National Large Solar Telescope

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The National Large Solar Telescope (NLST) aims primarily to carry out observations of the solar atmosphere with high spatial, spectral and temporal resolution. A comprehensive site characterization programme, that commenced in 2007, has identified an excellent site in the Ladakh region at the Pangong lake, India. With an innovative optical design, NLST is an on-axis Gregorian telescope with a low number of optical elements to reduce the number of reflections and yield a high throughput with low polarization. In addition, it uses high-order adaptive optics to produce close to diffraction limited performance. To control atmospheric and thermal perturbations of the observations, the telescope will function with a fully open dome, to achieve its full potential atop a 25 m tower. The post-focus instruments include broadband and tuneable Fabry–Perot narrow band imaging instruments and a high-resolution spectropolarimeter.

Keywords: Adaptive optics, high angular resolution, magnetic fields, solar telescope.

Introduction

The Indian Institute of Astrophysics (IIA), Bengaluru has proposed a 2 m state-of-the-art National Large Solar Telescope (NLST) for carrying out high spatial, spectral and temporal observations of the Sun with a view to obtaining a better understanding of the fundamental nature of magnetic fields and other phenomena in the solar atmosphere. Observations have established that the solar magnetic field is structured in the form of magnetic elements with a horizontal size of just a few kilometres. Several numerical simulations indicate that crucial physical processes like vortex flows, dissipation of magnetic fields and the generation of magnetohydrodynamic (MHD) waves can occur efficiently on length scales even as small as 10 km (ref. 1). Such waves are likely candidates for transporting energy to the upper atmosphere of the Sun. Spatially resolved observations are, therefore, essential to shed light on the different physical processes involved. Unfortunately, even the largest current solar telescopes are limited by their apertures to resolve solar features to this level at visible wavelengths. On a global scale, the energy stored in magnetic fields is eventually dissipated in the higher layers of the solar atmosphere, for instance, in the form of flares and coronal mass ejections (CMEs) that release energetic solar plasma into the interplanetary medium.

In the last decade, two major solar facilities have become operational. These are the German 1.5 m GREGOR telescope and the US 1.6 m New Solar Telescope (NST) at Tenerife and Big Bear respectively. It will be several years from now when the next generation of 4 m class and higher aperture will be commissioned. The 4 m Daniel K. Inouye Solar Telescope (DKIST) at Haleakala, Hawai, is currently under development. In addition, a 4 m telescope called the European Solar Telescope (EST) has been proposed by a European consortium, which if approved, is expected to see first light around 2026 or later. This has offered a window of opportunity for India to build a 2 m National Large Solar Telescope (NLST) in the next few years. The choice of a 2 m aperture is based on: (a) scientific objectives; (b) using a tested design and technology based on the experience gained in the construction of the GREGOR 1.5 m solar telescope; (c) timely realization of the project in less than five years and (d) keeping costs optimal, without compromising on science capabilities. Compared to GREGOR and NST, NLST is expected to have both a higher spatial and spectral resolution.

With its innovative design that uses a low number of optical elements to reduce the number of reflections, NLST will achieve the highest throughput with low polarization compared to other operating telescopes of similar size. It will be equipped with a high-order adaptive optics (AO) package to produce close to diffraction limited performance[2,3]. With the suite of planned backend instruments, NLST will enable observations with a high spatial resolution that will shed light on the physical processes occurring in the solar atmosphere.

The best spatial resolution that the present generation of solar telescopes can attain during moments of good seeing with the use of AO is limited to about 0.09 arcsec at 600 nm. In addition to the requirement of good angular resolution, a high photon throughput is also necessary for spectropolarimetric observations to accurately measure vector magnetic fields in the solar atmosphere with a good signal-to-noise ratio. With an aperture of 2 m, NLST will be able to resolve structures with sub-arcsec resolution in the solar atmosphere as well as to carry out spectropolarimetry with a high time cadence.

