NVST Focal Plane Detection System Postprint

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Abstract

During continuous observations, the 1 m New Vacuum Solar Telescope undergoes thermal deformation in its opto-mechanical structure due to temperature changes caused by solar radiation, manifesting primarily as real-time focus variation that produces defocus aberration and affects the quality of observational data. To solve this problem, a focus detection system was designed based on a focus scanning detection algorithm in conjunction with the telescope' s system structure. First, the focus variation of the 1 m New Vacuum Solar Telescope was analyzed and the overall structure of the focus detection system was designed; subsequently, the detailed design and implementation of the hardware and software systems were carried out, with particular emphasis on testing the system' s repeatability precision and focus detection accuracy, which demonstrated that the system meets the focus detection accuracy requirements of the telescope; finally, the operating results of the focus detection system on the telescope over a three-month period are presented: the system can monitor the telescope' s focus variation in real time, perform focusing adjustment according to the focus variation, and obtain excellent observational data.

Full Text

Focus Detection System for the 1-meter New Vacuum Solar Telescope

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Abstract

During continuous observation, the 1-meter New Vacuum Solar Telescope (NVST) experiences thermal deformation of its opto-mechanical structure due to temperature changes caused by solar radiation, manifested primarily as real-time focus variation that produces defocus aberrations and degrades observation data quality. To address this issue, we designed and implemented a focus detection system based on a focus-scanning detection algorithm integrated with the telescope' s optical and mechanical structure. First, we analyzed the focus variation characteristics of NVST and designed the overall system architecture. Then we detailed the hardware and software implementation, with particular emphasis on testing the system' s repeat positioning precision and focus detection accuracy, demonstrating that the system meets the telescope' s observational requirements. Finally, we present three months of operational results showing that the system can monitor focus variation in real time and adjust focus accordingly, yielding excellent observation data.

Keywords: Focus detection; New Vacuum Solar Telescope; Real-time focus variation; Repeat precision

1. Analysis of Focus Variation in NVST

The 1-meter New Vacuum Solar Telescope, operational since 2010, performs high-resolution imaging and spectroscopic observations of the Sun, acquiring substantial high-resolution solar data [**?**, **?**]. Although its opto-mechanical structure employs special thermal design [**?**], the system' s stability remains affected by solar radiation. During continuous observation, heat accumulation in the primary mirror tube causes thermal deformation, primarily manifested as real-time focus variation. When this variation exceeds the system' s depth of focus, defocus aberrations occur that compromise observation quality [**?**, **?**].

The relationship between focus position variation and mirror tube temperature change can be approximated as linear. Based on previous research results, the position change of mirror M3 relates to focus variation at focal plane F1 as:

$$\Delta F = 2.57\,\text{mm}/^{\circ}\text{C}$$

where β is the axial magnification of the terminal optical system. For NVST, $\beta = 8.67$, yielding the relationship between M3 adjustment and internal mirror tube temperature:

$$\Delta t = 0.30\,\text{mm}/^{\circ}\text{C}$$

Theoretical and measured values of focus variation are shown in [Figure 2: see original paper]. While theoretical values reflect the general trend of focus variation with temperature, significant differences exist. Measured data show faster focus changes than theoretical analysis, primarily because the theoretical model only considered temperature factors and used mirror tube arm temperature as an approximation for the internal system temperature, which cannot be directly measured. After opening the dome, the telescope experiences rapid temperature rise from solar irradiation and ambient temperature increase, requiring frequent focus adjustments. Approximately two hours after commencing observations, focus variation stabilizes.

[Figure 2: see original paper] shows the comparison between theoretical and measured focus position values. The defocus aberration requirement for high-resolution reconstruction is less than $\lambda/4$. From the defocus aberration formula:

$$\text{Defocus} = \frac{\lambda f^2}{d^2}$$

the defocus variation rate is inversely proportional to wavelength. NVST's multi-channel high-resolution imaging system has a shortest wavelength of $\lambda = 393.3$ nm, which is most sensitive to focus variation. Based on measured results at $\lambda = 393.3$ nm, the defocus aberration variation rate with temperature is:

$$\frac{d(\text{Defocus})}{dT} = 0.403\,\lambda/^\circ\text{C}$$

During periods of rapid temperature change (e.g., 4.5°C/hour), defocus aberration changes by 1.81λ per hour, requiring focus adjustment every 20 minutes. The system must complete one focus detection and adjustment cycle within 15 minutes.

