The Multi Application Solar Telescope

P. Venkatakrishnan[1,2,]*, Shibu K. Mathew[1,] Nandita Srivastava[1], A. R. Bayanna[1], Brajesh Kumar[1], Bireddy Ramya[1], Naresh Jain[1] and Mukesh Saradava[1]

[1]Udaipur Solar Observatory, Physical Research Laboratory, Udaipur , India
[2]Indian Institute of Astrophysics, Bengaluru , India

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Introduction

THE birth of solar physics in India started with observations of the total solar eclipse on 18 August 1868 by Pogson along with Janssen and Lockyer, when they successfully recorded in the flash spectrum, a hitherto unidentified spectral line close to the D line of sodium. This spectral line was subsequently identified with the new element helium. The great Bengal famines spurred the Royal Society to recommend the establishment of Kodaikanal Observatory in 1899, to study the effects of solar activity on the incidence of droughts. This observatory was later upgraded in 1960 on the recommendation of the Saha Committee. However, the site suffered from cloudy skies. Later, Arvind Bhatnagar, inspired by his mentors Vainu Bappu and Harold Zirin, established the Udaipur Solar Observatory (USO) in 1975, on an island in the middle of Lake Fatehsagar at Udaipur in the relatively cloud-free state of Rajasthan. In 1983, this observatory was taken over by the Department of Space, Government of India, to be managed by the Physical Research Laboratory (PRL), Ahmedabad. USO carried out high-quality observations of flares and other solar eruptions with modest equipment for several years. But the need for higher spatial resolution and sensitive polarimetry became evident with the advances in solar physics elsewhere in the world. PRL, after a thorough review, decided to locate a modern solar telescope having high angular resolution and polarimetric capability for detailed studies of the solar magnetic field on the island of USO. This telescope, called the Multi Application Solar Telescope (MAST) was operationalized in June 2015 (refs 1 and 2).

The design of a solar telescope differs from that of an ordinary stellar telescope because of the problem of heat generated at the focus. Generally, the focal length of the solar telescope has to be more than 40 times the diameter of its aperture to avoid burning or melting of optics kept close to the focus. For large apertures, this entails a long mechanical structure that will often bend or flex under its own weight and impede accurate tracking of solar features. Gabriel Lippmann (1845–1921), the inventor of colour photography (for which he was awarded the Nobel Prize in 1908), invented the coelostat that could track any astronomical object by compensating for the earth's rotation using a system of mirrors. However, this technique causes polarization of light on account of oblique reflections and is not suitable for sensitive polarimetry that is required for the measurement of weak solar magnetic fields. The modern designs use shorter focal length and deal with the focal plane heating by employing a heat trap. MAST is essentially such a relatively short-focus off-axis Gregorian–Coudé telescope (Figure 1) having a primary mirror of 50 cm aperture. A heat trap at the prime focus allows only 1% of the solar disc into the downstream optics and reflects the rest of the focused light. The absorbed part of this light is actively cooled. In layman's terms, this is equivalent to the ability to heat water in a paper cup as long as it does not evaporate and cause burning of the cup.

Selecting a location for the solar telescope has to be done carefully. The ground around the telescope will get heated during the day. This results in turbulence of air around and above the telescope causing image blurring, similar to the shimmering of images seen across a tar road on a hot summer's day. In order to mitigate this problem, it makes sense to locate a solar telescope in the middle of a large water body. Hence the choice of USO on an islet in the middle of Lake Fatehsagar. Udaipur has the unique advantage of benefitting from the wisdom of the local kings 500 years ago, who built a system of artificial lakes for water storage to provide against the severe scarcity of rainfall in the desert region. This very same scarcity of rainfall allows for a very large number

*For correspondence. (e-mail: venkatakrishnan@iiap.res.in)

of clear cloudless days for solar observations. We got a chance to check the efficacy of the lake in 2005, when it completely dried up. The image quality was systematically measured during this year followed by measurements in 2006 after an abundant monsoon filled the lake. A comparison of the seeing parameter r_0 for 2005 and 2006 (Figure 2) clearly showed an improved value in 2006 (ref. 3).

