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Abstract. For better understanding and forecasting of solar activity, high resolution observations for the Sun are needed. Therefore, the Chinese Large Solar Telescope (CLST) with a 1.8-m aperture is being built. The CLST is a classic Gregorian configuration telescope with an open structure, alt-azimuth mount, retractable dome, and a large mechanical de-rotator. The optical system with an all reflective design has a field of view of larger than 3 arc-min. The 1.8-m primary mirror is a honeycomb sandwich fused silica lightweight mirror with an ultra lower expansion material and active cooling. The adaptive optics system will be developed to provide the capability for diffraction-limited observations at visible wavelengths. The CLST design and development phase began in 2011 and 2012, respectively. We plan for the CLST’s start of commission to be in 2017. A multiwavelength tomographic imaging system, ranging from visible to near-infrared, is considered as the first light scientific instrument. The main system configuration and the corresponding postfocal instruments are described. Furthermore, the latest progress and current status of the CLST are also reported. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE)

Keywords: Chinese Large Solar Telescope; high resolution solar observations; adaptive optics; Gregorian; lightweight mirror; tomographic imaging.

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1 Introduction

Theoretical studies and numerical computations suggest that much of the interaction between the solar plasma and the magnetic field occurs on very small spatial scales of about 50 to 100 km in the solar atmosphere, corresponding to an angle resolution of 0.1 arc sec. Therefore, we need a more powerful facility for solar observing with higher temporal and spatial resolutions. The development of the solar telescope can be divided into three phases: submeter aperture size phase, two-meter aperture size phase, and four-meter aperture size phase. Before the 1990s, several sub-meter aperture size solar telescopes were built for solar observation, such as the Dutch open telescope (DOT) with a 45 cm aperture size, the Richard B. Dunn Solar Telescope with a 76 cm aperture size, the vacuum tower telescope with a 70 cm aperture size, the Swedish solar telescope with a 1-m aperture size, the new vacuum solar telescope with a 98 cm aperture size (NVST), and so on. Except for the DOT, most of these submeter class solar telescopes were made as a vacuum structure to avoid the mirror seeing effect. Therefore, a submeter telescope no longer meets the need of higher resolution observations. After several years’ effort, several two-meter class solar telescopes have been constructed, i.e., the McMath-Pierce (MMP) solar telescope, NST and GREGOR, and the two-meter aperture size solar telescope NLST of India is in the planning stage. Two four-meter class solar telescopes, which are the DKIST and the EST, are also planned to observe solar activity with high temporal and spatial resolution.

The majority of large aperture solar telescopes reside in America or Europe, and there is no two-meter aperture size solar telescope which is operational yet in Asia. In this paper, we discuss a two-meter class telescope, the Chinese Large Solar Telescope (CLST), to be built in China. After its completion, CLST will fill the gap of two-meter class solar telescopes in East Asia, adding to a network of telescopes able to observe the solar surface with high temporal and spatial resolution.

The 1.8-m CLST will have a clear aperture of 1.76 m. The CLST is a classic Gregorian configuration telescope with an open structure, alt-azimuth mount, retractable dome, and a large mechanical de-rotator. The optical system is an almost all reflective configuration with seven wavelengths ranging from visible to near-infrared is being considered as the first light scientific instrument. Spatial resolution is one of the highest goals, and it is the main driver for the large-aperture solar telescope development. The diffraction limit angular resolution of the CLST is about...
0.052 arc sec at the G-band wavelength, and it is better for revealing the fundamental astrophysical processes with a higher spatial resolution. The first driver of the CLST is to study the evolution of solar active regions at different altitudes and the research result will reveal the three-dimensional magnetic topology of the solar atmosphere.

Magnetic strength and direction, temperature and velocity structure, and the other dynamic parameters are also included in the CLST science goals. The research results may answer the accuracy of our hydrodynamic simulations for solar convection and reveal the relationship between the temperature and the height of the solar atmosphere. We also have an interest in the coupling mechanism between the magnetic and hydrodynamic fine structures, and their relationship to the dynamic processes for the other height. The higher spectral resolution and higher throughput of CLST should meet the requirements of these goals.

