Astronomical Techniques and Instruments, Vol. 1, March 2024, 95–104

Article Open Access

Solar adaptive optics systems for the New Vacuum Solar Telescope at the Fuxian Lake Solar Observatory

Lanqiang Zhang[1,2,3], Xuejun Rao[1,2], Hua Bao[1,2], Youming Guo[1,2,3], Jinsheng Yang[1,2], Nanfei Yan[1,2,3], Xian Ran[1,2,3], Dingkang Tong[1,2], Xinlong Fan[1,2], Zhongyi Feng[1,2], Changhui Rao[1,2,3]*

[1]*National Laboratory on Adaptive Optics*, *Chengdu* 610209, *China*

[2]*The Laboratory on Adaptive Optics*, *Institute of Optics and Electronics*, *Chinese Academy of Sciences*, *Chengdu* 610209, *China*

[3]*University of Chinese Academy of Sciences*, *Beijing* 100049, *China*

*Correspondence: chrao@ioe.ac.cn

Received: January 21, 2024; Accepted: February 22, 2024; Published Online: March 8, 2024; https://doi.org/10.61977/ati2024014

Citation: Zhang, L. Q., Rao, X. J., Bao, H., et al. 2024. Solar adaptive optics systems for the New Vacuum Solar Telescope at the Fuxian Lake Solar Observatory. *Astronomical Techniques and Instruments*, **1**(2): 95−104. https://doi.org/10.61977/ati2024014.

Abstract: Adaptive optics (AO) is essential for high-quality ground-based observations with large telescopes because it counters the impact of wavefront aberrations caused by atmospheric turbulence. The new vacuum solar telescope（NVST） is one of the most important high-resolution solar observation instruments in the world. Three sets of solar adaptive optics systems have been developed and installed on this telescope: conventional adaptive optics, ground layer adaptive optics, and multi-conjugate adaptive optics. These have been in operation from 2018 to 2023. This paper details the development and application of solar adaptive optics on the NVST and discusses the newest instrumentation.

Keywords: Solar observation; Adaptive optics; Multi-conjugate adaptive optics

1. INTRODUCTION

Solar activity is the source of space weather, caused by eruption events such as solar flares and coronal mass ejections. While these are observed in the solar corona, the roots of their energy accumulation, acceleration, and triggering lie in the lower layers of the solar atmosphere, namely the chromosphere and photosphere. The evolution of solar active regions is influenced by the interaction of plasma and magnetic fields within the solar atmosphere. Observational monitoring of the processes of occurrence, development, and decay necessitates resolution of the fundamental structures of plasma and magnetic fields. The structure and evolutionary characteristics of the plasma are controlled by the pressure scale height and the photon mean free path, both of which are approximately 70 km (a heliocentric angular scale of 0.1″). The spatial scale of the fundamental unit of the magnetic field, the magnetic flux tube, is even smaller, necessitating observations with spatial resolution better than 0.1″. Additionally, because of the typical span of solar active regions ranging from 1−2 ′[1], studying their evolutionary processes necessitates high-resolution monitoring with a large field of view. This is crucial for capturing the highly dynamic fine structure of solar active regions, and enables identification of the dynamic origins of solar eruptive activities.

The aperture of space-based solar telescopes is limited by technological development, and ground-based large aperture solar telescopes are still the best choice for studying the hyperfine structure of the Sun and its active regions. The increasing maturity of adaptive optics[2] ensures that ground-based telescopes can achieve high-resolution observations close to the diffraction limit. Owing to the vertical distribution of atmospheric turbulence, conventional adaptive optics (CAO) generally has a small corrected field of view, known as the isoplanatic angle, with a typical size of the order of 5−15″ for visible-wavelength solar observations at good observing sites[3]. A typical solar active region extends up to several arcminutes, and includes complex dynamic structures, such as sunspots, filaments, and plages. Wide-field next-generation adaptive optics systems such as multi-conjugate adaptive optics (MCAO)[4] and ground-layer adaptive optics (GLAO)[5] have been proposed to meet the observation requirements with high resolution. Both techniques are based on the principle of measuring and compensating for atmospheric turbulence aberration at different layers. MCAO senses the accumulative turbulence aberration from different sightlines and calculates the aberration caused by different turbulence layers, then compensates for the turbulence with several deformable mirrors (DMs) conjugated to different heights. Compared with CAO, more guide stars/regions would be needed for MCAO. From this perspective, the Sun is an ideal target to develop MCAO technology because photospheric structures such as sunspots and granulations can provide multiple “guide stars” in any configuration. Compared with MCAO, GLAO is generally used to improve image quality for large-aperture ground-based optical telescopes across a wide field of view. Homogeneous imaging performance can be obtained by compensating the aberration from ground layer turbulence. The fact that about 60% of the turbulence strength is concentrated in the first few kilometers above the telescope makes this concept attractive for solar observations that require homogeneous image quality improvement over a wide field of view rather than a diffraction-limited resolution[6]. The potential of GLAO with post-image processing has been demonstrated to produce diffraction-limited images[7].

A schematic of the principles of the three adaptive optics techniques is shown in Fig. 1. CAO, which detects the accumulated atmospheric turbulence wavefront aberrations in a certain direction based on the detection beacon, is shown in Fig. 1A, and a DM is set at the pupil plane to compensate for the corresponding wavefront aberrations. Owing to the anisoplanatism of atmospheric turbulence, the correction potential of CAO is limited. Only the center field of view is well corrected, and the imaging quality of the off-axis fields of view decreases rapidly. GLAO typically uses several wavefront sensors (WFSs) to average out the aberration from ground layer turbulence, and controls a DM conjugated to the ground layer. Considering that the turbulence is mainly distributed in the ground layer, GLAO could enhance the imaging quality within a wide field of view. GLAO is the first step towards realizing MCAO, as shown in Fig. 1B. Fig. 1C shows the MCAO technique, which obtains wavefront aberrations caused by atmospheric turbulence layers at different heights using three-dimensional wavefront sensing of atmospheric turbulence. Multi-wavefront correctors are set to conjugate the layers of atmospheric turbulence at different heights, and stratified correction is performed on the wavefront distortion caused by atmospheric turbulence, thus achieving high-resolution imaging with a large field of view close to the diffraction limit.

