



The Educational Adaptive-optics Solar Telescope at the Shanghai Astronomy Museum

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Abstract: The Educational Adaptive-optics Solar Telescope (EAST) at the Shanghai Astronomy Museum has been running routine astronomical observations since 2021. It is a 65-cm-aperture Gregorian solar telescope for scientific education, outreach, and research. The telescope system is designed in an “open” format so that the solar tower architecture can be integrated with it, and visitors can watch the observations live from inside the tower. Equipped with adaptive optics, a high-resolution imaging system, and an integral field unit spectro-imaging system, this telescope can obtain high-resolution solar images in the TiO and H α bands, and perform spectral image reconstruction using 400 optical fibers at selected wavelengths. It can be used not only in public education and scientific outreach but also in solar physics research.

Keywords: Astronomy museum; Sun observation; Adaptive optics; Integral field unit

1. INTRODUCTION

The Sun is undoubtedly the most familiar of all celestial bodies, and its activity is not only the object of solar physics research but also carries important concerns for the public, such as causing both communications disruptions and breathtaking auroral displays. However, observing the Sun in detail is challenging because of the need for strict control of internal temperature. One way to deal with this issue is the use of filters for observation at specific narrow bands so that most heat can be controlled by transfer into a cooling system. Another method is to not observe the entire solar disk but instead use a small fractional solar disk with all excess light rejected at the focus of the primary mirror, utilizing the geometry of the Gregorian telescope. These control methods are typically adopted for professional solar telescopes.

Solar telescopes are generally divided into two categories based on their optical systems. One is the heliostat system, with its supporting buildings usually designed as towers; most early solar telescopes used this configuration. Typical examples include the solar tower in the

Deutsches Museum (1925) and the Griffith Observatory (1935)^[1, 2]. Another type of solar telescope makes use of Gregorian guiding optics, such as the Beijing Planetarium solar vacuum telescope built in 2004 and the Nagoya City Science Museum solar vacuum telescope built in 2010.

In the recently opened Shanghai Astronomy Museum (SAM), an innovative solar telescope has been installed that satisfies not only the requirements of a popular show at the museum but also the needs of professional scientific research. SAM, as a branch of Shanghai Science and Technology Museum (SSTM), is a new venue for scientific outreach in the Pudong New Area, Shanghai. It is funded by the Shanghai Municipal People's Government, and is one of the largest planetariums in the world. The museum officially opened on July 17th, 2021, and has become an attractive new landmark. There are two independent buildings with astronomical domes. The dome close to the main building is the Xihe Solar Tower, with the name “Xihe” referring to the Sun god in ancient Chinese mythology. The second floor of the solar tower houses the EAST, situated on the shore of the East China Sea.

This paper outlines the innovative design and perfor-

mance of EAST at the Shanghai Astronomy Museum and introduces its professional function for scientific research and outreach.

2. DESIGN OF EAST

EAST is an advanced scientific research instrument, independently designed and manufactured in China^[3]. Its main body was developed and completed by the Institute of Optics and Electronics, Chinese Academy of Sciences, and its integral field unit (IFU) spectrograph and polarimetric system were built by the Yunnan Observatories, Chinese Academy of Sciences. Its highlight is that it performs the two-fold function of both public education and outreach and professional research.

Traditionally, solar telescopes at planetariums only record solar images, but the designer at SAM conceptualized the idea of “observing the Sun in the belly of a telescope,” meaning that visitors can directly witness a beam of sunlight entering the telescope and then observe the entire light path in a platform with complex optics, giving a fuller appreciation for the resulting images.

EAST has a primary mirror aperture of 65 cm and a horizontal Gregory-Coudé design has been implemented so that the light from the rear end of the telescope enters the demonstration space vertically (via the “core tube”) on the first floor, regardless of the solar visual trajectory. Under sunny weather conditions, observers inside the tower core can see a beam of sunlight coming from the sky onto an optical platform in front of them. The light travels through many optical components, forming several high-resolution images of the Sun at different wavelengths. Such a direct demonstration system can show the entire optical system used in the observation, with a novel design choice to show the real light path to public spectators.

The optical system of EAST is also equipped with a

professional adaptive optics (AO) system, which can quickly detect atmospheric disturbances and correct the wavefront through a control system. This minimizes the influence of atmospheric disturbances on image quality, greatly improving spatial resolution. With this system, EAST can obtain high-resolution images of local solar disk regions in the TiO band and the H α band, showing the solar photosphere and chromosphere, respectively. These images are of high enough quality to be used for solar physics research.

In addition to high-resolution solar images, visitors can also see full-disk images of the Sun. To meet this requirement, EAST includes three small solar telescopes with 12 cm apertures attached to the main telescope. These images were observed at three wavelengths: TiO, H α , and Ca K. This allows visitors to appreciate multi-wavelength full-disk solar images together with high-resolution localized dual-band images in the core chamber on the first floor, while learning about the working principles of the optical platform. In addition, visitors can see a rainbow image of sunlight through a prism, along with solar spectra recorded by professional spectrometers also used for scientific research.

