# NVST Long-term Tracking Error Analysis and Corrected Record

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**Date:** 2017-10-20T00:00:00+00:00

## Abstract

Owing to the structural characteristics of the 1 m solar telescope main body, photoelectric guiding system, and instrument derotator platform, the long-term tracking accuracy of the telescope remains relatively low even after the photoelectric guiding system is closed-loop. To address this problem, we first analyzed the causes of time-varying tracking errors based on the telescope' s structural characteristics, then investigated the error variation features through theoretical and experimental analysis, and studied how to detect image motion in the high-resolution imaging observation system at the coudé focus F3 using relevant algorithms, smooth high-frequency components, and separate low-frequency components for feedback to the telescope pointing and tracking system, thereby further improving the telescope' s long-term tracking accuracy. Finally, closed-loop tracking experiments were performed on the Ti0 channel of the high-resolution imaging observation system. The experimental results demonstrate that during the 4-hour closed-loop tracking period, the root mean square value of the tracking error was 0.52 arcseconds, indicating that implementing closed-loop tracking for the telescope using image motion from the coudé focus F3 imaging observation system can enhance the telescope' s long-term tracking accuracy.

## Full Text

## Long-term Tracking Error Analysis and Correction for the New Vacuum Solar Telescope

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**Abstract**

Due to the structural characteristics of the solar telescope main body, photoelectric guiding system, and terminal instrument derotation platform, the telescope' s long-term tracking accuracy remains low even after the photoelectric guiding system is closed-loop. To solve this problem, we first analyzed the reasons for tracking error variation over time based on the telescope' s structural characteristics, then theoretically and experimentally analyzed the error variation characteristics. We studied how to detect image motion in the high-resolution imaging observation system at the coudé focus F using correlation algorithms, smooth high-frequency components, and separate low-frequency components to feed back to the telescope positioning tracking system to further improve long-term tracking accuracy. Finally, closed-loop tracking experiments were conducted in the high-resolution imaging observation system channel. The experiments show that during one hour of closed-loop tracking, the RMS value of tracking error is 0.52 , demonstrating that closed-loop tracking of the telescope using image motion in the coudé focus F observation system can improve long-term tracking accuracy.

**Keywords:** New Vacuum Solar Telescope; Long-term tracking error; Coudé-focus imaging system; Closed-loop tracking

## 1. Introduction

The New Vacuum Solar Telescope (NVST) is an important solar observation facility in China, with the scientific objective of performing high-resolution imaging and spectroscopic observations of the Sun. This requires the telescope' s photoelectric guiding closed-loop tracking accuracy to reach 0.3 /30s and 1 /10min [1-2]. However, due to structural characteristics of the telescope main body, photoelectric guiding system, and terminal instrument derotation platform, the long-term tracking precision remains low even after photoelectric guiding closed-loop operation. This creates significant challenges for long-term imaging observations or spectral scanning observations of specific targets.

Since the target at the coudé focus F in the terminal observation system continues to drift over time, we first analyzed the reasons for the photoelectric guiding closed-loop tracking error variation from the overall telescope structure. Through theoretical and experimental analysis, we then proposed a coudé focus local solar image closed-loop tracking scheme. By detecting image motion in the high-resolution imaging observation system channel at the coudé focus point and using it for telescope closed-loop control, we can improve long-term tracking accuracy. This coudé focus local solar image closed-loop control method can effectively solve the problem of low long-term tracking precision.

## 2. Causes of Long-term Tracking Error

The NVST employs an alt-azimuth (AZI-ALT) mount. The photoelectric guiding system is a small telescope with an aperture of [missing value] mounted on the back of the main telescope tube, achieving closed-loop control by detecting the center of gravity of the full solar disk. The guiding system also provides full-disk solar images to facilitate selection of local observation targets on the solar surface.

All terminal systems are installed on a rotatable platform—the focal plane where the coudé focus F is located. The current terminal systems include a multichannel high-resolution imaging observation system (including a white-light channel), a spectrometer, and a large dispersion spectrometer. The image field rotation caused by alt-azimuth tracking must be eliminated.

The primary goal of the NVST tracking system is to keep a specific solar observation target stably centered in the field of view of its observation system for extended periods. The photoelectric guiding system is completely independent of the main mirror system. To achieve high-precision closed-loop control, the guiding system' s optical axis must be strictly parallel to the telescope' s main optical axis. However, due to various factors, this strict parallelism cannot be maintained during tracking. The main reasons for non-parallelism include gravity-induced deformation of the guiding mirror mounting structure [3-4], flexure of the telescope' s main optical axis, and thermal deformation of the guiding mirror.

Currently, the photoelectric guiding closed-loop tracking primarily corrects errors introduced by imprecise solar theoretical position, slow variation of the telescope encoder system, telescope mount installation, and atmospheric refraction. Errors caused by solar rotation can only be corrected through theoretical models. The image field at the coudé focus F of the telescope' s terminal system requires derotation. The NVST terminal system uses mechanical derotation [5]. Observation targets in the terminal system continue to drift over time due to tracking errors and derotation errors. Even after the photoelectric guiding system is closed-loop, observation targets in the terminal system continue to change.

Based on the above analysis, the telescope' s long-term tracking errors mainly consist of two parts: tracking errors caused by insufficient photoelectric guiding system capability, and tracking errors caused by derotation. We collectively refer to both as the telescope' s long-term tracking error, i.e., derotation error.