Currently, the inclusion of an adaptive optics system has gradually become essential for assessing the performance and competitiveness of a large-aperture solar telescope. Almost all solar telescopes with apertures of 1-m-class or larger are equipped with solar adaptive optics systems.

The National Solar Observatory (NSO) pioneered the development of the first routine operation solar adaptive optics system at the dunn solar telescope (DST) in 1998. This system was a low-order adaptive optics system, marking a significant milestone in solar observations. In 2002, NSO upgraded its capabilities by developing a high-order adaptive optics system, AO76, for the DST. This was designed to perform optimally under median seeing conditions[8]. Concurrently, the Kiepenheuer Institute for Solar Physics in Germany developed an adaptive optics system which was based on a similar hardware architecture as the low-order adaptive optics system, and mounted it on various solar telescopes in Europe, including the vacuum tower telescope (VTT), the balloon-borne telescope SUNRISE, and the GREGOR telescope[9]. With the help of solar adaptive optics , the typical 1-m-class, high-resolution solar telescope achieved great success in the first decade of this century. Diffraction-limited images at visible and NIR wavelengths were achieved in up to 95% of the observing time[10]. With the advancement of adaptive optics technology and the construction of 2-m-class solar telescopes, a new generation of higher-order solar adaptive optics systems has been successfully developed and deployed, including the AO156 for GREGOR[11], and the AO308 for the Goode solar telescope[12].

Meanwhile, as the potential of wide-field adaptive optics increases, several teams are engaged in research and development of solar MCAO and GLAO for the next generation of solar telescopes, and have built experimental systems in the last 20 years. Stellar observations with

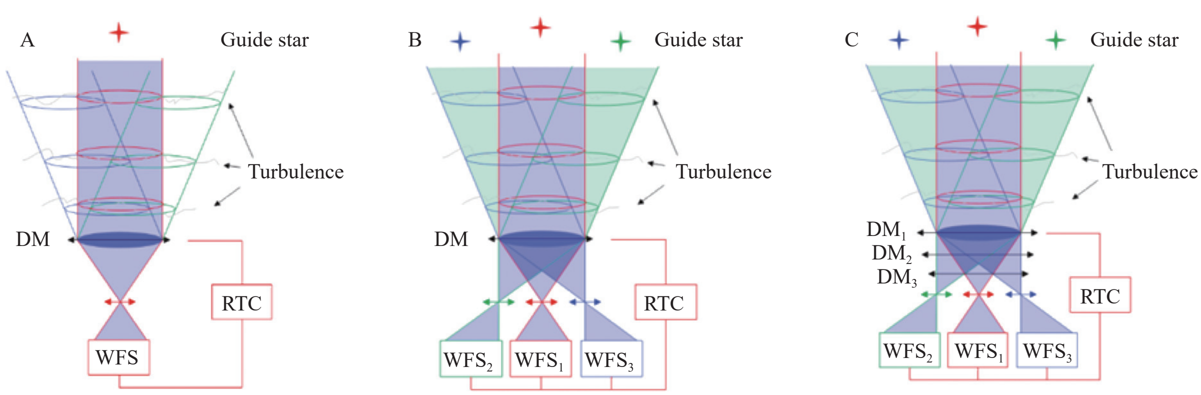

Fig. 1. The different architectures of CAO, GLAO, and MCAO. (A) CAO. (B) GLAO. (C) MCAO.

MCAO were first carried out by the MCAO demonstrator at unit telescope 3 of the Very Large Telescope. The first MCAO system has been routinely used for astronomical observations, GeMS of the Gemini South Telescope began to operate in 2012[13]. Substantial gain in solar observations with MCAO over those from conventional adaptive optics has yet to be shown. Two solar MCAO experiment systems were built first at the 70 cm VTT and the 76 cm DST[14,15]. Subsequently, the new 2-m-class solar telescope GREGOR, Goode Solar Telescope (GST, also known as "NST" before July 17, 2017), and the next-generation 4-m solar telescope EST and DKIST were all planned to incorporate MCAO[4,16–18]. A new solar MCAO system for GST named *Clear* was demonstrated in 2017, which is the first regularly operating instrument for solar observation. This system is capable of performing GLAO correction when only the ground-layer DM is used. In this case, the maximum FOV of the by-product GLAO system is limited by the detector size of the MCAO system. The NSO and BBSO have experimented with GLAO to improve its performance in the lower atmospheric layers. However, there is no professional GLAO system for solar observations.

The need for solar adaptive optics technology grew significantly in China after the year 2000. As of 2010, China aimed to build the first 1-m ground-based solar telescope, the NVST at the Fuxian Lake Solar Observatory of Yunnan Observatories, Chinese Academy of Sciences (YNAO). Wide-field adaptive optics researches were initiated, and experiments were carried out shortly afterward. Three solar adaptive optics systems were developed and installed on NVST during the period 2018 to 2023. The conventional 151-element adaptive optics was upgraded with a WFS and real-time controller (RTC). A new regularly operating GLAO system and a MCAO system with three DMs (the GLAO works as the first layer correction) were developed.

