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

Philip R. Goode[a,b], Wenda Cao[a,b], and BBSO Team[b]

[a]Center for Solar-Terrestrial Research, New Jersey Institute of Technology,
323 Martin Luther King Blvd., Newark, NJ 07102;
[b]Big Bear Solar Observatory, 40386 North Shore Lane, Big Bear City, CA 92314

ABSTRACT

The 1.6-m New Solar Telescope (NST) has been used to observe the Sun for more than three years with ever increasing capabilities as its commissioning phase winds down. The NST is the first facility-class solar telescope built in the U.S. in a generation, and it has an off-axis design as is planned for the 4 m Advanced Technology Solar Telescope. Lessons learned will be discussed. Current NST post-focus instrumentation includes adaptive optics (AO) feeding photometric and near-IR polarimetric sytems, as well as an imaging spectrograph. On-going instrumentation projects will be sketched, including Multi-Conjugate AO (MCAO), next generation (dual Fabry-Pérot) visible light and near-IR polarimeters and a fully cryogenic spectrograph. Finally, recent observational results illustrating the high resolution capabilities of the NST will be shown.

Keywords: Telescope, Photometry, Imaging, Solar observation

1. INTRODUCTION

After several years of effort, in January 2009, BBSO attained first light with its off-axis, 1.6 m clear aperture New Solar Telescope (NST). First diffraction limited observations with the NST came in the Summer of 2009, while the first observations corrected by adaptive optics (AO) came in the Summer of 2010 and first vector magnetograms in the Summer of 2011. The NST is the first facility class solar telescope built in the U.S. in a generation. We show in Figure 1 diffraction limited images of the photosphere (in TiO at 705.7 nm) and chromosphere (blue wing Hα). The left image in Figure 1 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 * .

The NST is used to observe the photosphere, chromosphere and up to transition region with unprecedented resolution to elucidate the fundamental nature of the dynamics of solar magnetism and its evolution. We use the NST in sustained campaigns, which has been at the core of BBSO's ability to provide unique 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.

The NST is the pathfinder for the Advanced Technology Solar Telescope (ATST) that will be built in Hawaii over this decade. Both the NST and the 4 m ATST have off-axis designs. This makes the NST the ideal testbed in all manner of ATST design and implementation issues. The NST will dominate U.S. ground-based observations at least until the latter part of this decade. After the ATST is online, the NST will still have an essential role because the NST will be the large aperture solar telescope in the U.S. working in sustained campaigns. It is expected that the ATST will be oversubscribed and will not be able to satisfy all requests for observations. Moreover, with the closure of mid-aperture solar telescopes currently operated by the NSO, observations that do not require ATST-size aperture may face difficulties in competing for ATST observing time. The NST can play a supplemental national role by enabling a broader scientific community to do research in high-resolution solar physics. The NST will also be more accessible than the ATST to junior researchers and researchers from small universities, in part due to a lesser competition for observing time.

P. R. Goode: e-mail: pgoode@bbso.njit.edu, Telephone: 1 973 596 3565
* *http://news.nationalgeographic.com/news/2010/11/ photogalleries/101130-best-space-pictures-2010/*

