

Closed-loop correction for slow-varying tracking error at the AIMS Coudé Focal Plane

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Abstract: The Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) project requires a root-mean-square tracking accuracy of 1" per 30 min to observe targets on the solar disk. Since the terminal scientific instruments in AIMS are positioned at the Coudé focus, the telescope and guiding optical path introduce slowly varying nonlinear tracking errors during solar tracking, which degrade long-duration tracking accuracy. To address this issue, we first analyze the mechanisms and characteristics of these slowly varying tracking errors at the Coudé focus, based on the optical-mechanical structure of AIMS and motion principles, and conduct actual measurements of the tracking errors. We have designed a closed-loop correction scheme in conjunction with the optical-mechanical mechanisms of AIMS, detailing both hardware and software implementations. Following over a year of testing and trial use on AIMS, results demonstrate that the system can stably perform closed-loop tracking of solar observation targets for over 30 min, with a tracking error of less than 1.0". Both the tracking duration and error value meet tracking accuracy requirements.

Keywords: AIMS telescope; Coudé focus; Tracking accuracy; Error detection; Closed-loop correction

1. INTRODUCTION

The Accurate Infrared Magnetic field measurements of the Sun (AIMS) project, funded in 2014 by the National Natural Science Foundation of China under the National Major Scientific Instrument Development Project (Ministerial Recommendation), is installed at the Saishiteng Mountain in Lenghu, Qinghai Province. It began scientific trial observations in September 2023. The core scientific objective of AIMS^[1] is to establish a mid-infrared observation system for astronomical observations and to overcome a century-old bottleneck in solar magnetic field measurements—the dependence on solar atmospheric models during polarization measurement inversion for magnetic fields, and the significantly lower accuracy in measuring the transverse component compared with the longitudinal component. AIMS aims to improve the current accuracy of solar magnetic field measurements by approximately an order of magnitude, achieving a measurement precision of 10 Gauss. Operating in

the mid-infrared band at the MgI 12.3 μm wavelength, AIMS directly records magnetic field strength by measuring Zeeman splitting, which requires high spectral resolution. The core scientific instrument of AIMS is a Fourier Transform Infrared (FTIR) spectrometer, paired with a high-performance mid-infrared detector, with a target spectral resolution of 0.004 cm^{-1} (corresponding to 0.06 nm at a wavelength of 12.32 μm). Its imaging capability also requires a large field of view (FOV), of 192" $\times$ 192".

Due to current challenges in developing large-area, high-performance infrared detectors comparable to those used in FTIR spectrometry, AIMS employs a solution using a 64 $\times$ 2 linear array detector with a pixel resolution of 1.5". Given the limitations of the linear array detector, achieving wide-field imaging with the FTIR spectrometer requires scanning technology, which takes at least 30 minutes to complete a single scan and acquire wide-field observation data. Therefore, AIMS requires a control system that enables the FTIR to select, locate, and precisely track solar surface observation targets. During the 30-min

scanning observation of a specific solar target by the FTIR spectrometer, the solar target image must maintain a root-mean-square (RMS) stability within 1.0" on the FTIR linear array detector and must not move outside the detector's field. When performing multiple consecutive scans, the target cannot be lost, or the images within the FOV will be incomplete. This means that AIMS requires the pointing and tracking control system to achieve stable tracking accuracy of 1.0" during a 30-min solar surface target observation, which is the core issue addressed by this study.

The type of tracking scheme used in the control system is closely related to the telescope's optomechanical structure. The main optomechanical body of AIMS consists of a 1-meter aperture off-axis Gregorian system and a horizontal-mount solar telescope (see Fig. 1). Scientific instruments, such as the FTIR spectrometer, are installed

at the Coudé focus, located at the rear end. Between the primary and secondary mirrors and the Coudé focus, there is a complex guiding optical path, a five-mirror depolarization system, and a collimation system.

During the initial trial operation of AIMS, the control system employed full-disk photoelectric guiding combined with the Coudé focus pointing tracking error model, as well as primary and secondary mirror optical axis bending error modeling, to track solar disk targets. However, this approach failed to achieve the desired results. After multiple tests over a 30-min observation period, the image deviation at the Coudé focus of AIMS exceeded 10.0", with a maximum measured deviation of 15.47". At this level of tracking accuracy, the core scientific instrument of AIMS, the FTIR spectrometer, cannot perform wide-field imaging observations, preventing AIMS from fulfilling its intended scientific objectives.