3. TELESCOPE DESIGN FOR PROFESSIONAL SCIENTIFIC RESEARCH

3.1. Overall System Design

Overall, EAST is composed of seven parts: the guiding optics, full-disk solar imaging system, AO system, high-resolution solar imaging system, IFU spectrometer, data acquisition and storage system, and public demonstration system. A schematic diagram is shown in Fig. 1.

The EAST optical system uses a horizontal total reflection Gregorian configuration, composed of a primary mir-

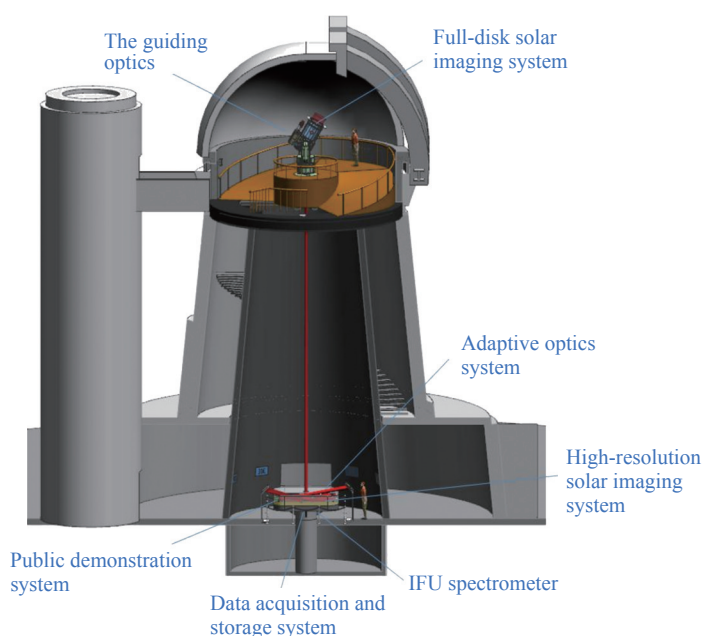


Fig. 1. Overall configuration of EAST.

ror with a 65 cm aperture, a heat stop, a ellipsoidal secondary mirror, a relay mirror, and glass windows. Each optical mirror is made from aviation-class ultra-low expansion (ULE) material, with a thermal deformation one order of magnitude lower than that of ordinary fused quartz material.

The optical configuration of the primary mirror is shown in Fig. 2, labeled M_1 . It has a focal length of 900 mm and a focal ratio of approximately $f/1.43$. This primary mirror is parabolic, while the secondary mirror, M_2 , is ellipsoidal. The telescope has a field of view of $6'$ and an observable wavelength range of 400–1 600 nm. The design of the optics makes it possible to obtain an image resolution close to the diffraction limit across the entire field of view.

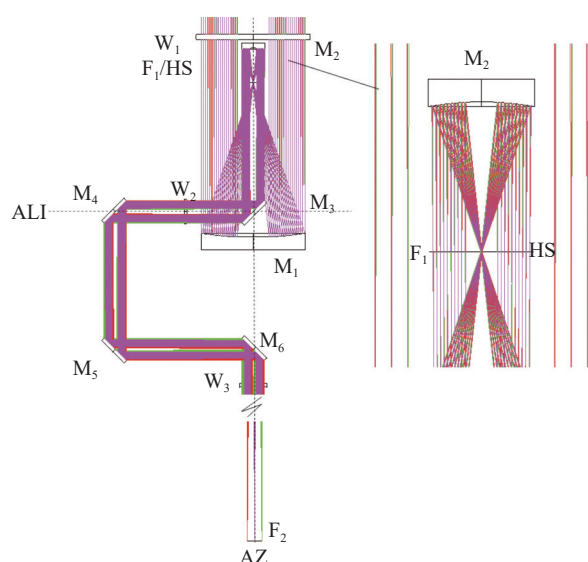


Fig. 2. Schematic diagram of the EAST main optical system (M-Mirror, W-Window, HS-thermal field diaphragm, F-Focus).

The mechanical subsystem of the primary mirror is composed mainly of three parts: azimuth shafting, pitch shafting, and main mirror barrel. The tracking accuracy of the telescope is $0.5''/30s$, or alternatively $5''/10min$. The barrel is fully sealed and air-pumped, with an internal thermometer and vacuum gauge to monitor internal temperature and degree of vacuum, and a warning will be issued if any deviation from the defined standard is detected.

The full-disk solar imaging acquisition system is a set of three small solar telescopes with identical 12 cm apertures attached to the primary barrel (Fig. 3), corresponding to the three bands. These can show the activity characteristics of the Sun at various atmospheric layers. All three auxiliary telescopes have a tracking accuracy of $0.5''$ during each exposure.