The development and application of solar adaptive optics systems on NVST are introduced in this article. The structure of this paper is as follows: Section 2 describes the progress of solar adaptive optics in China. The adaptive optics system configuration is outlined in Section 3, and the observational results of the new GLAO and MCAO systems are given in Section 4. Section 5 presents the conclusion and outlook for the systems.

2. THE PROGRESS OF SOLAR ADAPTIVE OPTICS AT NVST

The development of solar adaptive optics at the Institute of Optics and Electronics, Chinese Academy of Sciences is shown in Fig. 2. The dawn of solar adaptive optics research in China was in 1998 with the introduction of a foundational achievement: the development of a low-order tilt correction adaptive optics system for the 43-cm solar telescope at Nanjing University. This crucial breakthrough marked the nascent stages of solar adaptive optics exploration in China. Building upon this initial success, a 37-element adaptive optics system was devised and integrated into the 26-cm aperture fine structure telescope at YNAO. This testbed served as a crucial pathfinder to the adaptive optics system intended for the NVST, laying the technological groundwork for future developments in high-resolution solar observation.

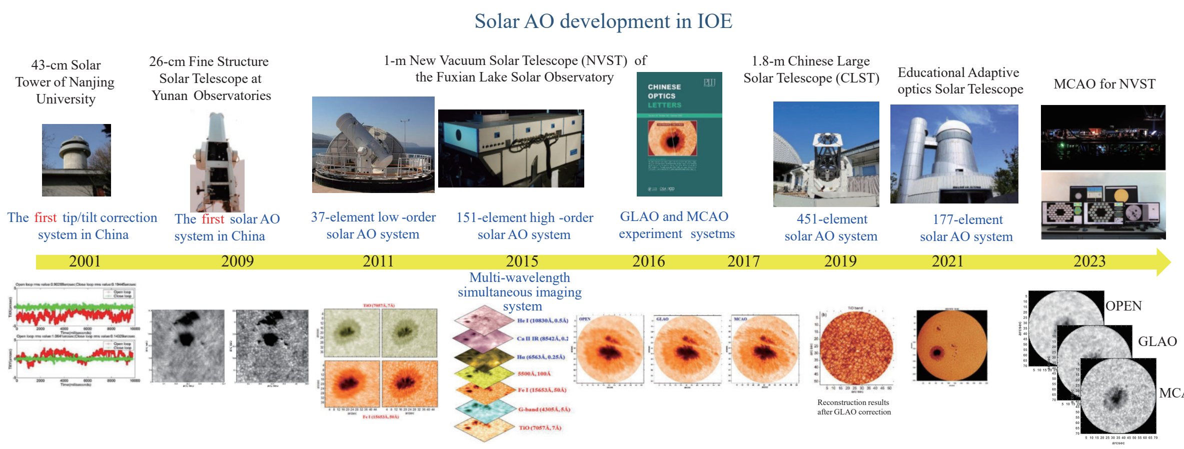

Fig. 2. The development of solar adaptive optics at the Institute of Optics and Electronics, Chinese Academy of Sciences.

The period between 2010 and 2015 was marked by a phase of rapid development in solar adaptive optics technology in China, and two generations of solar adaptive optics systems were successively installed on the NVST. The initial implementation of the low-order 37-element solar adaptive optics system was followed by the introduction of a high-order 151-element solar adaptive optics system[19,20]. These strides significantly elevated the observational capabilities and precision of the NVST, solidifying China's position at the forefront of solar adaptive optics innovation. Subsequently, the 1.8-m Chinese large solar telescope and the education adaptive optics solar telescope were built. Solar adaptive optics was successfully developed as first-generation instrumentation, and has played an important role during telescope operation[21].

Simultaneously, numerous technological explorations and experiments into wide-field adaptive optics were initiated with the NVST. In 2016, a pivotal milestone was achieved with the successful development and implementation of the solar GLAO prototype system at the NVST[22]. This breakthrough led to the capture of high-resolution images over 1', serving as an impressive inaugural demonstration of China's capabilities in wide-field adaptive optics . Expanding on this success, MCAO was considered and an experimental two-DM MCAO system was developed in 2017[23].

Subsequently, based on the 151-element adaptive optics , we developed two wide-field adaptive optics systems for the NVST. These systems can be switched between different correction modes to fit specific observational requirements.

3. THE CONFIGURATIONS OF THE THREE ADAPTIVE OPTICS SYSTEMS

The layout diagram of the three adaptive optics systems is shown in Fig. 3. The CAO system and GLAO system use newly designed wavefront sensors and share the same layout of front optical path and deformable mirror as the original 151-element adaptive optics system. The MCAO system is designed using a combination of high-order ground layer adaptive optics and low-order high altitude turbulence aberration correction[24]. Sunlight passes through high-order GLAO (or the 151-element adaptive optics system) on the upper layer with the help of the 45° mirror $HM_{45°}$, and is then fed into the NVST instrumentation after aberrations from high-altitude turbulence are corrected.

3.1. The Optical Design of Adaptive Optics Systems

The adaptive optics systems are distributed and mounted on a two-layer bench, as shown in Fig. 4. The upper layer accommodates a conventional adaptive optics system, the high-order GLAO system, and the two DMs for high-altitude turbulence corrections. The lower tier is primarily dedicated to the deployment of a multiple-direction Shack-Hartmann wavefront sensor (MD-WFS) integral to the MCAO system, as well as the reimaging module following different adaptive optics systems, and a scanning mechanism, which belongs to the two-dimensional spectrometer. All light beams corrected by the adaptive optics system will first enter the scanning mechanism and then be directed to different instruments. The CAO/GLAO and MCAO systems can be switched via a flip-type adjustment structure on the upper bench. The flip mechanism can switch between the beam splitter BS and the mirror M_4, and select whether the high-altitude correction (HAC) module is incorporated into the optical path. Correspondingly, the linear motion mechanism on the lower bench controls the mirror for interfacing before the scanning mechanism of the two-dimensional grating spectrometer, ensuring the entry and exit of light beams corrected by different system modes. This configuration ensures comprehensive adaptability to varying atmospheric conditions and scientific requirements.

