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The 1.6 m Off-Axis New Solar Telescope (NST) in Big Bear

Philip R Goode and Wenda Cao

Big Bear Solar Observatory, 40386 North Shore Lane, Big Bear City, CA 92314, USA

New Jersey Institute of Technology, Center for Solar-Terrestrial Research, 323 Martin Luther King Blvd., Newark, NJ 07102, USA

Abstract. The New Solar Telescope (NST) in Big Bear is the first facility-class solar telescope built in the US in a generation, and it has an off-axis design as is planned for the Advanced Technology Solar Telescope (ATST). The NST is in regular operation with adaptive optics (AO) correcting the light currently feeding photometric and near-IR polarimetric systems, as well as an imaging spectrograph. Here we show the high resolution capabilities of the NST. As well, we sketch our plans for, and reasoning behind the next generation NST instrumentation.

1. The NST

In January 2009, Big Bear Solar Observatory (BBSO) attained first light with its off-axis, 1.6 m clear aperture New Solar Telescope (NST). After further, initial alignment efforts, observations began to show fuzzy resolution (see Fig. 1) of about $0''.2$ in the photosphere (in TiO at 705.7 nm), after speckle reconstruction using the KISIP code (Wöger, von der Lühe, & Reardon 2006).

Fig. 1 also shows a degraded version of the NST observations that would correspond to the old 0.6 m solar telescope that was replaced by the NST. Although the NST result was heartening, it was clear that there was still a great deal of work to be done, which included improving the alignment of the NST and implementing adaptive optics (AO).

The NST has an off-axis Gregorian configuration consisting of a parabolic primary, heat-stop, elliptical secondary and diagonal flats. The NST has a $100''$ circular opening after the field stop that defines a $70''\times70''$ maximal square field of view (FOV). The focal ratio of the primary mirror is f/2.4, and the final ratio is f/52. The working wavelength range covers from 0.39 to 1.7 μm in the Coudé Lab two floors beneath the telescope, and covers all wavelengths including the far infrared at the Nasmyth focus bench attached to the side of the telescope. We emphasize that both the NST and ATST are off-axis designs. The first fuzzy, but science quality NST image taken in the TiO band, see Fig. 1, was taken at the Nasmyth focus. In fact all wavelengths are also available at a focus immediately before the light is fed to the Coudé Lab. An off-axis design was chosen principally because of its vastly reduced stray light, since there is no central obscuration to degrade the telescope's MTF (Modulation Transfer Function).

The wavefront sensing system for alignment and for the PM active optics resides before M3. The polarization modulator also resides there. Having the modulator so

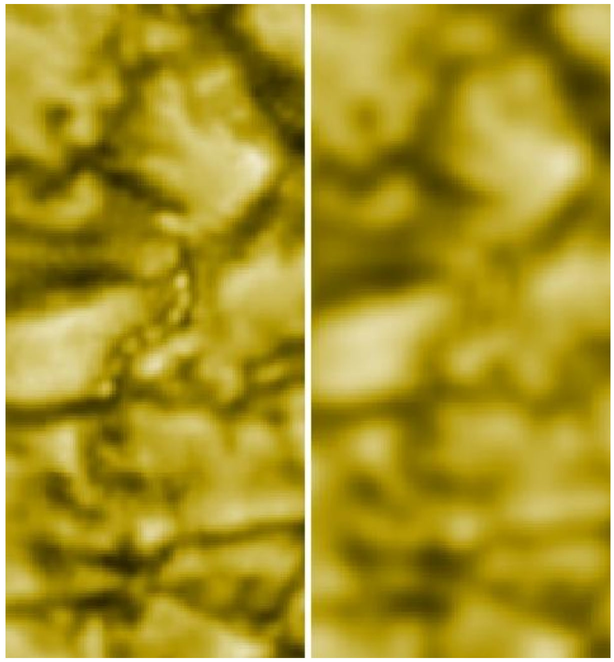

Figure 1. NST images with a FOV of $4'' \times 2''$ from March 30, 2009 are shown. Left: A reconstructed image in which seven fuzzy bright points appear side-by-side in a dark lane at the center of the FOV. These bright points are thought to be associated with magnetic field concentrations and are each about $0''.2$ in diameter. Right: The same image degraded to the resolution of the old BBSO 0.6 m aperture telescope in which the beads cannot be seen.