EAST is located in Lingang New City, Pudong New Area District, Shanghai, and the strong salt mist environment near the sea can potentially cause corrosion of the solar telescope system. To mitigate this, special measures are adopted to prevent salt corrosion. The mirror barrel is

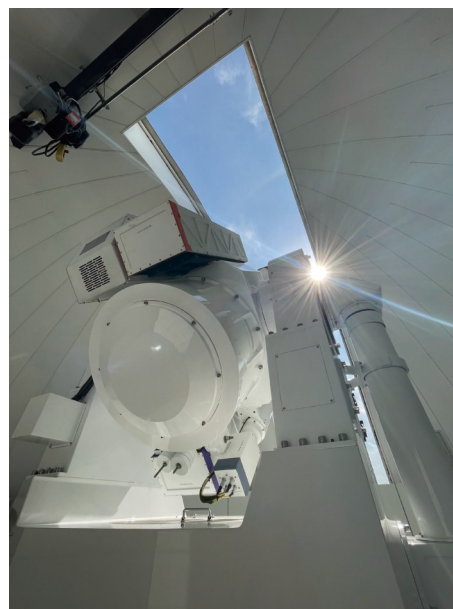


Fig. 3. The 65 cm solar telescope and three attached small telescopes.

completely enclosed and internally air-pumped, and the three necessary glass windows, W_1 – W_3 , are coated with a dielectric anti-reflection film (Fig. 2). Additionally, the mechanical structure surface is also coated with anti-corrosion paint, and the electronic system is given an anti-salt treatment.

3.2. Adaptive Optics and High-resolution Imaging Systems

For ground-based solar telescopes, atmospheric disturbance is a direct cause of image quality degradation. To eliminate the impact of atmospheric turbulence on optical systems, AO is adopted as an important means to maximize imaging resolution. It achieves optimal imaging performance by compensating dynamic wavefront errors caused by atmospheric turbulence in real time.

In China, presently operational large solar telescopes equipped with AO systems are the 1 m New Vacuum Solar Telescope (NVST)^[4] and the 1.8 m Chinese Large Solar Telescope (CLST)^[5, 6]. EAST, at Shanghai Astronomy Museum, is in a privileged position to be equipped with a professional AO system as a main feature, allowing EAST to operate in a professional capacity. To date, its achievements include the collection of observational data of solar activity used to study the magnetic structure of the Sun^[7].

The optical design of the AO system is illustrated in Fig. 4. Light entering the telescope is collimated by the lens collimator and then fed to the AO system, which consists of a tip-tilt mirror (TM), a deformable mirror (DM), a correlation Shack-Hartmann wave front sensor (WFS) and a high-speed real time controller (RTC).

Early-stage surveys reported that the seeing at the site has an average Fried parameter r_0 of approximately 4 cm, typical of strong turbulence. Consequently, the time and spatial sampling condition for the AO system operation is

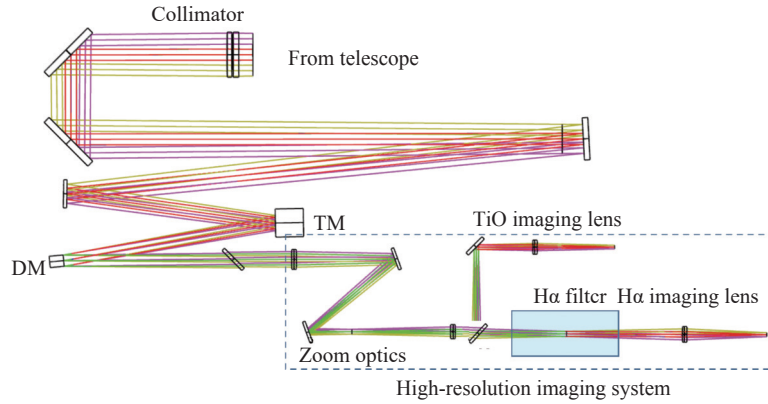


Fig. 4. Schematic diagram of AO system and high-resolution imaging system for EAST.

close to the performance limit of $r_0 \geq 3$ cm. Fig. 4 shows the design scheme of the AO system for EAST. The time detection frequency is above 2200 Hz, 177 DM correction units are configured at the back end, and the AO correction field of view is greater than 20". In addition, the design can also move the wavefront detection band to the longer-wavelength TiO band, which can further reduce the impact of turbulence, allowing more accurate wavefront measurements to be obtained.

The bands in which imaging can be performed at high resolution are TiO (705.7 ± 0.6 nm) and H α (656.28 ± 0.01 nm). The TiO band uses a filter manufactured by the Andover Company in the United States, with a bandwidth of ≤ 1.0 nm, and the H α band uses a Lyot filter based on a birefringent crystal, with a bandwidth of 0.025 nm. The field of view for high-resolution imaging in both bands is 4.1'. After AO correction, imaging resolution can reach 0.7". The imaging cameras employed in the EAST high-resolution imaging system are all scientific complementary metal oxide semiconductor (CMOS) cameras made by the German PCO company, with each chip covering 2048×2048 pixels.

