Astron. Nachr. / AN **331**, No. 6, 628 – 635 (2010) / **DOI** 10.1002/asna.201011389

NLST: India's National Large Solar Telescope

S.S. Hasan[1], **D. Soltau**[2,⋆], **H. Kärcher**[3], **M. Süß**[3], and **T. Berkefeld**[2]

[1] Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India
[2] Kiepenheuer-Institut für Sonnenphysik, Schöneckstraße 6, D-79104 Freiburg, Germany
[3] MT Mechatronics, Wilhelm-Theodor-Römheld-Str. 24, D-55130 Mainz, Germany

Received 2010 Jan 19, accepted 2010 Mar 29

Key words instrumentation: adaptive optics – instrumentation: high angular resolution – instrumentation: polarimeters – telescopes

This article introduces the new Indian 2 m telescope which has been designed by MT Mechatronics in a detailed conceptual design study for the Indian Institute of Astrophysics, Bangalore. We describe the background of the project and the science goals which shall be addressed with this telescope. NLST is a solar telescope with high optical throughput and will be equipped with an integrated Adaptive Optics system. It is optimized for a site with the kind of seeing and wind conditions as they are expected at a lake site in the Himalayan mountains. The telescope can also be used for certain night time applications. We also give the scientific rationale for this class of telescope.

1 Introduction

Currently there are two solar telescope projects which represent the efforts to build very large solar telescopes with diameters of 4 m. ATST (Advanced Technology Solar Telescope) is a funded US project with a clear time schedule (e.g., Keil et al. 2010). ATST has also international partners. EST is a project which currently performs a EU funded design study for a 4-m solar telescope (Collados et al. 2010) which certainly can only be built as an European international project. Both projects represent investments in unprecedent order of magnitude and their construction will only be finished after more than a decade after kick off. The Indian Institute of Astrophysics (IIA) has plans for setting up a 2-m class National Large Solar Telescope (NLST). Its innovative design, large collecting area, diffraction limit and postfocus instruments are aimed at understanding the fundamental nature of magnetic fields in the atmosphere of the Sun. NLST will be the largest solar telescope in the world for several years till the next generation of American and European facilities become operational.

NLST will enable us to observe solar features with unprecedented detail. Taking a cue from recent simulations, one needs at least a 2-m class telescope, operating at its diffraction limit, to observe processes occurring on spatial scales of tens of kilometers. The diffraction limit of a 2-m solar telescope at 500 nm is 0.06 arcsec which corresponds to about 40 km on the solar surface. Presently, the best spatial resolution that the existing generation of solar telescopes can attain during moments of good seeing and using adaptive optics is limited to about 0.13 arcsec (about 90 km). 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. Consequently, in order to resolve structures with sub-arcsecond resolution in the solar atmosphere as well as to carry out spectropolarimetry, a sufficiently large aperture telescope is required. Based on such considerations as well as practical reasons related to design and costs, India has proposed a 2-m class National Large Solar Telescope (NLST). NLST will be larger than the telescopes which are now close to completion such as GREGOR (the 1.5-m German telescope on Tenerife) or the newly commissioned 1.6-m NST (New Solar Telescope) at Big Bear. On the other hand, NLST is small enough not to run into the design problems which are related to the 4-m class projects such as the ATST and EST. NLST will be a state-of-the-art 2-m class telescope giving diffraction limited images at visible wavelengths. It will be a fully reflecting on-axis altazimuth Gregorian multi-purpose open telescope with the provision of carrying out night time stellar observations. Its field-of-view of 200 arcsec will enable access to the 0.38 to 2.5 micron wavelength range. The telescope utilizes an innovative design with low number of reflections to achieve a high throughput and low instrumental polarization. High order adaptive optics is integrated into the design that works with a modest Fried's parameter of 7 cm to give nearly diffraction limited performance. The telescope will be equipped with a suite of post-focus instruments including a high resolution spectrograph and a polarimeter.

[⋆] Corresponding author: soltau@kis.uni-freiburg.de

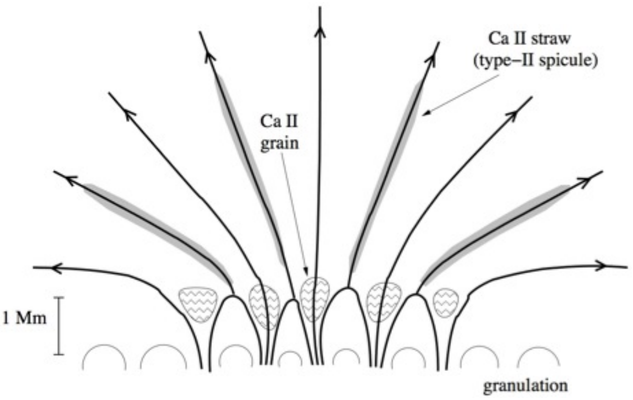

Fig. 1 Schematic diagram showing the structure of a magnetic network element on the quiet Sun. The thin half-circles at the bottom of the figure represent the granulation flow field, and the thick curves represent magnetic field lines of flux tubes that are rooted in the intergranular lanes. The Ca II bright grains are thought to be located inside the flux tubes at heights of about 1 Mm above the base of the photosphere (courtesy Hasan & Ballegoiijen 2008).

