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## Measurement of the Primary Beam of the Tianlai Cylindrical Antenna Using an Unmanned Aerial Vehicle Postprint

**Authors:** Jixia Li, Nanben Suo, Shenzhe Xu, Shijie Sun, Shifan Zuo, Could you clarify what you'd like to do with "Yougang Wang" ? For example:

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### Abstract

The Tianlai Cylinder Pathfinder Array consists of three adjacent cylindrical reflectors fixed on the ground, each 40 m long and 15 m wide, with the cylinder axis oriented along the North-South (N-S) direction. Dual linear polarization feeds are distributed along the focus line, parallel to the cylinder axis. Measurement of the primary beam profile of these cylindrical reflectors is difficult, as they are too large to be placed in an anechoic chamber. While the beam profile along the East-West (E-W) direction can be measured with the transit observations of bright astronomical radio sources, the beam profile along the N-S direction remains very uncertain. We present a preliminary measurement of the beam profile of the Tianlai cylindrical antenna along both the N-S direction and E-W direction in the frequency range of 700–800 MHz, using a calibrator source carried by an unmanned aerial vehicle (UAV) flying in the far field. The beam profile of the Tianlai cylindrical antenna is determined from the analysis of the auto-correlation signals from the cylinder array correlator, taking into account the emitter antenna beam profile, itself measured with a dipole antenna on the ground. The accuracy of the UAV-based determination of the cylinder beam profiles is validated by comparing the results with the one derived from bright astronomical source transits, and with simulated beams.

## Full Text

### Preamble

#### Measurement of the Primary Beam of the Tianlai Cylindrical Antenna Using an Unmanned Aerial Vehicle

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The beam profile of the Tianlai cylindrical antenna is determined from analysis of the auto-correlation signals from the cylinder array correlator, taking into account the emitter antenna beam profile, itself measured with a dipole antenna on the ground. The accuracy of the UAV-based determination of the cylinder beam profiles is validated by comparing the results with those derived from bright astronomical source transits and with simulated beams.

**Key words:** methods: miscellaneous -techniques: miscellaneous -balloons

## 1. Introduction

The Tianlai Cylinder Pathfinder Array (TCPA) is a radio interferometer designed to test techniques for 21 cm intensity mapping (IM; Chen 2012), which has the potential to measure the equation of state of dark energy from baryon acoustic oscillations (BAO) or constrain inflation models (Ansari et al. 2012; Xu et al. 2016). Like many other similar IM or Epoch of Reionization (EoR) experiments, such as CHIME (CHIME Collaboration et al. 2022), HIRAX (Newburgh et al. 2016), LOFAR (van Haarlem et al. 2013), MWA (Tingay et al. 2013), and HERA (DeBoer et al. 2017), TCPA is an interferometer array with a large number of receivers to achieve fast mapping speed.

These experiments often employ a very large number of array elements observing in drift-scan mode. To reduce cost, array elements are typically fixed or have adjustable pointing in declination only. These interferometers with fixed reflectors pose a challenge for calibration measurement of the beam pattern using bright celestial sources. The beam pattern of a radio telescope is usually measured using well-known bright radio point sources as calibrators. However, for many HI IM or EoR experiments with non-steerable antennas, this can only be performed along the East-West (E-W) direction when bright point sources transit through the beam. As the number of bright point sources available for such measurement is very limited, this can only be performed at a few fixed zenith angles or, equivalently, declination angles, which are too sparse to derive the beam pattern in the North-South (N-S) direction. The Tianlai cylinder array, which consists of three fixed cylinders aligned in the N-S direction, also faces this problem.

