

## Postprint of Astrometric Precision Evaluation for the Prime Focus of the Shanghai Planetarium Switchable Dual-Focus One-Meter Telescope

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### Abstract

The dual-focus switchable one-meter telescope at the Wangshu Observatory of the Shanghai Astronomical Museum is currently the largest aperture public outreach astronomical telescope constructed in China. This telescope employs a dual-focus design with manual switching between the primary focus and Nasmyth focus; the Nasmyth focus is primarily utilized for visual observations in public science popularization, while the primary focus is equipped with a large-format scientific-grade CMOS detector, achieving a field of view of  $1.5^\circ \times 1.1^\circ$ . The large field of view is not only suitable for conducting important live celestial event broadcasts, but can also be extensively applied to research projects including nova and supernova patrol surveys, as well as monitoring of small solar system bodies and artificial objects. Based on observational data, an analysis and evaluation of the astrometric precision of the telescope's primary focus was conducted. The results demonstrate that for stellar images with a signal-to-noise ratio greater than 5, the repeated measurement precision of stellar positions is better than 0.1 pixel; when the signal-to-noise ratio is 30, the repeated measurement precision is better than 0.05 pixel. Using the high-precision Gaia DR3 catalog as the reference catalog, analysis reveals that the CMOS observation images from the telescope's primary focus exhibit significant non-linear characteristics, necessitating a 3rd-order (20-parameter) model for reduction. For the test observational data, the observational precision for stars brighter than 15 mag is approximately 0.05 ; the observational precision gradually decreases with fainter magnitudes, reaching approximately 0.1 for stars of 17.5 mag.

## Full Text

### Preamble

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## Evaluation of Astrometric Performance at the Prime Focus of the Double-focus One-meter Telescope at the Shanghai Astronomy Museum

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### Abstract

The Double-focus One-meter Telescope (DOT) at the Wangshu Observatory of the Shanghai Astronomy Museum is currently the largest aperture telescope dedicated to popular science in China. The telescope employs a dual-focus design that allows manual switching between the prime focus and Nasmyth focus. The Nasmyth focus primarily serves visual observations for public outreach, while the prime focus is equipped with a scientific-grade CMOS sensor offering a field of view of  $1.5^\circ \times 1.1^\circ$ . This large field of view is suitable not only for live broadcast events of important astronomical phenomena but also for extensive research applications including surveys for novae and supernovae, monitoring of small solar system bodies, and tracking artificial satellites. Based on actual observation data, we analyzed and evaluated the astrometric precision at the prime focus. The results indicate that for star images with a signal-to-noise ratio (SNR) greater than 5, the repeatability of measured positions is better than 0.1 pixel; when the SNR reaches 30, the repeatability improves to better than

0.05 pixel. Using the high-precision Gaia DR3 catalog as a reference, our analysis reveals significant non-linear characteristics in the CMOS images obtained at the prime focus, necessitating a third-order (20-parameter) model for data reduction. For the test observations, stars brighter than 15 mag achieve an astrometric precision of approximately  $0.05''$ , with precision gradually decreasing for fainter stars to about  $0.1''$  at 17.5 mag.

**Key words:** telescope; plate parameter model; accuracy analysis

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## 1 Introduction

The Double-focus One-meter Telescope (DOT) at the Shanghai Astronomy Museum is an alt-azimuth telescope based on an R-C system with an effective primary mirror aperture of 1 m. It features a dual-focus design that allows manual switching between the prime focus and Nasmyth focus, as shown in [Figure 1: see original paper]. The telescope is installed at the Wangshu Observatory of the Shanghai Astronomy Museum in Lingang New City, Pudong District, Shanghai, and was installed and initially adjusted in 2021. The DOT telescope is primarily designed for nighttime public observations and astrophotography, while also supporting student education and selected research projects.