2 Science goals

2.1 Solar astronomy

Observations have revealed the presence of fine-scale flux tubes in the magnetic network on the Sun. In Ca II H or K line images, the network shows up as a collection of "coarse mottles" or "network grains" that stand out against the darker background. These features are continuously bright with intensities that vary slowly in time, in contrast to the "fine mottles" or "cell grains" which are located in the cell interiors and are much more dynamic (e.g. Rutten & Uitenbroek 1991). A possible interpretation of the Ca II observations is summarized in Fig. 1, where we show a vertical cross section of a magnetic network element consisting of several discrete flux tubes. Hasan & Ballegoiijen (2008) suggest that the Ca II network grains are located inside the magnetic flux tubes, and give rise to the bulk of the Ca II emission from the network element. The grains are thought to be located at heights between 500 km and 1500 km above the photosphere where the flux tubes are no longer "thin" compared to the pressure scale height (about 200 km), but are still well separated from each other. The Ca II straws (type-II spicules) have widths of order 100 km, and are located at larger heights (several Mm).

We suggest that the Ca II straws may be located at the boundaries between the flux tubes (from Hasan & van Ballegooijen 2008) where the widths of the flux tubes are much larger than 100 km. The physical processes that produce the enhanced emission in the network are still not fully understood. Is the network heated by wave dissipation, and if so, what are the properties of these waves? Unambiguous observations of waves would be required to settle this and related question. A major finding has taken place recently regarding the nature of magnetic fields in the internetwork (IN). New observations from the Hinode Stokes Polarimeter (SP) (with a spatial resolution of 0.3 arcsec) reveal the ubiquitous presence of horizontal fields with an average value of about 55 G (Lites et al. 2008). These observations show that, whereas the vertical magnetic field mainly occurs in the intergranular lanes at the network boundaries, the field in the internetwork regions is dominantly horizontal and well separated from the vertical fields. However, the situation may be more complex as pointed out by Stenflo (2010) on the basis of an independent analysis of the same data. More observations with good spatial and high spectropolarimetric sensitivity are needed to settle this question. When viewed at high resolution, sunspots reveal a complex and intricate structure, such as umbral dots, light-bridges and the interlocking-comb structure in the penumbra. Despite noteworthy progress on the theoretical front particularly through sophisticated numerical simulations in 3-D, there is still no general agreement on many features including the overall picture of whether sunspots are monolithic flux tubes or consist of a cluster of several flux tubes as originally proposed by Parker (1977) (for a recent review see Thomas 2010). Sunspots exhibit a range of oscillatory motions, including umbral flashes, oscillations and running penumbral waves. Sunspot seismology can serve as a probe to study the internal structure of these features. Furthermore, even after a century of its discovery, there is no universally accepted model for the Evershed effect. The above topics will form a part of the NLST observational programmes that will attempt to accurately determine the magnetic field topology with high spatial and spectral resolution. A study of active regions can provide useful clues to the solar dynamo believed to be located at the base of the convection zone.

Preliminary observations show that newly emerging flux has nearly constant twist. The measurement of the twist is important, both to infer the dynamical evolution of the magnetic flux tubes while they rise through the solar interior to the surface as well as to understand the role of the twist leading to instabilities and eventual dissipation of magnetic energy in the solar atmosphere. Current vector magnetograms show a persistent pattern of electric currents and helicity associated with strong magnetic fields of active regions. The knowledge we have gained so far of active regions is limited. Systematic observations of magnetic helicity in these regions are lacking. Such observations require vector magnetic field measurements on spatial scales of a few tens of kilometers combined with a temporal resolution of few seconds. A large field of view of the order of 5 arcmin is also essential in order to capture a full view of the entire active region.

The corona displays a myriad of phenomena that include loops, prominences, flares and CMEs, that are believed to be inherently magnetic in nature. Space observations from SoHO, TRACE and Hinode have provided considerable information on their properties. However, a detailed picture of the underlying physical mechanisms that are responsible for their occurrence is still lacking. A quantitative understanding of these processes requires an accurate determination of the magnetic topology through vector magnetograms at high spatial resolution. This would enable us to model the complex magnetic structure in the corona through a measurement of the field in the photosphere and corona, which provides the lower boundary for the field. Such investigations would also shed new information on mechanisms responsible for coronal heating.

2.2 High altitude advantages for infrared and UV observations

High altitude sites with low water vapor provide the advantage of carrying out observations in infrared (IR) wavelengths. It is well known that the negative hydrogen H^- ion (bound-free transitions) in the visible and H^- (free-free transitions) in the infrared (IR) wavelengths respectively are the principal sources of continuous opacity in the Sun. Furthermore, this opacity is lowest at $1.58\,\mu$m, and hence offers a window to observe the deep layers below the photospheric level at this wavelength. The Fe I lines at wavelengths close to $1.56\,\mu$m have high Landé g-factor and so are useful for the measurements of weak, small-scale magnetic fields (Solanki et al. 1992; Lin & Rimmele 1999; Socas Navarro & Lites 2004 and references therein). A large fraction of the solar magnetic flux is likely contained in these weak fields and their importance for the solar dynamo is not yet understood (Schüssler 2005). He I 10830 Å can be used to measure chromospheric magnetic fields, for example, in filaments, prominences and spicules (Lin et al. 1998). Simultaneous photospheric and chromospheric magnetic field measurements (Socas-Navarro 2005) performed with instruments such as the SPINOR (Spectropolarimeter for Infrared and Optical Regions (Elmore et al. 2005; Socas-Navarro et al. 2006) that provide crucial information about the 3-D structure of the magnetic field. NLST backend instruments will also be designed in a similar fashion for multiline polarimetry at visible and infrared wavelengths. In combination with the telescopes large photon collecting area, it will provide a unique tool for polarimetric investigations of the upper solar atmosphere. Scattering polarization is more pronounced at shorter wavelengths, due to a number of physical arguments. The near ultraviolet part of the solar spectrum therefore ideally complements the visible and near infrared portions of solar radiation, which are traditionally used in Zeeman imaging. A spectral line that has proven to be particularly suited for this purpose is the Ca I line around 422.7 nm. Observations in these wavelengths reveal complicated polarisation effects of both the Hanle and the Zeeman effects and are therefore of particular interest for the understanding of chromospheric magnetic fields.