In order to reconstruct the sky from its observation data, it is necessary to know the primary beam pattern of the cylinder (Zuo et al. 2019, 2021). The main lobe of the primary beam of the cylinder reflector is a narrow strip along the N-S direction passing through the zenith. The cylindrical form of the antenna suggests a natural multiplicative decomposition of the beam pattern along the E-W and N-S directions. Along the E-W direction, the pattern can be measured by observing the transit of bright point sources, which pass through the narrow strip of the primary beam and show up as a clear rise and fall of their signal strength (Li et al. 2020). However, measuring the N-S direction pattern is much more difficult. Previously, Sun et al. (2022) simulated the beam pattern for a single Tianlai cylinder with the feed array, and we used an analytical beam model fitted to this result in simulations of the Tianlai array imaging (Yu et al. 2023, 2024a) and beam-forming (Yu et al. 2024b). However, it is difficult to assess the accuracy of the beam model without actual measurement.

Some methods have been proposed to measure the beam pattern for cylinder telescopes, such as holographic beam mapping (Harp et al. 2011; Berger et al. 2016; Thompson et al. 2017) or using the Sun as a calibrator (Amiri et al. 2022). However, to use the holographic beam mapping method, a calibrated, large, steerable dish antenna is needed for cross-correlation, which is not avail-

able in many cases, including ours. The Sun calibrator method can only be used to measure the declination range of the ecliptic circle, i.e.,  $-23.5^\circ < \delta < 23.5^\circ$ , and the solar emission itself changes all the time, which affects the precision of the measurement.

In recent years, beam measurement using a calibrator source carried by unmanned aerial vehicles (hereafter called drones) has proven to be a promising technique based on its flexibility and cost-effectiveness (Chang et al. 2015; Zhang et al. 2021; Tyndall et al. 2025; Kuhn et al. 2025). For large, fixed antennas that do not fit into an anechoic chamber and cannot employ the holographic mapping method, this is practically the only feasible method at present. By flying over the antenna array in the far field, one can directly measure the beam pattern, not only for the main lobe of the beam but also for the side lobes.

However, to measure the beam pattern directly requires the source to be located in the far field zone of the antenna. The distance  $d$  of the far field is estimated to be  $d = 2D^2/\lambda$ , where  $D$  is the aperture of the antenna and  $\lambda$  the wavelength. This corresponds to  $d = 1125$  m for  $D = 15$  m and  $\lambda = 0.4$  m, for example, which then requires the drone to fly well above the usual height limit of a few hundred meters. Although it is possible, in principle, to derive the far-field beam patterns from near-field measurements, this would require measurements on a very fine grid and accurate phase measurements, which are very challenging to perform in the field. In this paper, we present our measurement of the beam pattern for the Tianlai Cylinders by a drone. In our measurement, we have flown our drone at a relative height of 1220 m.

This paper is organized as follows. In Section 2, we describe the experiment setup, including the Cylinder Array, the drone and the calibrator source it carries, the flight plan, and the data calibration method. In Section 3, we describe the calibration of the beam pattern of the calibrator source antenna, which is needed for correcting the cylinder beam measurement. Finally, the results of the cylinder beam pattern measurement are presented in Section 4. We conclude in Section 5.

## 2. The Experiment Setup

As noted in the Introduction, the TCPA is fixed on the ground. We fly our drone above the array, carrying an emitter that produces a bandpass-filtered noise signal used as the calibration signal. The TCPA correlator system operates simultaneously, recording the signal produced by the drone along with the sky signal and receiver noise. As the drone flies to different positions relative to the array, the variation of its signal strength is measured, and the beam pattern of the cylinder array is derived. Below we present the details of this experiment.

### 2.1. The Tianlai Cylinder Pathfinder Array

The TCPA consists of three adjacent parabolic cylinder reflectors fixed on the ground, each  $40 \times 15$  m, with their axes oriented in the N-S direction. Dual-

polarization dipole feeds are placed along the focus line of each cylinder (Chen et al. 2016). The cylinders are closely spaced in the E-W direction, as shown in Figure 1 (reproduced from Li et al. 2020). The reflectors focus the incoming radio signal in the E-W direction while allowing a wide field of view (FoV) in the N-S direction. At any moment its FoV is a narrow strip running from north to south through the zenith. The beam of the feeds limits the strip to about  $\pm 60^\circ$  from zenith (Sun et al. 2022; Cianciara et al. 2017). As the Earth rotates, the beams scan the northern celestial hemisphere. The latitude of the telescope site is  $44.15^\circ$ , so the FoV extends from  $-16^\circ$  declination up to  $+90^\circ$  and back down to  $+76^\circ$  on the other side.