far forward is a design advantage that helps us obtain vector magnetograms, which we were never able to do with the old 0.6 m telescope because, in part, there were always many (oblique) mirrors between the sunlight and the polarimeter's modulator.

By the Summer of 2010, first observations were made in the Coudé Lab two floors beneath the dome floor. In the Coudé Lab, we deployed the AO system used on the 0.6 m telescope, which has a 97 actuator deformable mirror (DM). With AO corrected light, improved optical alignment and speckle reconstruction we obtained diffraction images like those shown in Fig. 2, where we show images of the photosphere (in TiO at 705.7 nm) and chromosphere (blue wing Hα). The left image has been called the most precise image of the Sun's surface ever taken (*http://www.cieletespace.fr/node/5752*) and was chosen by the editors of National Geographic as one of the top ten space images of 2010 [1] .

The NST will significantly broaden and deepen BBSO's tradition of providing data from campaigns in coordination with data from NASA satellites. Now, these satellites include SDO, Hinode, RHESSI and STEREO. That is, the NST will provide unique high temporal and spatial resolution data to both complement and supplement efforts to understand the fundamental nature of the dynamics of solar magnetism and its evo-

[1] http://news.nationalgeographic.com/news/2010/11/ photogalleries/101130-best-space-pictures-2010/

lution. The NST is used to observe the photosphere and chromosphere with unprecedented resolution, which dovetails well with the overlapping satellite data that cover, round-the clock, a wider spectral range, but with lower spatial resolution than the NST. We are presently using the NST in sustained campaigns, which has been at the core of BBSO's ability to provide unique, complementary and supplementary data in support of the community's efforts to understand our star and its environs. Observing campaigns are essential to determine the origin of "space weather", which arises from solar magnetic storms and can have deleterious effects on satellites, as well as the terrestrial power grid and telecommunications.

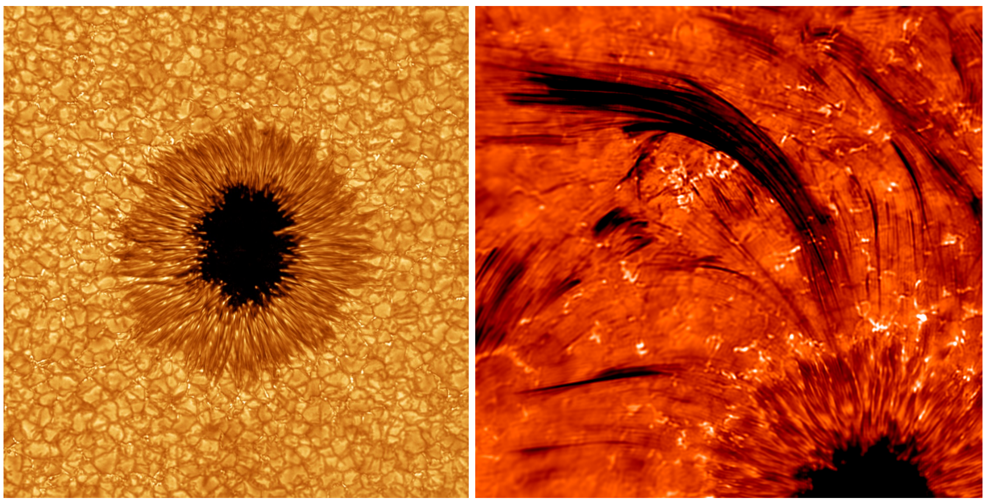

Figure 2. Left: A small sunspot observed on 2 July 2010. Right: Hα image of the same sunspot revealing the dynamical layer overlying the surface region shown in the full sunspot image. Most apparent are the long dark streaks, so-called "jets" arising from the bright magnetic regions on the edge of the penumbra. Both images benefited from adaptive optics, which enabled real-time correction for atmospheric distortion.

