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TPS based on trilateration for the feed measurement of FAST①

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Abstract

Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest sensitive single dish radio telescope in the world, in which the control and measurement of the feed is one crucial section of the FAST control system. Trilateration is presented to obtain three-dimensional coordinate for tracking feed focus cabin. Every three total stations chase prism movement to be attached on feed focus cabin and the prism position is determined from the measured distances based on the principle of trilateration. Therefore, feed position is determined from three prisms on the focus cabin. This study is to assess the accuracy and reliability of trilateration calculation on tracking focus cabin of FAST. Different arrangement of total stations on trilateration is theoretically studied. Through experiment, the proposed method shows that the accuracy is better than that of the polar coordinate measurement. The average root mean square error is lower than 0.6mm, which is found to have high accuracy and reliability.

Key words: Five-hundred-meter Aperture Spherical radio Telescope (FAST), trilateration, feed measurement, total station prism system (TPS), arrangement of total station

0 Introduction

FAST is an Arecibo-type antenna with 3 outstanding aspects: unique karst depression as the site; active main reflector which corrects spherical aberration on the ground to achieve full polarization and wide band without involving complex feed system; and light focus cabin driven by cables and servomechanism plus a parallel robot as secondary adjustable system to carry the most precise parts of receivers[1]. The part of main reflector which is illuminated by the feed is continually adjusted to fit the paraboloid of revolution in real time when tracking the radio source[2].

The focus cabin that carries feed is driven by six cables to follow the focus movement of active reflectors on the spherical focus surface. In the focus cabin, besides star framework, there is a parallel robot called Stewart which consists of an upper and a lower platform connected by six extensible limbs through spherical joints in the two planar platforms. Feeds are placed on the lower platform.

1 Measurement system of feed

The structure of the focus cabin is shown in Fig. 1. FAST feed measurement task is to provide real-time feedback data of moving feeds position for the astronomical observation, whose precision requirement is 3mm. FAST feeds measurement system uses total station prism system (TPS). In TPS, multiple prisms are attached on the edge of the moving planar platform in the