Dome and building

It is not enough to choose a good site. The building and dome should also be suitably designed to minimize turbulence (Figure 3). For MAST, we opted for a 'collapsible' dome that can be folded down to expose the telescope to the open sky. This avoids the problem encountered in conventional domes, where heat is trapped within and causes turbulence at the slit or opening through which light enters the dome. The material of the dome is a special fabric that can withstand long exposure to sunlight, and is also waterproof to withstand the monsoon. The mechanical frame that holds the fabric is made of a pair of three C-shaped metal bars that form two hemispheres, joined together along a vertical plane while in the closed condition. Each set of the three bars is driven by a hydraulic system powered by electrical pumps. The dome has its own software to control the opening and shutting of the structure which locks after proximity sensors guide electrically-driven screws into the respective sockets mounted on the boundary structural elements. The dome was fabricated by Armatic Engineering Company, Bengaluru.

The building has no sharp edges in order to avoid wind turbulence. It is painted with a paint that has the capability of strong emission in the infrared to minimize the heating by sunlight. It has two floors – the telescope floor, which is exposed during observations and the instrument floor which is air-conditioned to protect all the electronics. Sunlight is guided through a Coudé mirror system down to the instrument floor.

Mirror seeing and thermal design

The open dome configuration creates a different problem in that the telescope would become hot after long exposure to direct sunlight. This is avoided by having a sunshade that follows the motion of the sun across the sky with a hole large enough to allow sunlight to completely fall on the primary mirror without any obstruction (Figure 3). The rest of the sunshade is actively cooled to maintain the surface at the temperature of the ambient air, to avoid turbulence at the entrance window of the sunshade.

The primary mirror has a metallic reflecting coating that absorbs some of the incident sunlight. This increases the surface temperature of the mirror by several degrees above the ambient temperature. This will result in air turbulence at the mirror surface which can potentially degrade the final image quality. To avoid this, the mirror surface must be maintained to be within one a degree of the ambient temperature. Since the mirror substrate is Zerodur, its thermal response is much slower than the rate of change of the ambient temperature. Thus, the telescope manufacturer (AMOS, Belgium) has provided a complex thermal control based on a mixture of cooling and heating that successfully maintains the mirror temperature to within a degree of the ambient, right from 20° at sunrise to 48° at noon in summer at Udaipur. On our specification, the vendor has also provided a laminar airflow across the mirror surface that is expected to further improve the image quality.

Adaptive optics

In spite of all these precautions, the solar image will have considerable fluctuations that will result in a blurring of the solar features over an exposure time that is large compared to the 'turnover time' of the turbulent eddies in the path of sunlight. For typical conditions, this turnover time is a few hundredths of a second. The important goal of solar magnetic field measurement requires spectropolarimetry with few seconds exposure. During this exposure, the solar feature will move several hundred times randomly across the slit of the spectrograph, thereby producing a blur that would challenge any meaningful interpretations of the resulting data. Hence, we need to keep the solar feature rock-steady on the spectrograph slit during the exposure time. Also, full interpretation of the spectro-polarimetry requires a set of several polarimetrically modulated measurements of the same solar feature. Thus, the feature must be kept steady for several tens of minutes on the spectrograph slit. This requires adaptive optics (AO). With AO, we first detect the wavefront corrugations by imaging a solar feature through a lens-let array that will map the local tilts of the wavefront surface into relative shifts of the multiple images of the feature produced by the lens-let array (Figure 4). These local tilts are used to calculate the compensating depressions or elevations of a deformable mirror. When the distorted wavefront is reflected off the deformed mirror, the wavefront straightens producing an undistorted image. The wave-front sensing is done at a rate of 1000 frames/s while the resulting corrections are achieved by tuning three parameters, i.e. *P* (proportional), *I* (integral) and *D* (differential) of a control system which acts on the actuators of the deformable mirror and maintains image stability up to a bandwidth of 100 Hz. A prototype of such a system was developed and successfully tested at USO in 2010, while the actual system is currently being installed and tuned at the MAST focal plane[4].