The NST is a modern, off-axis 1.6 m clear aperture instrument (Cao et al. 2010; Goode et al. 2010) that offers a significant improvement in ground-based, high angular resolution and polarimetric capabilities (*http://www.bbso.njit.edu/nst_project.html*). Key milestones of NST commissioning are listed in Table 1. We are well into the commissioning phase.

To better understand the fine structure of the solar chromosphere, NST is equipped with a Fast Imaging Solar Spectrograph (*http://www.bbso.njit.edu/fiss.html*). This is a field-scanning slit spectrograph with high spectral resolving power (1.4×10^5) and fast scanning speed (10 seconds) to sufficiently cover a large field of view of $40'' \times 60''$. It has been developed and paid for by our international partners, the Korean Astronomy and Space Science Institute (KASI) and Seoul National University (SNU). The observable spectral lines range from visible to near infrared (0.38 μm — 0.92 μm). The major spectral lines of interest for studying chromospheric dynamics are Hα, Ca II H and K and Ca II 8542Å. Two different spectral lines can be recorded simultaneously using two identical CCD cameras. This feature enables one to distinguish between the

Table 1. Milestones in NST Commissioning.

Date	NST Milestone	Observations Enabled
January 2009	First Light with NST	Visible Light Photometry (0″.50)
Summer 2009	First Diffraction Limited Observations	Visible Light Photometry (0″.15)
Summer 2010	AO Corrected Observations	Visible & NIR Photometry (0″.10-0″.20)
Summer 2010	AO Corrected Magnetograms	Near IR (NIR) Vector **B** (0″.40)
Spring 2012	IRIM Upgrade to Dual FPI System	Higher Cadence Vector **B** in NIR (0″.20)
Summer 2012	AO-308 Observations	Photometry in Bluest Light (0″.05)
Fall 2012	VIM Installation	High Spatial Resolution Vector **B** (0″.10)
Summer 2013	First Observations with MCAO	AO Correction over Full 70″ × 70″ FOV
Fall 2013	CYRA First Light	Spectroscopy Covering 1.0- 5.0 μm

thermal and the non-thermal turbulence, so that a precise determination of temperature becomes possible.

We have also programmed a 32-node parallel computing cluster, so that we can perform real-time speckle reconstruction with a cadence of about 1 minute (for a 1k×1k camera). At present, we use this system for speckle reconstruction of each day's data, so there is no backlog in data reduction.

2. Adaptive Optics

The NST has a fully operational, nearly acromatic adaptive optics (AO) system on a vertical bench in the Coudé Lab for diffraction limited imaging, as illustrated in Fig. 2. The AO system incorporates a 97 actuator deformable mirror, a Shack-Hartmann wave front sensor with 76 subapertures, and a digital signal processor system. This is structurally the same "AO-76" used on the now-retired 0.6 m BBSO telescope and the Dunn Solar Telescope (DST) of the National Solar Observatory (NSO). NST images also routinely undergo post-facto reconstruction. The Kiepenheuer-Institut für Sonnenphysik's software package for speckle interferometry of AO corrected solar data (KISIP) is a post AO reconstruction algorithm allowing one to achieve the diffraction limit of the telescope over a larger field of view than the isoplanatic patch for most observations (Wöger, von der Lühe, & Reardon 2006).