The placement of the HAC DMs on two sliding guide rails facilitates precise adjustments. This adjustability is crucial for aligning DM height with specific atmospheric turbulence layers, thereby enhancing correction accuracy. A MD-WFS for the GLAO system on the upper layer not only measures wavefront distortions caused by ground layer turbulence but also measures the optical seeing and profile of atmospheric turbulence using the slope detection and ranging method[25,26], based on research by Wang et al[27,28]. The two DMs conjugated to high-altitude are placed on two sliding rails, and positions of the DMs could be adjusted based on the measured atmospheric seeing profile to obtain optimal performance. Additionally, to simplify system calibration and assembly, both DMs are mounted on a five-axis adjustment stage with a

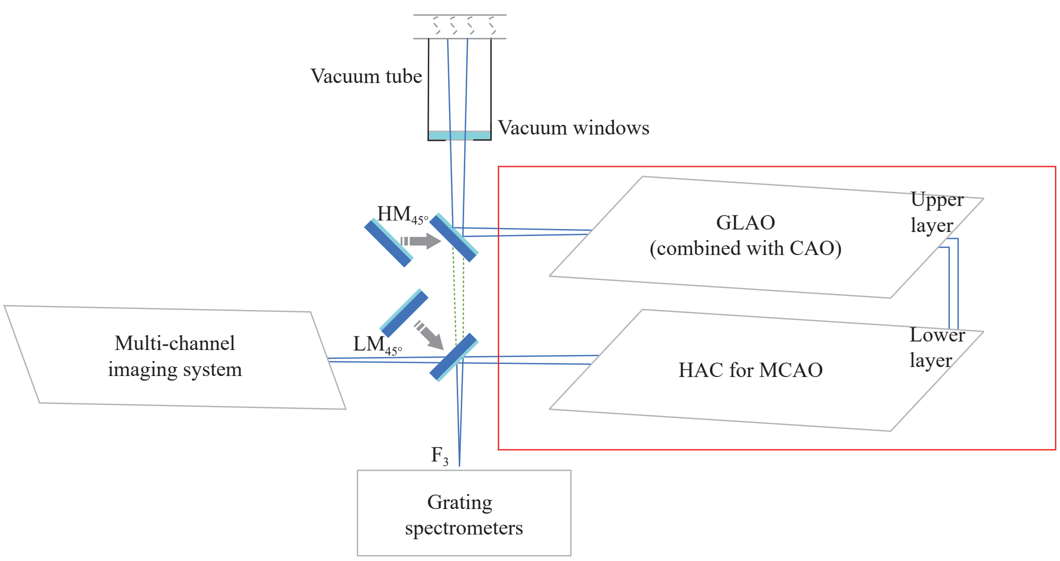

Fig. 3. Schematic diagram showing the configuration of the NVST.

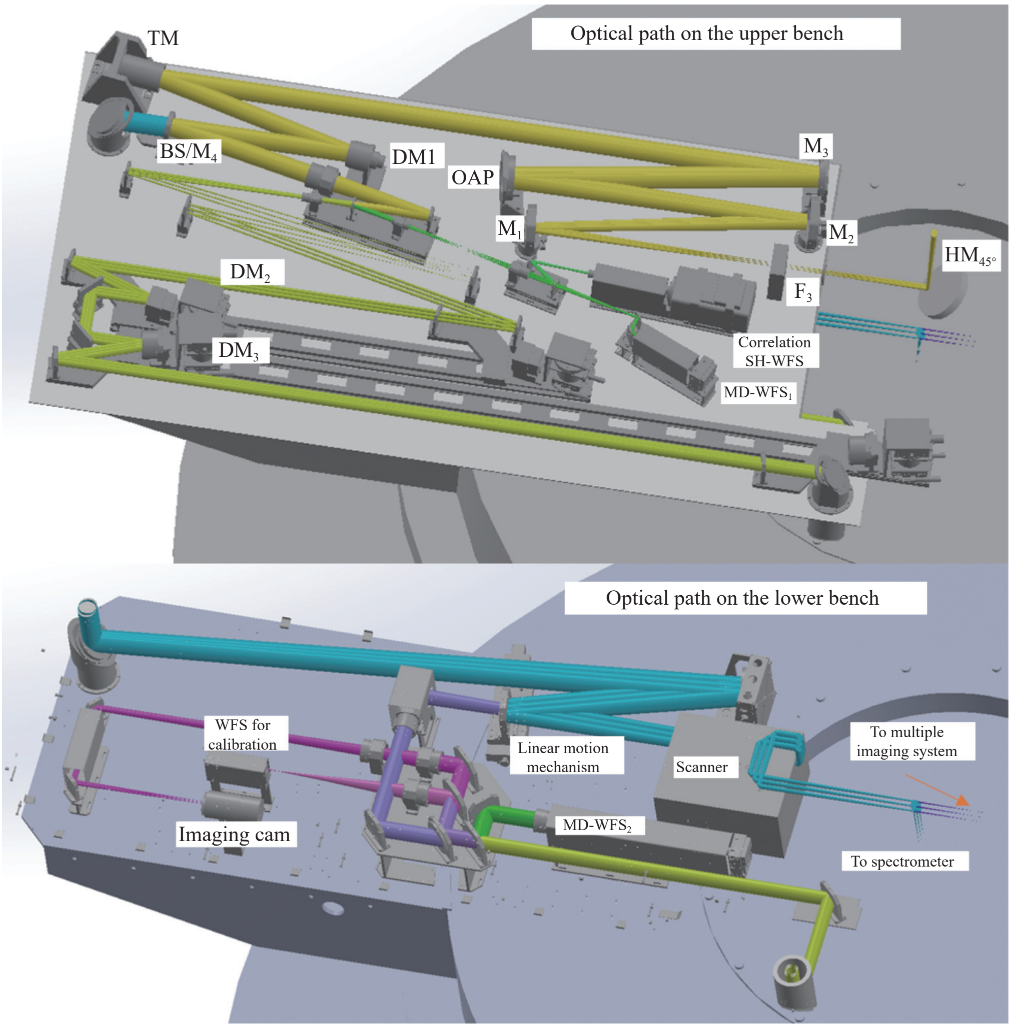

Fig. 4. The optical path of the adaptive optics systems at the NVST.