From east to west, the three cylinders are denoted as cylinders A, B, and C, respectively, and equipped with 31, 32, and 33 feeds, respectively. From north to south, the feeds in each cylinder are labeled with numbers 1, 2, 3, etc. The northernmost feeds A1, B1, and C1 are aligned, as are the southernmost feeds A31, B32, and C33, and the distance between the northernmost and southernmost feeds is 12.4 m. The currently installed feeds occupy less than half of the cylinder length; the remaining space is reserved for additional feeds for future upgrades. The feed spacings for the A, B, and C cylinders are slightly different: 41.33 cm, 40.00 cm, and 38.75 cm, respectively, to reduce the grating lobe (Zhang et al. 2016). The X and Y polarization denotes those along the N-S direction and E-W direction, respectively. Each signal channel is designated by its cylinder, feed number, and polarization axis. For example, the E-W or Y polarization signal of the 2nd feed in the middle cylinder will be noted as B2Y. The auto-correlations are denoted by the feed and polarization, e.g., C7XX. The TCPA is designed to observe the sky between 400 MHz to 1500 MHz by changing the filters before the mixers (Li et al. 2020).

Currently, filters centered on 750 MHz with a bandpass of 100 MHz are used, resulting in a frequency range of 700–800 MHz. We model the primary beam of the cylinder as a product of the N-S and E-W profiles:

$$B(\theta_{NS}, \theta_{EW}) = B_{NS}(\theta_{NS}) \times B_{EW}(\theta_{EW}),$$

where  $\theta_{NS}$  and  $\theta_{EW}$  denote the angle with respect to the Z-axis for the projected vector on the XZ and YZ planes, respectively, as shown in Figure 2.

## 2.2. The Drone and Noise Source

To measure the beam pattern of the cylinder reflectors, we use a calibrator noise source mounted on a drone to fly over the cylinder slowly in the far field zone. The cylindrical antenna does not have azimuthal symmetry and cannot be characterized by a single value for its aperture. In our case, the aperture along the E-W direction is 15 m, while along the N-S direction the reflector has no focus; its equivalent aperture is determined by the illumination angle of the feed, so we use the E-W aperture to determine the far field distance. For

the current observing frequency range of 700–800 MHz, the far field distance is 1050–1200 m. In this measurement campaign, the drone was flown at a height of 1220 m above the central feed.

The drone used in our experiment is of type DJI M300 Real-Time Kinematic (RTK), as shown in Figure 3, a commercially available drone; some relevant parameters are listed in Table 1. At the location of the TCPA, the ground elevation is about 1500 m above sea level. Starting from this site, the drone has a maximum endurance of about 55 minutes with an empty payload and low-level flight, but with a payload, and especially to attain the ground height of over 1000 m, the endurance is greatly reduced. The drone needs about 7 minutes to reach the height of 1220 m, and the equivalent endurance can be reduced by as much as 15 minutes. For a safe return flight and touchdown, a minimum of 12 minute endurance should also be reserved. In our experiment, the weight of the whole payload carried by the drone is about 0.75 kg, corresponding to a maximum endurance of 43 minutes. Therefore, the available time for the actual measurement work is limited to about 15 minutes during each flight.

The position of the drone is determined using differential Global Positioning Systems (differential GPS). The drone has an embedded RTK GPS module to ensure  $\pm 1$  cm location accuracy. The RTK base station is placed near the cylindrical antenna for operation. In actual flight, if a target position is set, the drone will drift around it, resulting in a hovering error of  $\pm 0.1$  m (see Table 1). At a distance of 1200 m, this introduces an angle error of only  $17''$ , thus the positional error is negligible. However, under strong wind, the drone will tilt itself to counteract the wind, which affects the beam pointing of the dipole antenna. To avoid this problem, measurements were made only under low wind speed conditions when the ground wind speed was less than  $2 \text{ m s}^{-1}$ .