DOT is currently the largest popular science telescope in China. Similar international facilities include the 1.5 m telescope at the Gunma Astronomical Observatory in Japan [1] and the 1 m reflecting telescope at the Gwacheon National Science Museum in South Korea [2], which combine public outreach with professional instruments such as spectrographs and scientific cameras for astronomical research. Likewise, the DOT telescope provides a visual observation system at the Nasmyth focus for public education, while the prime focus is equipped with a large-format scientific CMOS sensor. The large field of view is not only suitable for extended-object observations and live broadcasts of events such as lunar eclipses but also expected to support research programs including surveys for novae and supernovae and monitoring of solar system bodies and artificial satellites. Previous studies indicate that ground-based observations of solar system objects and artificial satellites typically achieve precision ranging from tens to hundreds of milliarcseconds. For example, Zhang et al. obtained positioning precision better than  $0.3''$  for near-Earth asteroids using the Lijiang 2.4 m telescope [3]; Yan et al. achieved  $0.03''$  precision for Neptune's satellites using the Yunnan Observatory 1 m telescope [4]; and Zhang et al. reported  $0.02''$ – $0.3''$  precision for observations of Neptune's and Uranus's satellites with the Shanghai Astronomical Observatory 1.56 m telescope [5, 6]. To demonstrate that the DOT telescope's prime focus can achieve comparable performance, its astrometric precision represents a critical performance metric that guides the selection of feasible research projects. Section 2 describes the telescope's main parameters and test observations, Section 3 presents the image processing and astrometric precision analysis, and Section 4 provides concluding remarks.

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## 2 Telescope Parameters and Observation Data

The prime focus of the DOT telescope has a focal ratio of  $f/2$  and operates at wavelengths of 400–800 nm. It is equipped with a scientific-grade color CMOS camera (QHY411) with a  $14,304 \times 10,748$  pixel array and a pixel size of  $3.76 \mu\text{m}$ , yielding a field of view of  $1.5^\circ \times 1.1^\circ$ . The QHY411 camera has a response bandwidth of 400–1000 nm with a peak quantum efficiency of 0.92. During observations, the camera is cooled by a semiconductor system to approximately  $-30^\circ\text{C}$  below ambient temperature.

To evaluate the astrometric precision at the prime focus, we observed three fields on September 6, 2023. The observation details are listed in . The exposure time was 10 s without filters, and the camera operated in binning=2 mode, corresponding to a spatial resolution of  $0.73''/\text{pixel}$ . [Figure 2: see original paper] shows a typical observation image, and [Figure 3: see original paper] presents the histogram of stellar full-width at half-maximum (FWHM), with mean values of 2.76 pixels ( $2.0''$ ) in the x-direction and 2.48 pixels ( $1.8''$ ) in the y-direction.

**Table 1** Positions of the three observed field centers and number of reference stars

Field No.	RA (J2000)	Dec (J2000)	No. of Images	Avg. Reference Stars
1	$22^h59^m10^s$	$30^\circ26'41''$	20	2400
2	$22^h58^m47^s$	$30^\circ56'33''$	25	2500
3	$22^h58^m47^s$	$29^\circ56'41''$	25	2300

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## 3 Observation Image Processing and Astrometric Precision Analysis

### 3.1 Observation Image Processing

The image processing pipeline includes preprocessing, star detection and centroid measurement, and star identification. In preprocessing, we apply bias, dark, and flat-field corrections to the raw images. lists the preprocessing image information. We then fit the image background with a polynomial to remove non-uniformities caused by sky background [7]. Star detection employs the “connected domain method” [8], centroid calculation uses the “two-dimensional corrected moment” method [9], and star matching utilizes the “arc-length matching” method [10]. The Gaia DR3 catalog serves as the reference star catalog [11, 12].

**Table 2** Preprocessing image information

No.	Image Type	Exposure Time (s)	Frames
1	Bias	0	10 (dome and lens cap closed)
2	Dark	10	10 (dome and lens cap closed)
3	Flat	0.1–0.5	10 (evening, zenith region)

### 3.2 Repeatability Analysis of Measured Stellar Coordinates

We assessed the repeatability of stellar coordinate measurements using consecutive frames of the same field, which reflects the influence of image noise on positional measurements. First, we used common stars and polynomial fitting to remove field translation, rotation, and differential atmospheric refraction between images. Then, for each common star, we calculated the standard deviation of multiple measurements of its centroid coordinates ( $x$  and  $y$ ) to characterize repeatability. Using 20 frames with dense stellar fields containing approximately 2,400 stars, [Figure 4: see original paper] shows the distribution of standard deviation versus SNR. The repeatability improves with increasing SNR: for SNR  $> 5$  (corresponding to magnitude  $\$10.7$ ), the repeatability is better than 0.1 pixel; at SNR = 30 (magnitude  $\$10.15$ ), it improves to better than 0.05 pixel. At higher SNR values, stars become increasingly saturated, causing a slight degradation in repeatability.