2.3 Night time astronomy

We propose to use NLST for carrying out stellar observations during the night using a FEROS type high resolution spectrograph. The broad areas that will be investigated are

- activity monitoring in Ca, He and Balmer lines,
- cycles on solar-like stars,
- Doppler imaging,
- radial velocity monitoring,
- extrasolar planets,
- elemental abundances.

3 Technical aspects

3.1 The telescope optical design

The following considerations determined much of the design:

- The telescope should have a diameter of 2 m. On the one hand this diameter is significantly larger than that of all other existing solar telescopes. On the other hand this diameter is still small enough that one can buy a suitable substrate for the primary mirror off the shelf and that one can find enough polishers to have a real competition among them.
- The number of optical components should be as small as possible. This consideration is important to provide the image sensor with as much photons per pixel and second as possible.
- Adaptive Optics should be an integrated part of the optical design.
- Structure and dome should be optimized for local environmental conditions including natural air flushing.

Figure 2 shows the optical layout. A 2 m parabolic primary mirror (M1) forms a focus at the cooled fieldstop F1. The f-ratio here is $f/1.75$. M1 itself will also be cooled. This is why M1 will be lightweighted. The backside of M1 will show pockets in which cooled air will be blown which keep the thin front shell at a temperature close to ambient. The cooled field stop rejects and absorbs 99% of the incoming flux of about 3 kW. A central hole determines the field of view which will be 200 arcsec in diameter. The elliptical secondary mirror M2 picks up F1 and forms a secondary image at F2. Here the f-ratio is $f/8$. Close to F2 there is space for a polarimetric unit which can contain either a modulator package or a calibration unit. Another elliptical mirror (M3) transfers F2 to the science focus F3 where the final f-ratio is $f/40$.

A folding flat M4 is needed to guide the beam through the elevation axis to the azimuth axis which in our design is located beside the telescope tube. The elevation axis is close to M1 which allows a relative high position of M1 with respect to the dome platform. Such a configuration helps the natural airflush to cool the telescope and to keep the temperature close to ambient.

Without any additional optics M3 would form a pupil well inside the telescope structure. As a result an additional relay optic behind the science focus would become necessary in order to produce a suitable pupil on a deformable mirror. We want to avoid this and chose another solution: A weak negative lens close to focus F2 shifts the pupil outside the telescope structure to the mirror ensemble M5/M6.

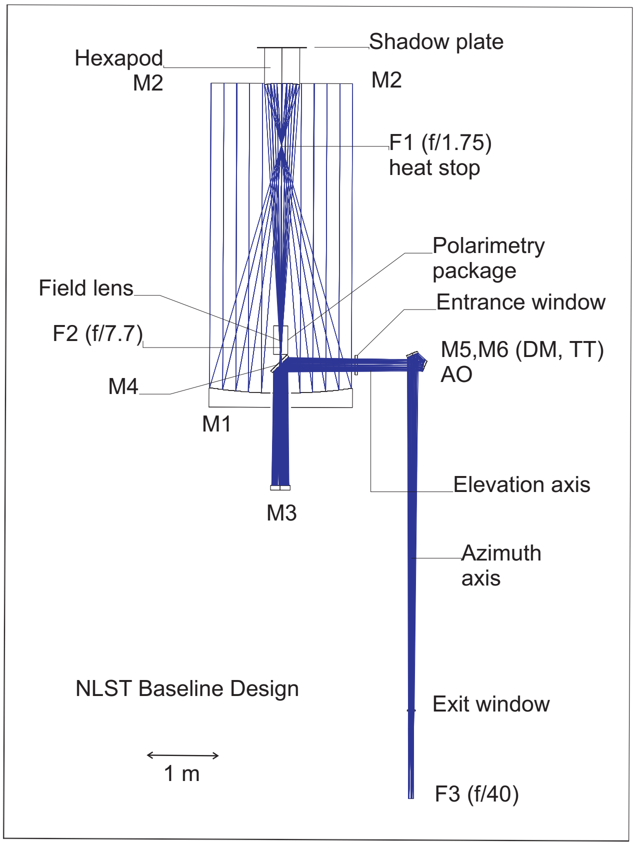

Fig. 2 (online colour at: www.an-journal.org) The optical scheme of the NLST.