The drone carries a noise emitter, which includes a dipole antenna mounted below the drone and an electronics box mounted above the drone, connected by a radio frequency (RF) cable. The block diagram of the calibrator noise source system is shown in Figure 4. A noise source generator produces a wide-band noise signal with a flat spectrum spanning 0.1 MHz to 1500 MHz. To increase the signal power, the noise is amplified by about 20 dB by a broadband RF amplifier (a Mini-Circuits ZX60-33LN-S+, with operating frequency range 0.5–3 GHz). A low-pass filter (Mini-Circuits VLF-800+) with ultra-flat  $0.6 \pm 0.2$  dB passband ripple is inserted before the amplifier, followed by a 710–850 MHz bandpass filter (Mini-Circuits model VBFZ-780-S+) to suppress out-of-band noise which may affect the operation control and location system of the drone. An attenuator is used to adjust the emitted signal level.

We measured the stability of the noise source circuit over a period of 60 minutes with a spectrum analyzer and estimated the noise power by averaging over the observational bandwidth. The result is shown in Figure 5. The time interval between two measurements is 1 minute. The variation during each measurement is within  $\pm 0.02$  dB, which is close to the precision limit of the spectrum analyzer. However, a steady decrease of about 0.1 dB can be observed for the whole

duration of the measurement, probably due to decreasing battery power. Within the 10 minute measurement time of the cylinder beam, the variation of the drone noise source signal can be ignored.

The dipole antenna is made of an aluminum tube of diameter 7 mm and length 105 mm for each half of the dipole. It is fixed to a bracket made by a 3D printer, which is the white part mounted below the drone in Figure 3. The dipole antenna resonates at 645 MHz, with a quarter-wave coaxial balun ensuring impedance matching and current balancing.

### 2.3. The Flight Plan

Ideally, one could measure the antenna beam pattern by taking measurements at many different points on a spherical surface centered on one of the antenna feeds. However, this would require a very large amount of time. In a simplified treatment, we may regard the cylinder beam as a product of its central pattern along the N-S direction and the pattern in the E-W direction, as assumed in Equation (2). We then choose two circular flight paths centered around a particular feed with a radius of 1220 m. A number of waypoints along this circular curve are preset. At each point the drone will hover for 20 s, with its noise source broadcasting and TCPA receiving. The flight plan is illustrated in Figure 6. Here, the feed is at the origin marked by O. In the N-S flight, the curve is the flight route. The zenith angle  $\theta_{NS}$  refers to the angle between the drone as seen by the measured feed and the zenith direction, that is  $\theta_{NS} = \angle L'OZ$  when the drone is at point L'. We define  $\theta_{NS}$  to be negative when the drone is in the northern part and positive in the southern part. Similarly, in the E-W flight we define the angle  $\theta_{EW}$  to be positive in the eastern part and negative in the western part. As the Tianlai primary beam is narrow in the E-W direction and wide in the N-S direction, the maximum zenith angle  $\theta_{NS}$  in the N-S direction we measure is  $\pm 70^\circ$ , and  $\theta_{EW}$  in the E-W direction is  $\pm 3^\circ$ .

The dipole antenna for the noise emitter carried by the drone produces a linearly polarized signal along the direction of the dipole, and only the corresponding polarization of the cylinder feed is sensitive to its emission. In order to measure the response for both polarizations of the feeds, two flights are needed for each path, with the dipoles pointing to the N-S direction and E-W direction once each.

For the E-W flight, the main beam ( $-3^\circ$  to  $3^\circ$ ) is very narrow, so a step size of  $0.3^\circ$  is used. For the N-S flight, since the beamwidth is very wide, larger zenith angle steps of  $5^\circ$ ,  $10^\circ$ , and even  $15^\circ$  are used. These zenith angles of the measurements for the two flight curves are listed in Table 2.