## 3. Derotation Error Simulation Analysis

The image rotation in the telescope terminal system is determined by its system structure. Figure 2 shows the telescope' s optical path diagram. The image rotation in the optical system M passing through the telescope' s altitude axis is the image rotation during alt-azimuth tracking. Ideally, the image rotation components in the terminal system at the coudé focus F plane consist of three components: rotation about the azimuth axis, rotation about the altitude axis, and rotation of the main optical axis. The rotation centers of these three components should completely coincide and be the same point as the rotation center of the terminal system derotation platform. However, during telescope installation, these rotation centers cannot be made to coincide perfectly.

Taking the target surface in the telescope's high-resolution imaging system as an example for analysis, the method and steps are: first assume the system has no tracking error. The rotation centers of the three image rotation components are calculated using the method from reference [5]. O is the rotation center of the derotation platform, with coordinates expressed in image pixels. The simulation time is selected on the summer solstice, 30 minutes before solar transit, when image rotation is fastest.

Figure 3 shows the simulation results. The trajectories of star images are not concentric circles, indicating that the centers of the three image rotation components of the telescope are inconsistent and do not match the rotation center of the derotation platform. When the derotation platform is activated for derotation, derotation errors still exist in the star images, consistent with the simulation analysis results.

## 4. Long-term Tracking Error Measurements

When measuring the telescope' s long-term tracking error, different methods were used to reflect both photoelectric guiding closed-loop tracking error and derotation error. When measuring photoelectric guiding closed-loop tracking error, a solar active region was selected as the target [5]. The measurement time was chosen when the image field rotation was slow to minimize derotation error impact. The test time was selected at transit, and the measurement time was kept short to reduce tracking errors.

The photoelectric guiding closed-loop tracking error is shown in Figure 4. The test was conducted in Beijing time, with an image field rotation speed of 1.6 /s. The high-resolution imaging observation system channel recorded target images. To reduce atmospheric effects, the error value was obtained by averaging the correlation displacement of 30 images. The sampling totaled 600 images within one hour. The test results show that after photoelectric guiding closed-loop operation, the image moved at speeds up to 9.8-13.6 /s within one hour.

Derotation error measurements primarily track star trajectories. When the derotation platform is not activated, the high-resolution imaging observation system channel recorded the changing trajectories of four stars: SAO 91781 (0h 14m 4.08s, 15°16 26 ), SAO 75012 (1h 55m 32.39s, 20°53 12 ), SAO 93954 (4h 29m 34.29s, 19°12 46 ), and SAO 77336 (5h 38m 37.11s, 21°8 55 ). The rotation trajectories of these star images are not concentric circles, indicating that the centers of the telescope' s three image rotation components are inconsistent and do not coincide with the derotation platform' s rotation center.

## 5. Implementation of Coudé Focus Image Closed-loop Control

The above simulation and measurement analysis shows that if we can detect image offset in the telescope' s coudé focus terminal system in real time, we can feed this offset back to the telescope tracking system for closed-loop control [6]. Based on this feedback control concept and the current system structure, this paper establishes a closed-loop tracking control system using the TiO channel of the high-resolution imaging observation system at the coudé focus.

When the imaging observation system is closed-loop, the photoelectric guiding closed-loop stops working (they cannot work simultaneously, as determined by the acquisition system working mode). To address the telescope' s long-term tracking error, the TiO channel continuously and rapidly acquires images. Correlation algorithms are used to calculate the offset, which is then averaged to smooth turbulence and random wind-induced image jitter. The 30-second average is used to generate the feedback control signal for image motion.

Figure 6 shows the structure diagram of the imaging observation channel closed-loop control system. Since the telescope' s field of view is 3 ×3 and observes only about one percent of the solar surface, image motion detection uses correlation algorithms [7-8]. The specific method involves introducing this detection algorithm into the observation system, with the workflow shown in Figure 7.

## 6. Coudé Focus Closed-loop Tracking Experiments

Based on the above closed-loop control system established using the TiO channel of the high-resolution imaging observation system, closed-loop tracking experiments were conducted on the telescope. A sunspot was selected as the target. During closed-loop experiments, the system continuously detected image offset in the TiO channel and performed closed-loop tracking.

Two sets of test results were obtained. The first test ran from 16:14:37 to 17:54:45 (1 hour 40 minutes), with an RMS tracking error of 0.62 (Figure 8a). The second test ran from 9:35:22 to 13:36:01 (4 hours 1 minute), with an RMS tracking error of 0.52 (Figure 8b). The random fluctuation RMS value is significantly smaller than 0.32 . The results show that this closed-loop method can effectively solve the telescope' s long-term tracking error problem. The tracking error under the coudé focus observation system closed-loop control no longer varies with time.

## 7. Conclusion

Theoretical analysis and experiments demonstrate that the telescope' s long-term tracking error is mainly caused by insufficient photoelectric guiding tracking capability and derotation error. The characteristic of derotation error is synchronous offset of the entire field of view. By detecting image motion in the telescope' s coudé focus high-resolution imaging observation system and using it for closed-loop telescope tracking, long-term tracking error can be improved. The TiO observation system closed-loop tracking experiments well prove this point: during four hours of closed-loop tracking, the tracking error does not vary with time, achieving an RMS value of 0.52 , which shows significant improvement compared to photoelectric guiding closed-loop alone.

To make this method a routine closed-loop tracking mode for the NVST, further research is needed on image motion detection when the target is a quiet region on the solar surface, and a professional closed-loop tracking system independent of the high-resolution observation system should be established in the terminal system at the coudé focus.

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