### 3.3 Plate Parameter Model Analysis

The plate parameter model describes systematic differences between the measured coordinate system on the image and the ideal celestial coordinate system, including translation, rotation, scale differences, and field distortion. Common models include first-order (6 parameters), second-order (12 parameters), third-order (20 parameters), and fourth-order (30 parameters). The DOT telescope's prime focus has a large field of view of approximately  $1.5^\circ \times 1.1^\circ$ , which can introduce significant non-linear imaging characteristics requiring empirical determination of the optimal model.

Using Gaia DR3 as the reference catalog, we followed standard astrometric procedures to compute reference star positions at the observation epoch, correcting for differential atmospheric refraction and aberration. Ideal coordinates ( $\xi, \eta$ ) were calculated using gnomonic projection. We examined reference star residuals and standard deviations for different plate models, selecting the model with the fewest parameters that yielded the smallest standard deviation and random residual distribution. For all 70 images observed on September 6, 2023, [Figure 5: see original paper] shows the standard deviation results for different models. The third-order model produces standard deviations consistent with higher-order models, with a mean standard deviation of  $0.066''$  across all images.

Notably, when using first- and second-order models, the standard deviations for the last 10 images differ significantly from the first 60, while third- and fourth-

order models show stable results. This occurs because weather changes reduced the number of reference stars in the last 10 images by nearly half, which substantially affects model fitting when using inadequate plate models. Additionally, the “ $3\sigma$ ” clipping of outliers artificially reduces the standard deviation for first- and second-order models. Using images 60 and 61 as examples, [Figure 6: see original paper] shows residual distributions for different models. First- and second-order models exhibit significant systematic distortion in residuals, while the third-order model yields randomly distributed residuals consistent with the fourth-order model. This demonstrates that the third-order plate parameter model is optimal for DOT prime focus observations, accurately describing the imaging characteristics.

### 3.4 Astrometric Precision Analysis

To analyze the astrometric precision of the DOT telescope’s prime focus, we used Gaia DR3 as the reference catalog with third-order plate modeling to examine positional residuals across different magnitudes. For stars brighter than 18 mag, Gaia DR3 provides positions, parallaxes, and proper motions with precision better than 0.1 mas, making the reference star residuals entirely reflective of instrumental errors. We calculated RMS errors in 0.5 mag bins using  $\text{RMS} = \sqrt{\sum \Delta^2/n}$ , where  $\Delta$  is the observational error for each reference star and  $n$  is the number of reference stars.

[Figure 7: see original paper] shows the distribution of residuals, RMS errors, and reference star counts versus magnitude. Stars brighter than 15 mag achieve a precision of approximately  $0.05''$ , with precision gradually decreasing to about  $0.1''$  at 17.5 mag.

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## 4 Conclusion

The DOT telescope is currently the largest popular science telescope in China. Its Nasmyth focus serves public visual observations, while the prime focus is equipped with a large-format scientific CMOS sensor providing a  $1.5^\circ \times 1.1^\circ$  field of view. This large field is suitable for both live broadcast events of important astronomical phenomena and research applications including surveys for novae and supernovae, monitoring of small solar system bodies, and tracking artificial satellites.

Based on actual observations, we analyzed the astrometric precision at the prime focus. The results show that for star images with  $\text{SNR} > 5$ , the repeatability of measured coordinates is better than 0.1 pixel, improving to better than 0.05 pixel at  $\text{SNR} = 30$ . Using Gaia DR3 as a reference, we compared four plate models and found significant non-linear characteristics in the CMOS images, requiring third-order (20-parameter) terms in the plate model. For the test data, stars brighter than 15 mag achieve a precision of approximately  $0.05''$ , decreasing to about  $0.1''$  at 17.5 mag. This test demonstrates that the DOT

telescope's prime focus delivers astrometric performance comparable to conventional ground-based telescopes, providing a valuable reference for future research programs.

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