Since this lens is close to the focus F2 it does not affect the image in focus F3 provided that there is no dust or other pattern on this lens which then would be visible in F3. The choice of this lens adds another degree of freedom to the design and determines the position (or the size) of the pupil. In the design which is shown in Fig. 2 the diameter of the pupil is 153 mm. This is a comfortable diameter in terms of the need of the Adaptive Optics. So M5 and M6 will be the tip tilt mirror and the deformable mirror respectively. As a result we have only 6 mirrors and one lens before the science focus F3. A consequence of this design is that the exit pupil is not in infinity but 6100 mm in front of F3. This has to be taken into account when designing the postfocus instruments

3.2 Adaptive optics

Adaptive optics is an integrated part of the optical design. That means that no additional optics is needed to provide a suitable pupil for the deformable mirror. In case of NLST we have the ensemble M5/M6 close to the telescop's pupil. The tip tilt mirror will be at a position which is exactly in the pupil whereas the deformable mirror will be at a position which corresponds to a height of approximately 30 m above the telescope. The deformable mirror will have 25 actuators across the telescope's diameter which corresponds to a subaperture diameter of 80 mm. This number matches on one hand the expected seeing conditions and represents on the other hand an optimum with respect to the signal to noise ratio for a solar wave front sensor. This is because the solar granulation as a low contrast target can be better resolved with a larger subaperture whereas the fitting error gets smaller with a small subaperture. Simulations show that the best compromise can be reached with subaperture sizes of about 80 mm. Since the deformable mirror is used under an angle of incidence of 22.5 degrees the actuator spacing will be different in x and in y. Figure 3 shows the actuator pattern which includes about 500 illuminated actuators.

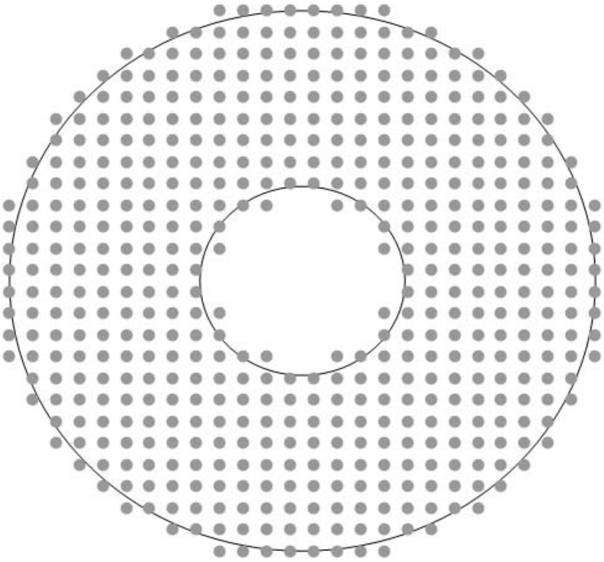

Fig. 3 The actuator pattern on the NLST deforable mirror. Note its elliptical shape and the uneven actuator spacing in x and y. This is because the deformable mirror is used under 22.5°.

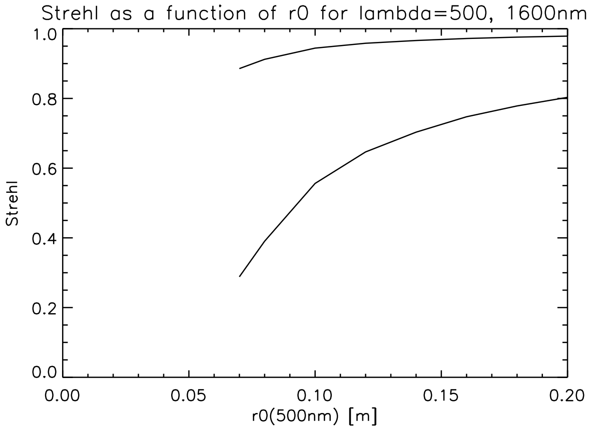

Fig. 4 Simulated Strehl ratio as a function of r_0 for two different wavelengths.

Given some preliminary site characterization data (see below) which show that during a significant fraction of the time the Fried parameter r_0 is larger than 75 mm. Figure 4 shows for two wavelengths (500 nm and 1600 nm) the Strehl ratio that NLST can reach as a function of r_0.

NLST is a project with emphasis on fast realization and a limited technical risk. This is why we abstain deliberately from implementing a multi-conjugate adaptive optics system (MCAO) into NLST. With NLST a high quality wide field of view can be obtained by combining AO with short exposures (facilitated by the high throughput of the telescope) and post facto image restoration techniques such as phase diversity.

3.3 Spectropolarimeter

Polarimetric investigations form a major objective of NLST. We need to minimize instrumental polarization which will adversely affect the performance of the telescope. The F2 focus is unaffected by instrumental polarization because the layout is rotationally symmetric up to that point, which we find is the natural place for either a calibration unit or a modulation unit. In both cases such a device contains at least one polarizer and one retarder with variable retardance. The polarimetry package will be placed in a space which extends 400 mm in the vertical direction and has a width three times the beam diameter. A 2-m aperture telescope would require about 2.5 s (at 630 nm) to carry out a single polarimetric observation (Keller 2003), which corresponds to an optimal exposure time of about 10 s to determine the 4 Stokes parameters needed for measuring the vector magnetic field with a high time cadence and good spatial and spectral resolution. The instrument will have flexibility to observe any given line or a combination of lines either on the disk or off limb so that a broad range of scientific problems can be investigated.

