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SOLAR ADAPTIVE OPTICS SYSTEM FOR 1-M NEW VACUUM SOLAR TELESCOPE

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Abstract. The 1-m New Vacuum Solar Telescope (NVST), located at Full-shine Lake Solar Observatory, Kunming, Yunnan, is the largest solar telescope in China recently. A 37-elemnt low-order solar adaptive optics (AO) system had been developed and installed on the telescope in 2011, and AO-corrected high resolution solar images were obtained at wavelength 430.5nm, 705.7nm and 1555nm simultaneously. The low-order AO system can yield diffraction limited images only in the near infrared under good seeing and in the visible under excellent seeing, which cannot satisfy the requirement of Solar Physics study. A high-order AO system, which consists of fine tracking loop with a tip/tilt mirror and a correlation tracker, and a high-order correction loop with a 127-element deformable mirror, a correlating Shack-Hartmann wavefront sensor and a real-time controller, is under development. A multi-conjugate adaptive optics (MCAO) experiments are also carried on the telescope. This paper summarizes the progress of the solar adaptive optics in China and presents the observational results of the low-order AO system. The design of the high-order AO system and MCAO experimental prototype are given.

1 Introduction

High-spatial-resolution solar telescopes are needed for solar physics study. Adaptive Optics (AO) is an indispensable tool that allows high resolution observation of the Sun using ground-based telescopes， This technology aids the telescope for diffraction limit imaging by compensating the atmosphere aberration in real time.

A number of attempts were made during the last three decades to develop solar AO system. The first adaptive optics experiments with the Sun were performed at the Dunn Solar Telescope (DST) by Hardy in 1979 – 1980 [1]. The experiment indicated that solar AO is much more different from night time AO, which faces a set of problems, such as stronger turbulence, extended object wavefront sensing. A major milestone in the development of solar AO is the use of correlating Hartmann-Shark wavefront sensor, which is first used on the NSO (National Solar Observation) low-order solar AO system, this system was the first fully operational solar AO system that was also capable of tracking on granulation. The development of solar adaptive optics has excelled tremendously during the last 5 years. The AO-308 system designed for the 1.6m NST (New Solar Telescope) in America will incorporate a 357 actuators deformable mirror, a correlating Shack-Hartmann wave-front sensor with 308 subapertures, and a real-time controller, and the number of Zernike modes corrected will reach about 300. The AO system developed for the 4-m ATST will incorporate a 1313 actuators deformable mirror, a Shack-Hartmann wave-front sensor with 1232 subapertures, and a more complex real-time controller [2]. In Europe another 1.5m large solar telescope GREGOR will be outfitted with high order conventional AO

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systems, which contain a 196 actuators deformable mirror and acorrelating Shack-Hartmann wave-front sensor with 156 subapertures [3].

Meanwhile, solar multi-conjugate adaptive optics (MCAO) has developed very fast in recent years. MCAO is a technique that can break through the angular anisoplanatism and provide real-time diffraction limited imaging over an extended FOV of 1 – 2’, successful on-the-sky MCAO experiments have been performed at the DST and at the German VTT (Vacuum Tower Telescope) on the Canary Islands in 2003 – 2009 [4,5] , now the large solar telescope such as NST and GREGOR are planning to implement MCAO system, the 4 m aperture solar telescopes ATST and EST (Europe Solar Telescope) project are considered MCAO in their optical design and construction.

The development of solar AO in China also follows correlation tracker, low-order solar AO and high-order solar AO routine. A correlation tracker for the 43-cm Solar Telescope of Nanjing University had been successfully developed in 2002. A 37-element solar adaptive optics experimental prototype was designed for the 26-cm solar fine structure telescope at Yunnan Astronomical Observatory in 2008, and saw the first light in September 20098, 9. In 2010, the experimental prototype had been updated and installed at 1-m New Vacuum Solar Telescope (NVST) of Full-shine Lake Solar Observatory. The arrangement of subapertures of the Shack-Hartmann wavefront sensor was changed from square to hexagon in the updated system to achieve better compensation performance [6]. Moreover, the imaging channel of the system is updated to observe the sun in 3 - 4 wavelengths simultaneously.

