Second generation solar adaptive optics for 1-m New Vacuum Solar Telescope at the Fuxian Solar Observatory

Changhui Rao (饶长辉)[1,2], Lei Zhu (朱 磊)[1,2,*], Xuejun Rao (饶学军)[1,2], Lanqiang Zhang (张兰强)[1,2], Hua Bao (鲍 华)[1,2], Lin Kong (孔 林)[1,2,3], Youming Guo (郭友明)[1,2], Xue'an Ma (马学安)[1,2], Mei Li (李 梅)[1,2], Cheng Wang (王 成)[1,2], Xiaojun Zhang (张小军)[1,2], Xinlong Fan (樊新龙)[1,2], Donghong Chen (陈东红)[1,2], Zhongyi Feng (冯忠毅)[1,2], Xiaoyun Wang (王晓云)[1,2], Naiting Gu (顾乃庭)[1,2], and Zhiyong Wang (王志勇)[1,2,3]

[1]*The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, 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*

**Corresponding author: zhulei_cas@aliyun.com*

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A second generation solar adaptive optics (AO) system is built and installed at the 1-m New Vacuum Solar Telescope (NVST) of the Fuxian Solar Observatory (FSO) in 2015. The AO high-order correction system consists of a 151-element deformable mirror (DM), a correlating Shack–Hartmann (SH) wavefront sensor (WFS) with a 3500 Hz frame rate, and a real-time controller. The system saw first light on Mar. 16, 2015. The simultaneous high-resolution photosphere and chromosphere images with AO are obtained. The on-sky observational results show that the contrast and resolution of the images are apparently improved after the wavefront correction by AO.

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In order to solve the fundamental problem of the solar magnetic field, solar observations with a spatial resolution better than 0.1 arc sec are required. A large solar telescope with an aperture of a few meters in size and adaptive optics (AO)[1,2] can be used to obtain high-resolution solar images.

For solar AO, the main challenges are the worse and time-varying daytime seeing. The higher spatial and temporal correction capabilities are crucial to visible high-resolution observation in contrast with the nighttime astronomy. Furthermore, the solar wavefront sensor (WFS) has to work on low-contrast, extended, time-varying objects such as solar granulation[3].

In 2002, a tilt-correction adaptive optical system for the 43-cm solar telescope of Nanjing University had been successfully developed by the Institute of Optics and Electronics (IOE), Chinese Academy of Sciences[4]. In 2008, the first solar AO system in China, a 37-element AO experimental system was successfully built for the 26-cm fine structure solar telescope at the Yunan Astronomical Observatory, which saw its first light in Sept. 2009[5,6]. This experimental prototype had been modified and tested at the 1-m New Vacuum Solar Telescope (NVST) of the Fuxian Solar Observatory (FSO) in 2011[7]. In 2013, the first-generation solar AO system with a 37-element deformable mirror (DM) and a 30-subaperture Shack–Hartmann (SH) WFS operated at the frame rate of 2100 Hz had been developed for the 1-m NVST of the FSO. Due to limits of the spatial bandwidth, this system can only work well in good seeing conditions. In order to achieve diffraction-limited observations for a wider range of seeing conditions, the second-generation solar AO system with a 151-element DM and a 102-subaperture SH WFS was built and installed at the NVST in 2015. First light was seen in March 2015. We present the optical layout and the main parameters of the AO system and experimental results, such as images without/with AO.

The 1-m NVST, located on the northeast shore of Fuxian Lake, in Yunnan, China, was integrated and installed on site in 2010 and its first light observation without AO was achieved on Sept. 1 of the same year. The average seeing (Fried parameter r0) of the FSO obtained in the period from 1998 to 2000 was about 10 cm. The wind blows mostly from the lake with mean velocities no more than 6 m/s and the sunshine duration of the FSO is about 2200 h per year[8].

Figure 1 shows the optical configuration of the NVST. The optical design is an altazimuth-mounted Gregory–Coudé-type telescope. The clear aperture of the telescope is 985 mm and the effective focal length before instruments is 45 m.