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Broad scientific objectives

NLST is envisaged as a versatile instrument that will enable a broad class of problems to be investigated, to shed light on the complex interaction of magnetic fields with plasma in the solar atmosphere. It is well known that the magnetic field plays a crucial role in modulating solar variability and activity. Understanding how magnetic fields are generated and maintained on the Sun is basic to understanding the origin and nature of the solar cycle and variability, and to predict in advance its behaviour both on short and long timescales. Another key issue that NLST will address is the magnetic coupling between the interior and solar atmosphere that involves an investigation of dynamical processes in magnetic elements, which transport energy to the chromosphere and corona. This will be carried out through high spatial resolution magnetic field measurements at various heights from the photosphere to the lower corona. Recent advances in local helioseismology, based on measurements of travel times for wave packets travelling between any two points on the solar surface have made it possible to obtain 3D images of flows, temperature and density inhomogeneities, and magnetic field in the solar interior. NLST will facilitate a closer look at the uncertainties due to surface interaction between the sunspot magnetic field and acoustic waves. It will enable mapping of wave phases in the photosphere to examine: (a) the influence of magnetic fields on acoustic waves; (b) mode transformation and its signature on subsurface layers and (c) sunspot fine structure, umbral dots, penumbral filaments and light bridges.

Other areas of focus include measurement of weak magnetic fields in the internetwork regions where a significant fraction of field is below 400 G (ref. 4); the thermal structure of the chromosphere, particularly cool pockets with temperatures as low as 3600 K (ref. 5); prominences and filaments; energetic phenomena and activity. An important goal of NLST will be to observe the magnetic field and dynamic changes that occur during solar flares. NLST will also contribute towards a better understanding of CMEs by combining optical data in the optical and radio wave bands to determine the connection between the changes that occur at chromospheric layers through H_α observations and type-III radio bursts during flares. NLST will also carry out observations in near infrared (1–5 μm) wavelengths, that are relatively unexplored for imaging the Sun and measuring the magnetic fields. The near infrared band provides a good diagnostic for studying granulation, sunspots and cool regions in the solar atmosphere.

The optical baseline design

NLST is essentially a three-mirror, Gregorian on-axis telescope with a 2 m aperture primary mirror with a final *f*/40 focal ratio. It has been optimized to ensure high optical throughput with the minimum number of reflecting surfaces: the telescope has only six mirrors to provide an AO corrected image at the observing platform. The left panel in Figure 1 shows the optical scheme. There are three mirrors (M1, M2 and M3) with power, and four flat mirrors, including the deformable mirror (DM) M5 and