This paper is organized as follows: In section 2, we briefly describe the telescope and the optical layout of the AO imaging system. The recently experiment results which observed with AO in wavelength 430 nm, 705.7 nm and 1555 nm simultaneously are presented in section 3. Section 4 is the detailed optical design for 127-element high-order AO system and some prepared for MCAO experiment. Section 5 summarizes this work.

2 OVERVIEW OF 1-m NVST AND AO SYSTEM

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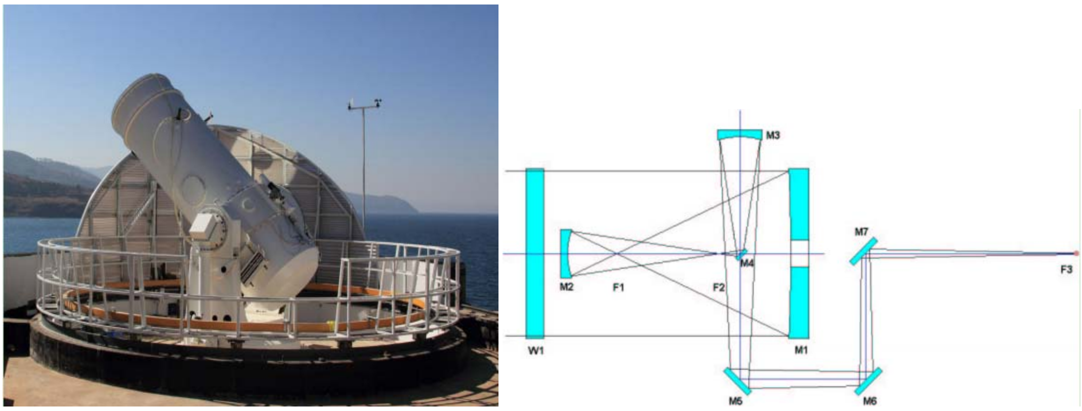
2.1 1-m New Vacuum Solar Telescope at Full-shine Lake Solar Observatory

You The 1-m NVST is a new generation solar telescope in China. The telescope is located at Full-shine Lake Solar Observatory, Kunming, Yunnan, and carries out the first light observation without AO in September, 2010. Figure 1 shows the telescope picture (left) and the optical diagram of NVST (right). An optical window (W1) with 1.2 meter diameter is placed on the top of the vacuum tube to keep inner air pressure low than 70 Pa. The optical system after W1 is a modified Gregorian. There is a 3 arcmin field diaphragm (heat stop too) on primary focus (F1) to prevent more energy enter into following system. After primary mirror (M1), the secondary mirror (M2) converge light rays to F/9 and focus at F2. For fear of polarization crosstalk, polarimeter can be inserted into the light path near F2 before the turning point of light rays. The M4 is a small flat mirror and reflects light rays to horizontal direction. As focusing mirror, M3 converge light rays to final focus through reflector M5 M7. The pure aperture of telescope is 985 mm and the effective focal length before instruments is 45 meters [7].

2.2 37-Element Low-order Solar Adaptive Optics Imaging System

The optical layout of the 37-element AO system for NVST is illustrated in Figure 2. The beam from telescope focal plane is collimated by an off-axis parabolic collimator, which images the entrance pupil onto the deformable mirror (DM), proceeded by the tip/tilt mirror (TTM). Theoretically, the TTM need also to be located at the pupil image so that it does not introduce pupil wander at the wavefront sensor when it corrects the global wavefront tilt, but this make the optical system complex that need one more reimaging optic system, and the spaces are limited on our bench. The DM is reimaged into a new exit pupil position with a 16mm diameter by the pupil reimaging optics system (which combined by two off-axis parabolic mirrors). The two wavefront sensors and three science imaging systems connect behind the exit pupil by beam splitter and optical relay systems. Three waveband are imaged simultaneously with the wavelength 430.5nm, 705.7nm and 1555nm, respectively.