Back-end instruments

The final science results depend upon the back-end instruments that use the light gathered by the telescope and directed into the instruments after correction by the AO system. MAST has the provision of four ports for deploying four independent sets of back-end instruments. Presently, we have a narrow-band spectrally tunable imaging polarimeter[5] and a multi-slit spectro-polarimeter as the first light back-end instruments (Figure 5). The imaging polarimeter was developed at USO while the spectro-polarimeter was developed at ISAC/ISRO. The imaging polarimeter is spectrally tuned by a pair of lithium niobate crystal-based Fabry–Perot etalons that are controlled by high electrical voltage[6]. The polarization modulation is done by liquid crystal wave-retarders, while a Glan–Thomson prism analyses the modulated light. The imager is optimized for two spectral lines, one for photospheric magnetic fields and the other for chromospheric magnetic fields. Essentially, we exploit the polarization of spectral lines produced by magnetic fields in the solar atmosphere to obtain a 2D map of all three components of the vector magnetic field. By measuring at both
photospheric and chromospheric heights, we can get information about the 3D structure of the solar magnetic fields. Such data will be truly state-of-the-art at present. The multi-slit spectro–polarimeter consists of a grating spectrograph with multiple slits. By panning the solar image across the slits, we can generate a 2D map of the spectral profiles which can be later used to calculate the vector magnetic fields. There different advantages and disadvantages of both the imaging and spectrographic modes of measurement. Using both the modes, we can maximize the information on the solar magnetic fields.

Science plans

An H-alpha Lyot filter for chromospheric images and a G-band filter for photospheric images have been deployed at a different port of MAST to obtain trial images during the testing of the telescope. The images produced were of exceptional quality, thus vouching for the performance of the telescope (Figure 6). This holds great promise for accomplishing the science goals for which MAST was built. As mentioned earlier, one of the primary aims of MAST is to monitor the evolution of the vector magnetic fields of solar active regions in the photosphere and chromosphere.

Data on the three components of the vector magnetic field allow us to calculate the magnetic stresses which are basically the primary reservoir of all the energy that is released during the violent solar eruptions like solar flares and coronal mass ejections. These events have direct consequences on terrestrial phenomena like geomagnetic storms, which can affect the functioning of earth-orbiting satellites. The long-term goal is to be able to predict such violent outbursts of the sun. This capability of space weather prediction will be extremely useful for our indigenous burgeoning space programmes. Achieving this goal is not easy, and requires intense and dedicated efforts. For this, the possession of modern indigenous solar telescopes like MAST is important. In addition, MAST will serve as a valuable tool for providing ground-based support to the upcoming ADITYA solar space mission. The ADITYA project is described elsewhere in this special issue of *Current Science*.

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doi:

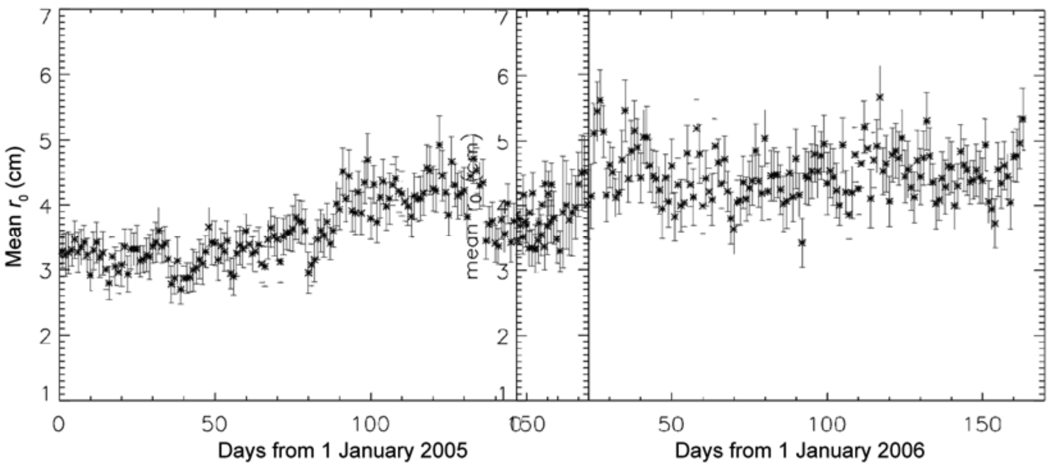

Figure 2. Plot of r_0 for two different years (left) When the lake was dry (right) When the lake was full. There is an increase in r_0 and thus good seeing when the lake is full.

Figure 3. The telescope enclosed in a dome made of tensile cloth. (Left) Dome opened for observations (Right) Dome in the closed position.