Figure 2 illustrates the optical layout of the AO system, which is mounted after F3 of the telescope. Sunlight from the telescope is collimated to a beam with an aperture of 62 mm to feed onto a tip-tilt mirror (TTM) and then DM, which is conjugated to the entrance pupil. The reimaging

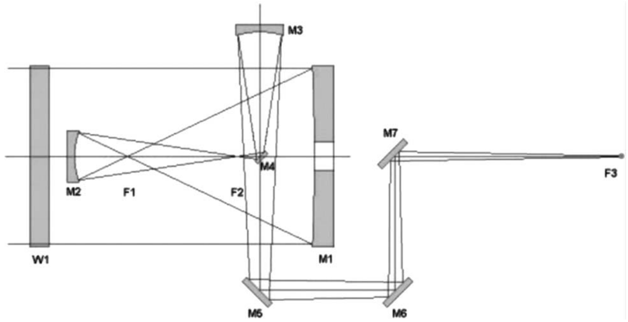

Fig. 1. Optical diagram of the NVST.

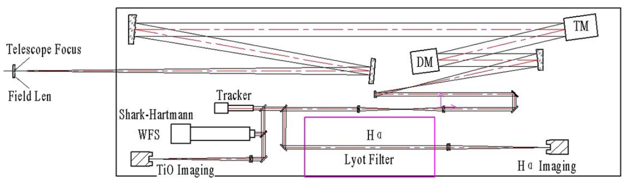

Fig. 2. Optical layout of the AO system.

optics system, which consists of two off-axis parabolic mirrors, collimates the beam into a 16 mm aperture and images the DM to the lenslet array of the SH WFS. The first dichroic beam splitter transmits the beam at a wavelength of 500 nm to the correlation tracker camera as well as the correlating SH WFS. The imaging system following the AO system permits simultaneous imaging in two channels, Hα 656.3 nm and TiO 705.6 nm, respectively.

The AO system is composed of a fine-tracking loop with a TTM and a correlation tracker, a high-order correction loop with a 151-element DM and a correlating SH WFS based on the Absolute Difference algorithm, and a real-time controller[9].

In the fine-tracking loop, the correlation tracker is the same as the first-generation AO system. The TTM with an aperture of 90 mm is newly manufactured by the IOE. The main specifications of the fine tracking loop are as follows.

- Field of view (FOV) of the live image: $19.2'' \times 19.2''$;
- FOV of the reference image: $9.6'' \times 9.6''$;
- Frame rate of the camera: 3100 fps;
- Tilt range of the TTM: $\pm 5'$;
- Resonant frequency of the TTM: about 2000 Hz;
- Original figure error of the TTM: 0.078λ PV and 0.013λ RMS ($\lambda = 632.8$ nm).

In the high-order correction loop, the arrangements of the DM's actuators and the subapertures of the WFS are shown in Fig. 3, which denotes the actuators and the subapertures as circles and the hexagonal grids, respectively.

The main parameters of the high-order correction loop are listed as follows:

- Geometry of the subapertures: 13×13;
- FOV per subaperture: $12'' \times 10''$;
- Frame rate of the camera: 3500 fps;
- No. of the actuators of the DM: 151;
- Stroke of the DM: ± 2.5 um;

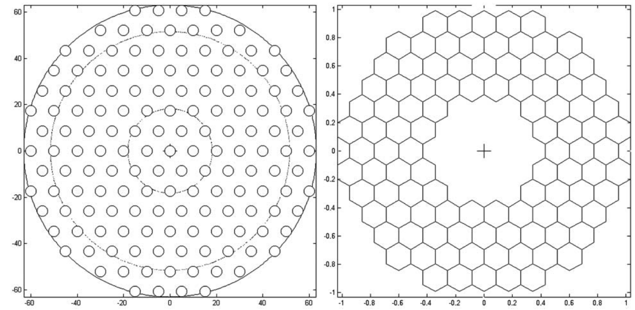

Fig. 3. Matching arrangement of the DM's actuators and the subapertures of the WFS.

- Flatted figure error of the DM: 0.098λ PV and 0.0094λ RMS ($\lambda = 632.8$ nm).

The second-generation AO system was integrated into the solar telescope and saw first light on Mar. 16, 2015. Figure 4 shows the simultaneous photosphere and chromosphere images without/with AO after dark and flat-field processing. AO-corrected images have a higher contrast and better resolution compared with uncorrected images. There are more details in corrected images, such as granules in the photosphere and some fine structures in the chromosphere.

