# Research on the Application of Tip-Tilt Mirror Image Stabilization Control System in NVST (Postprint)

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

## Abstract

Due to the 1 m solar telescope' s adoption of an open observation mode with the dome moved away from the telescope, the telescope tracking system is significantly affected by wind, manifesting as large-amplitude low-frequency jitter in images during observations. To address this issue, an image stabilization system based on a two-dimensional tip-tilt mirror was first designed in the titanium oxide high-resolution imaging channel, according to the telescope's existing optical system and the characteristics of focal plane image jitter under wind load effects. Subsequently, based on the measured characteristics of the two-dimensional tip-tilt mirror system, the system transfer function was established and a controller was designed. In-depth numerical simulation analysis and experimental results demonstrate that under level 5-6 wind conditions, the tip-tilt mirror image stabilization system operating at 25 Hz can control the root mean square value of the 1 m solar telescope' s focal plane image jitter within 0.5" , indicating that the two-dimensional tip-tilt mirror image stabilization system can effectively stabilize image jitter caused by random wind loads on the telescope.

## Full Text

## Abstract

The New Vacuum Solar Telescope (NVST) employs an open observation mode where the dome is moved away from the telescope, making the tracking system highly susceptible to wind disturbances that manifest as significant low-frequency image jitter. To address this issue, we designed a two-dimensional tip-tilt mirror image stabilization system for the TiO high-resolution imaging channel based on the existing optical configuration and characteristics of focal-plane image jitter under wind loading. Using measured performance data of the tip-tilt mirror system, we established its transfer function and designed an appropriate controller. Extensive numerical simulation and experimental analysis demonstrate that under five to six-level wind conditions, the system can control the RMS value of NVST focal-plane image jitter below 0.5  when operating at 25 Hz, confirming that the two-dimensional tip-tilt mirror stabilization system effectively compensates for telescope image jitter induced by random wind loads.

**Keywords:** Random wind loads; Image jitter; Two-dimensional tip-tilt mirror; Control system; Numerical simulation

## 1. System Structure Design

The cross-sectional structure of the 1 m NVST is shown in Figure 1: see original paper. Terminal instruments are mounted on the spectrograph' s upper platform, which rotates synchronously with the focal-plane image. The NVST high-resolution imaging system currently has two channels: a 656.3 nm H  channel and a 705.8 nm TiO channel [14]. For the tip-tilt mirror experiment, the mirror was installed in the TiO channel optical path without beam splitting, as illustrated in Figure 1: see original paper.

The tip-tilt mirror is a two-dimensional piezoelectric steering platform (model XS-340.4SL) from CoreMorrow, with a 30 mm diameter mirror and 6 mm thickness. The controller is model XE-501D. The closed-loop operation proceeds as follows: at the start of closed-loop operation, the reference position on the TiO channel image is established. When random wind loads cause image jitter, the system calculates the image offset relative to the reference position using the TiO channel data. This offset is then converted into a control voltage signal that drives the tip-tilt mirror to rotate and return the image to the reference position. The control schematic is shown in [Figure 2: see original paper].

## 2. Measurement of Image Jitter and Mirror Characteristics

### 2.1 NVST Focal-Plane Image Jitter Measurement

Random wind loads acting on the NVST tube manifest as image jitter in both the servo system error and the photoelectric guidewire full-disk image monitoring system. In the high-resolution imaging system, we focus on image jitter in the TiO channel. When observing stars, we use a centroid algorithm to calculate position offsets; when observing solar active regions, we use correlation algorithms. For this study, we selected stars as observation targets.

The measured image jitter in X and Y orthogonal directions and its spectrum distribution are shown in [Figure 3: see original paper], with corresponding RMS and peak-to-valley values listed in . The data indicate that the image jitter range is approximately ±10 , establishing that the tip-tilt mirror' s maximum deflection angle must exceed this value. The primary frequency components are below 25 Hz, suggesting that the bandwidth required for image stabilization is not particularly high.

### 2.2 Tip-Tilt Mirror System Characterization

The mirror system characteristics include static and dynamic properties. Static characteristics comprise maximum deflection angle and voltage response linearity, while dynamic characteristics involve step response and frequency response.

For static testing, we inserted a laser into the TiO channel optical path and measured the laser spot centroid variation with input voltage to the XE-501D controller (voltage range: -10 V to +10 V). Dynamic testing utilized the controller’ s internal piezoresistive position sensor feedback signal rather than camera data, as camera exposure and readout times cannot meet the dynamic test requirements. The XE-501D controller can operate in either open-loop or closed-loop mode; however, the closed-loop mode corrects nonlinearity at the cost of reduced response speed. Since the image stabilization system requires faster response and operates as an outer control loop that can compensate for mirror nonlinearity, we employed open-loop mode for the controller.