3.4 Narrow band imaging

Narrow band imaging will provide observations that will enable a study of a large class of problems such as (a) the determination of shear in active region magnetic fields, (b) evolution of magnetic fields during filament eruption, (c) emergence of magnetic flux, and (d) flare induced changes in spectral line properties. The proposed narrow band imager for the NLST is based upon the dual Fabry-Pérot (FP) étalons placed in tandem.

3.5 The telescope structure

In order to keep the number of mirrors small we decided to have the intersection between elevation axis and azimuth axis not within but beside the telescope tube.

Figure 5 shows the proposed configuration. The structure is very open and allows the air to flow which as low resistance as possible. The structure is stiff and finite element analysis and mode analysis show a first resonance frequency at about 10 Hz. The asymmetric mounting has an interesting feature: The telescope has two azimuth positions for each elevation. In strong wind situations this allows to select a lee side position of the tube. There is a price for this asymmetric mounting: The dome has to become larger.

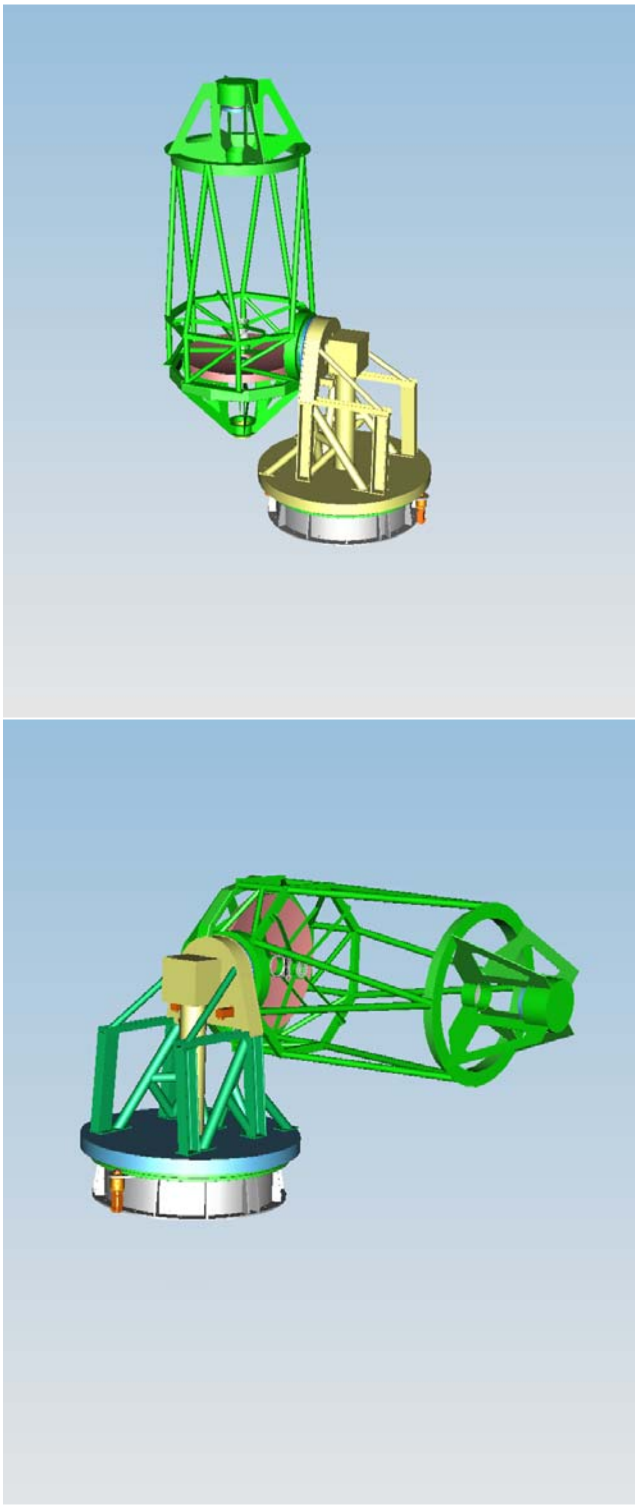

Fig. 5 (online colour at: www.an-journal.org) NLST mechanical structure.

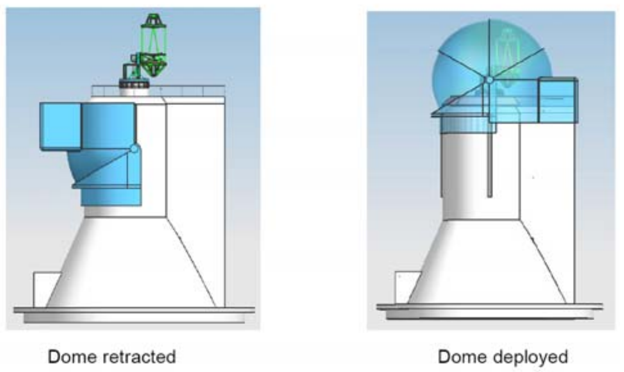

Fig. 6 (online colour at: www.an-journal.org) Concept of a fully retractable dome for NLST.

3.6 The dome

The dome is part of the seeing concept: Natural air flush wherever it is possible. The dome is fully retractable as it is shown in Fig. 6.