In this manuscript, we will introduce the optical configuration of the CLST in Sec. 2, and the corresponding mechanical system will be introduced in Sec. 3. In Sec. 4, the progress of the primary mirror and the thermal controlling system will be described. The initial design of the solar adaptive optics system for the CLST is also described in Sec. 5. Currently, the enclosure and building of the CLST are being considered, and these are described simply in Sec. 6. Finally, we conclude the current status and the next steps of the CLST in Sec. 7.

Table 1  The parameters of the optics system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture size of M1</td>
<td>$\Phi$1800 mm</td>
</tr>
<tr>
<td>Radius of curvature of M1</td>
<td>6120 mm</td>
</tr>
<tr>
<td>Field of view (FOV)</td>
<td>$\geq 0.3$ arc sec</td>
</tr>
<tr>
<td>Wavelength cover</td>
<td>380 to 2500 nm</td>
</tr>
<tr>
<td>Image space F#</td>
<td>F/54.5</td>
</tr>
<tr>
<td>Focal length</td>
<td>$\sim 96$ m</td>
</tr>
<tr>
<td>Aperture size of M2</td>
<td>$\Phi$490 mm</td>
</tr>
<tr>
<td>Radius of curvature of M2</td>
<td>1280</td>
</tr>
<tr>
<td>Conic constants of M2</td>
<td>$-0.32$</td>
</tr>
<tr>
<td>Aperture size of M3</td>
<td>$\Phi$390 mm</td>
</tr>
<tr>
<td>Radius of curvature of M3</td>
<td>3772</td>
</tr>
<tr>
<td>Conic constants of M3</td>
<td>$-0.6$</td>
</tr>
<tr>
<td>Clear aperture (TTM)</td>
<td>$\sim 0.90$ mm</td>
</tr>
<tr>
<td>Clear aperture (DM)</td>
<td>$\sim 0.62$ mm</td>
</tr>
</tbody>
</table>

From the spot diagram figure, the only a bit of field curve is contained in this optics system. The corresponding field curvature and distortion are both shown in the left of Fig. 3. The field curvature plot shows the distance from the image surface to the paraxial image surface as a function of the point of the FOV.

Currently, a 151-element lower order solar adaptive optics system will be used to correct the ground layer turbulence. In the future, we will equip a 511-element high solar adaptive optics system and multiconjugate solar adaptive optics system.

![Fig. 1 Optical configuration of the Chinese Large Solar Telescope (CLST) telescope (main optics system).](image)
The configuration of the CLST structure depends on the optical layout. The CLST will employ an alt-azimuthal mount, maintaining precise pointing and tracking under wind speeds up to 20 m/s. The CLST’s structure will keep the optical components well-aligned independent of the orientation of the telescope, and it will be a very stiff steel construction. For minimizing thermal deformation of the mechanics system, all parts exposed under sunlight will be painted white with a TiO2 paint under consideration. The configuration of the mechanics system of the CLST is shown in the Fig. 4. As shown in Fig. 4, the CLST’s structure will consist of two main parts, i.e., the elevation part and the azimuth part. The total height of the mechanical system will be about 8 m above the bottom base, and the total weight will be about 22 tons. The elevation structure includes the top ring with the M2 and the heat-stop support structures, the tube, the M4, and the polarization calibration and modulation units support structure, M3 and M1 support structure.