The AO-76 system tracks on granulation for the NST, while with the old 0.6 m telescope we were only able to track on pores, which reflects to some extent the problems of retrofitting an AO system on a powerful telescope that was not designed to support AO. The success of AO-76 on the NST was no surprise, rather it was foreseen in a detailed and realistic error budget analysis (Rimmele 2008, private communication) that included AO residuals, telescope and instrument error budgets, and the steady, good BBSO seeing (an AO correctable $r_0 \sim 6$ cm all day long, which is sufficient for AO-76 to usually lock on granulation). The steady 6 cm Fried parameter is in the mid-visible wavelength range and was determined by the ATST site survey (*http://atst.nso.edu/site*) in Big Bear. The Fried parameter, r_0, is the coherence length of the atmospheric turbulence. For telescope apertures larger than r_0, resolution is seeing limited. In the summer of 2010, AO was able to lock on granulation for extended periods of time. In the winter, attaining AO lock for extended periods was more problematic because of generally poorer seeing than in summer. The error budget analysis of Rimmele (2008, private communication) showed that AO-76 will yield, in the detector plane, a high Strehl ratio of about 0.7 in the near infrared (1 μm) under median BBSO seeing conditions. However, in the visible (0.5 μm), AO-76 will deliver a sufficient Strehl (~0.3, which would imply diffraction limited imaging of the solar disk) only under exceptional seeing conditions. Thus, in visible light our observations using AO-76 are better at the red end of the visible spectrum. The low Strehl matters especially for polarimetric observations, which range from difficult to impossible to interpret. The problem here is that the requisite opposite polarity measurements, which are subtracted from each other, are often closely (tenths of arcsecs) spaced together. Thus, truly diffraction limited observations, especially of the magnetic field will be rare in the visible spectrum, even though they would be critical for the highest possible spatial resolution.

Therefore, we are developing, in collaboration with NSO, an AO system based on a commercially available, 357 actuator DM (AO-308), which, based on the same kind of error budget analysis, we realistically expect to achieve a Strehl ratio of 0.3 in the detector plane in the visible (0.5 μm) for median BBSO seeing conditions, (Rimmele 2008, private communication). The Strehl, generally used to quantify the performance of an AO system, is the ratio of the maximum intensity in the AO corrected image in the detector plane to that from a theoretical, perfect imaging system operating at the diffraction limit.

The AO-308 project is well-underway, and we have purchased two 357 actuator DM's from Xinetics that has a special faceplate made of silicon instead of ULE (ultra-low expansion glass) because silicon has about 100 times the thermal conductivity of ULE to conduct away the heat on the DM from the Sun. The other elements of AO-308 are a more complex Digital Signal Processor (DSP) system from Bittware (DSPs are about 10 times faster than those for AO-76) and a faster wavefront sensing camera (Phantom V7.3 from Vision Research) with Quasar providing the camera to DSP and DM to DSP interfaces. Each hardware element and its connections to its partners has been successfully tested. What remains is DSP control and the GUI, with the former being built on the programming from AO-76, and this is well underway and being tested. The optical design of AO-308 is close to that of AO-76 requiring only the replacement of two optical elements in the AO-76 feed. We expect to test the AO-308 system in the Summer of 2012 and have full operation shortly thereafter.

With AO-308 feeding light to our optical instruments in the Coudé Lab, BBSO will collect a richer spectrum of data. In particular, we can correct light near 400 nm with AO-308, whereas such corrections are possible with AO-76 only under extra-ordinarily good seeing.

