Postprint of Research on Prime Focus Feed Switching Scheme for Xinjiang Qitai 110-meter Radio Telescope

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Date: 2017-09-26T00:00:00+00:00

Abstract

With the continuous advancement of radio astronomy research, scientists' demands for telescope resolution and sensitivity are ever-increasing, concurrently requiring broader observation bandwidths. In single-aperture telescopes, the low-frequency band is received via the prime focus, enabling more compact feed dimensions. To ensure no interference with the feed functionality of the secondary focus in dual-reflector antennas, the placement and switching scheme for the prime focus feed must be highly efficient and rational. This study investigates the 110 m fully steerable radio telescope constructed in Qitai, Xinjiang, and analyzes the feasibility of applying two schemes to this telescope by referencing the Italian SRT 64 m and German Effelsberg 100 m radio telescopes, while proposing a novel scheme for rapid prime focus feed switching utilizing linear modules. Modeling and simulation of the linear module mechanism were conducted, and aperture plane signal blockage was analyzed. The results indicate that this scheme can effectively meet the operational requirements of the telescope.

Full Text

Study on Primary Focus Feed Switching Scheme for the 110 m Radio Telescope

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Abstract

With the continuous advancement of radio astronomy research, scientists demand increasingly higher resolution and sensitivity from telescopes, as well as broader observing bands. For single-aperture telescopes, low-frequency bands are received at the primary focus, where feed horns can be more compact. To avoid affecting the normal operation of secondary focus feeds, the placement and switching scheme for primary focus feeds must be highly efficient and rational. This paper analyzes the feasibility of applying two existing schemes to the proposed 110 m radio telescope in Qitai, Xinjiang (QiTai Telescope, QTT), using the Italian SRT 64 m telescope as a reference, and proposes a novel primary focus feed switching scheme employing linear modules. Through modeling and simulation of the linear module mechanism and analysis of aperture signal blockage, the results demonstrate that this scheme effectively meets the operational requirements of the telescope.

Keywords: feed switching method; radio telescope; primary focus receiver; linear module

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1. Introduction

Over the past decade, radio telescope technology in China has developed rapidly, with increasingly larger apertures and higher precision. The Shanghai 65 m fully steerable radio telescope was completed at Sheshan in 2012, covering a frequency band of 1.6–46 GHz and employing active surface technology with an adjustable main reflector [1]. The Five-hundred-meter Aperture Spherical radio Telescope (FAST) in Pingtang, Guizhou, was completed in 2016 [2]. The planned Xinjiang Qitai 110 m fully steerable radio telescope (QTT) will significantly enhance China' s capabilities in astrophysics, astrometry, and space exploration.

The QTT will operate across a frequency range of 150 MHz to 115 GHz. High-frequency feeds are better suited for placement at the secondary focus due to their smaller size and lower background noise reception, while low-frequency feeds can be installed at the primary focus with more compact and rational structures [4]. The telescope must accommodate multiple receivers at both primary and secondary foci. Internationally, several large telescopes feature feed systems at both foci, including the German Effelsberg 100 m telescope [5] and the U.S. Green Bank Telescope (GBT) [6].

The Effelsberg telescope employs a central opening in the subreflector (Fig. 1a). When the primary focus feed is in use, the central panel opens and the required feed extends through it; after operation, the feed retracts and the panel closes. Since the opening lies in the geometric optics shadow region, this telescopic barrel approach avoids additional blockage of the main reflector that would reduce efficiency. The GBT' s primary focus switching scheme places feeds on a crossbeam, with a screw and motor drive at the rear rotating the assembly about a pivot above the subreflector (Fig. 1b). Different feeds on the crossbeam can be moved to the primary focus position, enabling switching between multiple primary focus receivers.

The Italian SRT 64 m telescope uses a similar crossbeam approach (Fig. 1c). Its primary focus switching is simple and fast, completing in minutes. However, as an offset telescope, the GBT can more easily implement primary focus switching, though it causes aperture blockage that reduces antenna efficiency. The SRT' s feeds remain beside the subreflector support legs when not in use and are pushed to the primary focus by actuators when needed, causing no aperture blockage but requiring longer switching times of 2–4 hours per change.

