$$\Omega_X = 7.03 - 0.62 \times \cos(EL) - 0.35 \times \sin(EL) \tag{9}$$

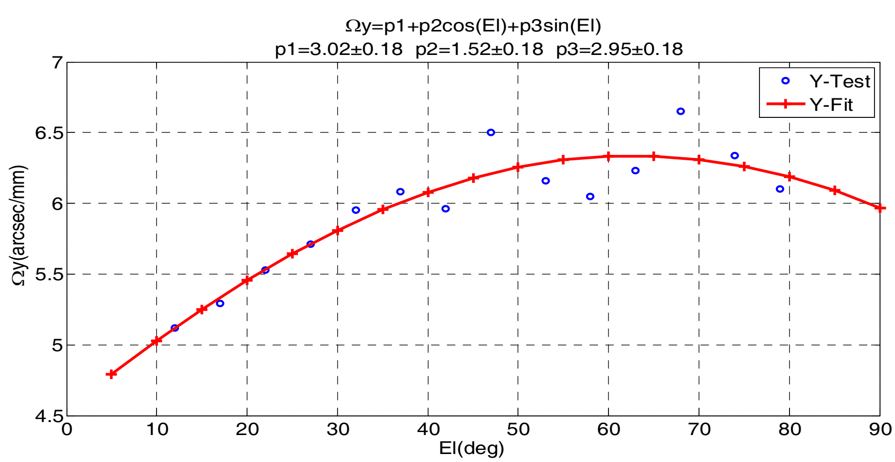

Figure 8. Ω_Y Model: the elevation-pointing deflection caused by a unit displacement in the Y direction.

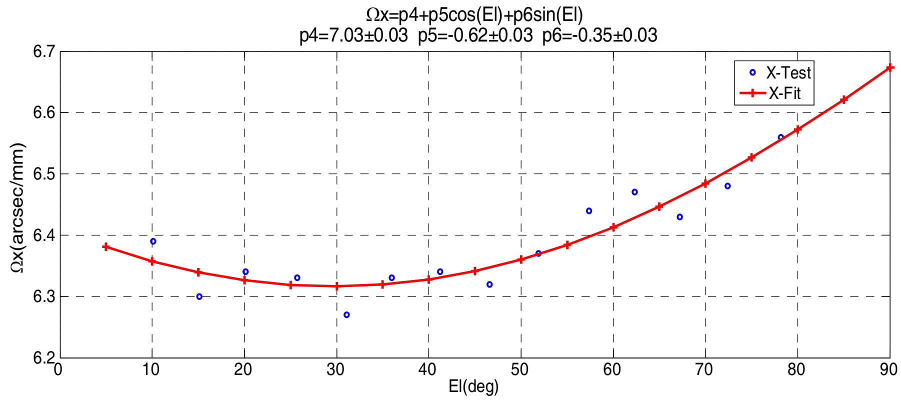

Figure 9. Ω_X Model: the azimuth-pointing deflection caused by a unit displacement in the X direction.

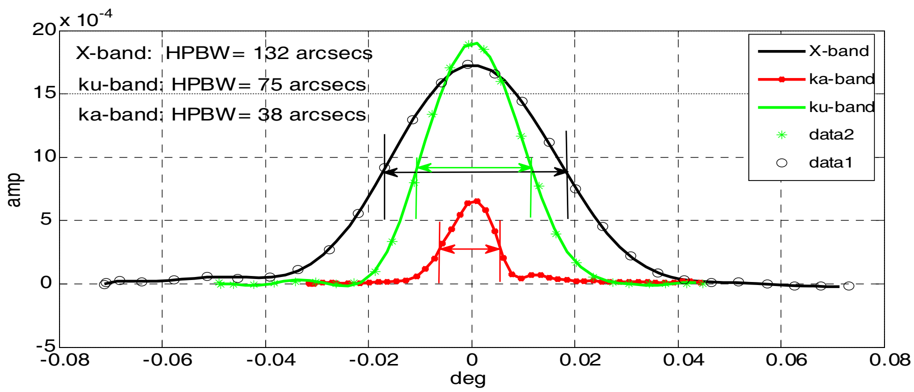

Figure 10. The HPBWs of the antenna working in X, Ku, and Ka bands, respectively.