We use the drone auto-pilot to execute all flights. Nevertheless, a strong wind warning may interrupt the process, so manual control to resume the auto-pilot is occasionally needed. Also, when the drone is in the center line of the beam where the antenna gains are the strongest, it is necessary to decrease the level of the noise calibrator emission power to avoid saturating the receiver on the

TCPA. This is executed by adjusting the attenuator, with the attenuation factor divided out in the data processing to compensate for this decrease of power.

The Sun can generate a strong signal at this band throughout the daytime, which can bias the measured signal level. To avoid this, the experiment is carried out at night. This has the additional advantage that at night, the ambient temperature is more stable, which yields a more stable system gain, especially after midnight. Also, moments when bright radio sources such as Cyg A and Cas A transit are avoided to ensure the drone is the only bright source in the beam when the measurement is taken. Our experiments were done between midnight and dawn before sunrise, when the temperature variation is the least. The system gain can be regarded as almost constant during each 15 minute flight.

#### 2.4. Data Processing Procedure

We use the TCPA correlator to record the data. This correlator is based on a Roach+GPU framework and can compute visibilities from all 192 polarized signals of the cylinder array, in the frequency range of 700-800 MHz with a resolution of 122 kHz (Wang et al. 2024), and 4 s visibility integration time. For the 20 s hovering time of the drone, about four data points for each zenith angle are obtained, from which we calculate the average value of the auto-correlations  $V_{ii}$  for each of the 192 signals.

The observed visibilities can be written as (here we omit the subscripts denoting the array element pair)

$$V_{\text{obs}}(\nu, t) = V_{\text{dns}}(\nu, t) + V_0(\nu, t),$$

where  $V_{\text{obs}}(\nu, t)$  is the observed output from the correlator,  $V_{\text{dns}}(\nu, t)$  is the contribution of the drone noise source, and  $V_0(\nu, t)$  is the visibility output without the drone, which includes the sky signal and the receiver noise. The noise source on the drone is set to a sufficiently high power level for better signal-to-noise ratio, but still within the range of linearity of the system. The visibility of the drone noise source can then be obtained as  $V_{\text{dns}} = V_{\text{obs}} - V_0$ . However, the gain of the receiver may also drift during different days and flights. To address this problem, we model the gain as varying according to  $g(\nu, t) = (a \cdot t + b)$ ; i.e., it is frequency-independent and varies linearly with time.

In Figure 7, we show the visibility data for feed A25 XX polarization at frequency 720 MHz. The background sky data (from 2024 July 7th) are shown as the blue curve, showing a continuous and slowly varying sky and receiver noise signal over about 5 hr during the night. The peaks or increases of the signal level during the transits of Cyg A (at time offset of about 3000 s), the Milky Way (at time offset of about 4500 s), and Cas A (at time offset of about 15,000 s) can be clearly seen. The orange curve shows the data during five flight sessions during the experiment on 2024 July 8th. The noise source signal level from the drone is much higher than the background signal, about 10-15 times stronger

at the center of the beam and shown truncated in this plot. Note that for the orange curve, when Cyg A transits the antenna beam, we paused the drone experiment and the noise source is kept powered off. Visibility data from two time slices, (1616 s to 2079 s) and (13,356 s to 16,654 s), are used to linearly fit the background sky curve with the assumption that the gain varies linearly with time and is independent of frequency, as noted above, so that

$$V_{\text{fit}}^{\text{sky}}(\nu, t) = (a \cdot t + b)V_{\text{sky}}(\nu, t).$$

The green curve shows the fitted sky background. Finally, we obtain the sky-removed visibility,

$$V_{\text{dns}}(\nu, t) = V_{\text{obs}}(\nu, t) - V_{\text{fit}}^{\text{sky}}(\nu, t).$$

If the noise source could be switched on and off during the calibration flight, then it would be relatively straightforward to measure  $V_{\text{obs}}$  and  $V_0$  as the on and off values, respectively. Unfortunately, during the experiment this is not done; the drone continuously broadcast its noise signal. Instead, we used data taken one day before the drone experiment (2024 July 7th) as the baseline data to derive  $V_0$ , while the data taken on 2024 July 8th and 9th, during which the drone experiments were performed, are used for  $V_{\text{obs}}$ . For the beam pattern determination analysis, we convert  $V_{\text{dns}}(\nu, t)$  to  $\hat{V}_{\text{dns}}$  by averaging the visibility over the time when the drone hovered for 20 s.