A comparison of the contrast of the region [marked in Fig. 4(b)] in the photosphere image without/with AO is shown in Fig. 5. The contrast of the region increases from about 1.7% to about 3% when the loop is closed. The contrast of the granulation is defined as

$$C_{\text{granulation}} = \frac{(\text{sub\_image})_{\text{std}}}{(\text{sub\_image})_{\text{mean}}}, \tag{1}$$

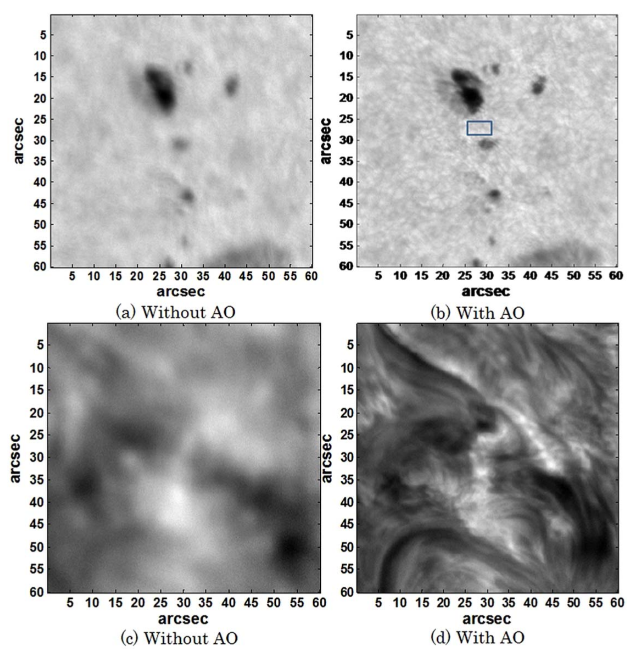

Fig. 4. Simultaneous photosphere (a,b) and chromosphere (c,d) images without/with AO.

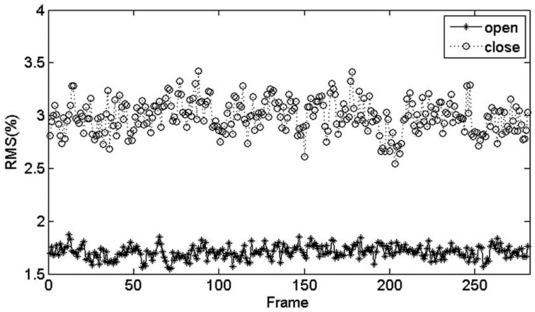

Fig. 5. Contrast of the granulation in the photosphere image without/with AO.

where the symbols $(\,)_{\mathrm{std}}$ and $(\,)_{\mathrm{mean}}$ signify the standard deviation and mean value of the matrix enclosed in braces, respectively.

In conclusion, we demonstrate that the second-generation AO system is operational and can be installed on the NVST. The performance of the system will be studied carefully, and some updates will be done to make the system combine with the NVST's post-focus instrumentation. The AO system will improve the scientific productivity of the NVST and help the astronomer study the Sun with high resolution to address fundamental physics questions related to solar fine structure.

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REFERENCES

1. T. R. Rimmele, Proc. SPIE **5490**, 34 (2004).
2. O. von der Luhe, D. Soltau, T. Berkefeld, and T. Schelenz, Proc. SPIE **4853**, 187 (2003).
3. T. Rimmele, K. Richards, S. Hegwer, D. Ren, S. Fletcher, and S. Gregory, Proc. SPIE **4839**, 635 (2003).
4. C.-H. Rao, W.-H. Jiang, C. Fang, N. Ling, W.-C. Zhou, M.-D. Ding, X.-J. Zhang, D.-H. Chen, M. Li, X.-F. Gao, and T. Mi, Chin. J. Astron. Astrophys. **3**, 576 (2003).
5. C. Rao, L. Zhu, X. Rao, C. Guan, D. Chen, S. Chen, J. Lin, and Z. Liu, Appl. Opt. **49**, G129 (2010).
6. C. Rao, L. Zhu, X. Rao, C. Guan, D. Chen, J. Lin, and Z. Liu, Chin. Opt. Lett. **8**, 966 (2010).
7. C. Rao, L. Zhu, N. Gu, X. Rao, L. Zhang, C. Guan, D. Chen, S. Chen, C. Wang, J. Lin, and Z. Liu, Proc. SPIE **8447**, 46 (2012).
8. Z. Liu, J. Xu, B.-Z. Gu, S. Wang, J.-Q. You, L.-X. Shen, R.-W. Lu, Z.-Y. Jin, L.-F. Chen, K. Lou, Z. Li, G.-Q. Lu, Z. Xu, C.-H. Rao, Q.-Q. Hu, R.-F. Li, H.-W. Fu, M.-X. Bao, M.-C. Wu, and B.-R. Zhang, Res Astron. Astrophys. **14**, 705 (2014).
9. L. Zhu, N. Gu, S. Chen, L. Zhang, X. Wang, X. Rao, M. Li, and C. Rao, Proc. SPIE **8415**, 150 (2012).