(a) (b)

Fig. 1. New Vacuum Solar Telescope and its wind screen (a) and the optical diagram of NVST (b)

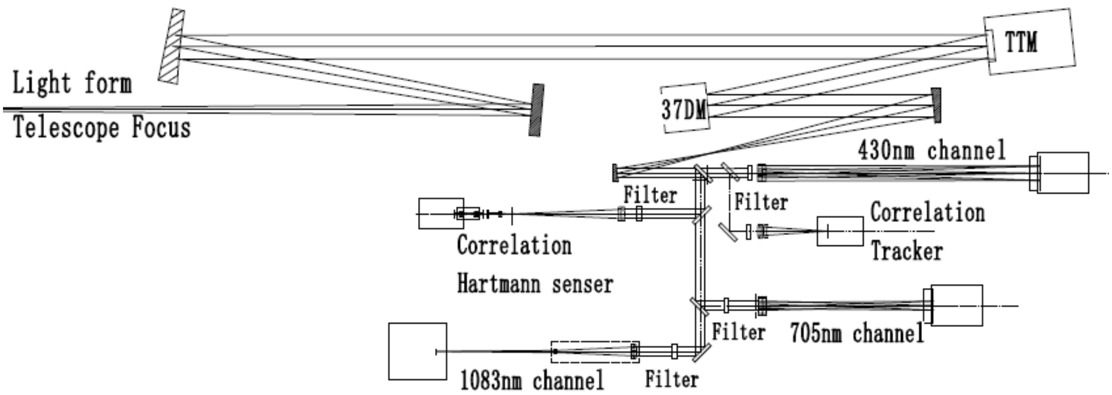


Fig. 2. The optical layout of the AO imaging system

2.3 Specifications of the System

The main specifications of the system are listed as follows.

Fine tracking loop:

- FOV (field of view) of live image: 19.2″ × 19.2″ ;
- FOV of reference image: 9.6″ × 9.6″ ;
- Frame rate of camera: 3100 fps;
- Clear Aperture of TTM: 58mm;
- Tilt range of TTM: ±4’;
- Resonant frequency of TTM: about1100Hz;
- Original figure error of TTM: 0. 124λ PV and 0.020λ RMS (λ=632.8nm).

High-order correction loop:

- Geometry of subapertures: hexagon, 30 effective subapertures ;
- FOV per subapertures: 24″ × 20″ ;

- Frame rate of camera: about 800 fps;
- Clear Aperture of DM: 40mm;
- No. of the actuators of DM: 37;
- Stroke: ±2um;
- Resonant frequency of DM: more than 2000Hz;
- Original figure error of DM: 0.171λ PV and 0.034λ RMS (λ=632.8nm).

The TTM and DM are both manufactured by The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences.

3 EXPERIMENTAL RESULTS

The latest observations were performed during August and September, 2012. The result showing in figure 3 is obtained on September 4 in three imaging channels, simultaneously, using sunspots as the beacon. The images are processed after dark and flat field. The exposure time is 10 nm. The results show that the contrast and resolution of the obtained solar images are improved evidently after the wavefront correction by this AO system.