3 Mechanical System of the Chinese Large Solar Telescope

The configuration of the CLST structure depends on the optical layout. The CLST will employ an alt-azimuthal mount, maintaining precise pointing and tracking under wind speeds up to 20 m/s. The CLST’s structure will keep the optical components well-aligned independent of the orientation of the telescope, and it will be a very stiff steel construction. For minimizing thermal deformation of the mechanics system, all parts exposed under sunlight will be painted white with a TiO2 paint under consideration. The configuration of the mechanics system of the CLST is shown in the Fig. 4. As shown in Fig. 4, the CLST’s structure will consist of two main parts, i.e., the elevation part and the azimuth part. The total height of the mechanical system will be about 8 m above the bottom base, and the total weight will be about 22 tons. The elevation structure includes the top ring with the M2 and the heat-stop support structures, the tube, the M4, and the polarization calibration and modulation units support structure, M3 and M1 support structure.

Fig. 4 The three-dimensional (3-D) sketch of mechanical design for the CLST.
Considering relaxing sensitivity against misalignment, the M2 will be supported by a modified hexapod system. An invar suspension ring supporting the heat-stop unit at the primary focus will be located at the lower part of the spider legs. Sun shields will also be located on the top ring to protect the top ring, spiders, and tubes against direct irradiation by the sunlight. M4 and the polarimetric calibration and modulation unit are connected by a four-leg radial spider at the lower position of the telescope tube. The orientation of the spiders will overlap with the spiders of the top ring to avoid additional shadow of the primary mirror. The thickness of the spiders will be 12 mm to minimize the width of the spider shadow in the pupil image. The supporting and cooling system of M1 will be located at the bottom end of the tube. The CLST will take the classic whiffletree supporting system, as shown in Fig. 5, and 18 attachment points will support the weight of M1. Two triangular plates are supported from each of three bars that are centrally supported from three points equally spaced on a circle of a certain radius. Twelve of 18 attachment points are located on the outer ring and the rest of points are located on the inner ring. The position of the 18 supporting points has been optimized to minimize the deformation of the M1 at different elevation angles. The M3 unit is mounted behind the M1 support and cooling systems and it will be able to adjust the position of the F3 by moving M3.

The azimuth structure consists of the azimuth fork, the rotating platform, the azimuth bearing, drives, encoders, and the azimuth cable twister. The azimuth structure and the elevation structure are connected by the forks via the elevation bearing. The azimuth fork is designed as transparent as possible to allow for natural wind flushing for better thermal controlling, and is mounted on the rotating platform with drive units and bearings. The drives are prestressed gear servo drives diametrically arranged. The diameter of the prestressed cross-roller bearing is about 2.2 m, and the maximum jitter of the azimuth bearing is below 2 arc sec. A Renishaw incremental optical encoder tape is mounted at the inside of the bearing. Four sensor heads will be included in the encoder to read the tape in order to achieve the required precision. The full rotation angle of the azimuth structure ranges from −270 deg to 270 deg, and the azimuth cable twister with two chains will synchronously rotate with the azimuth structure.

### 4 Primary Mirror and the Thermal Controlling System

The CLST includes eight reflecting mirrors and two refraction windows, and ULE® and SiC material are mainly considering for these reflecting mirrors. Under the current design, M1 will be made by using ULE® material. The Institute of Optics and Electronics (IOE), Chinese Academy of Sciences (CAS) will make the mirror blank and polish the surface of M1. M2 and M3 will also be fabricated in IOE, CAS. The substrate materials under consideration are ULE and SiC. Only M1 will be equipped with an active thermal control system to avoid mirror seeing, and the other mirrors will be cooled passively. The diameter of the M2 is about φ490 mm and the tertiary mirror M3 has a φ390 mm diameter.

The M1 mirror blank drawing is shown in Fig. 6, and consists of the face sheet, honeycomb sandwiches, and the bottom sheet. The design of the honeycomb sandwiches structure will reduce about 70% of the weight. There are about 300 pockets on the backside of the M1, and the single pocket is a hexagonal shape. These pockets will be used to cool the mirror surface from the backside of the face plate. The M1 will be coated with protective aluminum, and the other mirrors, besides the feed optics, will be coated with protective silver. In the future, we will consider coating protective silver on M1 because of its higher reflectance, and the heat absorption will be greatly reduced. Currently, the honeycomb sandwiches have been finished, and the actual picture is shown in Fig. 7.