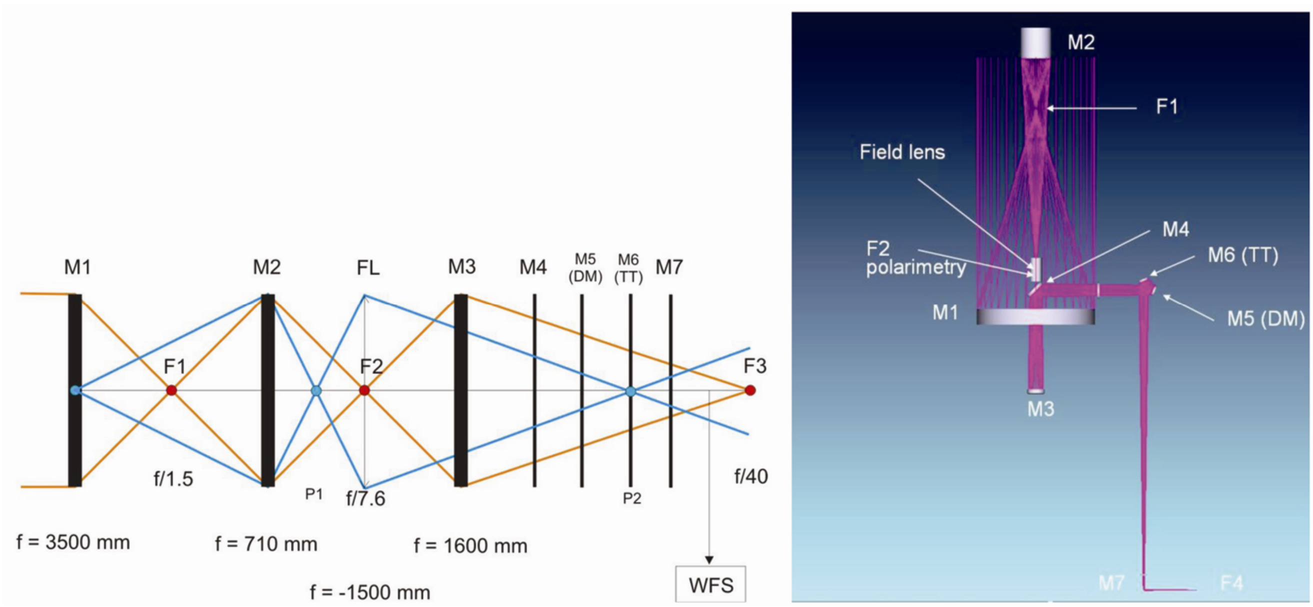

Figure 1. (Left) NLST optical scheme and (right) schematic optical layout.

tip/tilt (TT) mirror M6. The imaging is shown in orange and the pupil imaging in blue. The M2 mirror magnifies the image by a factor of 5 and produces an image at the secondary focus F2. Close to this focus is a weak negative field lens which is used to provide a pupil on the tip/tilt mirror (M6). The right panel in Figure 1 schematically depicts the optical layout of the telescope: a 2-m parabolic primary mirror M1 (*f*/1.75) forms an image of the solar disk with a diameter of 34 mm at the prime focus F1. Here we have the largest heat concentration of about 2.8 MW/m^2. A reflecting and cooled heat stop rejects and dissipates all the energy which does not pass through the stop. The primary mirror that receives a heat load of 3 kW is cooled from below using cold air to keep it close to the ambient temperature. This cooling is further facilitated by the natural air flow owing to the open design of the telescope. A beam, providing a field of view (FOV) of 200 arcsec, passes through the field stop. An elliptical mirror M2 creates a *f*/7.7 beam and forms a secondary focus F2 at a distance of 600 mm in front of M1 and about 200 mm above the elevation axis. The F2 image is picked up by another elliptical mirror M3 which changes the *f*-ratio to *f*/40 in the beam that produces a final image at F3. Here we have the desired image scale of 2.5 arcsec mm^{-1}.

M4 is a flat mirror with a central hole that reflects the beam into the elevation axis. The mirror group M5/M6 reflects the beam into the azimuth axis which in our design is besides the telescope. By means of the field lens in F2 the pupil is imaged on M6, which can serve as the tip/tilt mirror of AO. M5 is a deformable mirror. F3 is about 6200 mm below the elevation axis which allows for convenient access of the focus stations in the building. A mechanical turntable behind the telescope moves the whole post-focus assembly and so compensates for the rotation of the image due to the altitude–azimuth telescope system. Several ports for post-focus instruments are provided.

NLST is designed to have an integrated high-order AO system without an additional pupil imaging. We use an optimal sub-aperture size of 80 mm which is sufficient to resolve solar granulation with adequate contrast. A Shack–Hartmann-type wavefront sensor (WFS) is used. The WFS camera has to be fast enough to handle a 3 kHz frame rate which results in a high pixel rate of 1.3 giga pixels/s.

Focal plane instruments

The focal plane instruments consist of a (i) broad band imager; (ii) narrow band imager and (iii) spectropolarimeter.

Broad band imager

The main component of the broad band imager is a spectral filter with a bandwidth of 0.3–1 nm. There are several broad band filters that can be used to observe the photosphere and chromospheric regions of the Sun. We plan to use broad band filters for H_α, Ca II K, CN band, G band and 1083.0 nm observations.