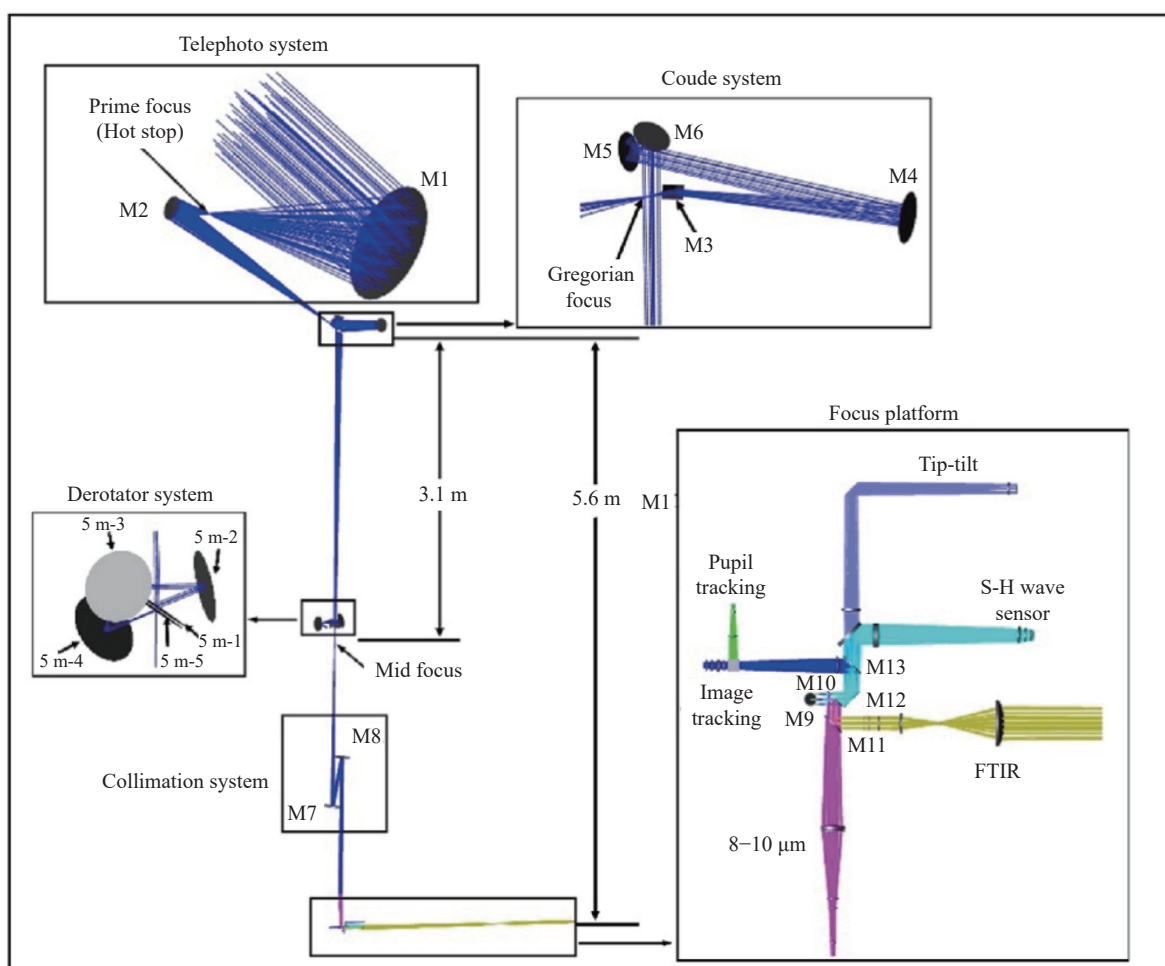


Fig. 1. The optical system of AIMS^[1]. The primary optical assembly, formed by M1-M2, is an off-axis Gregorian system. M3-M6 show the folded optical path, and the five-mirror derotator (composed of five flat mirrors) is positioned between M6 and M7. M7-M8 form the collimating optical path. Beyond M9 is a complex beam-splitting system that directs light to respective terminal scientific instruments.

AIMS is also intended to adopt precision tracking technologies from other solar telescopes, to address its tracking challenges. The first approach is the correlation tracking technique, commonly used in high-precision solar tele-

scope tracking. This method determines the displacement of solar surface images through a correlation algorithm and feeds the data back to a fast steering mirror for closed-loop tracking^[2,3]. These technologies have been

implemented in China's 1-meter New Vacuum Solar Telescope (NVST)^[4,5], the 1.8-meter Chinese Large Solar Telescope (CLST)^[6,7], the 1-meter Swedish Solar Telescope^[8–10], Germany's 1.5-meter telescope GREGOR^[11–13], the U.S. 1.6-meter Goode Solar Telescope^[14–16], and the 4-meter Daniel K. Inouye Solar Telescope (DKIST)^[17–19]. The correlation tracking system for AIMS is still under development, and its limited range of motion currently cannot effectively resolve the tracking issues. Therefore, the pointing and tracking control system must reduce the error magnitude within a working range comparable to the FOV before tracking accuracy can be improved to the sub-arcsecond level. As another consideration, Yuchao Chen and colleagues utilized a high-resolution data acquisition system on the NVST to extract image offsets at the NVST Coudé focus, and fed this information back to the telescope's pointing and tracking control system to correct slow-varying tracking errors^[20]. We have conducted experiments applying this method to AIMS, but this introduced new issues. Specifically, when correcting tracking errors caused by relative motion in the guiding optical path, through pointing and tracking adjustments, excessive realignment of the primary and secondary mirror optical axes relative to the guiding optical path causes vignetting. This occurs because the limited aperture size of the mirrors in the AIMS five-mirror depolarization system restricts the optical path, adversely affecting the normal working FOV at the AIMS Coudé focus. Consequently, this method is unsuitable for AIMS. However, if AIMS cannot achieve precise tracking of solar observation targets, its core scientific instrument, the FTIR spectrometer, will be unable to conduct stable observations, causing AIMS to fail in achieving its scientific objectives. This means that it is imperative to develop a new precise tracking control solution tailored for AIMS.