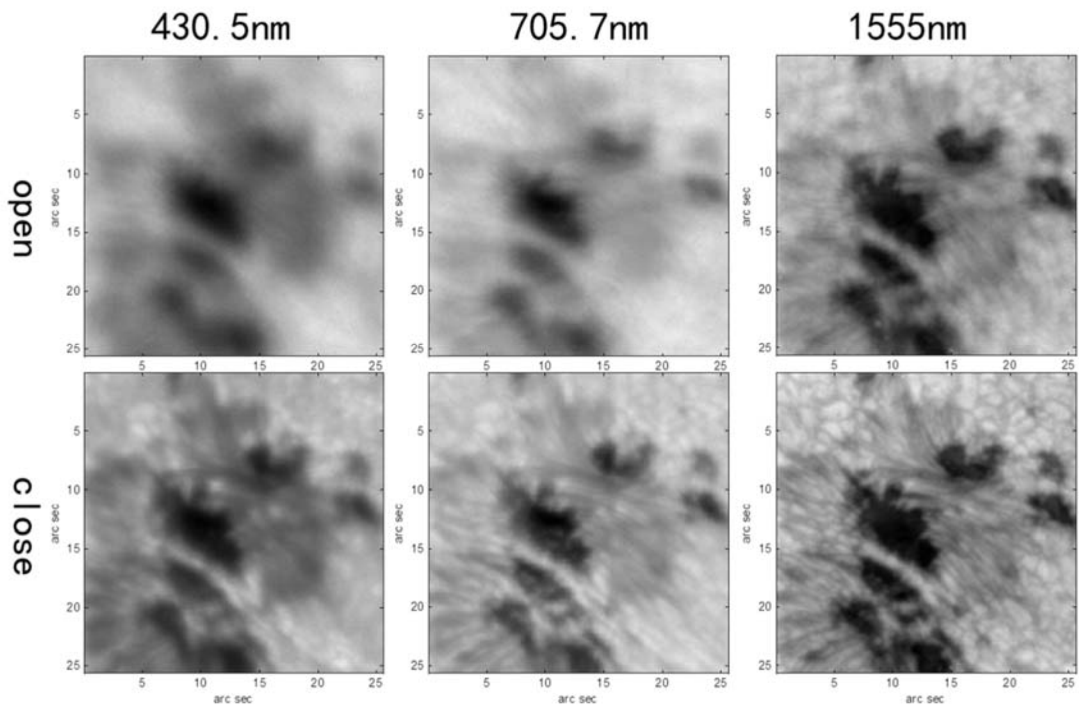


Fig. 3. Images of the sunspots without/with AO in three waveband imaging channel, simultaneously

4 DESIGN OF HIGH-ORDER AO SYSTEM AND LARGE FOV WFS

4.1 High-order AO system design

In this year, a 127-element high-order AO system is planned to mount instead of the low-order AO system for the NVST. Now the optical design is finished and real time control system is under debugging. The optical layouts of the high-order AO system are shown in figure 4 and figure 5, respectively. Because of the space limited, two layers optical bench design is considered, the fold mirror directs the sunlight into the top optical bench, after collimated the light is directed to TTM and DM. The beam reflected by DM is split by beam splitter M|BS into two channels, one transmits to the wavefront sensing and science imaging and the other reflects to the low optical bench. Parabolic mirror C2 and C3 reimage DM to a 16cm output pupil , then the light is split by a dichroic beam splitter BS1 which is transmissive for the 400 - 600 nm wavelength range and reflects the 600 - 1600 nm to the low bench for science imaging. The transmitted beam are used for the correlation tracker and the correlating Hartmann-Shack wavefront sensor (HSWFS), also for 430 nm science imaging, while the reflected beam in the low layer could be imaged in several channels.

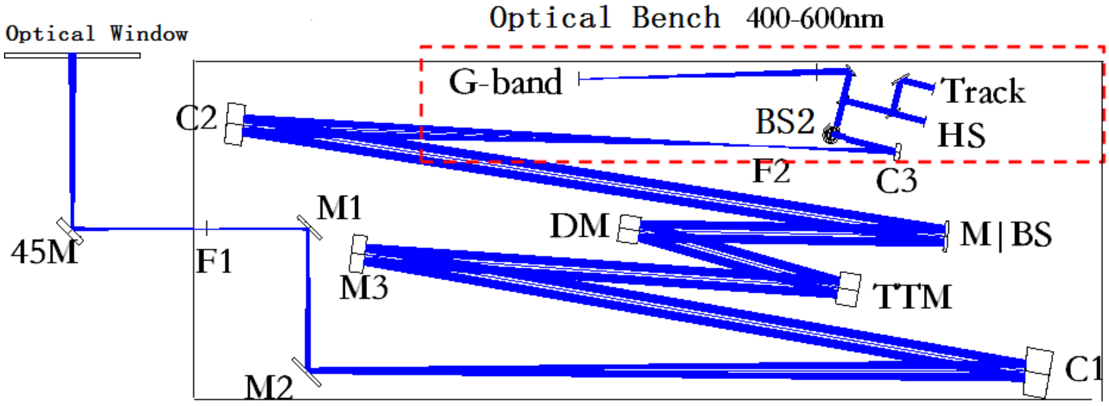


Fig. 4. The optical layout of the high-order AO system on top bench, two layers bench is obtained.