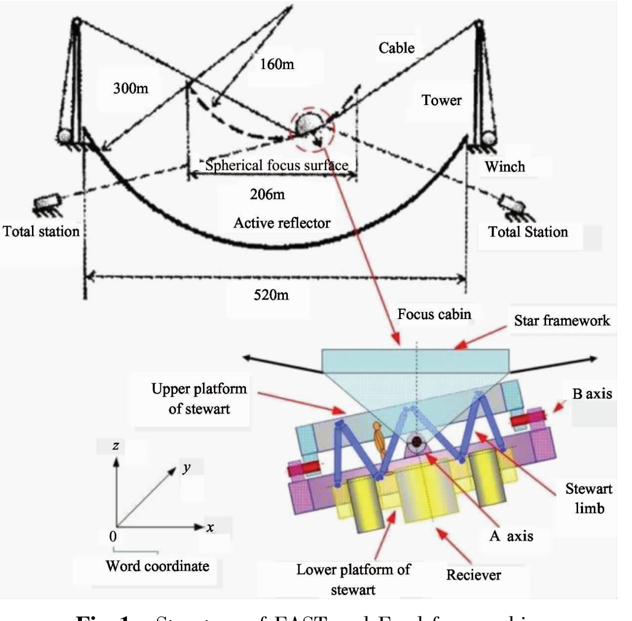

Fig. 1 Structure of FAST and Feed focus cabin

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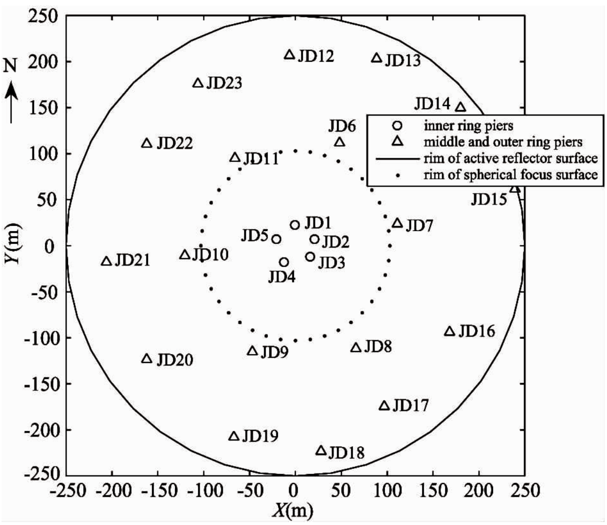
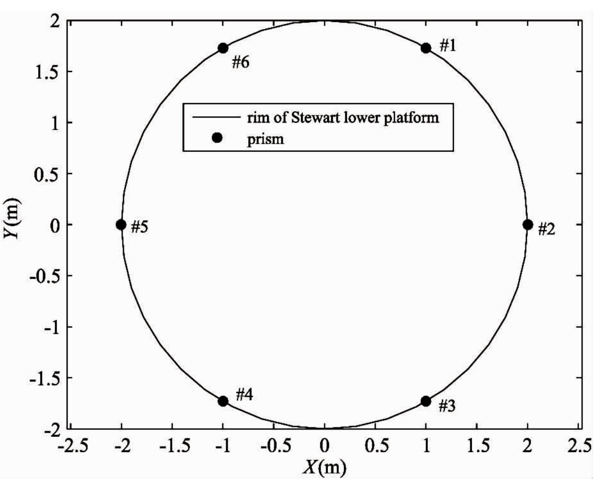
focus cabin of FAST. Multiple total stations, each of which is mounted on top of a stable pier, chase the movement of the prisms, and the position of prisms is continuously measured, thus the position of the feed is obtained.

1.1 Piers

23 steady piers (JD1-JD23) for measurement are built in the main reflector field of FAST, as shown in Fig. 2. The piers deformation is less than 1 mm by long term monitoring. These piers are divided into three rings, called inner ring, middle ring and outer ring. The feed measurement system is designed to use several total stations which will be mounted on piers in the middle and outer ring. Three metal plates where total stations are mounted on top of each pier so as for total stations working at the same time.



(a) Distribution map of piers



(b) Distribution map of prisms on Stewart lower platform

Fig. 2 Distribution map of piers and prisms

1.2 Measuring instruments

As the development of modern geodetic measurement instrument, most of the main tasks can be fulfilled with these instruments implicitly by their integrated applications[3-5]. The total station has automatic target recognition (ATR) function which can fulfill the need of tracking feed focus cabin of FAST. In ATR mode it can provide 0.6mm + 1 ppm enhanced measurement accuracy to prism and 1″ angular accuracy[6].

1.3 Targets

Prisms are uniformly fixed on the rim of the lower platform of Stewart in the feed focus cabin where the lower platform of Stewart approximates a circle with radius of 2m. They are facing to the total station when the focus cabin is at the lowest point of spherical focus surface.

2 Benefits of trilateration

Due to the electronic distance measurement which can be interfered by the environment effect, there will be many possible errors in the measurement result[7]. Shown by total stations monitoring experiment results at FAST site, the accuracy of measurement data including horizontal angle, vertical angle and distance is greatly influenced by surrounding atmospheric disturbance[8]. The distance measurement error brought by atmospheric conditions can be greatly reduced by certain correction methods or formulas[9]. However, there is not any effective model or formula to correct angular measurement error at present. Trilateration is usually used for field measurement[10,11]. It was also applied in GBT (Green Bank Telescope) measurement[12]. Inspired by it, trilateration is proposed to be applied in the FAST feed measurement to solve the problem. Instead of angles, only distance is used in trilateration. Through experiments and calculations, measurement coordinate precision of target is improved remarkably.

3 Trilateration method

3.1 Principle of trilateration

The position of uncertain points can be got by using trilateration calculation through three other known points[13].