### 3. Calibration of the Drone Emitter

The measured signal strength is proportional to the beam of the cylinder antenna in the direction of the drone with respect to the cylinder, but it is also proportional to the beam of the noise emitter antenna in the direction of the cylinder with respect to the drone. As shown in the left panel of Figure 8, the received signal strength is

$$V = B_{\text{cyl}}(\theta_{\text{cyl}}) \cdot B_{\text{dns}}(\theta_{\text{dns}}),$$

where the vector OP and PO can be expressed by the angles  $\theta_{\text{cyl}}$  and  $\theta_{\text{dns}}$ . Thus, to measure the cylinder beam using the drone, we first need to know the beam pattern of the antenna mounted on the drone (hereafter called drone beam  $B_{\text{dns}}$ ). While the beam pattern of a dipole antenna is well known, the presence of the drone can affect this beam. It is therefore necessary to first measure the drone beam. The drone beam is in turn measured by a dipole antenna on the ground (hereafter its beam is called ground dipole beam  $B_{\text{ground}}$ ), mounted about 10 cm above the ground surface during the measurement, as shown in the right panel of Figure 8. In this case, we would have

$$V = B_{\text{dns}}(\theta_{\text{dns}}) \cdot B_{\text{ground}}(\theta_{\text{ground}}).$$

We will first use Equation (6) to measure  $B_{\text{dns}}(\theta_{\text{dns}})$ , assuming that the beam of the ground dipole  $B_{\text{ground}}(\theta_{\text{ground}})$  is known, then use Equation (5) to measure  $B_{\text{cyl}}(\theta_{\text{cyl}})$ .

### 3.1. The Beam of the Ground Dipole

We use the FEKO electromagnetic (EM) simulation software to simulate the E-plane (parallel to the dipole) of the ground dipole antenna. The relative permittivity or dielectric constant of the ground is set to  $\varepsilon_{\text{Gnd}}/\varepsilon_0 \simeq 3.66$  and its conductivity  $\sigma_{\text{Gnd}} \simeq 0.082 \text{ S m}^{-1}$ , corresponding to measured values, although not at the exact position of the antenna during the measurements. These parameters are measured using the standard four-probe method (Snowden et al. 1985; see also Suonanben et al. 2024). The ground is set to be infinitely large. In the real case, the experiment ground is nearly flat and has no obstructions over 200 m.

In Figure 9, we show the simulated beam in the E-plane (top panel) of the ground dipole antenna beam. The beam is symmetric about a zenith angle of  $0^\circ$ . The beam can be approximated as a Gaussian function of zenith angle. At the high-frequency end, the beamwidth is slightly narrower than at the low-frequency end, as expected. Hereafter the raw drone beam is called  $B_{\text{dns\_raw}}$ , so that  $B_{\text{dns\_raw}} \propto B_{\text{dns}} \cdot B_{\text{ground}}$ . Then, we can obtain the real drone beam after calibrating by the ground dipole antenna beam:

$$B_{\text{dns}}(\theta_{\text{dns}}) = \frac{B_{\text{dns\_raw}}(\theta_{\text{dns}})}{B_{\text{ground}}(\theta_{\text{ground}})}.$$

### 3.2. The Beam of the Drone Dipole

In the experiment to measure the drone beam pattern  $B_{\text{dns}}$ , the drone flies from one side to the other side of the ground dipole in an arc with radius of 100 m, and hovers at zenith angles from  $-75^\circ$  to  $75^\circ$  with a step of  $5^\circ$ . Both the E and H planes are measured. In the E-plane flight, the dipole direction is the same as the flight route direction, while in the H-plane, the flight route directions are perpendicular to the dipole. The polarization of the ground dipole is always the same as the drone dipole. The ground dipole antenna receives the signal from the drone dipole. A spectrum analyzer is used to measure and record the received signal between 700 and 800 MHz.