2. Overall System Structure Design

The scanning focus detection algorithm requires continuous acquisition of multiple frames at different focus positions, with position recording for each frame. To eliminate atmospheric turbulence effects, multiple image sets must be scanned and averaged. The overall structure of the NVST focus detection system is shown in [Figure 4: see original paper].

Based on this algorithm and NVST' s specific optical structure, detailed system parameters are specified in . The system uses one of NVST' s high-resolution imaging channels for beam splitting at $\lambda = 705.8$ nm. After algorithmic processing to determine focus position, the position information is converted to M3 adjustment values for observer notification or direct transmission to the focusing system, forming a closed-loop auto-focus system.

Key requirements include: - Scanning step size must be less than 758 μm (half the depth of focus at $\lambda = 705.8$ nm) - Scanning range must exceed 15.15 mm (twice the depth of focus) - Position resolution of 1 μm - Image acquisition frequency of 15 fps - Completion of one focus detection cycle within 6 minutes

summarizes the precision requirements for the defocus detection system.

3. Hardware and Software System Design

Hardware Design: To implement image acquisition scanning, a motorized translation stage is installed at the focal plane of the focusing imaging system, with a CCD camera mounted on the stage. Image acquisition and stage control are managed by a single computer. Camera and stage selection parameters are listed in .

The stage' s motion direction must align with the optical axis within $15.4'$ to ensure the focus remains within the scanning range. This angular tolerance is verified by measuring laser spot centroid displacement over a 10 cm travel range. The camera and stage positions are calibrated against other high-resolution imaging channels using parfocal alignment.

Software Design: The software system performs camera control, data acquisition, stage synchronization, and focus position calculation. Implemented using multi-threading [**?**], the system comprises: 1. Main thread: Interface and message handling 2. Image acquisition and processing thread 3. Stage control thread

The software interface and workflow are shown in [Figure 6: see original paper] and [Figure 7: see original paper]. One complete focus detection requires 6 minutes.

4. System Performance Testing

Translation Stage Precision Test: The stage operates in two modes: position mode and velocity mode. Position mode specifies a scan start point and step size, acquiring one frame after each movement. Velocity mode uses constant speed with continuous frame acquisition during motion. For atmospheric smoothing, multiple image sets are acquired and averaged, requiring high repeat positioning precision between sets.

Test results ([Figure 8: see original paper]) show: - Position mode: RMS repeat precision of $0.78\,\mu$m across 50 points - Velocity mode: RMS repeat precision of $5.72\,\mu$m across 50 points

Position mode demonstrates superior stability and meets system requirements.

Focus Detection System Test: This comprehensive test evaluates the entire system including stage, CCD, and detection algorithm. The procedure involves: 1. Pointing NVST at any solar region and acquiring flat and dark fields 2. Manually adjusting M3 to change focus by random amounts 3. Measuring focus variation with the detection system 4. Calculating deviation between measured and applied changes

Results from 50 tests ([Figure 9: see original paper]) show an RMS detection error of $490\,\mu$m.

From the depth of focus perspective, NVST' s depth of focus is:

$$\delta = \pm\frac{\lambda f^2}{d^2}$$

For $f/d = 25.9$ and $\lambda = 705.8$ nm, the half-depth of focus is $947\,\mu$m. The system' s RMS error of $490\,\mu$m is within this limit, meeting requirements.

From high-resolution statistical reconstruction perspective, the detection precision should be less than $\lambda/8$. Using the defocus formula with the measured RMS error yields a defocus aberration of 0.128λ, which satisfies the $\lambda/8$ criterion.

5. Operational Results

The system has been tested and commissioned on NVST. It effectively monitors focus variation during routine observations. [Figure 10: see original paper] shows focus adjustment over one day, demonstrating that: - Focus changes rapidly after opening the dome - Continuous adjustment is needed during the first two hours - Focus stabilizes after approximately two hours - Subsequent variation is slower but still requires periodic adjustment due to changing solar altitude and radiation

The system provides focus adjustment values to observers and can be integrated with NVST's focusing mechanism for closed-loop control, significantly improving observation efficiency and data quality.

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[10] (Reference to multi-threading implementation in software design)

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