Fig. 5 gives example images from the two high-resolution observation channels. For comparison, the left panels are obtained without AO correction while the right ones use speckle reconstruction based on AO correction^[8]. The correction of the AO system removes static aberration and some low-order aberrations of the system, which can significantly improve imaging quality, but using speckle image reconstruction technology through the statistical analysis of multiple short exposure images can further improve high-resolution images.

3.3. Full-disk Solar Imaging System

The three bands of the full-disk solar imaging telescopes are TiO (705.7 nm), H α (656.3 nm), and Ca K (393.4 nm), with bandwidths of ≤ 5.0 nm, ≤ 0.06 nm, and ≤ 0.1 nm respectively. The TiO band has the widest band-pass, so it uses the Andover high performance interference filter. Because the band passes of H α and Ca K are narrower for observational goals, Lyot birefringent filters are custom manufactured.

The full-disk imaging system is also used for guiding and controlling, to ensure that the pointing and tracking accuracy of the 65 cm telescope can be corrected in

real time, against wind or other vibrations. To achieve this function, the full-disk solar telescope has a field of view larger than 64' in the TiO band, and for the two telescopes in H α and Ca K bands, the field of view is smaller than 32' to ensure sufficient resolution.

3.4. Thermal Control Measures

One of the greatest challenges for solar telescope design is heat control. The larger the telescope aperture, the more heat will accumulate inside it during observation, potentially causing corresponding thermal deformation of various optical components. To ensure optimal performance, the design of the thermal control subsystem is crucial, particularly active control of the thermal field diaphragm and passive control of thermal structures such as the main barrel and mechanical frames.

The thermal field diaphragm (labeled HS in Fig. 2) uses active thermal control measures at the primary mirror focus to reject excess heat using liquid refrigerant. The main measures include: (1) Selecting an appropriate copper alloy with excellent thermal conductivity. With a specially designed thermal field diaphragm at the main focus, 96% of solar radiation is reflected out into the surrounding environment. (2) Using a specially designed water-cooled heat exchanger device, the diaphragm can be effectively cooled. Effective thermal control design ensures that the difference between the operating temperature inside the tube and the surrounding ambient temperature is within ± 1 °C. Fig. 6 shows the measured temperature variation during 8-hour observations for EAST.

Passive thermal control of structures such as the main barrel and mechanical frame of the telescope is primarily achieved by material coating or radiation shielding, to suppress thermal deformation or increasing temperature of structural parts. Principal measures include: (1) a "solar shield" used for shielding the entire tube from direct sunlight. (2) a coating on the surface of the sun shield and frame structure, consisting of a layer of TiO₂, using its high reflectivity to reduce absorption of solar radiation and prevent thermal deformation of the structure.

For its intended goal of demonstrating observations, EAST comprises a tower structure, allowing visitors to easily see the details of the telescope. However, this causes inevitable air disturbance within. To achieve stable air