3.7 The building

The building will contain one or two instrument platforms with diameters in the order of 10 m. These steel structures will be rotatable in order to compensate for image rotation. See Fig. 7.

CFD calculations which included dome and building led to a design where the wind is guided by the shape of the upper part of the building in order to protect the telescope itself from wind induced vibrations.

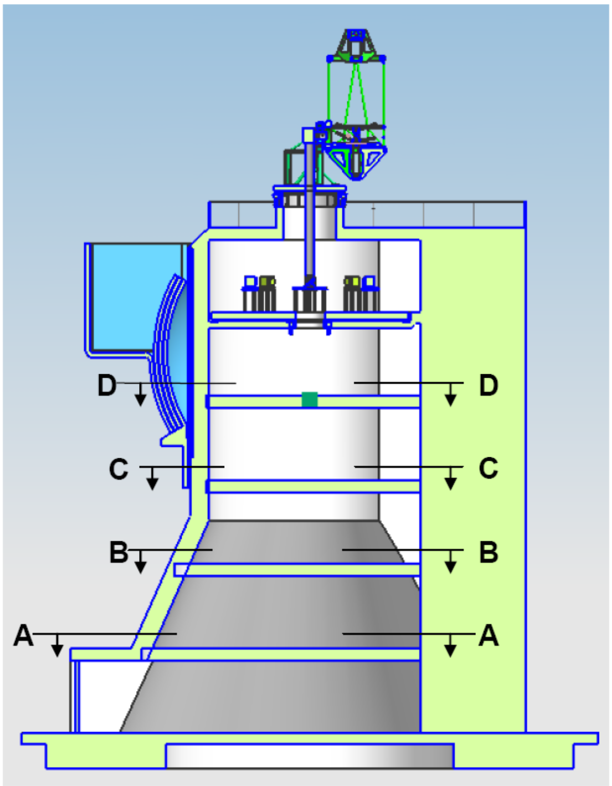

Fig. 7 (online colour at: www.an-journal.org) Concept of the NLST building with rotatable instrument platforms.

4 Site characterization

Critical to the successful implementation of NLST is the selection of a site with optimum atmospheric properties. Absence of clouds is one of the primary criteria. Another is the frequent presence of good seeing over long periods of time. Also of importance are good clear skies. Several surveys were taken up and carried out successfully during the latter part of the 20th century, leading to the discovery of some of the best sites in the world for solar observations.

Some of the major surveys include the Caltech survey in southern California during 1970s (Zirin & Mosher 1988), the Large European Solar Telescope (LEST) survey of 1970s and 80s (Brandt & Righini 1985), the ATST survey of 1990s to 2000s (Socas-Navarro et al. 2005). The Caltech survey covered, for the first time, a wide variety of topographies and showed the advantages of lake sites and also found that coastal and sea level inland sites do not provide the desirable conditions of seeing. It must be noted here that John Evershed, who spent a couple of years observing the Sun from lake sites in Kashmir, had realized the advantage of a water body for providing a good site for solar observations (Evershed 1915). Surveys in China (e.g., Li et al. 2004) showed that the Tibetan plateau has the best of astronomical sites at the high altitudes of over 3000 m. Some of the measurements at solar observatories in India, at the Kodaikanal Observatory at altitude of 2343 m (Bagare 1995) and at the Udaipur Solar Observatory at altitude of about 700 m (Kumar et al. 2007) show that the seeing is moderate at these inland sites, at averages of 2 arcsec and 3 to 4 arcsec respectively. The day time seeing is comparable to these at the Nainital solar facility, at an altitude of about 2100 m. Benefiting from the experiences of above cited earlier surveys, a preliminary study of the Indian geographical bounds was carried out during early 2006. It was noted that the Indian sub-continent faces the two major monsoons. Also, the coastal and inland sites, as shown by the Caltech survey, do not provide the best of locations. It was realized that the mountain desert conditions of Ladakh provide good number of sunshine hours with minimal precipitation and have the other advantages of high altitude. Hanle, at an altitude of 4500 m in the Great Himalayan range in Ladakh, with known good conditions for astronomical seeing for night sky, and the advantage of available infrastructure, was chosen as one of the sites for evaluation. Similarly, Devesthal which is in the Shivalik Hills of the Central Himalayan range and has been shown to have good night sky conditions, for the proposed 1.3-m and 3.6-m stellar telescopes, was also chosen for detailed evaluation since it provides another topographical environment at an altitude of 2500 m.

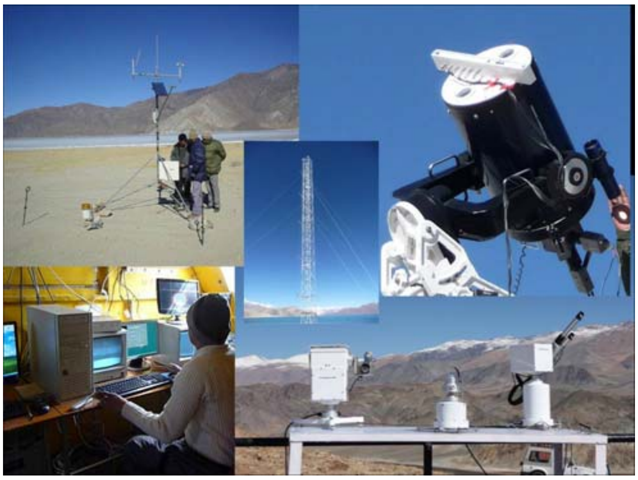

Fig. 8 (online colour at: www.an-journal.org) Impressions from the site testing campaign. The *upper right panel* shows the Shabar instrument.