locking mechanism. This arrangement ensures mirrors can be tuned with the precision and stability crucial for maintaining optimal system performance.

3.2. The Wavefront Sensors

Three WFSs are used in these adaptive optics systems. The arrangements of the sub-apertures and the sub-images of sunspots for the three WFSs are shown in Fig. 5. A new high-order correlation SH-WFS with 15×15 sub-apertures has been developed for CAO correction. Two MD-WFSs are employed to sense the wavefront aberrations caused by turbulence in the ground layer and high altitudes. The MD-WFS_1 with 9×8 sub-apertures is used for GLAO correction and turbulence profile measurement. Nine guide regions corresponding to different lines of sight are extracted in the focus images of MD-WFS_1. The guide regions from the same direction can be reformed as a new sub-image array, and used to measure the wavefront from that line of sight. Based on this method, the wavefront aberrations from multiple directions can be measured simultaneously using MD-WFS_1. The MD-WFS_2, which is placed downstream of DM_0 on the lower-layer bench, has a smaller sub-aperture but wider detection field of view, 30 effective sub-apertures (accounting for secondary mirror obstruction), and 19 guide regions employed to measure the wavefront for high-altitude correction. Mikrotron 3CXP cameras are used as detectors for the three WFSs. The parameters of the compound wavefront sensor are shown in Table 1.

CAO is designed for observing solar activity, using sunspots as beacons. The resolution of the wavefront sensor is 1 arcsec per pixel. Considering the requirements of closed-loop GLAO based on solar granulation, the image resolution of the sub-aperture is set to 0.6". This is slightly larger than the typically accepted 0.5", so that a larger detection field of view can be obtained using fewer pixels during the cross-correlated calculation of wavefront sensing. This system adopts an overall field of view of 42"×37", with up to 9 guide regions of 24 pixels each. Some guide regions can be manually rejected if the detection accuracy is deemed insufficient. The GLAO mode can be changed to a low-order CAO correction mode by selecting only one guide region for wavefront sensing. The parameters of the MD-WFS_2 are the same as those used in the experimental MCAO system, except that more guide regions are employed for three-dimensional wave-

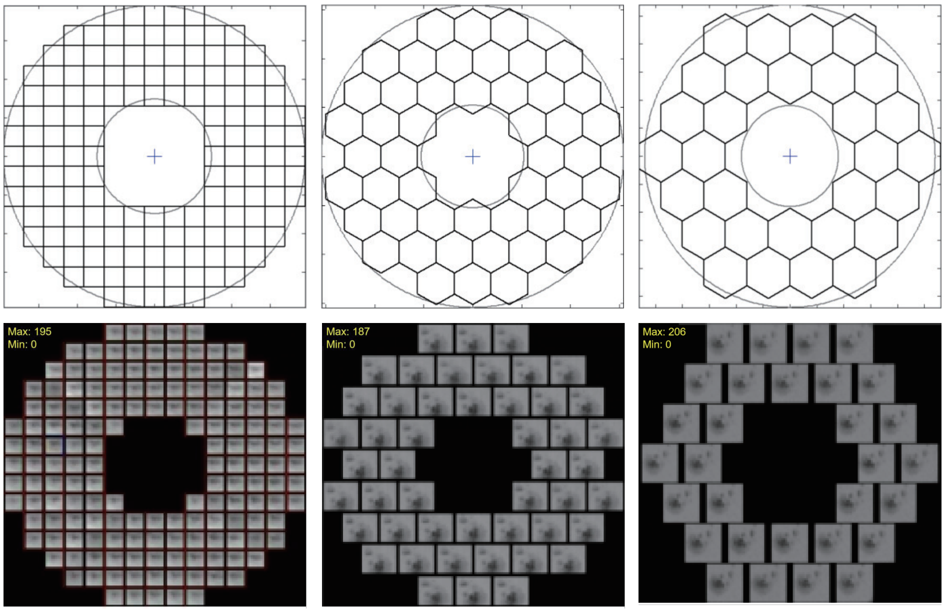

Fig. 5. Arrangement of the sub-apertures and sub-images of sunspots for the three WFSs.

Table 1. The main parameters of the WFSs

Specification	Correlation SH-WFS	MD-WFS_1	MD-WFS_2
No. of microlens	15×15	9×8	7×7
Shape of microlens	square	hexagon	hexagon
Guide regions	1	9	19
Field of view	24″×24″	42″×37″	60″×52″
Pixel scale/(")	1	0.6	0.5
Frame frequency/Hz	3 500	2 100	1 500

front sensing.

3.3. The Deformable Mirrors

As the central component of the adaptive optics system, the DM determines the adaptive optics performance limits. The number and pitch of actuators of the DM corresponds to the system scale. A DM with small pitch can reduce the overall size of the system. In the NVST adaptive optics systems, there are a total of three deformable mirrors. DM_1, for CAO and GLAO, is inherited from the 151-element adaptive optics system, and the other two deformable mirrors, DM_2 and DM_3, are previously used for HAC in MCAO systems. We developed all three of these DMs at The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences. They use a compact design with an actuator spacing in the DMs for the middle- and high-turbulence correction of 3.5 mm and 2.8 mm, respectively. The main parameters of these mirrors are given in Table 2.