By considering AIMS tracking requirements and the optomechanical system structure, we thoroughly analyze the generation mechanism and characteristics of AIMS Coudé focus tracking errors and propose a closed-loop control scheme based on folded-axis optical axis correction. This approach involves real-time detection of AIMS tracking errors at the Coudé focus, followed by feedback to the M5 mirror near the pupil plane in the guiding optical path, to adjust the optical axis, thereby correcting slow-varying tracking errors at the Coudé focus. In this paper, Section 2 provides an in-depth analysis of the generation mechanisms and characteristics of tracking errors on the AIMS Coudé focus, Section 3 introduces the design of the slow-varying tracking error closed-loop correction system, Section 4 presents the experimental results of this correction system, and Section 5 offers a summary and conclusions.

2. MECHANISM AND CHARACTERISTICS OF THE TRACKING ERROR

2.1. Tracking Error Mechanism

During the AIMS observation process, the solar disk target image continuously moves and changes on the

Coudé focal plane, for a few different reasons^[21–26]. Firstly, tracking errors arise from imperfections in the manufacturing and installation of the optical-mechanical system. After the initial installation of the telescope, these errors are on the order of several arcminutes and vary slowly with the telescope's pointing. In addition, errors caused by astronomical factors, such as atmospheric refraction and movement of the target with the Sun's rotation, also result in slowly varying tracking errors that can be compensated for using models. Image jitter is also introduced by the telescope's axis servo system. These errors are typically within one arcsecond and vary at frequencies on the order of tens of hertz. The measured RMS value of the AIMS axis servo error is better than 0.1", rendering its impact on tracking at the Coudé focal plane negligible. A final problem is that high-frequency image jitter, caused by random atmospheric turbulence, usually varies at frequencies of several tens of hertz, with magnitudes of a few arcseconds. With AIMS, we intend to use a correlation tracking system to correct for this.

Among the four types of error mentioned above, the slow-varying tracking error introduced by the AIMS optomechanical system is closely related to manufacturing and installation errors of its components. These errors include tracking errors caused by misalignments between the telescope mount coordinate system and the theoretical coordinate system, tracking errors resulting from bending and sagging of the primary and secondary mirrors during tracking, and tracking errors introduced by relative motion among system components during tracking and field derotation^[8]. To address tracking errors arising from misalignments between the telescope mount coordinate system and the theoretical coordinate system, AIMS employs an all-sky photoelectric guiding and pointing model. This compensates for tracking errors caused by bending and sagging of the primary and secondary mirrors during tracking by establishing predictive models in advance. Nevertheless, AIMS still experiences tracking errors exceeding tens of arcseconds, primarily caused by relative motion occurring during the telescope's tracking and field derotation processes among the AIMS backend guiding optical path. Other sources of tracking errors are the five-mirror derotation system and the primary and secondary mirror assemblies.

In the AIMS optomechanical system (shown in Fig. 1), the main optical path preceding M9 divides into four segments: the M1-M2 optical axis, which experiences flexure with telescope elevation; the M3-M5 folded path axis, requiring alignment with the telescope's elevation mechanical axis; the M6-to-derotator axis, which must coincide with the azimuth mechanical axis, and; the derotator-to-M7 axis, maintaining alignment with the derotation mechanical axis (the post-M7 optical axis remains fixed during pointing/tracking).

Under actual operating conditions, inherent manufacturing and installation tolerances prevent perfect alignment among these optomechanical axes. Their projection onto

the focal plane of the error-detection camera at the Coudé focus follows the geometric model shown in Fig. 2.

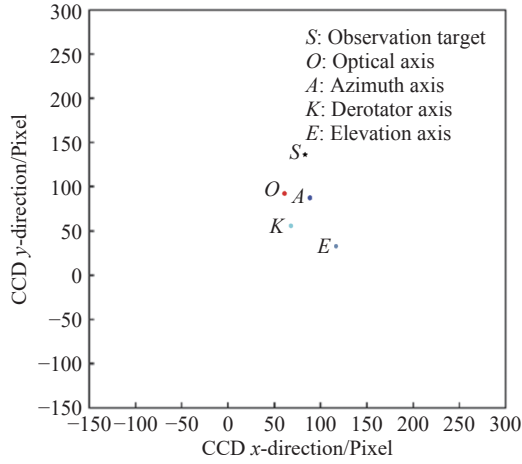


Fig. 2. Geometric distribution of projections from the AIMS mechanical axis centers onto the Coudé focal plane.

During AIMS tracking^[27], S rotates around O as the object-space field rotation, according to the relation

$$\theta = \arccos\left(\frac{\sin \varphi - \sin E \sin \delta}{\cos E \cos \delta}\right), \quad (1)$$

where θ is the object-space field rotation angle generated by the alt-azimuth coordinate system, E is the elevation angle, φ is the geographical latitude of the telescope site, and δ is the right ascension of the observation target.

S rotates around E as the image-space field rotation, following the relation

$$E = \arcsin(\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos H), \quad (2)$$

where H is the hour angle of the observation target.

S rotates around A as the image-space field rotation, following the relation

$$A = \arccos\left(\frac{\sin \delta - \sin E}{\cos E \cos \varphi}\right), \quad (3)$$

and S rotates around K as the Coudé focus derotation, according to the relation

$$\theta_k = \theta + A + E + C, \quad (4)$$

where θ_k is the derotation angle of the five-mirror assembly and C is a constant related to instrument orientation.