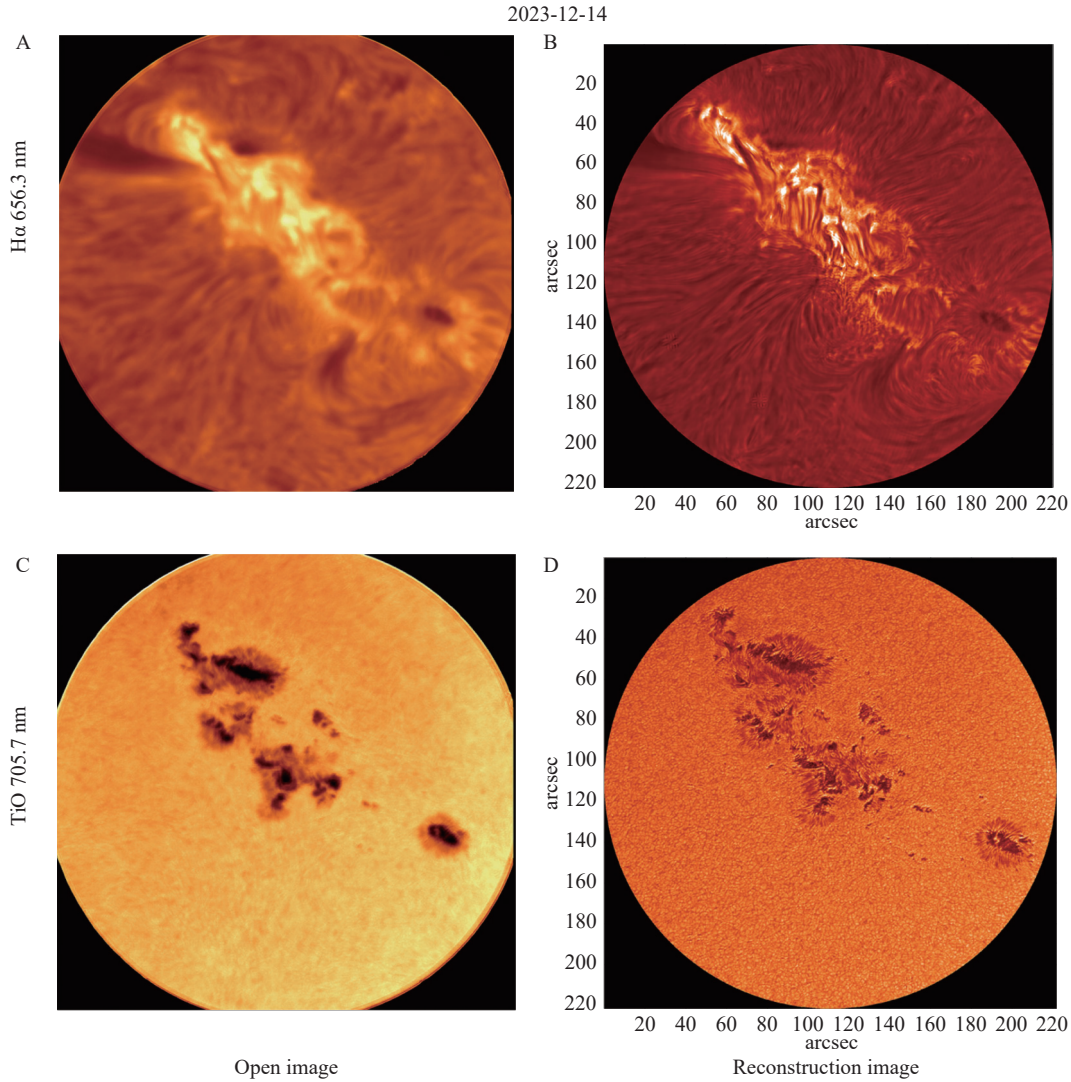


Fig. 5. Images of two high-resolution imaging channels (A and B show H α , C and D show TiO). A and C are the open loop images, B and D are images with speckle reconstruction based on the AO correction.

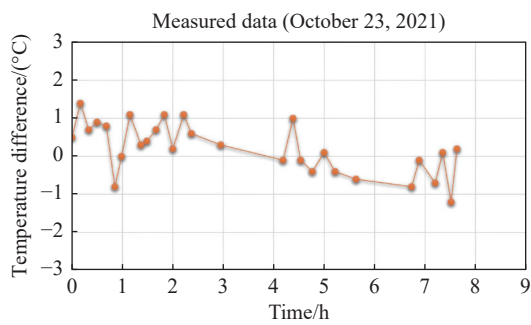


Fig. 6. Measured temperature variation for EAST.

flow conditions, the core cylinder of the solar tower is equipped with a multi-stage air conditioner to control the inner temperature of the 18-meter-high core cylinder at a constant temperature of 22 ± 0.5 °C. A layer of glass partitioning is installed at 3 m above ground level, to control air turbulence caused by visitors. In addition, the dome pier of the tower is specially designed with 8 adjustable windows, which can be opened during observation, allowing heat to escape the dome by convection.

3.5. IFU Polarimetric Spectro-imaging System

An advanced polarimetric spectro-imaging system connects the telescope and the spectrometer, consisting of polarimetric and IFU systems. The first observatory using such an IFU spectro-imaging system in China is the FASOT telescope at Yunnan Observatories^[9-11]. It is capable of recording full Stokes spectra or spectro-imaging polarimetry of all sample spatial points distributed within the two-dimensional field of view in real time. The data obtained by this system can be used to infer physical quantities in the solar atmosphere such as vector magnetic field and line-of-sight velocity, allowing researchers to study the structure and evolution of vector magnetic fields and matter flows in the solar atmosphere. The goal is to elucidate the mechanisms behind solar activity.

The spectro-imaging IFU system installed on EAST consists of five parts: the IFU front coupling system, the IFU body, the IFU slit-fed spectrometer, the electronic control system, and the image demonstration system. The optical component of the system is shown in Fig. 7. The IFU

system is formed by a 20×20 array of microlenses, each with an aperture of $127 \mu\text{m}$. This is coupled to an array

of 400 optical fibers, re-woven into a pseudo-slit feeding the spectrograph.