Figure 10 shows the E-plane (top) and H-plane (bottom) of the drone beam  $B_{\text{dns}}$ , after correcting for the ground dipole profile as expressed in Equation (7). As can be seen from this figure, the beam pattern of the dipole antenna mounted on the drone is different from that in free space; for example, it has two lobes

in the downward direction, probably caused by induction and reflections from the main frame of the drone.

#### 4. Measurement Results of the Cylinder Beam

Having measured the drone beam needed for making corrections, we can now measure the beam of the cylinder. Take the E-plane measurement for the XX polarization of feed A25 as an example. First, the designated channel is extracted from the data file using the tlpipes software (Zuo et al. 2021). The sky background is removed using the adjacent-day data as discussed in Section 2.4. The time-ordered data are shown in the top panel of Figure 11. The times when the drone is hovering at the waypoints can be recognized; these locations are then transformed to zenith angles  $\theta$  of the drone relative to feed A25, and the amplitude of the received signal is obtained by averaging over the duration of the hovering, as shown in the bottom panel of Figure 11. This sky-removed visibility of the drone  $\hat{V}_{\text{dns}}$  is proportional to both the cylinder beam and the drone beam:

$$\hat{V}_{\text{dns}} = B_{\text{cyl}}(\theta_{\text{cyl}}) \cdot B_{\text{dns}}(\theta_{\text{dns}}),$$

where  $B_{\text{cyl}}$  is the cylinder beam that we want to measure, and  $B_{\text{dns}}$  is the drone beam obtained in Equation (7). Using Equation (8), the cylinder beam  $B_{\text{cyl}}$  is obtained by dividing the drone beam measured in Section 3.2 from the visibility  $\hat{V}_{\text{dns}}$ .

The final result of the measurement is shown in Figure 12 for the N-S profile of a feed (A25 XX), where the amplitude has been re-normalized at  $\theta_{NS} = 0^\circ$  and shown in logarithmic (dB) scale. The results for two frequencies (747.0 and 751.8 MHz), averaged in frequency over 0.98 MHz, are plotted, showing similar beam profiles for these two neighboring frequencies. From Figure 12, we see this N-S beam profile of the cylinder has a peak at  $\theta_{NS} = 0^\circ$ , and as we move away from the peak to the two sides, the beam declines, first to a “shoulder” at  $\theta_{NS} \sim \pm 30^\circ$ , then steepens at  $\theta_{NS} \sim \pm 60^\circ$ . The shape is slightly asymmetric, with the “shoulder” more apparent on the  $\theta_{NS} < 0$  side, i.e., the northern part of the N-S beam. We also plotted the simulation result on the same figure for comparison, which does not have any shoulder, with a symmetric profile and monotonic decline from the peak. Thus, at the shoulder the difference can be as large as 3 dB.

The measured beams for different feeds are very similar to each other. In Figure 13, we show the N-S beam profiles of the XX polarization for four different feeds, which have very similar profiles. The results from different flights are also generally in agreement with each other, showing that the result of the measurement is robust. As an example, in Figure 14, we plot the N-S beam profile of feed A18 XX polarization using data from three flights. The second flight took place 22 hr after the first flight, and the third flight took place 2 hr after the second

flight, i.e., 24 hr after the first flight. The results are consistent with each other and also similar to that of A25 XX. In these measurements, the differences between the feeds are comparable to the difference in the measurement result for the same feed from different flights.