The cooling system of the M1 consists of three independent cooling units. About 300 inflow nozzles (IN) connected with the primary mirror cell are inserted into honeycomb of M1, and three ventilators drive air to cool the backside of the face sheet of the M1 through these inflow nozzles. Over 100 return flow nozzles are used to guide the returning air, and a closed circulation is formed in the primary mirror cell. In the bottom of the three ventilators, three group heat exchangers are equipped to cool the circulated air. The cooling medium is chosen to be a glycol water solution, and it will be cooled by the refrigerating machine. For keeping the same temperature between the face sheet of M1 and the surrounding air, there are three parameters that can be adjusted during thermal controlling. These three parameters are the flow rate of the circulated air by adjusting the power of three ventilators, the flow rate of the circulated cooling liquid by adjusting the velocity of the feed liquid pump, and the temperature of the circulated cooling liquid by adjusting the power of the refrigerating machine.

![Fig. 5 The sketch map of the whiffle tree structure of the M1.](image5)

![Fig. 6 The 3-D sketch of the mirror blank of the primary mirror.](image6)
The heat-stop is the most efficient device for a large aperture-size solar telescope and it blocks about 99% of the solar radiation to protect the subsequent optics elements. In our newest design, the reflective surface will be a protective silver coating, and about 5% of the solar radiation will be absorbed and converted into thermal energy.

To validate the thermal controlling system of M1 and the heat-stop, we have built a prototype system. The experimental primary mirror (a) and the corresponding heat-stop (b) are shown in Fig. 8, and the ventilator, temperature sensors, heat exchangers are all attached behind of mirror cell. In successive papers, we will report some experimental results in detail.

5 Solar Adaptive Optics System Design and Future Considerations

The CLST will configure a high-order solar adaptive optics system (SAO) and multiconjugate solar adaptive optics (MCSAO) to correct the static aberration of the optics system and the dynamic aberration caused by atmospheric turbulence. We will equip a low-order solar adaptive optics system first for the CLST, and the optics design of this system is shown in Fig. 9. In the future, a 511-element higher order SAO system and a MCSAO system with two or more deformable mirrors will be replace it step by step. The corrected FOV of low-order or high-order solar adaptive optics system will be about 10''–20'', and it will be enlarged to about 1' by MCSAO.

As shown in Fig. 9, the telescope light is directed to the lower order SAO system, and it is collimated by the off-axis parabolic mirror collimator. The low-order SAO system is composed of the high speed TTM, the pupil deformable mirror (DM) with 151 actuators, the correlation tracking sensor (Tracker), and the correlation Shack–Hartmann wavefront sensor (CHS WFS).

A zoom optics system is also shown in Fig. 9, and it is used to convert the diameter between DM and HS. A practical TTM is finished as shown in Fig. 10, and the corresponding parameter is also listed in Table 2. The optimal arrangement between the actuators of the DM and the subapertures of CHS WFS is shown in Fig. 11, and the corresponding correcting ability for the first 65 modes Zernike aberrations is also shown in Fig. 12. The other parameters of the low-order SAO system are listed in Table 2.

Solar adaptive optics technology has developed for over 10 years in IOE, CAS. In 2002, we developed the correction tracker system for a tilt-correction adaptive optical system at the solar tower of Nanjing University and the corresponding correction tracking algorithms for lower contrast extended objects. In 2003, we built a tilt-correction adaptive optical system for the 43 cm solar telescope. In 2010, a 37-element solar adaptive optics system for the 26 cm solar fine structure telescope at Yunnan Astronomical Observatory was developed and the first solar high resolution image with AO was acquired in China. Several years later, a new 37-element solar adaptive optics system was equipped in the new vacuum solar telescope, and the corresponding real-time controller was also updated. Meanwhile, the postfocus processing method for adaptive optics solar image was also researched, and some demonstration results have been obtained. Now, we are developing a 127-element solar adaptive optics system based on the NVST system, and the corresponding observed results will be published in successive papers.
6 Enclosure and Building