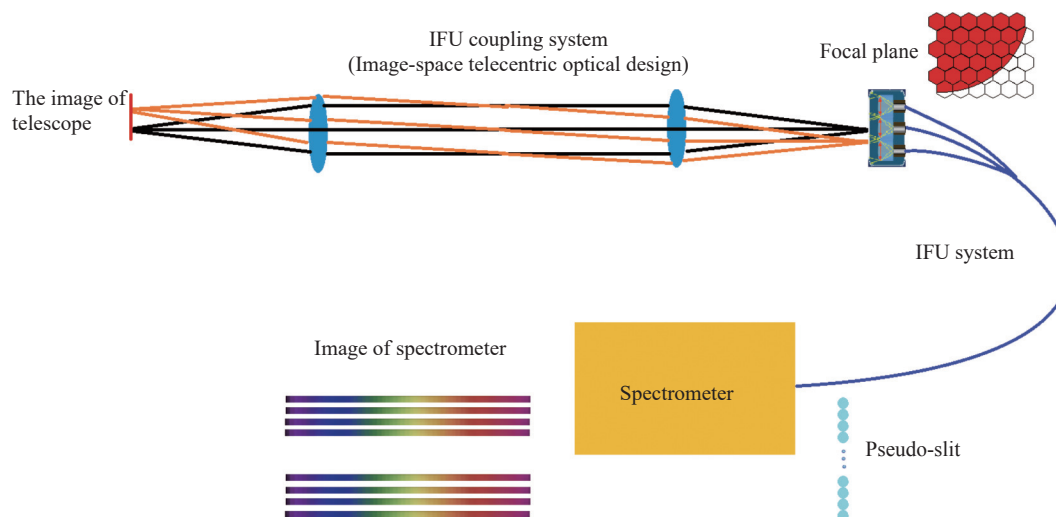


Fig. 7. Schematic diagram of the IFU spectral imaging system.

The optical imaging system in front of the IFU is shown in Fig. 8. The light from the telescope enters the first imaging system, is collimated, and then enters the polarimeter consisting of a rotatable $1/4$ wave plate and a polarizing beam splitter. Polarimetric modulation is performed by rotating the wave plate. In the second imaging system, formed by the microlens array, the solar disk image is segmented so that a light beam from each microlens (corresponding to a spatial point on the solar surface) is transmitted into each corresponding IFU optical

fiber. The working field of view of the IFU is $20'' \times 20''$, corresponding to each spatial point occupying $1''$ in the sky plane.

The spectrometer is another core component for spectro-imaging performance. This system is located in the basement below ground level of the solar tower, consisting of the collimation system, rotatable grating system and imaging system. The spectral resolution is 25000, and the working band is 430–640 nm.

The electronic control system of the spectrometer is a key component. Different observational bands are available by controlling the rotation of the grating and the corresponding filter wheel. Polarimetry is performed by managing the rotation angle of the $1/4$ wave plate. The chip of the imaging camera has a size of 4096×4096 pixels.

Example spectra acquired by this system are shown in Fig. 9. A two-dimensional map containing 20×20 spatial points can be reconstructed according to the alignment of the spatial points in the microlens array at sample wavelength points, as shown in Fig. 10. Using the polarimetric observation mode, the Stokes parameters I , Q/I , U/I , and V/I at each sample wavelength point can be obtained for every pixel (see Fig. 11), allowing further physical information of the observed region to be determined.

4. DEMONSTRATION PLATFORM FOR PUBLIC EDUCATION AND OUTREACH

EAST can obtain excellent imaging quality for scientific research, but it must also satisfy another important function in scientific education and outreach. The elaborately designed demonstration platform is, therefore, a key component of the overall system.

To ensure a stable air environment, the optical path

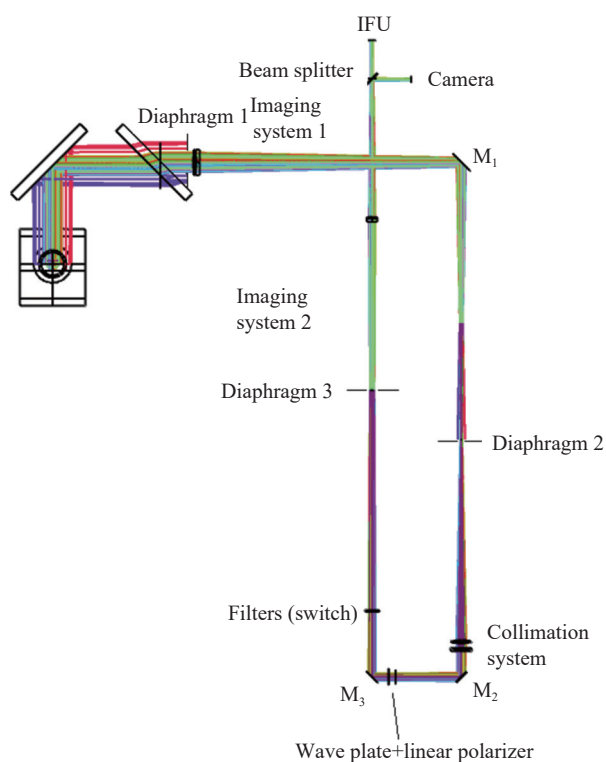


Fig. 8. Schematic diagram of the IFU front-end optical system.