Regarding the cause of the asymmetry seen in the measurement result, we considered several possibilities. First, there is measurement error in the drone. If the drone is slightly tilted during its flight due to wind, or if its beam profile has some error, it could induce an asymmetry. However, this result is relatively stable over different measurements (as discussed below with Figure 14), which suggests that this may have more to do with the cylinder rather than with the drone. It could be due to slight error in the installation of the reflector or the feed, but based on theodolite measurements, this error should be much smaller. It seems to us that the most likely cause is ground reflections from nearby hills. In the simulation, the cylinder antenna is placed on flat land, but in reality there are hills to the north and south of the cylinders. The asymmetric landscape may be the cause of the observed differences in the north and south sides, though this still needs to be verified by further experiments and analysis in the future.

The simulation result has some kind of “jitter” with angle due to cross-coupling between different feeds, which varies with both frequency and angle. This is not apparent in the measurement result, mainly because the sampling over the angles is not sufficiently dense. The number of measurement points is limited by the duration of the flight. In future work, the sampling could be made denser by dividing the measurement path into several parts, completing one part with more points each time.

The E-W direction beam profile measured by the drone is shown in Figure 15, where the simulation result and the beam profile measured by the transit of a bright source are also shown for comparison. Here we again see that the overall shapes of the simulation are similar, but there are subtle differences between the actual measurement and the simulation. Both the drone measurement and the source transit measurement yield beam profiles that are slightly asymmetric, slightly broader than the simulation result, with higher side lobes. The drone measurement is somewhere between the simulation and the point source transit measurement result.

Note that these results are obtained after subtracting the noise background, and away from the peak, when the noise is dominant, the inaccurate estimate of the signal may lead to an apparently broader beam profile. As the drone measurements generally have a higher signal-to-noise ratio than the transit measurements, they may suffer less from this effect and thus appear to match better with the simulation. In addition, surface errors can affect the broadening of the measured beam. Another factor that may lead to an apparently broader profile is the finite size of the bright source, in this case Cyg A. It is well known that Cyg A is not a point source but has a size of about  $2'$  (the separation of its two radio lobes) (Carilli & Barthel 1996), while the primary beam of a Tianlai cylinder is about  $2''$ , so the size of Cyg A is too small to affect this measurement.

Finally, as yet another feed example, we show the main beams for feed A26 in both E and H planes and in XX (N-S) and YY (E-W) polarizations in Figure 16, at 747.0 MHz and 751.8 MHz. The XX polarization result is again similar to the previous example, but in the case of YY polarization H-plane, the peak of the profile is not at  $\theta = 0^\circ$ , and the beam has a small dip near the center  $\theta = 0^\circ$ , which may be due to some cross-coupling effect. For the E-W profile, we also find the first sidelobes are not completely symmetric. This may be caused by different reflections on the east and west sides, as cylinder A is located on the east side of the array, and to its east there is also the dish array. These factors may affect the sidelobe of the beam in the E-W direction.

## 5. Conclusion

Measuring the beam pattern of a radio telescope antenna is an important part of telescope calibration. In many modern 21 cm experiments, the telescope antenna is fixed on the ground or can only be moved between observations. In these cases, only the E-W direction beam can be measured conveniently by observing the meridian transit of astronomical sources, while measuring the North-South beam profile poses a significant challenge. The TCPA is an example of these. The use of a drone offers a simple and efficient means to determine the beam profile of such telescope antennas, especially along the N-S direction.

In this paper, we detail a drone-based far-field beam measurement method, where the N-S beam patterns were measured by hovering the drone at specific points. By comparing E-W beam measurements with astronomical observations, the drone measurement methods and techniques were validated. This approach can be applied to various antenna beam measurements and array beam characterizations, contributing to advancements in precision radio astronomy and 21 cm IM surveys. We find the beam profiles obtained from the measurement are generally similar to the EM simulation. However, differences do exist in the “shoulder,” sidelobes, and beamwidth, because there are simplifying assumptions and treatments in the simulation, which do not capture all aspects of the actual instrument in every detail, e.g., reflections from the surrounding terrain and objects, surface imperfections, and cross-coupling noise in the reflector.

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