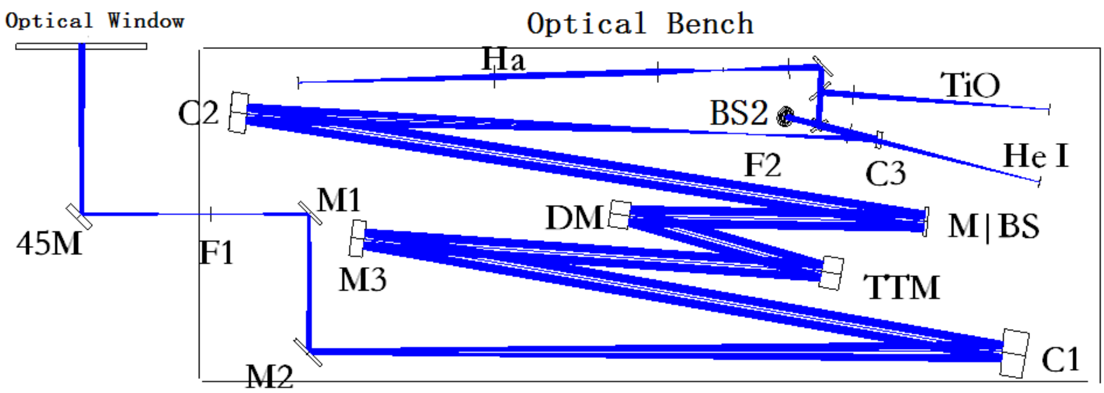


Fig. 5. The optical layout of the high-order AO system on low bench, two layers bench is obtained.

The beam reflected by M|BS into the low bench is another optical interface for spectrum imaging and other science experiment, which will not discuss in detail.

4.2 Large field of view wavefront sensor

Three diameter wavefront sensing of atmosphere turbulence is the key step to realize Multi-Conjugate Adaptive Optics (MCAO) technology. Normally, multiple guide stars are needed for tomographic wavefront reconstruction. The sun is the ideal target for MCAO, because it is extended and displays small scale structure everywhere on its surface, any number and any configuration of “guide stars” can be created. For this purpose, large field of view (FOV) Hartmann-Shark wavefront sensor has been designed, as showing in figure 6, only 7 subapertures are used to content the full rate of 960 frames per second. Each subaperture covers 1’ FOV with 120 pixel. The first experiment was carried out In January 2013, but failed for the worst seeing and limited experiment time. Next step a new large FOV SHWFS will be prepared which has 7×7 subapertures and fits out a new camera.

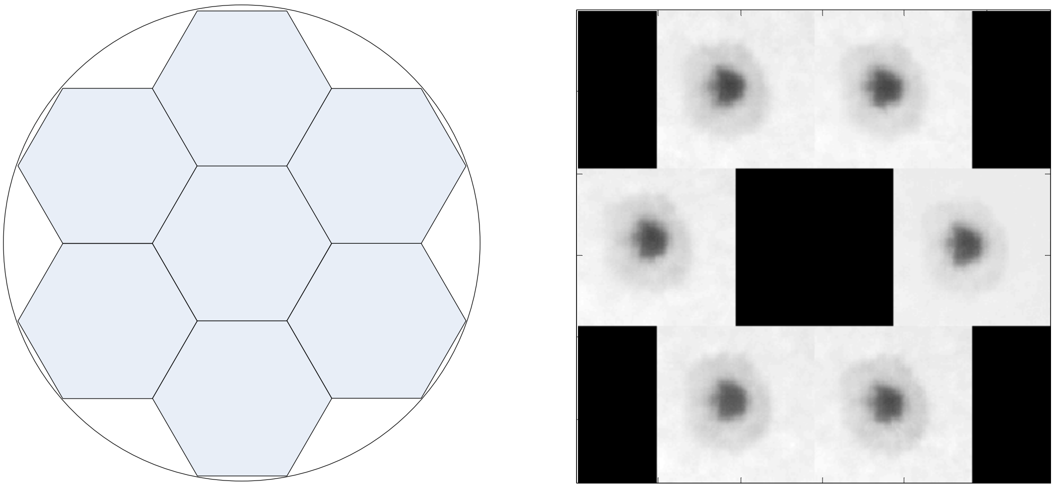


Fig. 6. Pupil and focus geometry of Large FOV SHWFS

5 CONCLUSIONS

The 37-element low-order solar adaptive optics system at 1-m NVST has been built and successfully tested. The results demonstrate that it is effective apparently to improve the resolution of the obtained solar images by using this AO system. Next a 127-element high-order AO system will be mounted for the NVST. Now the optical design is finished and real time control system is under debugging, at the same time , the experiment for MCAO are under prepared.

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