2. QTT Primary Focus Feed Switching Scheme

The QTT is a shaped Gregorian antenna with a large subreflector, making the German Effelsberg scheme unsuitable. The shaped surface imposes precision requirements on the central region of the subreflector that are difficult to maintain with a panel opening mechanism. The Italian SRT approach would result in a bulky switching mechanism for QTT' s larger subreflector, causing greater blockage and making repeatable positioning difficult to guarantee. Based on these considerations, we propose a primary focus switching scheme driven by open-type ball-screw linear modules.

2.1 Technical Requirements The switching mechanism must achieve receiver switching between primary foci through mechanical motion while ensuring: 1. Accurate alignment of feed phase centers with the focal point 2. Precise repositioning of primary focus receivers 3. Minimal antenna blockage 4. High transmission accuracy 5. Automated operation to reduce workload 6. Lightweight structure with adequate stiffness

During primary focus observations, the mechanism must deliver receivers to the primary focus position and enable switching between multiple receivers.

2.2 Mechanism Design In preliminary QTT studies, the primary focus is configured with three receivers covering 0.15-0.16 GHz, 1–2 GHz, and 0.6–4 GHz bands. Based on feed structural characteristics, we propose a switching mechanism driven by open-type ball-screw linear modules, comprising a focus positioner and a feed switching mechanism.

Focus Positioner: This consists of two open-type ball-screw linear modules and a feed mounting crossbeam. In the working position, the crossbeam is located at the center of the subreflector (Fig. 3a). In the idle position, it resides beside the subreflector without causing blockage (Fig. 3b). The positioner has only two positions, and switching requires pointing the telescope to the zenith.

Feed Switching Mechanism: This comprises a single open-type ball-screw linear module with primary focus feeds arranged on the nut surface. Taking the transition from idle to working position as an example, the two linear modules of the focus positioner move synchronously to transport the crossbeam to the working position. The feeds are arranged on the switching mechanism as shown in Fig. 4. Feed 2 is located at the center of the screw; moving one feed width switches to Feed 1, while moving in the opposite direction switches to Feed 3. The linear module' s reciprocating motion enables switching between three feeds.

2.3 Structural Dimensions For a 110 m radio telescope, the typical main-to-subreflector diameter ratio is 10:1. With a 110 m main reflector diameter and 11 m subreflector, and an f/D ratio of 0.33, the optimized focal length is 36.3 m. The feed mounting crossbeam length can be 12 m, with feeds installed in pre-positioned boxes on the crossbeam.

In the focus positioner, the open-type ball-screw linear modules must have sufficient travel to deliver feeds to the focal position. Considering minimum travel requirements, the stroke is set at 3.3 m. In the feed switching mechanism, the distance between adjacent feed centers is 1.5 m, allowing three feeds to reach the primary focus. The linear module stroke is 3 m, providing adequate margin.

Table 1 lists the masses of major components for the QTT primary focus switching mechanism.

Weight of the QTT primary focus positioner

The screw pair dimensions for both mechanisms are selected based on operational requirements.

2.4 Screw Pair Selection for Focus Positioner The QTT primary focus switching mechanism must complete feed changes within minutes. With a screw pair length of 3.3 m and a requirement to transport the feed switching mechanism to the primary focus within 210 seconds, the maximum velocity is 1,800 mm/min. Setting the maximum screw speed at 120 r/min and lead P = 15 mm, the expected dynamic load rating must satisfy both operational time and preload requirements.

The maximum axial load on the focus positioner screw occurs when the antenna points to the horizon. Calculations yield an expected dynamic load rating C = 104.4 kN. Using a fixed-fixed support configuration with maximum axial deformation = 2.5 m, support distance L = 7,000 mm, and support coefficient a = 0.039, the minimum thread root diameter is calculated as d = 65.4 mm.

Based on these results, the focus positioner uses a pair of GD 8016-4 screw pairs with internal circulation, fixed flange, and gasket preload. The selected screw has a thread root diameter d = 68.6 mm and rated dynamic load C = 115.483 kN, exceeding the required minimum and satisfying structural strength requirements (Table 2).