4. PERFORMANCE TEST

For the receiving antenna, its pattern characterizes the ability of receiving electromagnetic radiation from all directions. In order to describe the antenna's main lobe, we can use the angle between two half-power points in the main lobe to represent its size which is also known as the half-power beamwidth (HPBW) and can be used to determine the spatial resolution of the antenna. The HPBW is represented by the following equation.

$$HPBW = 1.22 \times \lambda/D \tag{10}$$

where λ is the working wavelength of the antenna (unit: m) and D the diameter of the antenna aperture plane (unit: m). The unit of the HPBW is rad. From the above equation, the HPBWs of different bands are not the same for a given antenna. By performing a Gaussian fitting for the elevation-scanning data, the half beamwidth of the fitting wave can be obtained. When the antenna works in X, Ku and Ka bands, the wavelength is 3.6 cm, 0.9 cm, and 2.2 cm, respectively, and the corresponding HPBW is 139.4 arcsecs, 85.1 arcsecs, and 35 arcsecs, respectively. Figure 10 illustrates the HPBWs of the antenna when it works in X, Ku and Ka bands, respectively.

We choose a clear night to minimize the impact of the temperature and other environmental factors on the performance measurement of the subreflector model. The efficiency of the antenna is measured in both the left-circular-polarization (LCP) and right-circular-polarization (RCP) channels by using the radio source 3C84 at Ku band. In each elevation-angle measurement position, the two cases of the subreflector model with running and fixing are conducted to measure the aperture efficiency. The antenna is moved in the elevation from 10° to 85° with an interval of 1° and then the corresponding efficiency can be measured. The efficiency curves are obtained by performing a polynomial fitting for

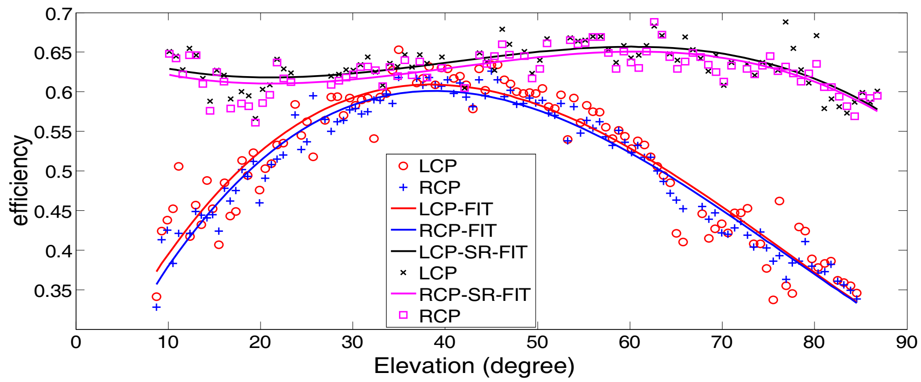

Figure 11. Efficiency test when the subreflector works in various states in Ku band.

the acquired data at each angle of elevation. Before measuring the efficiency in each case, a five-points method is used to correct the point and correct the residual error of the pointing model in the entire zone [8]. Test results show that the subreflector model could effectively improve the efficiency of the telescope in both high and low elevations. Figure 11 shows the test results of the antenna efficiency where "LCP-FIT" represents the efficiency test when the subreflector is fixed to a left rotation, "RCP-FIT" represents the efficiency test when the subreflector is fixed to a right rotation, "LCP-SR-FIT" represents the efficiency test when the subreflector is randomly moved to a left rotation, and "RCP-SR-FIT" represents the efficiency test when the subreflector is randomly moved to a right rotation, respectively. When running the subreflector model, an antenna efficiency of about 60% at Ku band is reached in the whole elevation-angular range.

5. CONCLUSION

In this paper, we have studied the effect of the displacement of subreflector on the antenna's performance and obtained the measured results by moving the antenna in elevation. The model of subreflector with dynamic adjustment has been built by using the Gaussian fitting, least square method, and binomial fitting, respectively. A new fitting formula, which is different from the one of low-frequency bands, is proposed to fit the data, and it can greatly reduce the fitting error, leading to an improvement of the model's accuracy. The polynomial in the model can be used as a reference for the telescope in high frequencies. In addition, we have also investigated the effect of the displacement of the subreflector in the pointing of the antenna and built the point compensation model. Finally, the performance of the antenna has been tested, and the results show that the compensation model can effectively improve the efficiency of the antenna.

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