2.2. Tracking Error Characteristics

Once the telescope is installed, measuring the positions of these projected axis centers at the Coudé focus can theoretically allow error variations to be inferred. However, practical engineering constraints prevent this approach^[28]. Accurate instrumentation for direct measurement at Coudé focus of AIMS is physically unfeasible, projection points dynamically shift because of environmental

factors and telescope attitude changes, and coordinate mapping, from Coudé focus measurements to individual instrument focal planes, cannot be reliably achieved. Additionally, residual time-varying errors persist in both the photoelectric guiding system and primary-secondary mirror flexure, despite model-based compensation. These uncorrected errors ultimately manifest as tracking errors at the Coudé focus, and consequently, neither theoretical modeling nor empirical measurement can establish an ideal error-correction model meeting the slow-varying tracking error requirements of AIMS. Liu et al. conducted simulations revealing key characteristics^[29,30]. Error variation exhibits nonlinear behavior, peak variation rate occurs during summer solstice meridian passage, and error consistency across the entire FOV enables correction via either error modeling or closed-loop control. Machine-learning-assisted modeling was shown to improve pointing accuracy. Though integrated during the commissioning of AIMS, this approach still failed to satisfy tracking precision requirements, because of time-varying errors and environmental interference. Multiple open-loop tracking error measurements at the Coudé focus confirmed 30-min error amplitudes exceeding 10". Fig. 3 shows three representative sets of these open-loop tracking error magnitudes over time.

3. CLOSED-LOOP COMPENSATION SYSTEM FOR SLOW-VARYING TRACKING ERRORS

To address the slow-varying, nonlinear tracking errors at the AIMS Coudé focus over time, we have designed a closed-loop error-correction system, based on the optomechanical structure of AIMS (Fig. 4).

Photospheric images are acquired by splitting a beam using the Coudé focus beam-splitting system. Subsequent attenuation, filtering, and focal-reduction imaging produce images meeting resolution and FOV specifications. We have selected the 550 nm photospheric band to capture sunspots in active regions or granulation under favorable seeing conditions^[31,32], facilitating correlation-algorithm-based image offset calculations while optimizing hardware costs. The M13 mirror is located in the complex spectroscopic system behind M9. Considering factors such as pixel resolution, FOV, image size, and image quality, the optical system disperses light at the M13 mirror at the Coudé focus, with an effective focal length of 13.0 meters and a pixel resolution of 0.1" per pixel. Imaging employs a scientific-grade Andor Zyla 4.2 and a scientific Complementary Metal-Oxide-Semiconductor (sCMOS) camera with a 2K × 2K detector, 16-bit depth, and 3.4' × 3.4' FOV. Optical filtering uses a 550 nm center-wavelength filter with a 5 nm bandwidth, while the attenuation system maintains an Analog-to-Digital Unit (ADU) greater than 2/3 of 16-bit full-well capacity to ensure an optimal signal-to-noise ratio in raw images.

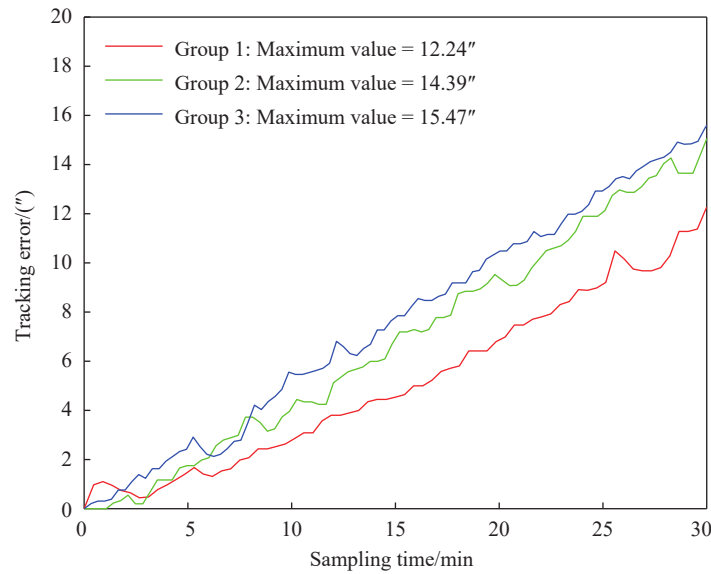


Fig. 3. Open-loop tracking errors at the AIMS Coudé focus. The three curves in the figure show the open-loop tracking errors of three groups of Kord surfaces.