In collaboration with NSO, we are also developing a Multi-conjugate Adaptive Optics (MCAO) system for the NST that will substantially expand the effective isoplanatic patch of diffraction limited observations in the FOV. Our plan is to use our three DMs in the NST MCAO, but with two 357 actuator DMs at the outset. The expansion of the diffraction limited FOV should be sufficient to cover entire active regions enabling spectroscopic and polarimetric observations, which include, for instance, flares that might occur at anytime and anywhere in an active region. Therefore, the MCAO system will sharply reduce a major limitation of conventional AO systems, the insufficiently large isoplanatic patch, and, thus provide the tool to effectively study, with the requisite high temporal cadence and with the NST's unprecedented spatial resolution, fundamental scientific questions like the onset and evolution of flares, flare triggering mechanisms, magnetic reconnection events and many other dynamic solar phenomena, which would be best performed with diffraction limited observations over an extended FOV. At present, we are without MCAO and make relatively slow (about 5 s) cadence observations (compared to sub-second ones required for studies of event triggerings). For these, we presently use AO-76 (soon AO-308) combined with speckle reconstruction, while for appreciably higher cadence we will suffer some from the gradual roll-off in resolution as we move further from the isoplanatic patch. Of course, the NST is a 2 m^2 "light-bucket" that can be used to accumulate sufficient photons for very high temporal cadence observations of rapid phenomena in visible light, as well as in the NIR.

3. Next Generation Focal Plane Instrumentation

The IRIM (InfraRed Imaging vector Magnetograph) system developed by BBSO is in operation (Cao et al. 2011) on the NST using light fed from AO-76. In addition to the SDO line-of-sight magnetogram in the uppermost panel of Fig. 3, we show the Q, U, and V components of a vector magnetogram in Fig. 3. We note that severe polarization problems precluded obtaining vector magnetograms from the old, 0.6 m BBSO telescope and that BBSO vector magnetograms from that era were from a 20 cm aperture telescope. The superior optical design of the NST and good polarization calibration have already enabled us to obtain vector magnetograms with minimal cross-talk, as is clear from Fig. 3 where there is no apparent cross-talk of the line-of-sight component in the two transverse components.

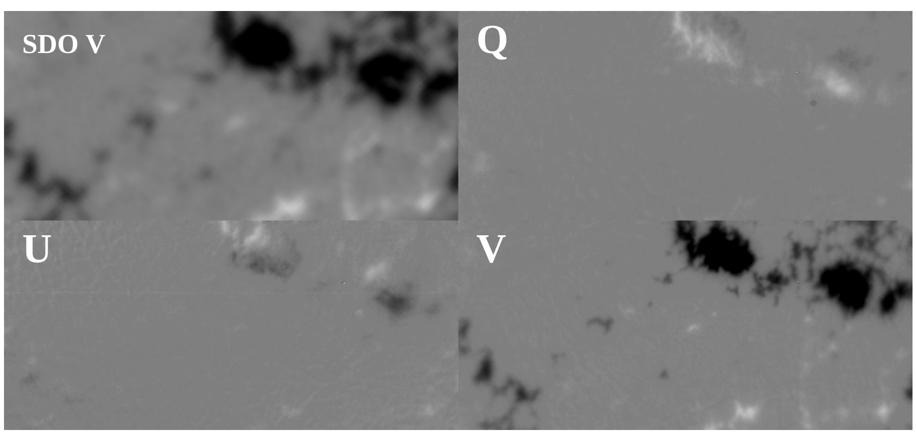

Figure 3. Top left: Stokes V image of SDO/HMI for comparison to IRIM vector magnetogram of a cluster of pores near AR 11121 at 231E 391S, taken on Nov. 09, 2010; Top right: calibrated Stokes Q image; Bottom left: calibrated Stokes U image, and bottom right: calibrated Stokes V image. Dual-beam technology was employed to minimize seeing-induced noise. The center of the strongest pore has a longitudinal magnetic field strength of about 1 kG. In the dual beam mode shown, the FOV of IRIM is about $50'' \times 25''$.