Table 2. The main parameters of the DMs

Parameters	DM_1	DM_2	DM_3
Number	151	313	373
Arrangement	triangle	triangle	square
Spacing/mm	6	3.5	2.8
Stroke/μm	±2.25	±2.5	±2.0
Full aperture/mm	$\geqslant \Phi 70$	$\geqslant \Phi 70$	$\geqslant \Phi 60$
Effective clear aperture/mm	$\geqslant \Phi 61.8$	$\geqslant \Phi 56$	$\geqslant \Phi 56$

Fig. 6 shows the surface errors after flattening of DM_2 and DM_3. Because the placement of the two DMs for HAC do not correspond to the pupil, any surface errors should be strictly controlled. The rms surface errors of DM_2 and DM_3 are 11.6 nm and 8.9 nm, respectively.

3.4. The Real-time Controller

Compared with the previous CAO system, the RTC has undergone significant changes. First, the field programmable gate array (FPGA) + Multi-core CPU hardware architecture replaces the previous “FPGA + DSP” architecture. Second, the previously used absolute difference square algorithm has been replaced by a cross-correlation algorithm with a preprocessing step, which can improve the accuracy of slope calculation. According to different requirements for latency and jitter, the RTC can be divided into hard real-time calculations (HRTC) and soft real-time control (SRTC). HRTC is responsible for processing WFS images and driving the DM in real-time, and SRTC mainly handles tasks with lower latency requirements, such as the graphical user interface (GUI) of the RTC. The hardware architecture of the RTC for adaptive optics systems is shown in Fig. 7, which includes the RTC for CAO and GLAO systems. In this hardware architecture, FPGA is responsible for transmitting the raw

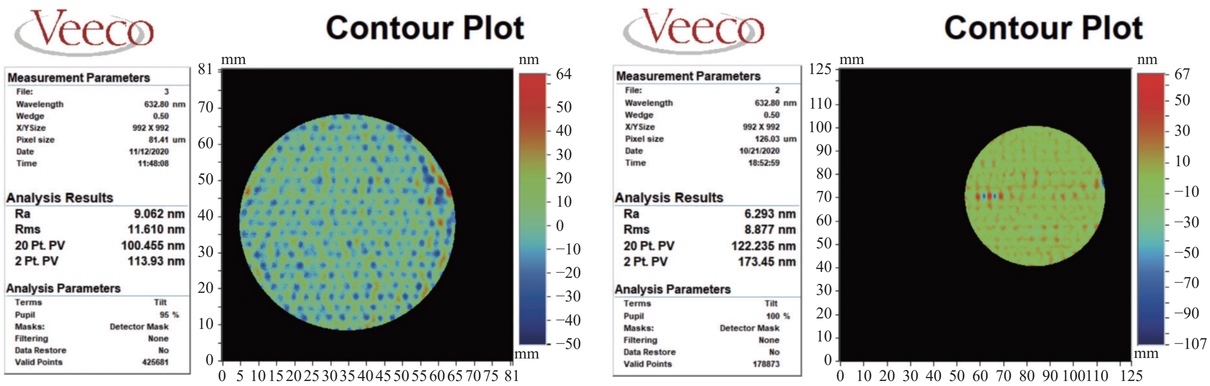

Fig. 6. The surface errors after self-flattening of the DM_2 and DM_3.

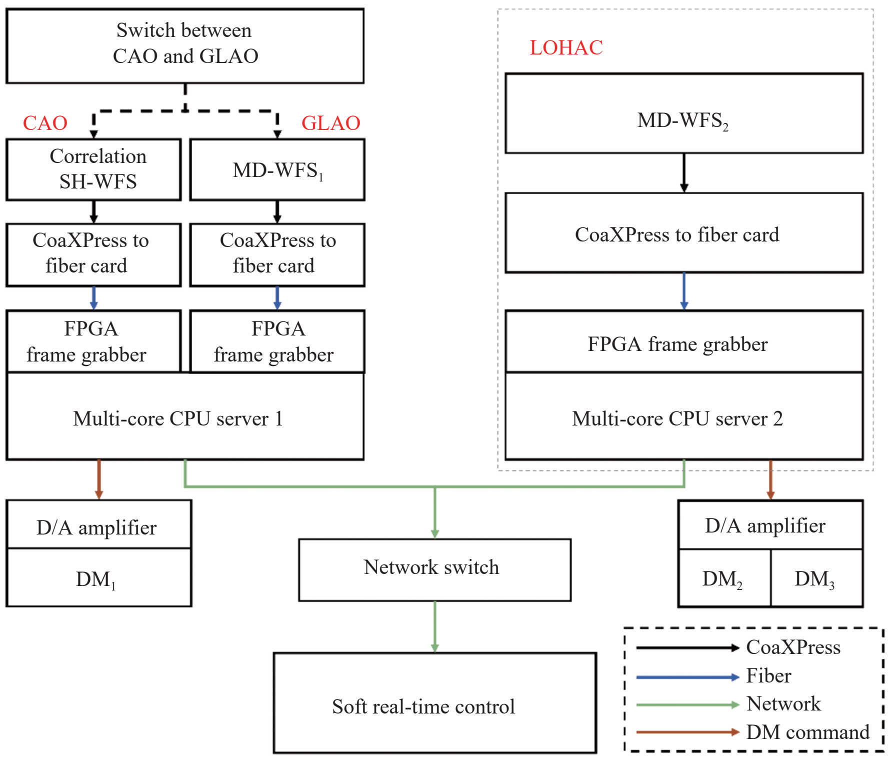

Fig. 7. Hardware architecture of the RTC in the adaptive optics systems.

image data to the CPU, which is responsible for real-time calculation.