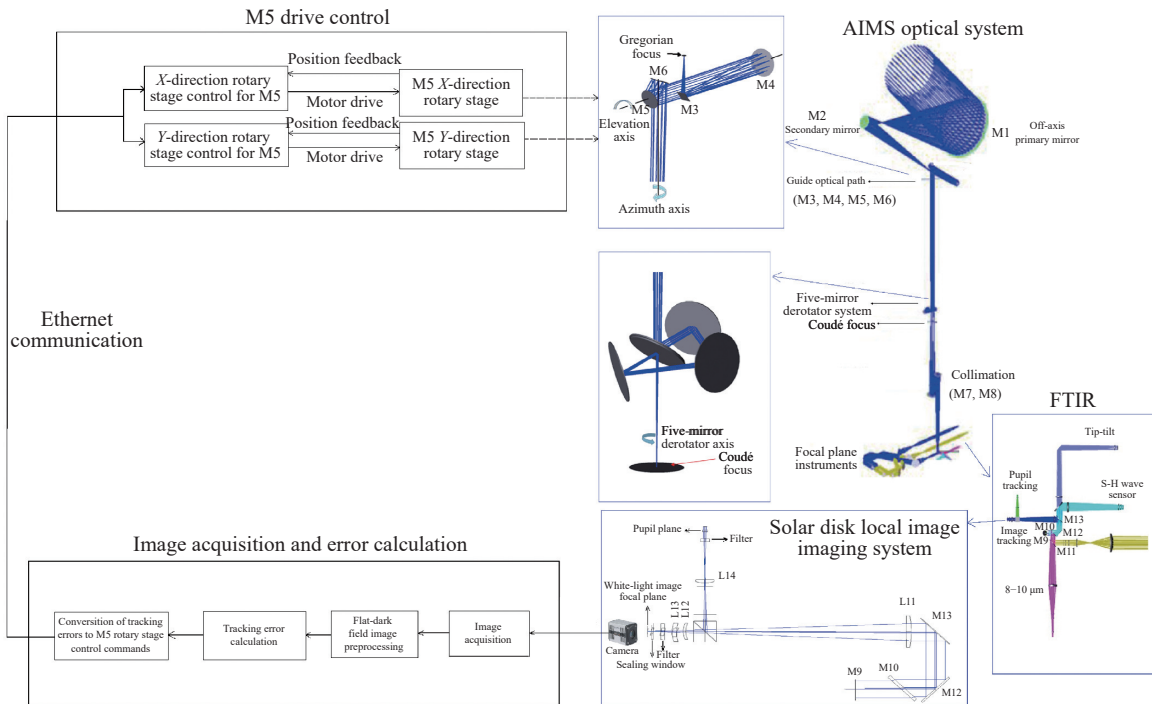


Fig. 4. Schematic of the AIMS slow-varying tracking error closed-loop correction system. The system comprises three functional modules, to acquire photospheric images from the solar disk, to acquire images and calculate error, and for two-dimensional orthogonal fine-steering control of the M5 mirror. Critical aspects of the local photospheric imaging and M5 mirror fine-steering are determined by hardware design/selection, which is tightly coupled with the existing optical system of AIMS. The image acquisition and error computing module is software-controlled, and serves as the operational link between imaging and mirror actuation.

The fine-steering control of the M5 mirror (see Fig. 4) implements an orthogonal two-axis rotation system, with the x -axis driven by a BGS50CC stage and the y -axis by a BGS80CC stage, both controlled by SMC100CC drivers. BGS50CC and BGS80CC are two different models of angular stages, and the SMC100CC is the controller for both of them. They are all manufac-

tured by Newport Corporation. When mapped to the imaging coordinate system, this configuration achieves resolutions of $0.15''$ over $\pm 2.57^\circ$ in the x -direction, and $0.14''$ across $\pm 3.51^\circ$ in the y -direction. During AIMS pointing and tracking operations, differential field rotation across optical subsystems induces relative rotational motion between the M5 mirror's stage assembly and the Coudé

focal plane. Consequently, image offsets (tracking errors) computed in the camera coordinate frame must be transformed into control commands for the two-axis stage of the M5 mirror.

The relationship for angle conversion can be expressed as

$$\theta_{M5} = A_T + 2\theta_k + C_{M5}, \quad (5)$$

where θ_{M5} is the angle between the x - y coordinate system of the M5 mirror actuator, projected onto the imaging system, and the native x - y coordinate system of the camera, A_T is the telescope's azimuth angle. A_T and θ_k can be obtained directly from the telescope pointing/tracking system, and C_{M5} is a constant related to the optical configuration and camera orientation of AIMS, determined using empirical measurement as -103.4278° .

The conversion relationship of the displacement stage in the x -direction can be expressed as

$$M5_{dx} = R_x (D_x \cos \theta_{M5} + D_y \sin \theta_{M5}), \quad (6)$$

where $M5_{dx}$ is the rotation amount of the M5 mirror in the x -direction, D_x and D_y are the displacement components in the x and y directions of the image, respectively, calculated in the camera coordinate system, R_x is the proportional coefficient in the x -direction from the computer image motion to the M5 two-dimensional stage, with a measured value of $0.855''$ per pixel.

The conversion relationship of the displacement stage in the y -direction can be expressed as

$$M5_{dy} = R_y (-D_x \sin \theta_{M5} + D_y \cos \theta_{M5}), \quad (7)$$

where $M5_{dy}$ is the rotation amount of the M5 mirror in the y -direction, and R_y is the proportional coefficient in the y -direction from the computer image motion to the M5 two-dimensional stage, with a measured value of $0.781''$ per pixel.

By combining Equation (5) to Equation (7), the calculated image displacement can be converted into the control signal for the M5 mirror stage. Image processing and error computation involve real-time acquisition of photospheric images and their conversion into rotation angles for the x and y axes of the M5 mirror. Prior to error computation, the first step performs image preprocessing, including flat-field and dark-field corrections. A reference image is then created, and correlation algorithms are used to calculate solar target offsets (i.e., tracking errors).

The cross-correlation matrix, $C_{LR}(x, y)$, can be found using the relation

$$C_{LR}(x, y) = \text{IFFT} \{ \text{FFT} [I_R(x, y)] \times \text{FFT}^* [I_L(x, y)] \}, \quad (8)$$

where $I_R(x, y)$ is the reference image, $I_L(x, y)$ is the currently acquired image, IFFT is the Inverse Fourier Transform, FFT is the Fourier Transform, and FFT^* is the Conjugate Fourier Transform. The cross-correlation matrix yields two-dimensional correlation curves along the x and

y directions. The peak location is identified, and a centroid calculation is performed within its vicinity to determine image displacement. This pixel offset is converted to tracking error using the pixel scale, then transformed into M5 mirror control commands using Equation (5)–Equation (7). To mitigate atmospheric turbulence effects, the process is repeated for multiple acquisition cycles. Control values are averaged before being sent to the M5 stage system. On receiving commands, the M5 mirror is rotated to adjust the optical path, recentring the solar image at the Coudé focus to the predefined reference point, completing one closed-loop correction cycle for a specific solar target. For subsequent cycles, when tracking error falls below $0.1''$, the reference image is updated to accommodate solar feature evolution. This iterative process enables continuous closed-loop tracking of solar observation targets. The system workflow is shown in Fig. 5.