Measurement instrument such as total station is installed on point P; three prisms are fixed on point A, B and C. Thus distances between point P and A, B, C can be got by measuring, labeled by $l1$, $l2$, $l3$. Given that the 3D coordinate of point A, B and C is already known, which is $[X_1, Y_1, Z_1]^T$, $[X_2, Y_2, Z_2]^T$ and $[X_3, Y_3, Z_3]^T$, 3D coordinate of point P can be obtained by trilateration using Eq. (1).

$$\begin{cases}(X_1 - X_P)^2 + (Y_1 - Y_P)^2 + (Z_1 - Z_P)^2 = l1^2 \\ (X_2 - X_P)^2 + (Y_2 - Y_P)^2 + (Z_2 - Z_P)^2 = l2^2 \\ (X_3 - X_P)^2 + (Y_3 - Y_P)^2 + (Z_3 - Z_P)^2 = l3^2\end{cases} \tag{1}$$

3.2 Arrangement of total stations based on trilateration

In feed measurement, total-station prism system (TPS) is used to measure three dimensional coordinate of feed. To determine 3D coordinate based on trilateration, nine total stations are required in minimum. Every three total stations chase the movement of a prism which is attached on the edge of feed focus cabin. The position of the prism is determined from the measured distances based on the principle of trilateration. Therefore 3D coordinate of feed is determined according to three prisms position and feed location on the platform (feed location on the lower platform is already known after factory settings called system parameters).

In ATR mode total station can provide 0.6mm + 1ppm enhanced measurement accuracy to prism. There is a restriction for the position of total stations[14,15]. Following this restriction, analysis of measurement accuracy for feed moving on the spherical focus surface is studied as follows under different arrangements of total stations. In the calculation, prisms #1, #3, #5 are chosen as targets, feed is on the center of the lower platform. The accuracy of feed position on the spherical focus surface in the following arrangements is shown in Fig. 3.