There are two multi-core CPU servers, and the computational tasks of each server differ in the three different adaptive optics systems. In the CAO system, server 1 uses information from the correlation SH-WFS to acquire high-order aberrations in the central field of view, controlling DM_1 for high-order correction. In the GLAO system, server 1 captures wavefront information from the MD-WFS1, reconstructs the ground layer turbulence, and controls DM_1 for ground layer correction. In the MCAO system, both multi-core CPU servers are used to process the wavefront information from the two WFSs. The adaptive optics system running on server 1 can switch between the CAO system and the GLAO system. For the GLAO system, the images from MD-WFS_1 are not only used by server 1 to extract the aberration from the ground layer turbulence, but also sent to the SRTC for measuring atmospheric turbulence profile. Server 2 calculates the slopes in real-time based on the images from MD-WFS_2 and conducts atmospheric tomography to reconstruct the aberration from high-altitude turbulence. The results are used to control DM_2 and DM_3, enabling layered correction of atmospheric turbulence.

Three GUIs were developed for different adaptive optics systems. The adaptive optics system and GLAO system have independent GUIs. For the MCAO system, the GUIs of the GLAO and the HAC work simultaneously. Fig. 8 shows the SRTC in operation. The two top monitors display the telescope control system interface. The three lower monitors display the HAC GUI on the left, the GLAO GUI in the middle, and the TiO band imaging system on the right.

Fig. 8. Soft real-time control system in operation.

4. OBSERVATIONAL RESULTS

The MCAO system was developed and mounted in two steps. First, a solar GLAO system was developed and mounted at the NVST in the summer of 2021. Initially, a MD-WFS was employed for detecting the aberration from ground-layer turbulence, demonstrating the GLAO system[5]. After that, the compound WFS was developed instead of the high-order on-axis WFS and the MD-WFS for both CAO and GLAO. It is worth mentioning that the tracker in the fine tracking loop of the CAO system was removed. The first two Zernike modes from MD-WFS$_1$ were extracted for the tip/tilt mirror control. The HAC was mounted during the summer of 2022. Various optical and mechanical alignment and testing tasks were carried out in the following months. The observed results of three-layer turbulence aberration correction were recorded in February 2023.

After the installation of the MCAO system in the Coude room of the NVST, a closed-loop test was conducted on an indoor simulated granulation target. Fig. 9 shows the imaging effects of the simulated granulation with the open loop, GLAO closed loop, and MCAO closed loop. The image quality improves significantly after MCAO correction. The images in Fig. 10 show observation results from the three adaptive optics systems on February 5, 2023. The system maintains a stable closed loop for approximately 1 hour.

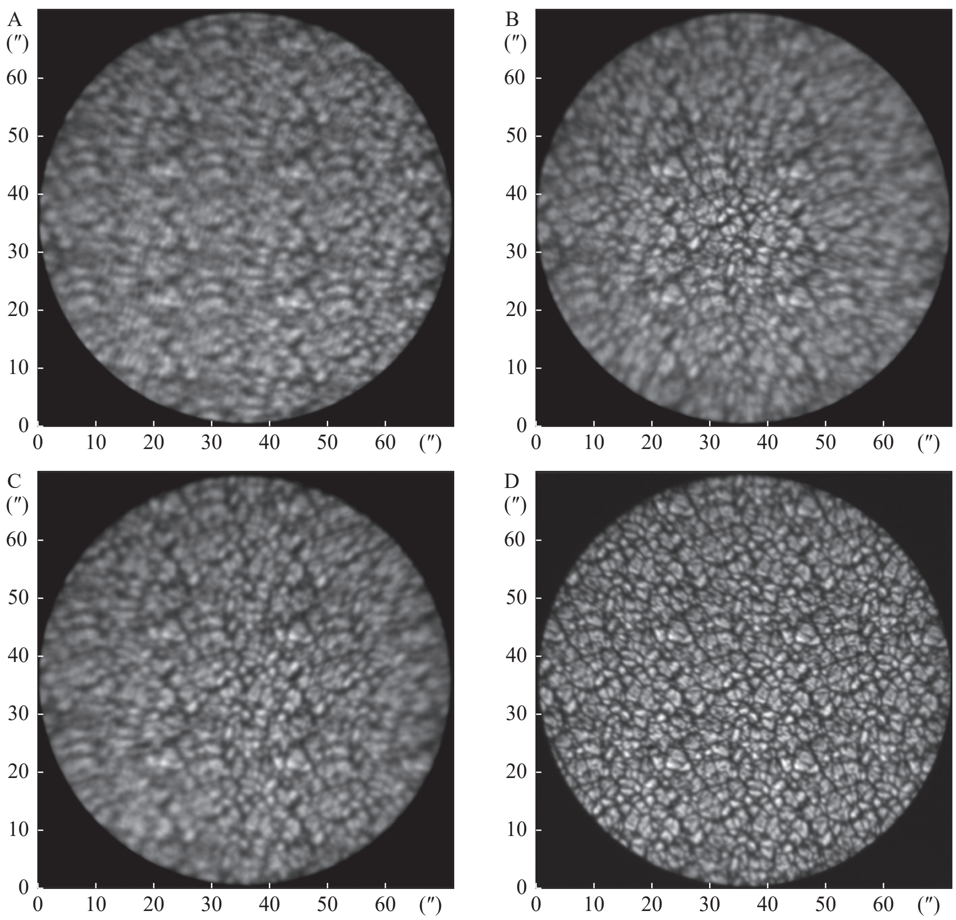

Fig. 9. Observational results of simulated granulation after the integration of the MCAO system at NVST. (A) Open loop. (B) CAO closed loop. (C) GLAO closed loop. (D) MCAO closed loop.