The open-loop dynamic and static characteristics in both orthogonal directions are shown in [Figure 4: see original paper]. The data reveal a nonlinear relationship between deflection angle and control voltage. Through polynomial fitting, we obtained the voltage-deflection angle relationships:

For X-direction:

$$\theta_x = -1.47 + 1.65V^5 - 7.951V^4 + 7.936V^3 - 2.5V^2 + 1.146V$$

For Y-direction:

$$\theta_y = -0.139 + 0.049V^5 - 0.299V^4 + 1.838V^3 - 2.17V^2 + 4.46V$$

where $\theta_x$ and $\theta_y$ represent deflection angles in X and Y directions (in arcminutes), and $V$ is control voltage. The maximum deflection angles for the TiO channel are 17.544 and 13.275 respectively.

Step response characteristics depend on control voltage amplitude. At 1 V input, X-direction step response time is 460 s and Y-direction is 6.3 ms, yielding maximum frequency responses of approximately 1 kHz and 80 Hz respectively. At 10 V input, response times are 6.052 ms and 6.3 ms, with X-direction response time of 460 s and Y-direction of 6.3 ms.

## 3. Numerical Simulation of Closed-Loop Control System

### 3.1 Transfer Function Establishment

The control schematic in [Figure 2: see original paper] can be represented as a transfer function block diagram [Figure 5: see original paper]. Besides the mirror as the controlled object, other components’ transfer functions are readily obtainable. The key is determining the mirror system’ s transfer function.

During step response testing, the system exhibits microsecond-level delay, and the piezoresistive sensor feedback voltage (or mirror rotation angle) varies linearly with time—a ramp response. The transfer function can be simplified as:

$$G_{Mirror}(s) = \frac{K_{Mirror}}{s} e^{-t_{d,Mirror} s}$$

where $t_{d,Mirror}$ is the mirror system delay (60  s) and $K_{Mirror}$ is the slope representing angular velocity versus time (in milliseconds), independent of control voltage amplitude. From Figure 4: see original paper and (c), we obtain $K_X = 2.994$ and $K_Y = 4.130$.

System delay components include: digital-to-analog conversion (several microseconds), camera exposure time (several milliseconds), image readout time, and centroid calculation time. For 300×300 pixel images, total system delay is approximately 20 ms.

### 3.2 PID Controller Design and Parameter Optimization

Numerical simulation based on the transfer function was performed in MATLAB to design a PID controller. Performance metrics include RMS value of residual image jitter after correction. The PID controller uses the form:

$$G_{PID}(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s\right)$$

where $K_p$ is proportional gain, $T_i$ is integral time constant, and $T_d$ is derivative time constant. The design objective is minimizing RMS error while ensuring fast response with minimal overshoot.

With system delay fixed at 20 ms and control frequency at 25 Hz, we evaluated various $K_p$, $T_i$, and $T_d$ combinations. shows RMS error values for different PID parameters. Analysis reveals that when $K_p = 0.013$, $T_i = 0.001$, $T_d = 0.00005$, both X and Y directions achieve near-minimum RMS values with overshoot below 5%. The unit step response curves for these parameters are shown in [Figure 6: see original paper].

The relationship between control performance, delay time, and sampling frequency was also investigated. Figure 7: see original paper shows that with 20 ms delay, RMS error decreases with increasing control frequency up to 30 Hz, beyond which improvement becomes negligible. Figure 7: see original paper demonstrates that for frequencies of 20 Hz, 25 Hz, 50 Hz, and 100 Hz, RMS error remains relatively constant for delays below 40 ms but increases significantly beyond this threshold. The maximum allowable delays are 88.352 ms for X-direction and 80.625 ms for Y-direction before correction becomes ineffective.

summarizes simulated image jitter performance at different control frequencies with 20 ms delay. At 25 Hz, the system achieves RMS errors of 0.4076  in X and 0.4588  in Y directions. [Figure 8: see original paper] shows the simulated error time series at 25 Hz with 20 ms delay.

## 4. Experimental Validation

Based on numerical simulation results, we conducted closed-loop experiments under high wind conditions with the telescope fully exposed and facing the wind.

With the system in open-loop, image jitter under corresponding wind conditions is shown in Figure 9: see original paper and (b). When the tip-tilt control loop is closed at frequencies of 21.9 Hz, 27.9 Hz, and 38.8 Hz, the resulting image jitter is shown in Figure 9: see original paper. lists RMS error values versus control frequency. While performance generally improves with increasing frequency, the results also depend on wind direction and interaction geometry. At 38.8 Hz, both X and Y directions achieve RMS values below 0.5 , demonstrating effective stabilization.

## 5. Conclusion

Through numerical simulation and experimental validation, we have demonstrated that a tip-tilt mirror image stabilization system can effectively compensate for random wind-induced image jitter in the NVST operating under five to six-level wind conditions. With system delay of 20 ms and control frequency of 25 Hz, the system controls image jitter RMS below 0.5 . The CoreMorrow XS-340.4SL piezoelectric tip-tilt mirror provides sufficient dynamic performance for this application. Multiple experiments confirm the simulation predictions, validating the effectiveness of this approach for stabilizing wind-induced image jitter in solar telescopes.

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