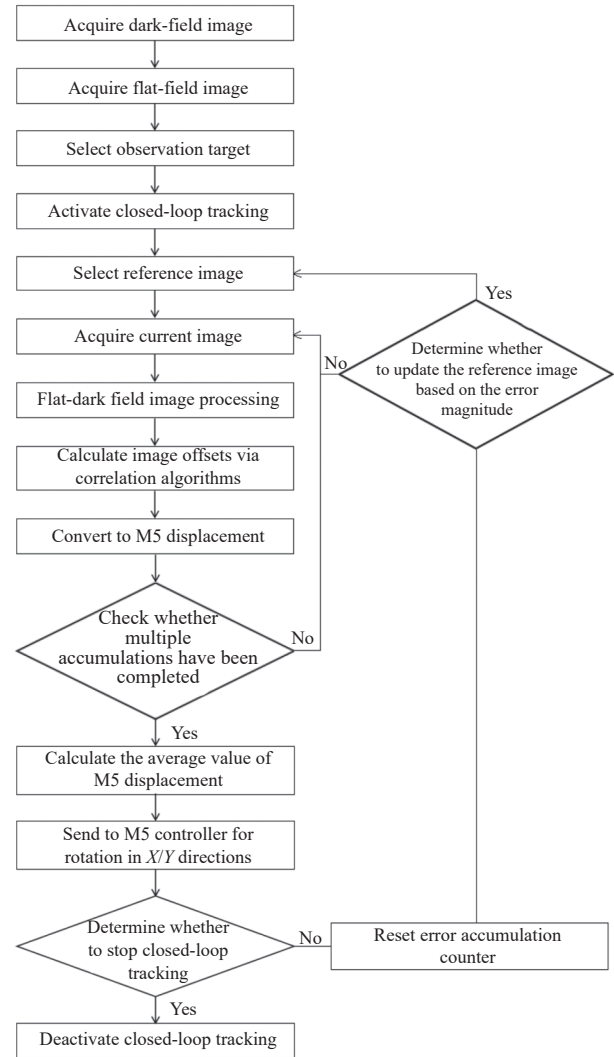


Fig. 5. Workflow of the closed-loop correction system.

The operating frequency of the system is primarily influenced by the rate of change of the open-loop tracking error on the Coudé focus plane, the system's resolution, and the smoothing effect on random atmospheric turbulence. According to the measured results shown in Fig. 3, the maximum change in the Coudé focus plane

open-loop tracking error over 30 minutes is $15.47''$, corresponding to a rate of change of $0.0086'' \text{ s}^{-1}$. The resolution of the error-detection system is $0.1''$, while the control resolution of the M5 mirror turntable in the error-correction system is $0.14''$ and $0.15''$ in two orthogonal directions. Therefore, the detection system can identify a minimum error change occurring over 11.6 s, and the execution system can correct a minimum error change occurring over 16.3 s. Using correlation algorithms to detect errors, the time required from image exposure, acquisition, and flat-field correction to completion of the correlation algorithm depends on the size of the active region during observation, ranging from 0.5 to 1.0 s. After multiple experimental tests, smoothing high-frequency image jitter caused by random atmospheric turbulence, using 20 image frames, is considered optimal. After smoothing, the RMS value of the error detection is less than $1.0''$, and under good seeing conditions, the RMS value can reach approximately $0.5''$. Consequently, the control cycle should be set to between 10.0 and 20.0 s, corresponding to a frequency range of 0.1 Hz to 0.05 Hz. When the control cycle is less than 10 s, the Coudé focus plane open-loop tracking error change of $0.086''$ is already smaller than the error-detection system's resolution of $0.1''$, rendering further reduction of the control cycle ineffective. When the control cycle is 20 s, the Coudé focus plane open-loop tracking error change is $0.172''$, which is close to the resolution of the M5 error-correction system, and is therefore reasonable.

4. EXPERIMENT ON THE SLOW-VARYING TRACKING ERROR CLOSED-LOOP CORRECTION SYSTEM

4.1. Closed-loop Stellar Tracking Experiment

Because point sources facilitate more straightforward calibration than extended sources, we initially chose a stellar point source for system testing to validate workflow integrity, parameter correctness, and control logic. Stellar positions were calibrated via centroid algorithms, to determine image offsets.

After flat/dark-field correction, the centroid coordinates (x_c, y_c) are computed as

$$x_c = \frac{\sum_{i=1}^m \sum_{j=1}^n i \times j \times f(i, j)}{\sum_{i=1}^m \sum_{j=1}^n j \times f(i, j)} \quad (9)$$

and

$$y_c = \frac{\sum_{i=1}^m \sum_{j=1}^n i \times j \times f(i, j)}{\sum_{i=1}^m \sum_{j=1}^n i \times f(i, j)}, \quad (10)$$

for an image size of $m \times n$ pixels (where m is the x -direction and n is the y -direction), and where $f(i, j)$ is the grayscale value at pixel coordinate (i, j) .