Fig. 9. Spectra acquired by the spectrometer.

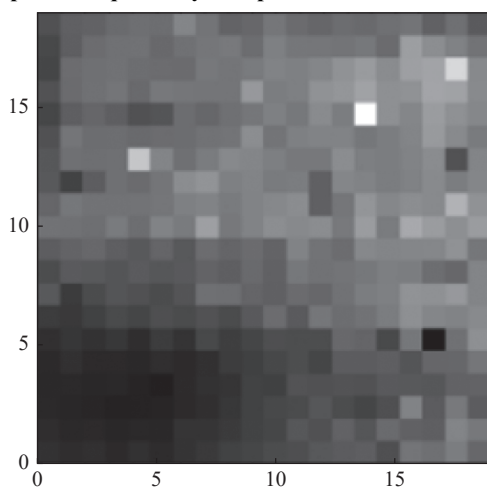


Fig. 10. Reconstructed two-dimensional map.

of professional telescopes is usually closed, but the solar tower of EAST features an "open" mode for solar observation. A $3\text{ m} \times 3\text{ m}$ optical platform (Fig. 12) is placed in the demonstration area of the core chamber, where an

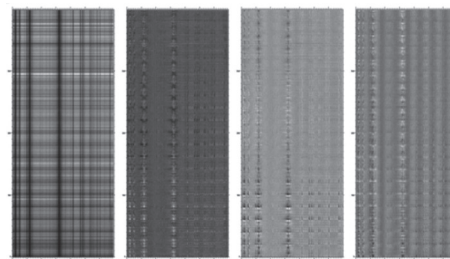


Fig. 11. Revised-results of the polarimetric observation.

assembly of optical components, including the AO instruments, is situated. When visitors enter this area, they can enjoy a "Live Show of Solar Observation" from sunlight to image (Fig. 13). At the beginning of the live show, a video will introduce the basic structure and working principles of the entire solar tower. Then, a beam of light enters from the above dome, passing through multiple lens groups on the optical platform. Some LED light strips are included on the optical platform to assist in the demonstration of the light path.

The sunlight guided by the solar telescope is divided into four channels. The first channel of light is used for displaying the "rainbow" of the sunlight after dispersion by a prism. The second channel of light shows a real-time solar photospheric image, allowing visitors to observe sunspots when they are present. The third light beam is transmitted into the underground room for spectro-imaging, and the fourth light beam enters the high-resolution camera, allowing visitors to see high-resolution real-time imaging of the sun in the two bands and compare the different imaging qualities, with and without AO.

An assembly of 6 display screens is installed on the wall of the core chamber to demonstrate the overall structure of the solar tower, the working principles of the AO system, and real-time solar images; these include high-resolution local solar images in two bands and full-disk solar

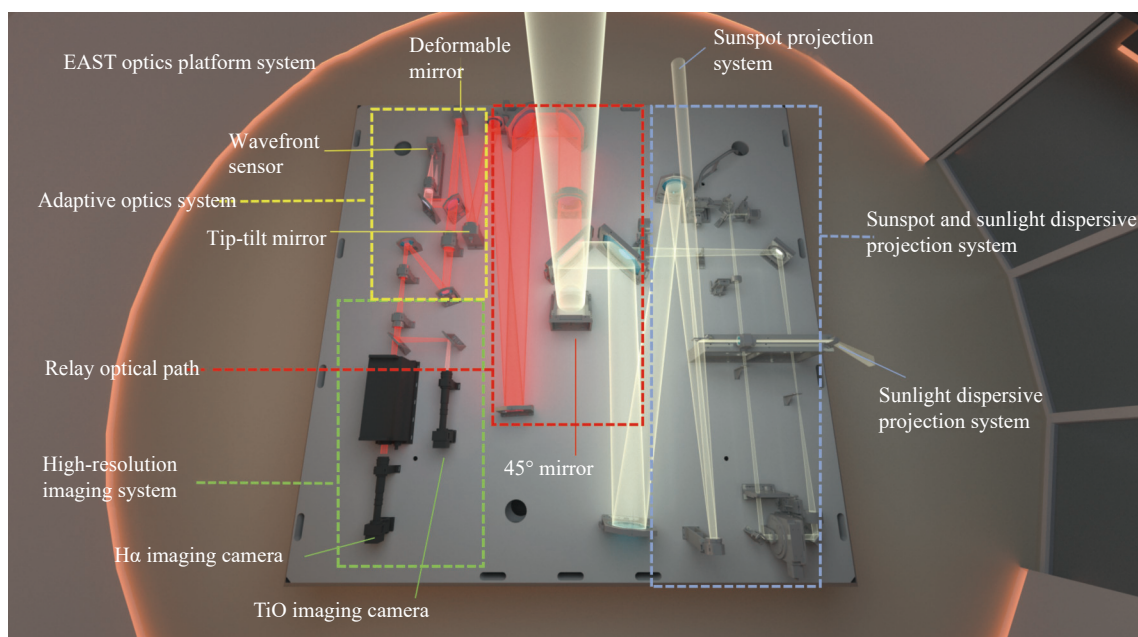


Fig. 12. Schematic diagram of the EAST optical platform layout.