For protecting the telescope from harmful weather conditions and strong wind, the CLST will be installed in an enclosure. To keep a uniform temperature in the optical path, the CLST will employ a retractable design, which is shown in Fig. 13. This kind of design is similar with GREGOR and EST, but they also have some differences. The diameter of the enclosure is about 16 m. The retractable enclosure will be able to open completely, and it is better for negating the degradation local seeing effect by balancing the temperature difference. As shown in Fig. 13, we design a windscreen with a different height, and it can adjust the velocity of the wind. More than that, a reflective heat-stop can be used to reflect most sun radiation when the dome is open so that only a bit of the energy is absorbed. Wind shake on the telescope structure and wind buffeting on the M1 surface will be two main challenges in our future work, although the windscreen can relieve the risk in some instances.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Resonant frequency (TTM)</td>
<td>~2 kHz</td>
</tr>
<tr>
<td>Stroke (TTM)</td>
<td>±4’</td>
</tr>
<tr>
<td>Number of actuators</td>
<td>151, triangle distribution</td>
</tr>
<tr>
<td>Stroke</td>
<td>±2 μm</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>≥1000 Hz</td>
</tr>
<tr>
<td>Number of subapertures</td>
<td>102, hexagonal distribution</td>
</tr>
<tr>
<td>Frame frequency (WFS)</td>
<td>1500 to 3000 Hz</td>
</tr>
<tr>
<td>Working wavelength</td>
<td>500 to 600 nm</td>
</tr>
</tbody>
</table>

Fig. 11 The optimal arrangement between the actuators of deformable mirror (DM) and the subapertures of correlation Shack–Hartmann wavefront sensor (CHS WFS) [(a): DM, (b): WFS].

Fig. 12 The correcting ability simulation results for the first 65 modes Zernike aberrations of the low-order SAO system.
The pier of the CLST will be a tower with a 10 m diameter, and the primary mirror (M1) is placed at about a 20-m height above ground. It will have a better seeing effect by minimizing the wind flow updraft. The CLST will employ a mechanical rotator plate to cancel the image rotation or pupil rotation. The mechanical de-rotator has two floors, and the diameter of the top layer is about 9 m. Several kinds of postfocus instruments, such as SAO, MCSAO, multi-wavelength broad-band imager, and a narrow-band tunable spectropolarimeter, will be placed at the top floor. The visible and NIR grating spectropolarimeter will be installed at the bottom floor. The detailed design and the corresponding analysis on the pier and the mechanical rotator will be published in another paper.

7 Summary and Next Steps

Now we have finished the conceptual design at the system level for the CLST, and the detailed designs for the optics system and mechanical system are also achieved. The mirror blank of the M1 was started last year, and it will be finished in several months. Then it will be polished and coated at the Institute of Optics and Electronics, Chinese Academy of Science (IOE-CAS). According to the project schedule and experience, the M1 will achieve the design requirement of the CLST in July of next year. On the other hand, we will carry on the thermal controlling experiments based on the prototype thermal controlling system during the next several months, and the experimental results will help us to build the thermal controlling system for the CLST. The other optical elements, such as M2, M3 and the feed optics, will be designed, manufactured, polished, and coated before 2016.

In last days of this year, we will finish the detailed optical and mechanical design of the postfocus instruments, and the optical and mechanical elements will be manufactured in the next two years. We plan some experiments in the laboratory to validate the performance of these postfocus instruments. According to the project schedule, the enclosure and the building at the new site will be finished before 2016, and the conception design has been achieved now.

Currently, we have finished the preliminary site investigations, and the sites on the northeast and northwest of China are the main choices. The atmospheric parameters measurements are being done at several candidate sites including Wuming Mountain site, located in Dao city, Sichuan province. Initial testing results have been obtained, and more monitoring data will be given in the following papers.

In 2016, the CLST will be integrated into our institute. We plan to install the CLST on the site in 2017.