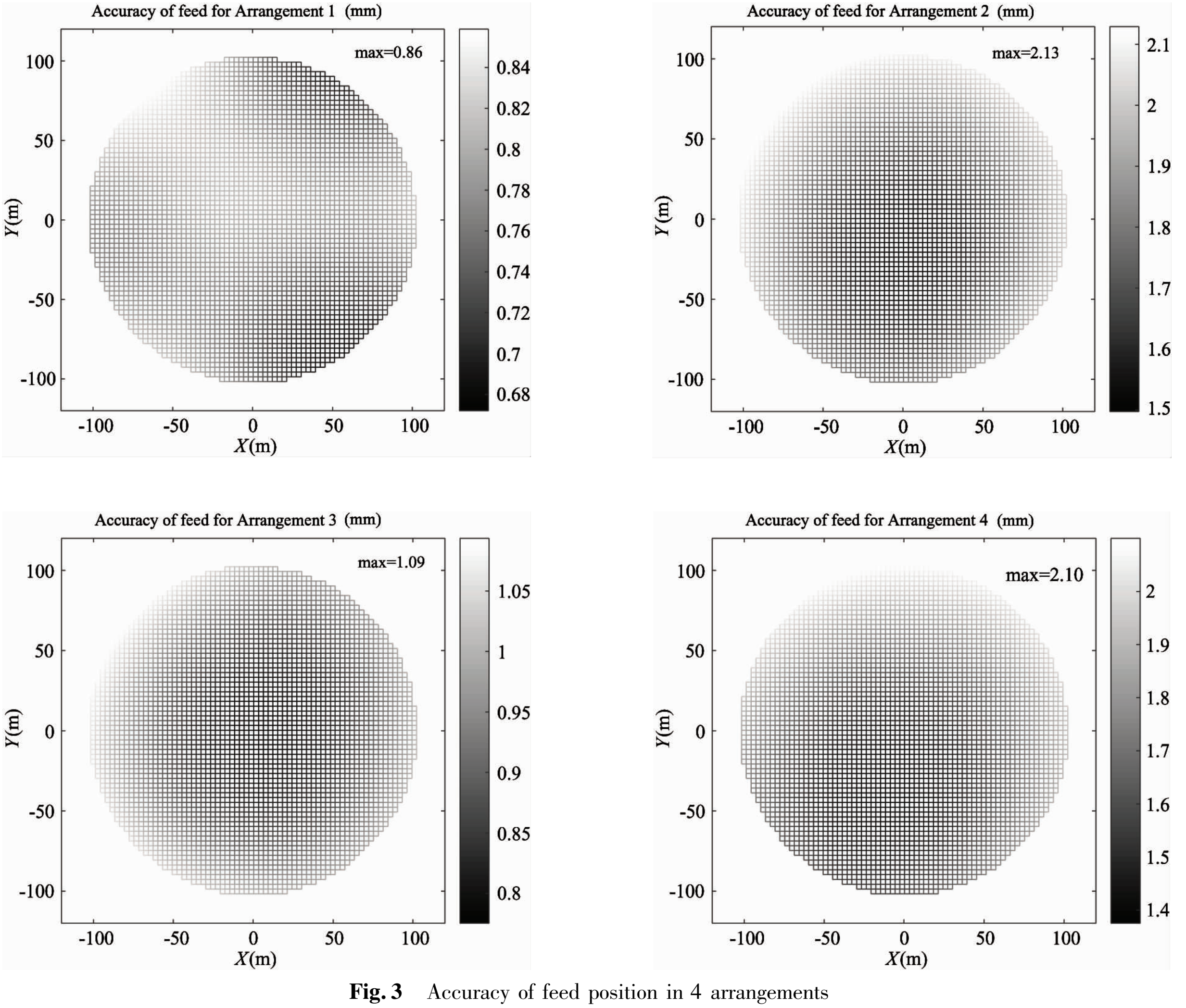


Fig. 3 Accuracy of feed position in 4 arrangements

3.2.1 Arrangement 1

Every three piers are chosen which are evenly distributed around the prism to the greatest extent. Therefore, in total nine piers are chosen. Three total stations are mounted on three piers which are JD6, JD17 and JD21 to chase prism #1. Similarly, JD8, JD13, JD21 are chosen to chase prism #3, JD10, JD13 and JD17 to chase prism #5.

3.2.2 Arrangement 2

For a certain prism, the nearest pier from middle loop and other two nearest piers from outer loop are chosen. Three total stations are mounted on three piers which are JD6, JD12 and JD13 to chase prism #1. Similarly, JD10, JD20 and JD21 are chosen to chase prism #5, JD8, JD16, JD17 are chosen to chase prism #3.

3.2.3 Arrangement 3

For a certain prism, the nearest two piers from middle loop and one nearest pier from outer loop are chosen. Three total stations are mounted on three piers which are JD7, JD11 and JD13 to chase prism #1. Similarly, JD7, JD9 and JD17 are chosen to chase prism #3, JD9, JD11, JD21 are chosen to chase prism #5.

3.2.4 Arrangement 4

For a certain prism, the nearest two piers from middle loop and one nearest pier from outer loop are chosen. For the other two prisms, the nearest one pier is chosen from middle loop and two nearest pier from outer loop. Three total stations are mounted on three piers which are JD7, JD11 and JD13 to chase prism #1. Similarly, JD8, JD16 and JD17 are chosen to chase prism #3, JD10, JD20, JD21 are chosen to chase prism #5.

3.3 Conclusion for arrangement of total stations

Through the analysis, the precision of location for feed measurement is relevant to the arrangement of total stations. Moreover, the precision is higher when the total stations are more evenly distributed or nearer.

4 Experiment and results

An experiment is made at the FAST project site in which mean value is used as truth-value. In this experiment, one total station is installed on pier JD10. Six targets are set on other six piers JD1, JD2, JD3, JD20, JD21, JD22 respectively (JD1, JD2 and JD3 are almost of the same height of 10m, JD20, JD21 and JD22 are almost of the same height about 20m) as shown in Fig. 4. The total station uses ATR mode to measure the targets circularly and measures each target once for 5 times repeated measurement. The cycle time is about 200s. Horizontal angle, vertical angle and the distance from total station to targets are measured, meanwhile the meteorological parameters is recorded.

4.1 Polar calculation

Commonly 3D coordinate can be obtained by the following steps: First, Due to atmosphere interference, the distance between total station and prisms can be corrected by Eq. (2) and Eq. (3).