The control commands for the M5 mirror fine-steering system are derived using Equation (5)–Equation (7), followed by 30-frame averaging to mitigate atmospheric turbulence effects. Closed-loop control of the M5 mirror is then executed. Multiple 30-min tracking experiments demonstrate tracking error RMS values consistently below $1.0''$. Experimental results are presented in Fig. 6, in which panels A, B, and C show the x and y directional tracking errors on the camera focal plane, and panels D, E, and F show the vector sums of x and y displacements, representing deviations from the reference point, with RMS values of $0.55''$, $0.56''$, and $0.61''$, respectively. The stable closed-loop stellar tracking demonstrates proper functioning of the system.

4.2. Closed-loop Active-region Tracking Experiment

In this experiment, solar observations targeted an active region on the solar disk. Correlation algorithms detected displacements of the solar active region, with 20-frame averaging applied to mitigate atmospheric turbulence effects. Closed-loop control of the M5 mirror was then implemented.

Solar observation results (see Fig. 7) include closed-loop tracking errors for solar active regions under three tracking durations of 30 min (with RMS error of $0.74''$), 60 min (with RMS error of $0.52''$), and 120 min (with RMS error of $0.77''$). These results demonstrate the capability of the system to stably track solar observation targets for over 30 min via closed-loop control, with all RMS tracking errors below $1.0''$. With the implementation of this closed-loop error-correction system, the AIMS Coudé focal plane meets the tracking accuracy requirements in both stable tracking duration and RMS error metrics.

5. CONCLUSIONS

We have analyzed the mechanism and characteristics of slow-varying tracking errors at the AIMS Coudé focus, which are primarily attributed to quadratic nonlinear slow-varying complex errors. These are induced by misalignment among the optical axis, elevation axis, azimuth axis, and derotator axis during the optomechanical manufacturing and alignment of AIMS. Given the nonlinear temporal evolution of these errors, traditional modeling approaches have proved inadequate. Using the optomechanical architecture of AIMS, we propose an M5 mirror-based closed-loop correction scheme and have developed corresponding hardware/software systems, which we have used to conduct experimental validation. Without closed-loop correction, 30-min slow-varying tracking errors reached several arcseconds ($> 10''$). With the closed-loop system engaged, stable solar target tracking exceeded 30 min with an RMS tracking error of below $1.0''$, representing an order-of-magnitude precision improvement over open-

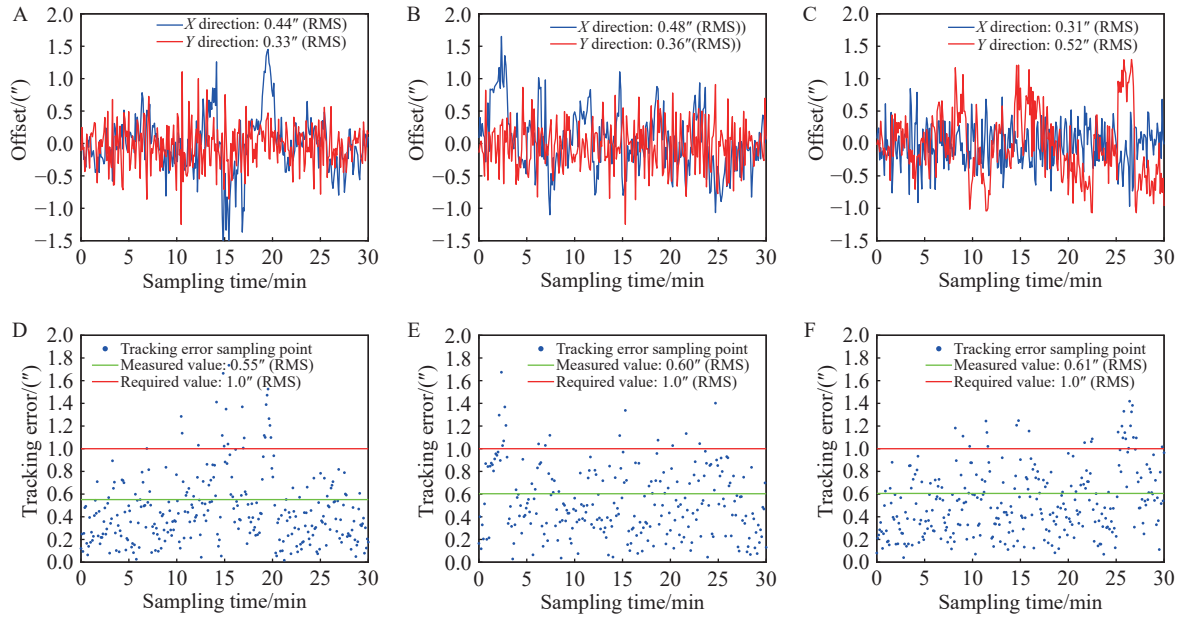


Fig. 6. Three sets of stellar-referenced closed-loop tracking errors. (A) x/y offset during closed-loop tracking of a star in the eastern sky region. (B) x/y offset during closed-loop tracking of a star in the central sky region. (C) x/y offset during closed-loop tracking of a star in the western sky region. (D) Closed-loop tracking error for a star in the eastern sky region. (E) Closed-loop tracking error for a star in the central sky region. (F) Closed-loop tracking error for a star in the western sky region.