5. CONCLUSIONS

Successful breakthroughs in solar adaptive optics have provided a new tool in the field of high-resolution solar imaging observation. The use of solar adaptive optics to obtain high-quality observational data promises an enhanced understanding of the physical features of solar activity phenomena, thereby promoting further development of solar physics research and forecasting of space weather. This is accentuated by the significant success of

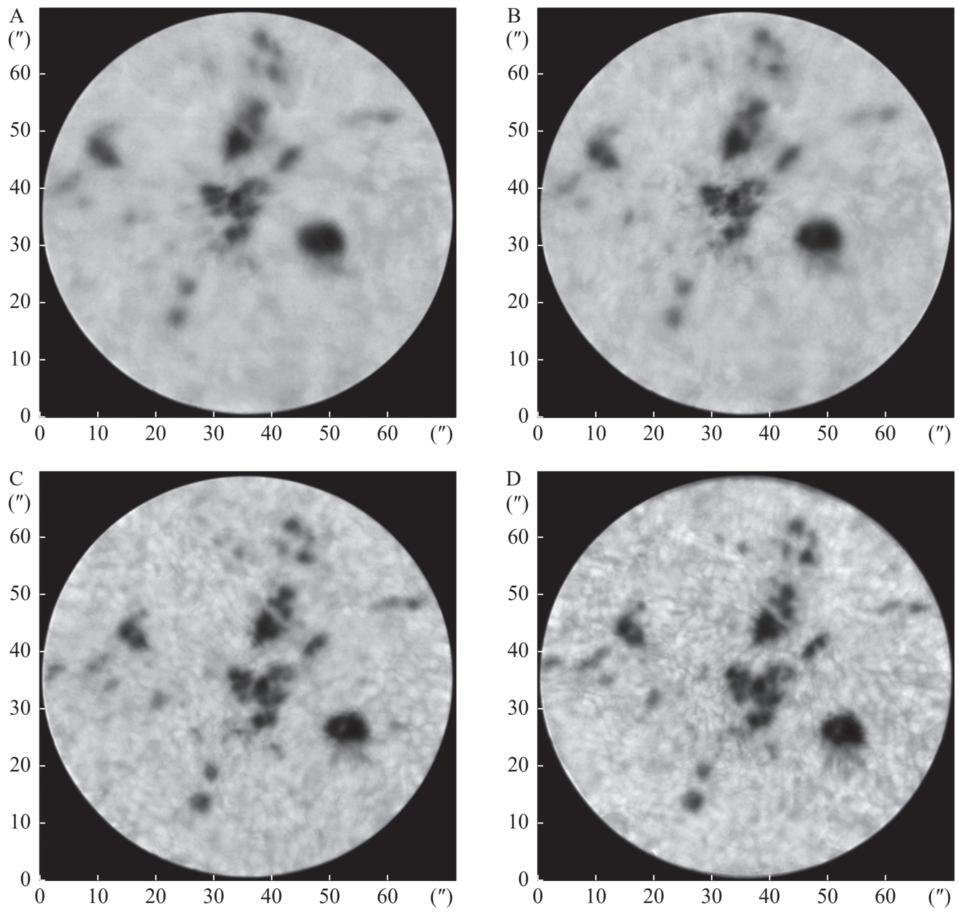

Fig. 10. The solar active observation results on February 5, 2023. (A) Open loop. (B) CAO closed loop. (C) GLAO closed loop. (D) MCAO closed loop.

the solar GLAO and MCAO systems. Solar physicists can conduct high-resolution observations of the evolutionary processes in large field of view solar active regions. They provide high-quality data support and scientific basis for in-depth researches into the structure, generation, and evolution of the solar magnetic field, as well as solar storm forecasting. For future larger-aperture solar telescopes, the development of the MCAO system will become increasingly important. First, the MCAO system needs to further increase the field of view. Second, techniques that aim to enhance system performance while reducing system complexity, such as deformable secondary mirrors[29] and intelligent adaptive optics[30], are also development directions of future MCAO systems.

In response to the advanced scientific requirements for wide-field, high-resolution imaging of solar active regions, three sets of solar adaptive optics systems, namely CAO, GLAO and MCAO, have been installed on the NVST for different observation requirements. Following successful assembly and calibration, the systems have been integrated with the NVST, and the efficacy of different adaptive optics systems has been validated.

The CAO and GLAO systems are currently deployed on the NVST for operational observational activities. However, the MCAO system, limited by the complex optical path, suffers from significant light loss. Subsequent considerations include upgrading the MCAO system to make it suitable for regular observational use.

ACKNOWLEDGEMENTS

This work is funded by the National Natural Science Foundation of China (11727805, 12103057), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2021378). We are grateful to Prof. Xiaoli Yan and his team at YNAO for their help during the system setup and on-sky observations.

AUTHOR CONTRIBUTIONS

Changhui Rao and Lanqiang Zhang conceived the idea and initiated the project. Lanqiang Zhang, Xian Ran, and Nanfei Yan mainly wrote the manuscript and produced the figures. Xuejun Rao and Jinsheng Yang conducted the optical design, Hua Bao handled the electronic control system and software development. Youming Guo provided control algorithm support. Dingkang Tong worked for the assembly and installation. Xinlong Fan and Zhongyi Feng developed the wavefront correctors for the system. Changhui Rao supervised the project. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

Changhui Rao is an associate editor-in-chief number for Astronomical Techniques and Instruments and was not involved in the editorial review or the decision to publish this article. The authors declare no competing interests.

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