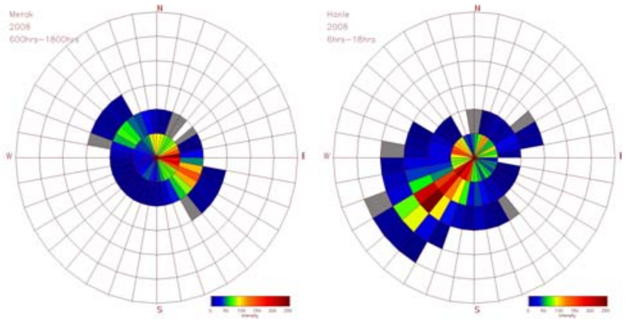

Fig. 9 (online colour at: www.an-journal.org) Polar plots of wind speed and directions at Merak and Hanle. The concentric circles show wind speed in steps of 5 m s^{-1}. The number density of points is colour coded. The favourable wind conditions at Merak is cognizable. The heavy wind conditions at Hanle, reaching 25 m s^{-1} can be seen in the *left panel*. These conditions prevail in the post noon hours.

Reconnaissance was carried out for lake sites in the Ladakh region of Great Himalayan range and in the Shivalik Hill range. The available access to the southern skies for observing the Sun during most parts of the year at this northern latitude and the obstructions by surrounding hills to solar observations, as well as the prevailing wind conditions which are expected to favour the day time seeing, were examined. This led to the identification of Pangong lake site for detailed characterization. Pangong lake appeared promising specially due to the following advantages: (a) about 40 km stretch of the lake within India, (b) the several land incursions mostly surrounded by water body of the lake, (c) the almost east west elongation, (d) the wind ducting from east to west which is expected to be favourable for day time conditions, (e) the large flat land at the southern shore allowing good access to the southern declination, (f) the atmosphere has low water vapor content, and (g) the region is unaffected by the monsoon.

Starting early 2007, and until recently, regular observations of seeing and other related parameters outlined above were carried out at Hanle for over two years, and at Merak for over one year. At Devesthal the AWS and micro thermal observations started in October 2009, whereas SDIMM observations began in December 2009. Data collection, archival, reduction, analysis and studies are being carried out on a regular basis at the NLST lab at Bangalore. The highlights of the results so far are that Hanle has good conditions of seeing in the morning hours while the afternoon periods get very heavily windy for most of the days. Figure 8 gives some impressions of the campaign.

The total annual sunshine hours are in the range of 1600 to 1750 hours. Good spells of sub arcsecond periods do occur for significant durations. These are being studied in detail and quantified. The aerosol and dust content studies have been studied and the results show that the aerosol content is extremely low, typical of the mountain site. The dust is generally low except during windy conditions when winds from Saharan region from south-west seem to be moving into the region (Verma et al. 2010).

Two years of results obtained so far suggest that the site at Merak provides continuous spells of excellent seeing (about 540 hours annually with a Fried parameter $r_0 > 7$ cm at a height of 8 m). The thermal fluctuations stabilize at heights of a few meters. The wind speeds of a few meters per second for most part of days helps stabilize the thermals. The prevailing wind is very advantageous since it passes over several kilometers of water body.

The wind direction is also remarkably steady, guided and ducted by the mountain ranges on both sides. The total annual sunshine hours is comparable to Hanle, being in the range of 1700 hours but most of the day is useful on clear days, unlike at Hanle where heavy winds affect the conditions. It is worth pointing out that there are a significant number of hours (over 100 in a year) with $r_0 > 10$ cm. Consequently, Merak is comparable to the best sites in the world for solar observations such as Haleakala and BigBear. Observations at Devesthal have just begun. The meteorological data collected earlier shows that the annual sunshine hours are comparable to those at Hanle and Merak. The seeing conditions, the prevailing conditions of wind, and the effects of the topography of the land will be studied in detail. The edge of a ridge that has been selected as the site for evaluation in Devesthal is located close to the site proposed for the 3.6-m stellar facility on the hill. The location is expected to provide the best of day time conditions that can be obtained in the Shivalik hill range.

5 The current status

The detailed concept design of NLST has been carried out by MT Mechatronics, Germany with technical support from the Kiepenheuer Institute, Freiburg. A detailed concept design report is now ready and a comprehensive proposal is under preparation for submission to our funding agency. The fabrication of NLST is expected to begin by late 2010