Fabry–Perot-based narrow band imager

The narrow band imaging system uses two Fabry–perot (FP) etalons in series[6]. A set of collimating lens and imaging lens forms an intermediate image near the two FPs and then another set of collimating and re-imaging lens forms the final image on the CCD camera. A pre-filter (PF) with a 3 Å passband is kept in the collimating beam to isolate the required wavelength band. The CCD camera will cover a 90 arcsec FOV in the final image plane. The PF set is mounted on an automatic filter wheel assembly and the whole unit will be enclosed within a thermally stabilized oven to avoid any variation in the filter passband. A field stop at the telescope focal plane would restrict the FOV to 90 arcsec and it also prevents the scattered light from entering into the instrument. Since the system is dual FP in series, there will be ghost images formed by the reflection between the two FPs. Simulations show that the intensity of the ghost images is about 12% of the transmitted beam for the first reflection and 5% of the transmitted beam for the second reflection. The ghost can be removed by tilting the FPs by a small angle of 0.1°. The instrument will have a spectral resolution greater than 200,000 at 600 nm and will operate in the wave band 500–900 nm with a signal-to-noise ratio better than 500.

Spectropolarimeter

The NLST spectropolarimeter is based on the SPINOR[7] (Spectropolarimetry for the Infrared and Optical Region) design, and consists of a polarimetric modulation unit and a flexible spectrograph unit. The polarimetric modulation unit will be placed close to the secondary focus (F2) of the telescope. The modulator will consist of an achromatic rotating wave plate. Just before the modulator optics, a calibration unit will be placed. This is required to calibrate any residual polarization from the telescope. Due to this calibration mechanism, the achieved accuracies in polarization measurement can be as high as 10^{-4}.

A flexible spectrograph unit at the focal plane of the telescope is used to record the spectral line profiles. A lens with a focal length of 1200 mm collimates the light beam passing through the slit. A high blaze angle grating (63° and 79 lines/mm) will be used as the dispersing element. The lower number of lines per millimetre minimizes any partial polarization effect from the grating, which is unavoidable in high density gratings. The high blaze angle compensates for the lower density and hence retains the higher spectral resolution. A large format