GD 8016-4 screw parameters

2.5 Screw Pair Selection for Feed Switching Mechanism The feed switching mechanism selection follows a similar process, but with maximum axial load F = 5,000 N. Calculations yield a minimum thread root diameter d = 22.25 mm and expected dynamic load C = 22.51 kN. The selected GD 4010-4 screw pair features internal circulation, flange mounting, double-nut gasket preload, with thread root diameter d = 32.9 mm and rated dynamic load C = 34.358 kN, meeting the structural strength requirements (Table 3).

GD 4010-4 screw parameters

3. Scheme Analysis

3.1 Impact on Antenna Efficiency Blockage by the subreflector and its support structure creates a shadow on the antenna aperture, reducing gain and raising sidelobe levels [9]. For a given aperture size and operating frequency, antenna gain is calculated by:

$$G = \eta \left(\frac{\pi D}{\lambda} \right)^2$$

where G is antenna gain, D is aperture diameter, is wavelength, and is antenna efficiency.

Antenna efficiency is affected by multiple factors:

$$\eta = \eta_t \cdot \eta_s \cdot \eta_a \cdot \eta_p \cdot \eta_u \cdot \eta_m \cdot \eta_\phi \cdot \eta_e$$

where _t is spillover efficiency, _s is blockage efficiency, _a is illumination efficiency, _p is polarization efficiency, _u is surface tolerance efficiency, _m is mismatch efficiency, _ is phase efficiency, and _e is other losses.

For the QTT, blockage efficiency _s dominates the efficiency loss due to subreflector and support strut blockage, typically calculated using geometric optics [10]. The primary focus switching mechanism adds blockage ΔA over the main reflector:

$$\eta_s = 1 - \frac{\Delta A}{A}$$

where A is the antenna aperture area. The mechanism projects approximately 26.7 m^2 onto the main reflector, representing 0.28% of the total main surface area and causing 0.49% blockage loss.

Table 4 compares primary focus switching schemes for QTT and SRT. The QTT mechanism causes slightly less blockage than SRT' s, though QTT has a larger subreflector (11 m vs. 7.5 m). The QTT crossbeam is only 12 m long versus SRT' s, resulting in a less bulky structure.

Comparison of primary focus positioner of QTT and SRT

3.2 Feed Offset Analysis Ideally, the feed phase center coincides exactly with the focal point, but support deformation and installation inaccuracies cause offset. For QTT' s primary focus feeds, offset occurs in two forms: axial (along the paraboloid axis) and transverse (perpendicular to the axis). Axial offset reduces gain and raises sidelobe levels while maintaining the main beam direction; transverse offset causes beam deviation, asymmetric patterns, and increased sidelobe levels on one side [11].

The QTT' s shortest operating wavelength at primary focus is 1.5 cm. Design specifications require both axial and transverse deviations to be less than 15 mm. Simulation results under self-weight show maximum axial offset of about 5 mm when the antenna points to zenith, and maximum transverse offset of about 14.6 mm when pointing to horizon (Fig. 5). These values are within acceptable limits, with the transverse offset slightly below the minimum allowable deformation. Future implementation of a feed position measurement system could enable two-dimensional adjustment to further reduce pointing errors.

[Figure 5: see original paper] Simulation of feed offset at QTT primary focus

4. Conclusion

Through investigation and analysis of primary focus switching schemes for large international radio telescopes, and considering QTT' s structural parameters and design features, we propose a front-fed switching scheme suitable for the QTT. This scheme features:

1. Simple structure using open-type ball-screw linear modules for reliable, precise positioning and smooth transmission
2. Smaller blockage of the main reflector compared to similar antennas
3. High positioning accuracy
4. Potential for weight reduction to 1/3 of current mass through material improvements
5. Expandability for additional primary focus feeds in future upgrades

The analysis demonstrates that this switching scheme meets the operational requirements for the QTT primary focus system.

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Note: Figure translations are in progress. See original paper for figures.