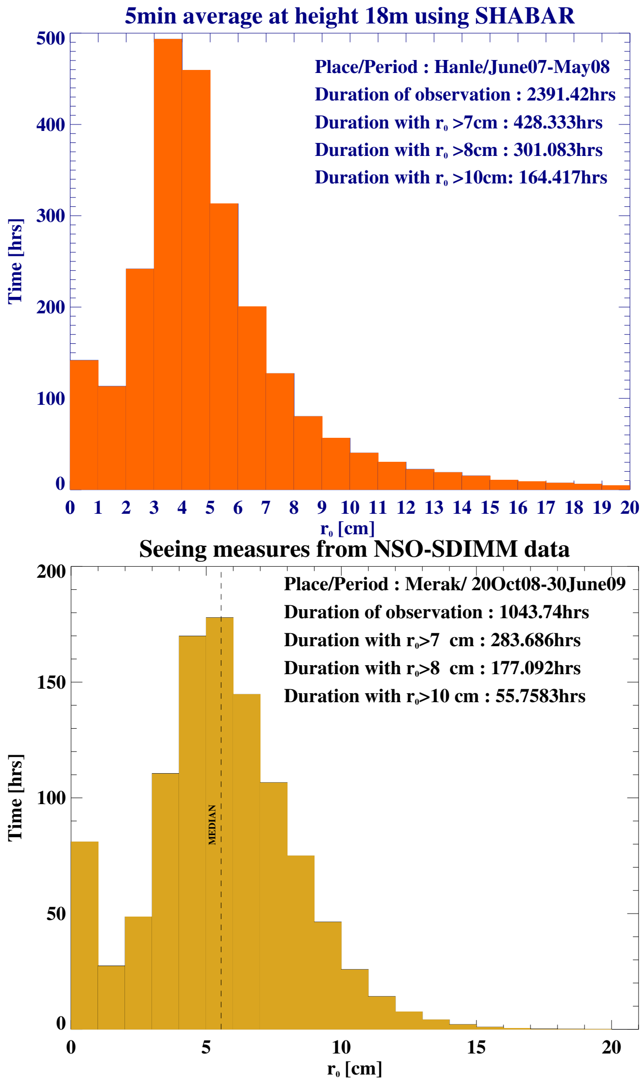

Fig. 10 (online colour at: www.an-journal.org) Histograms of r_0 at Hanle (*top panel*) and (b) Merak (*bottom panel*).

and be completed by early 2014. The backend instruments for day-time observations will be made in house and work on a prototype spectropolarimeter has already commenced. The spectrograph for night-time astronomy will be developed by the Hamburg Observatory, Germany.

6 Summary

A 2-m class telescope (NLST) has been proposed for carrying out solar astronomy at high altitude. NLST will be a state-of-the-art telescope that will permit high resolution studies of the solar atmosphere. An innovative design with minimal number of mirrors, high throughput and high order adaptive optics will provide close to diffraction limited performance. Its geographical location will fill the longitudinal gap between Japan and Europe. NLST will be the largest solar telescope with an aperture greater than 1.5 m, till ATST and EST come into operation.

References

Bagare, S.P.: 1995, BASI 23, 57
Brandt, P.N., Righini, A.: 1985, Vistas in Astron. 28, 437
Collados, M., et al.: 2010, AN 331, 615
Coulman, C.E., Vernin, J.: 1991, Appl. Opt. 30, 118
Elmore, D.F., Socas-Navarro, H., Card, G.L., Streander, K.V.: 2005, in: S. Fineschi, R.A. Viereck (eds.), *Solar Physics and Space Weather Instrumentation*, SPIE 5901, p. 60
Evershed, J.: 1915, PASP 27, 179
Hasan, S.S., Ballegooijen, A.A.: 2008, ApJ 680, 1542
Keil, S.L., et al.: 2010, AN 331, 609
Keller, C.U.: 2003, in: S. Fineschi (ed.), *Polarimetry in Astronomy*, SPIE 4843, p. 100
Kumar, B., Venkatakrishnan, P., Raja Bayanna, A., Venugopalan, K.: 2007, Sol. Phys. 241, 427
Li, S.-X., Fu, Y.-F., Huang, Y.-L., Li, J.-G., Mao, J.-T.: 2004, Chin. Astron. & Astroph. 28, 222
Lin, H., Rimmele, T.: 1999, ApJ 514, 448
Lin, H., Penn, M.J., Kuhn, J.R.: 1998, ApJ 493, 978
Lites, B.W., Kubo, M., Socas-Navarro, H., Berger, T., et al.: 2008, ApJ 672, 1237
Parker, E.: 1977, ApJ 230, 905
Rutten, R.J., Uitenbroek, H.: 1991, Sol. Phys. 134, 15
Socas-Navarro, H.: 2005, ApJ 631 167
Socas-Navarro, H., Lites, B.W.: 2004, ApJ 616, 587
Socas-Navarro, H., Beckers, J., Brandt, P., Briggs, J., Brown, T., et al.: 2005, PASP 117, 1296
Socas-Navarro, H., Elmore, D., Pietarila, A., Darnell, A., Lites, B.W., Tomczyk, S., Hegwer, S.: 2006, Sol. Phys. 235, 55
Solanki, S.K., Ruedi, I.K., Livingston, W.: 1992, A&A 263, 312
Schüssler, M.: 2005, AN 326, 194
Stenflo, J.: 2010, in: A.H. Andrei, A.S. Kosovichev, J.-P. Rozelot (eds.), *Solar and Stellar Variability – Impact on Earth and Planets*, IAU Symp. 264, p. 191
Thomas, J.T.: 2010, in: S.S. Hasan, R.J. Rutten (eds.), *Magnetic Coupling between the Interior and the Atmosphere of the Sun*
Verma, N., Bagare, S.P., Ningombam, S.S., Singh, R.B.: 2010, J. Atmosph. Sol. Ter. Phys. 72, 115
Zirin, H., Mosher, J.M.: 1988, Sol. Phys. 115, 183