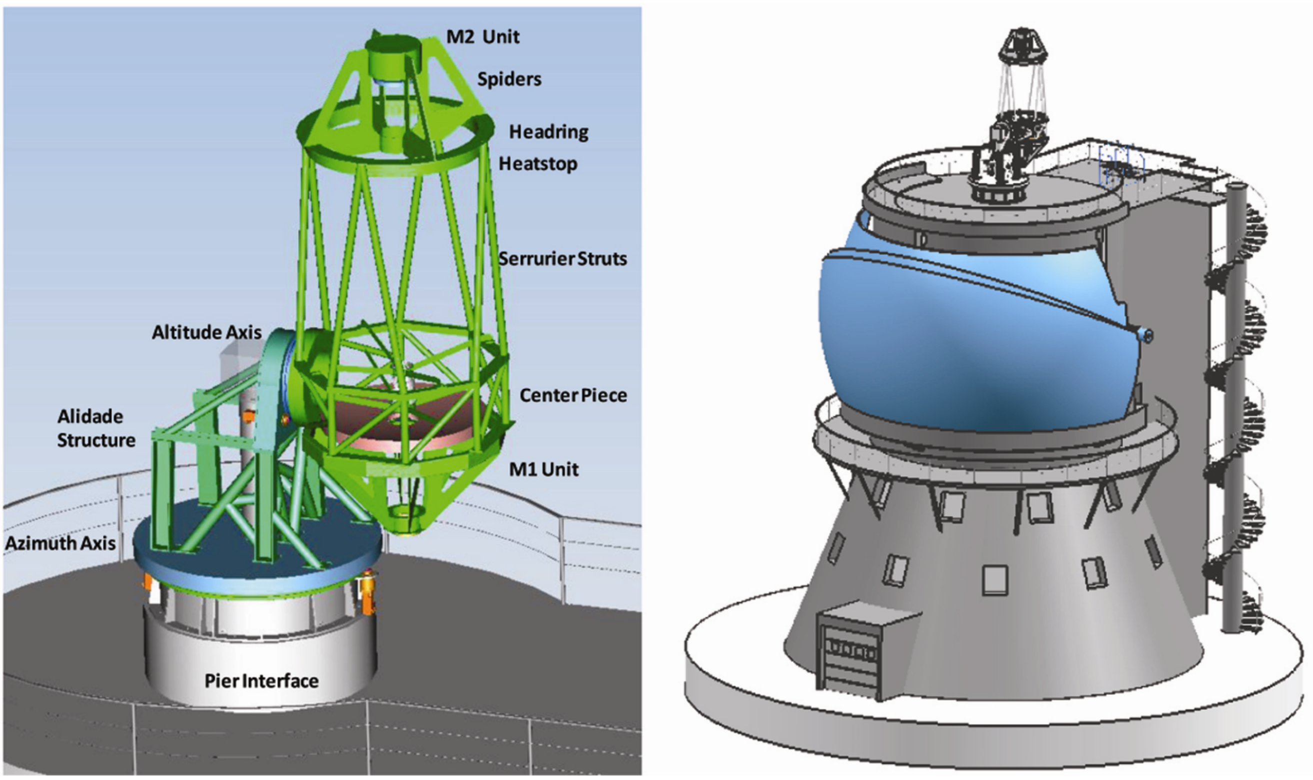

Figure 2. (Left) Overview of the telescope structure. (Right) Telescope and tower with the dome retracted.

grating (width about 200 mm) will be necessary to achieve a spectral resolution greater than 200,000. Such high spectral resolution is important in resolving the line profiles and hence yielding a higher accuracy in the estimated vector field measurements.

Mechanical design and dome

The left panel in Figure 2 schematically shows an overview of the telescope structure. The mechanical design approach was guided by the optical layout, particularly with a view to reducing the number of mirrors. The layout is especially suitable for open-air operations, that improve the seeing by optimal natural convection. All the structural components are made of carbon fibre composites with invar or stainless-steel fittings on account of their light weight and low thermal expansion.

The right panel in Figure 2 shows the telescope with a simple retractable dome that will cover it during the period when there are no observations. The dome sits on a semicircular base frame, which runs on three vertical tracks on the tower structure, and four retractable dome shells. The shape of the tower platform is optimized with regard to airflow. The height from the ground to the telescope axis is approximately 25 m and diameter of the cylindrical part of the dome is 10 m.

Site characterization

Site characterization for NLST has been carried out at the following three sites in North India: Hanle and Merak in Ladakh (Jammu and Kashmir) since 2007 and at Devasthal (Uttarakhand) since 2009 using a Solar Differential Image Motion Monitor (SDIMM), Shadow Band Ranger (SHABAR), automatic weather station (AWS), all-sky camera, an automatic sky radiometer and a micro-thermal data acquisition system, designed and built in-house[8]. The main parameters chosen for the study were the total annual sunshine hours, sky brightness, atmospheric seeing at various heights above the ground, microthermal conditions, and some additional meteorological parameters such as wind speed, aerosol distribution, etc. We quantify the 'seeing' conditions in terms of the Fried parameter r_0. An analysis of the site characterization data demonstrates that Merak is an excellent site, comparable to the best sites in the world for solar observations such as Haleakala and Big Bear, and consequently has been selected as the location for NLST.

Current status

The detailed concept design of NLST has been carried out by MT-Mechatronics, Germany with technical support from the Kiepenheuer Institute, Freiburg, Germany. A detailed project report was brought out, which provides details on the scientific and technical aspects (including a detailed concept design) of the project as well as a site characterization report. Environmental impact assessment and feasibility studies have also been carried out by independent agencies, which concluded that the project has no adverse environmental impact and that the proposed sites in the J&K region are feasible from geotechnical considerations for the construction of NLST.

The project is awaiting formal sanction from the Government of India. We expect that the fabrication of NLST will commence around 2019 and be completed within three years. The post-focus instruments will be made indigenously. Work on the development of a prototype narrow-band imager and spectropolarimeter has already commenced.

Summary

NLST will be a state-of-the-art 2 m class telescope for carrying out high-resolution studies of the solar atmosphere. An innovative design with minimal number of mirrors, high throughput and high-order AO will provide close to diffraction-limited performance. Space missions like Hinode and Solar Dynamics Observatory (SDO) provide uninterrupted coverage of the Sun, while NLST as a complementary facility will provide high spatial and spectral resolution observations. In the national context, the 0.5 m Multiple Application Solar Telescope (MAST) is already operational and the ADITYA space-based project under development will provide synergy with NLST. Its geographical location will fill the longitudinal gap between Japan and Europe.

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