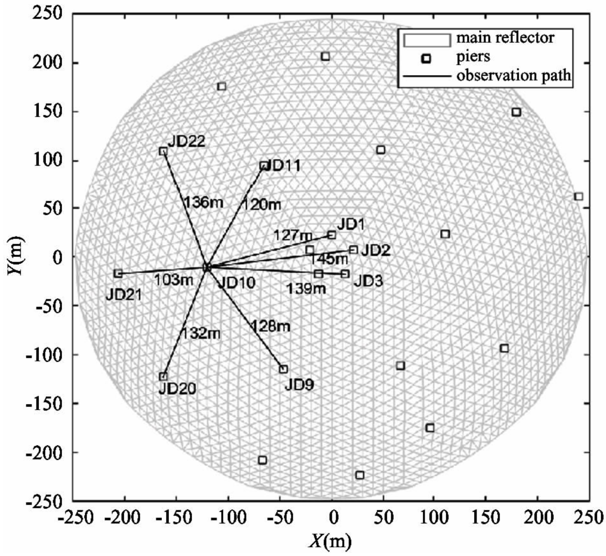


Fig. 4 Distribution for experiment

$$\Delta D_1 = 286.34 - \left[\frac{0.29525 \times p}{(1 + \alpha \times t)} - \frac{4.126 \times 10^{-4} \times h}{(1 + \alpha \times t)} \times 10^X\right] \quad (2)$$

$$Rc = R + \Delta D_1 \times R \times 10^{-6} \quad (3)$$

These are formulas for atmospheric correction where ΔD_1 is atmospheric correction (ppm), P is air pressure (mbar), t is air temperature (℃), h is relative humidity (%), $\alpha = 1/273.5$, $X = (7.5 \times t/(237.3 + t)) + 0.7857$, R is raw distance between total station and prisms, Rc is distance after correction.

Second, 3D coordinate of prism can be calculated by

$$\begin{cases} x = Rc \times \sin(\theta) \times \cos(\varphi) \\ y = Rc \times \sin(\theta) \times \sin(\varphi) \\ z = Rc \times \cos(\theta) \end{cases} \quad (4)$$

where θ is pitch angle, φ is roll angle.

$$RMSE = \mathrm{sqrt}((x - \mathrm{mean}(x))^2 + (y - \mathrm{mean}(y))^2 + (z - \mathrm{mean}(z))^2)) \quad (5)$$

Third, after polar calculation, the accuracy of targets before and after atmospheric correction is shown in Table 1. The average RMS errors after atmospheric correction is 1.24mm, which represents the average typical accuracy of polar measurement.

Table 1 Polar measurement results

Target	Raw RMSE (mm)	Correction RMSE (mm)
JD1	1.63	1.44
JD2	1.52	1.38
JD3	1.59	1.39
JD20	1.37	1.26
JD21	1.23	0.93
JD22	1.16	1.04

4.2 Trilateration calculation

Three prisms are chosen as the known points whose average values for 3D coordinates could be obtained by polar measurement to do trilateration calculation. All the calculation is done with the mathematical tool- MATLAB. Distance correction is done by Eq. (2) and Eq. (3) as well. The RMSE of trilateration calculation before and after atmospheric correction is shown in Table 2.

Table 2 Trilateration calculation results

Target	Arrangement	Raw RMSE(mm)	Correction RMSE(mm)	Accuracy improved(%)
JD10	JD1, JD2, JD22	1.92	1.63	15
JD10	JD1, JD2, JD3	5.85	5.58	4.6
JD10	JD1, JD3, JD20	1.62	1.44	11
JD10	JD1, JD3, JD22	1.42	1.15	19
JD10	JD1, JD20, JD22	0.84	0.84	15
JD10	JD20, JD21, JD22	0.93	0.57	38
JD10	JD1, JD2, JD21	1.22	0.59	50

5 Conclusion

Apparently the accuracy of trilateration calculation is related to the accuracy of distances between the three known points and the unknown point. The accuracy is improved after the atmospheric correction for distance shown in Table 2. It is also strongly related to the configuration of the three known points. If the three known points are reasonably distributed, the accuracy can be very satisfying. After atmospheric correction of distance, considering the trilateration for reasonable configuration used, the RMS error is lower than 0.6mm which is not only much lower than polar calculation but also can meet the requirements for the FAST control system. Therefore, confirmed by experiments, trilateration for feed measurement is effective.

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