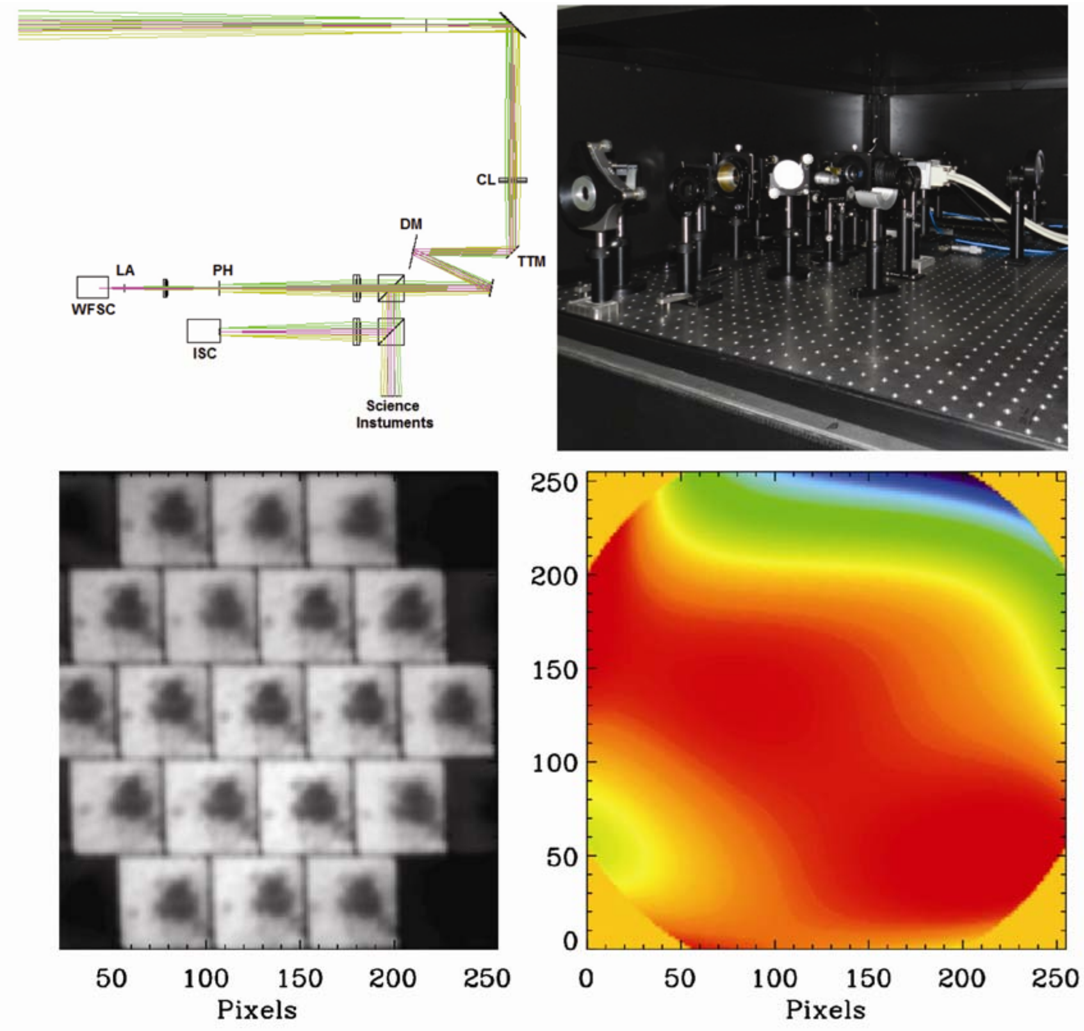

Figure 4. (Top left) Optical schematic of the AO system (Top right) The AO system integrated with MAST. (Bottom left) Images from the lens-let array used for calculating the shifts and thus the wavefront distortion. (Bottom right) Wavefront distortion calculated from the shift measurements.

Figure 5. The back-end instruments on an optical bench, including the AO, narrow-band imager and polarimeter.

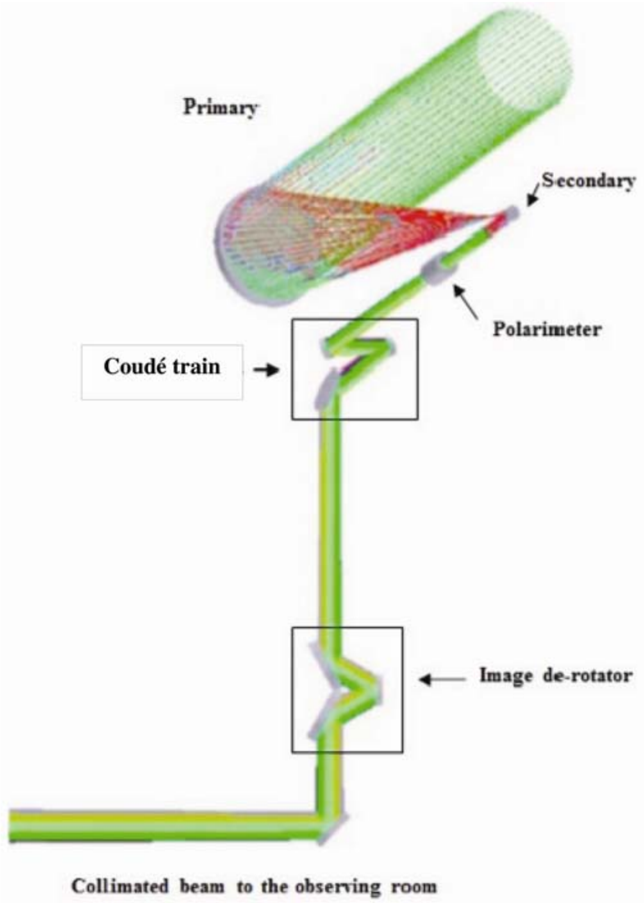

Figure 1. Optical layout of Multi Application Solar Telescope (MAST).

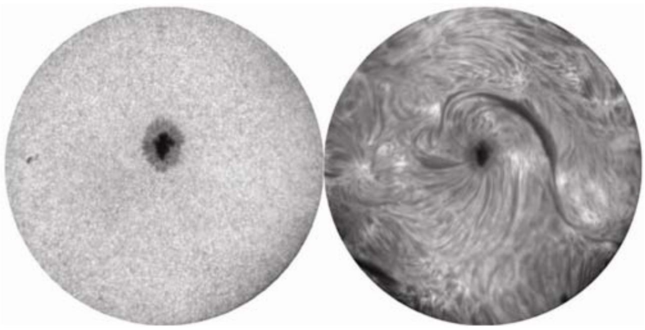

Figure 6. Sample images obtained using a 1 nm G-band filter (left) and a 0.05 nm H-alpha filter (right).