The NST magnetogram in Fig. 3 are from IRIM, which is one of the first imaging spectropolarimeters working at 1565 nm, and is used for observations of the Sun at its opacity minimum, exposing the deepest photospheric layers that can be seen. The temporal cadence for the IRIM vector magnetograms is 45 s, but it will be about five times faster when its Lyot filter is replaced by a second Fabry-Pérot Interferometer (FPI) in the Spring of 2012, so the second generation IRIM will be tested in Summer 2012. IRIM's first imaging polarimetric observations at 1565 nm were made at the diffraction limit on July 1, 2005 using BBSO's retired 0.6 m telescope (Cao et al. 2006). Stokes-V profiles were obtained from the FPI scan, and the data provide access to both the true magnetic field strength and the filling factor of the small-scale magnetic flux elements. The strength of IRIM is its extreme sensitivity and high spatial resolution, which allows us to study weak and small-scale magnetic fields in the quiet Sun. One might think that the quality of magnetograms from the NST with triple the aperture of the old telescope would be compensated by roughly tripling of the wavelength of the observations (ignoring the factor of eight difference in aperture of the NST and that of the old BBSO magnetograph). But this is not true, after all, Zeeman splitting increases quadratically with wavelength, so IRIM can more precisely detect magnetic flux. Thus, we will now be able to extract the true magnetic field strength and the filling factor for the small-scale magnetic flux elements (Cao et al. 2006). Additionally, the terrestrial atmosphere is more benign in the NIR with the mean Fried parameter at BBSO being about 25 cm (under the standard assumption of Komolgorov turbulence), which is four times that at 0.5 μm. Even with AO-76 corrected light, this much larger Fried parameter is essential in the observations of faint features, which otherwise would tend to drift in and out of sharpness. The focal plane Strehl in the NIR is sufficient to enable sustained diffraction limited images with AO-76 under typical BBSO observing conditions. Depending on the number of spectral positions chosen for the line scans in IRIM operations, we will have as short as a 45 s cadence for vector magnetograms. The expected polarization accuracy will be our nominal $10^{-3} I_c$. The spatial resolution will be around $0''.2$ for direct imaging, and $0''.4$ for magnetograms.

We are upgrading IRIM to a dual FPI system (replace Lyot filter with second FPI), so that we can fine tune to any wavelength between 1.0 and 1.7 μm, rather than being confined by the Lyot filter to the 1.6 μm regime with IRIM. The upgraded instrument is called NIRIS (NIR Imaging Spectro-polarimeter). NIRIS will have all the capabilities of IRIM with five times the cadence. It has a broader wavelength coverage over the NIR that will enable NIRIS to measure the magnetic field in the upper chromosphere and base of the corona using the He I 10830 Å line. Such measurements have been made with spectrographs, like SOLIS. NIRIS will be on-line in 2012 (see Table 1). NIRIS is discussed by Cao et al. (2012) in these proceedings.

The weakness of IRIM is the spatial resolution, but this problem will be solved using our Visible Imaging Magnetograph (VIM). VIM was in use on the old BBSO telescope and obtained spectroscopic data and line-of-sight magnetograms. IRIM and VIM have the same basic design and operational modes and both magnetograph systems were ready to be integrated into the NST at first light, but since fully diffraction limited operation of VIM will require AO-308, we chose to bring IRIM on line first. Soon, we will have AO-308 and VIM for science that requires vector magnetograms of the highest spatial resolution ($0''.1$).

The CrYogenic infRAred Spectrograph (CYRA) spanning 1.0 to 5.0 μm will help the NST achieve its scientific potential of a new and improved probing of the fundamentals of the Sun's atmosphere with its dynamic magnetic field, the origin of space weather. CYRA will be a substantial improvement over the two current solar IR spectrographs – one operating at the National Solar Observatory (on the McMath-Pierce telescope) and the other at the Institute for Astronomy (Mees Solar Observatory, University of Hawaii), both of which are based on warm optics except for the detectors and order sorting filters, whereas CYRA will be fully cryogenic. CYRA will be a significant advance, particularly for high-spatial and high-cadence and high Zeeman sensitivity observations of the Sun's atmosphere from the photosphere through the chromosphere and into the corona, as well as observations of dimmer targets such as sunspot umbrae and off-limb features.

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