Fig. 13. On-site photo of "Live Show of Sun Observation" in the EAST core tube.

images in three bands, as well as solar spectrum imaging obtained by the IFU system. The entire demonstration is simultaneously accompanied by audio commentary. In the core room, visitors can not only witness sunlight "falling from the sky" but also gain an in-depth understanding of the working principles of solar telescope instrumentation.

As an instrument open to the public, the demonstration platform should be operable under any weather conditions, so the "Live Show of Solar Observation" system is designed with two demonstration modes: sunny mode and cloudy mode. In sunny mode, visitors can see real sunlight beams and thus real-time imaging of the sun. In cloudy mode, a set of spotlights installed in the dome will illuminate, simulating the same effect. In this simulation mode, visitors can see a beam of artificial "sunlight" and the solar images shown on-screen are previously recorded.

The first-floor exhibition hall of the solar tower will also include a variety of exhibits related to the solar tower and knowledge of the sun, including the construction process of the solar tower and some notable solar images recorded by spaceborne observatories. At the end of the tour, a "My Sun" exhibit is provided for visitors to take souvenir photographs. These can include a model of the Sun, as well as solar images acquired by EAST, and can be saved directly to visitors' mobile phones.

5. CONCLUSION

EAST at SAM provides an excellent opportunity for members of the public to directly get involved in solar observation. Visitors can not only see real-time solar images, but also learn about the working principles of the telescope in depth. Enthusiasts will also have the opportunity to practice observation as semi-professional operators.

Additionally, EAST is a professional-quality solar telescope that incorporates advanced AO and IFU systems. The entire telescope was developed in full accordance with the standards of research-grade astronomical equipment. Through operation, it has demonstrated excellent optical performance, obtaining high-quality solar images and spectra. Consequently, this solar telescope can satisfy the needs of public scientific education and outreach, and also be used to perform scientific observations. The data collected can be applied to professional solar physics research.

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AUTHOR CONTRIBUTIONS

Qing Lin and Zhimao Du conceived the idea and were principal authors of the manuscript. Xuejun Rao, Hua Bao, and Libo Zhong provided the technical design of the optics and the AO system. Yue Zhong, Yu Liang, and Hui Zhang provided the IFU system's technical design. Jiawen Yao provided solar images observed by EAST. Libo Zhong provided high-resolution reconstruction images. Yu Liang provided IFU reconstruction images. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

- [1] Fehlhammer, W. P., Fuessl, W. 2000. The Deutsches museum: Idea, realization, and objectives. *Technology and Culture*, **41**(3): 517–520.
- [2] Leslie, S. W., Margolis, E. A. 2017. Griffith observatory: Hollywood's celestial theater. *Early Popular Visual Culture*, **15**(2): 227–246.
- [3] Rao, C. H., Rao, X. J., Du, Z. M., et al. 2022. EAST-educational adaptive-optics solar telescope. *Research in Astronomy and Astrophysics*, **22**(6): 065003.
- [4] Liu, Z., Xu, J., Gu, Z. B., et al. 2014. New vacuum solar telescope and observations with high resolution. *Research in Astronomy and Astrophysics*, **14**(6): 705.
- [5] Rao, C. H., Gu, N. T., Zhu, L., et al. 2015. 1.8-m solar telescope in China: Chinese large solar telescope. *Journal of Astronomical Telescopes, Instruments, and Systems*, **1**(2): 024001.
- [6] Rao, C. H., Gu, N. T., Rao, X. J., et al. 2020. First light of the 1.8-m solar telescope—CLST. *Science China. Physics, Mechanics & Astronomy*, **63**(10): 109631.
- [7] Zheng, R. S., Liu, Y. H., Zhang, L., et al. 2023. The deformation of an erupting magnetic flux rope in a confined solar flare. *The Astrophysical Journal Letters*, **942**(1): L16.
- [8] Zhong, L. B., Tian, Y., Rao, C. H. 2014. Speckle image reconstruction of the adaptive optics solar images. *Optics Express*, **22**(23): 29249–29259.
- [9] Qu, Z. Q. 2011. A fiber arrayed solar optical telescope (FASOT). In Proceedings of Astronomical Society of the Pacific Conference Series.
- [10] Qu, Z. Q., Chang, L., Cheng, X. M., et al. 2014. Prototype FASOT. In Proceedings of Astronomical Society of the Pacific Conference Series.
- [11] Sun, W. M., Chen, X. D., Yan, Q., et al. 2023. Fiber Integral Field Unit System for Measurement of Solar Spectrum. *Spectroscopy and Spectral Analysis*, **43**(4): 1168–1174.