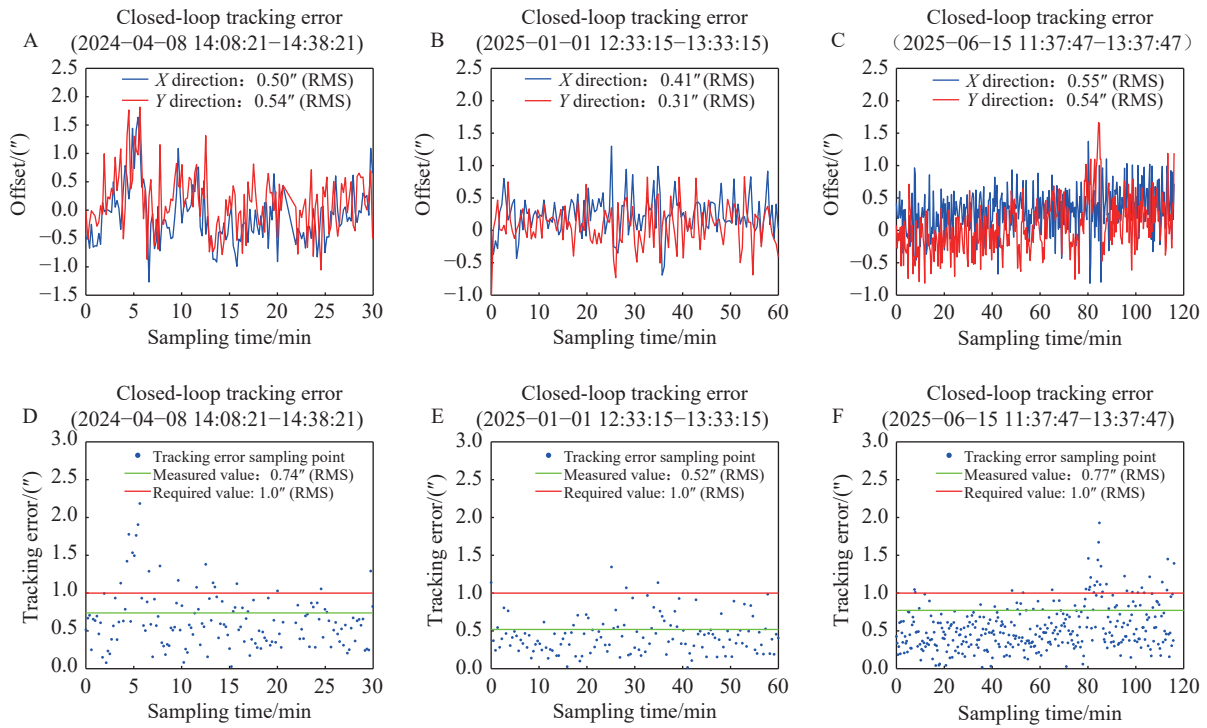


Fig. 7. Three sets of closed-loop tracking errors for solar disk targets. (A) x/y offset during 30-min closed-loop tracking. (B) x/y offset during 60-min closed-loop tracking. (C) x/y offset during 120-min closed-loop tracking. (D) Closed-loop tracking error for 30-min duration. (E) Closed-loop tracking error for 60-min duration. (F) Closed-loop tracking error for 120-min duration.

loop operation. This satisfies the tracking specifications of AIMS. Commissioned in April 2024, AIMS has maintained stable operation for over a year. This error-correction technique establishes a technical foundation for precision tracking in future large-aperture ground-based solar telescopes.

The tracking control method employed by AIMS differs from those used by other solar telescopes such as NVST, CLST, GREGOR, and DKIST. Due to variations in scientific objectives, backend instruments, and telescope optomechanical structures, the specific tracking accuracy requirements and technical solutions also differ. The

core scientific instrument of AIMS, the FTIR spectrometer, operates in the mid-infrared band and demands high spectral resolution, together with a large FOV. However, it uses a linear array detector, which requires long-duration scanning to observe solar disk targets, thereby necessitating extremely precise tracking. In contrast, NVST, CLST, GREGOR, and DKIST primarily perform high-resolution imaging of extended solar disk sources. Even if tracking deviations occur, image alignment can be corrected during post-processing. For AIMS, insufficient tracking accuracy prevents the FTIR spectrometer from acquiring original large FOV observational data, rendering large FOV observations impossible.

With a tracking accuracy of 1.0" per 30 minutes, AIMS has already acquired a substantial amount of scientific observational data, but this is not the ultimate goal. We are currently developing advanced tracking technologies to mitigate the effects of turbulence and intend to further reduce image jitter to within 0.3". Although our tracking control scheme effectively monitors active regions on the solar disk, the error-detection algorithm still fails to perform adequately when the observation target is a quiet region or the solar limb. This represents a critical issue that requires focused research and resolution in the future.

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AI DISCLOSURE STATEMENT

Wordvice.AI was employed for language and grammar checks within the article. The authors carefully reviewed, edited, and revised the Wordvice. AI-generated texts to their own preferences, assuming ultimate responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Zhijie Shi conceived ideas, designed and implemented the study, and wrote the paper. Dongguang Wang conceived ideas and designed the optical system. Songbo Xu contributed to the structural design and alignment. Yuliang Shen optimized the optical design, completed optical assembly and alignment, and assisted with the experiment. Hengyu Mu assisted with the experiment. Guangqian Liu conceived ideas, delivered comprehensive guidance on the control system design and experimentation, and also provided valuable recommendations for revision of the manuscript. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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