Acknowledgments

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References


Changhui Rao received his PhD degrees in optical engineering from the Institute of Optics and Electronics (IOE), Chinese Academy of Sciences (CAS) in 2001. He is a member of SPIE and OSA. He has been engaged in research on adaptive optics and optical propagation for more than 20 years. More than 200 papers have been published. He is the vice director of IOE, CAS, and the Key Laboratory on Adaptive Optics, CAS.

Naiting Gu received his MS and PhD degrees in optical engineering from the Institute of Optics and Electronics, Chinese Academy of Sciences, in 2009 and 2012, respectively. He has researched wavefront measurement technology and interferometry imaging technology for several years. Currently, he devotes himself to the observation of solar activity, including solar observation facilities, solar adaptive optics, and post-focus instruments.

Lei Zhu received his BS degree in electronic information science and technology from the University of Science and Technology of China, and his PhD degrees in physical electronics from Shanghai Institute of Technical Physics of the Chinese Academy of Sciences in 2003 and 2008, respectively. He majored in adaptive optics and lidar.

Jinlong Huang received his MS degrees in mechanical design from the Guilin University of Electronic Technology in 2007. He has researched mechanical design of large aperture size telescope, for several years. Currently, he devotes himself to mechanical design of the CLST.

Cheng Li received her BS degree in mechanical design from Sichuan University in 2006. Then she received her MS degree in measurement technology and instrumentation from the Institute of Optics and Electronics, Chinese Academy of Sciences, in 2012. She has been engaged in the structural design of the telescope since the beginning of her career in 2006.

Yuntao Cheng received his MS degree in mechatronics engineering from Harbin Institute of Technology in 2006. He has researched mirror blank design and engineering for several years. Currently, he devotes himself to mirror blank design and manufacturing of the CLST.

Yangyi Liu received his BS degree in mechanical engineering and automation from Chongqing University in 2012. Now he is an optical engineering PhD candidate at the Institute of Optics and Electronics, Chinese Academy of Sciences. Currently, his research interests include thermal control technology of solar telescopes. He is also a main member of the Chinese Large Solar Telescope (CLST) group on its thermal control system.

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Lanqiang Zhang received his MS and PhD degree in optical engineering from the Institute of Optics and Electronics, Chinese Academy of Sciences, in 2010 and 2014, respectively. He has researched multi-conjugate adaptive optics for several years. Currently, he majors in solar adaptive optics and multi-conjugate adaptive optics.

Hong Liu received his MS degrees in optics engineering from IOE, CAS, in 2006. He has researched mirror blank design and engineering for several years. Currently, he devotes himself to mirror blank design and manufacturing of the CLST.

Yongjian Wan received his PhD degrees in modern optics manufacturing from IOE, CAS, in 2007. Currently, he devotes himself to modern optics manufacturing of the CLST project.

Hao Xian received his MS degrees in adaptive optics from the University of Electronic Science and Technology of China in 2008. He has researched telescope technology and wavefront correction for several years. Currently, he is director of the Key Laboratory on Adaptive Optics, CAS, and he will be a consultant on the CLST project.

Hua Bao received his PhD degrees in biomedical engineering from Sichuan University in 2010. He has researched imaging processing and AO control for several years. Currently, he devotes himself to the post-process for solar images and development of solar AO software of the CLST.

Xiaojun Zhang received his PhD degrees in wavefront corrector design from Wuhan University of Technology in 2000. He has researched deformable mirror design and manufacturing for several years. Currently, he devotes himself to wavefront correcting technology of the CLST.

Chunlin Guan received his BS degrees in mechanical design from Wuhan University in 1987. He has researched deformable mirror technology for several years. Currently, he devotes himself to design and manufacturing of wavefront corrector in the CLST project.

Donghong Chen has researched active optics technology since 1985. Currently, she devotes himself to design and manufacturing of tip-tilt mirror of the CLST.

Biographies of the other authors are not available.