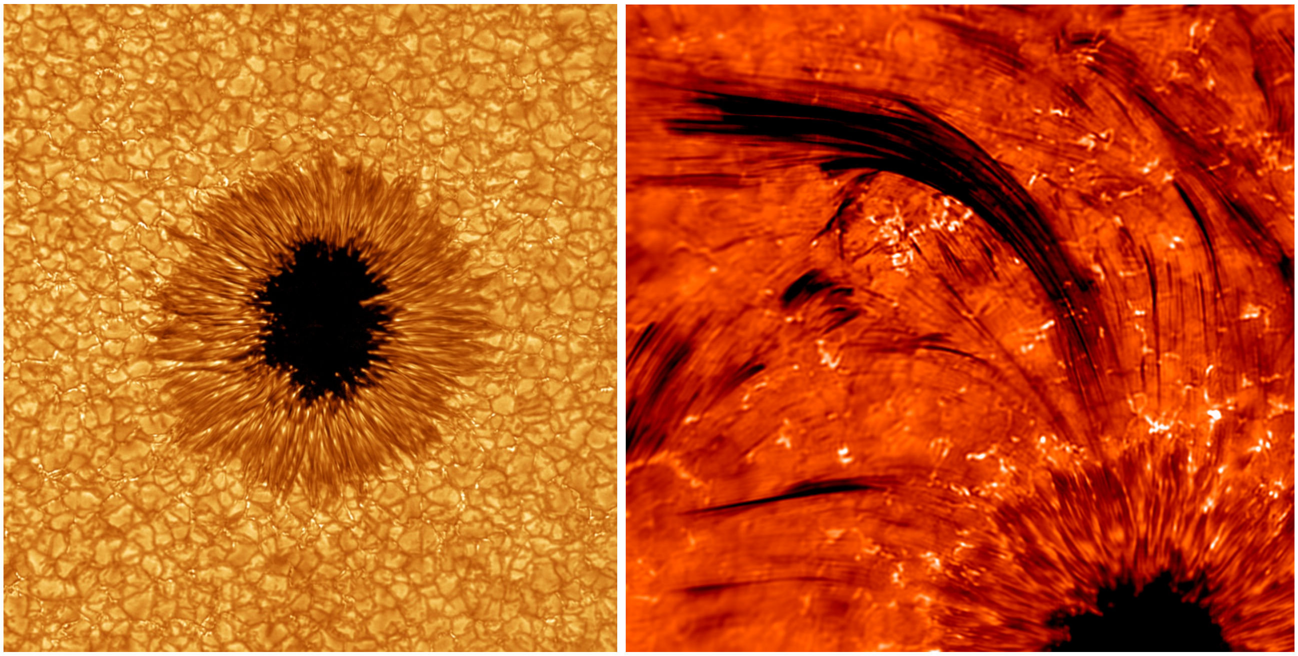

Figure 1. Left: A small sunspot observed in TiO at 705.7 nm on 2 July 2010. Right: Blue wing Hα image of the same sunspot revealing the dynamical layer overlying the surface region shown in the full sunspot image. Most apparent are long dark streaks called "jets" arising from the bright magnetic regions on the edge of the penumbra. Both images benefited from adaptive optics, which enabled real-time correction for atmospheric distortion.

2. NEW SOLAR TELESCOPE (NST)

The NST[1,2] is a modern, off-axis 1.6 m clear aperture instrument [†] that offers a significant improvement in ground-based, high angular resolution and polarimetric capabilities. Key milestones of NST commissioning are listed in Table 1. We are well into the commissioning phase.

The telescope is configured as an off-axis Gregorian system consisting of a parabolic primary, prime focus field stop and heat reflector (heat-stop), elliptical secondary and diagonal flats. The primary mirror (PM) is 1.7 m with a clear aperture of 1.6 m. The focal ratio of the PM is f/2.4, and the final ratio is f/52. The $100''$ circular opening in the field stop defines a $70''\times70''$ maximal square field of view (FOV). The working wavelength range covers 0.4 to 1.7 μm in the Coudé Lab two floors beneath the telescope and all wavelengths including the far infrared are at the Nasmyth focus optical bench attached to the side of the telescope structure. 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) at high spatial frequencies.

The PM of the NST was figured at the Steward Observatory Mirror Lab in Tucson. The PM was a test bed for Giant Magellan Telescope (GMT), which is to consist of six off-axis 8.4 m off-axis segments. The NST with its 1.7 m PM is a one-fifth scale version of the GMT, but with a single mirror. The original plan was to use a computer generated hologram (CGH) to alter the wavefront of the test interferometer to match the chosen aspheric of the NST. There were a series of problems manifested as daily variations of $\sim$150 nm in low order residual optical aberrations in the measured figure of the PM. The problems were resolved when it was realized that the interferometer and CGH had to be aligned every day with a laser tracker. The laser tracker was fixed in position to "see" both the CGH and the interferometer. Ultimately, it was decided two independent tests of the figure were required. The second method was a pentaprism scan, which is sensitive to low order aberrations. The net of both tests was a residual RMS figure error of 16 nm RMS.

[†] *http://www.bbso.njit.edu/nst_project.html*

Table 1. Milestones in NST Commissioning.

Date	NST Milestone	Observations Enabled	Resolution
January 2009	First Light with NST	Visible Light Photometry	$0''.50$
Summer 2009	First Diffraction Limited Observations	Visible Light Photometry	$0''.12$
Summer 2010	AO Corrected Observations	Visible and NIR Photometry	$0''.10$-$0''.20$
Summer 2011	AO Corrected Magnetograms	NIR Vector Magnetograms	$0''.40$
Summer 2012	AO-308 Observations	Visible Light Photometry in Bluest Light	$0''.05$
Summer 2012	IRIM Upgrade to Dual FPI System	Higher Cadence Vector Magnetograms in NIR	$0''.40$
Summer 2012	VIM Spectroscopy	High Spatial Resolution Spectroscopy	$0''.05$
Summer 2013	VIM Spectro-polarimetry	High Spatial Resolution Vector Magnetograms	$0''.10$
Summer 2013	First Observations with MCAO	AO Correction over Full $70'' \times 70''$ FOV	$0''.05$
Summer 2013	CYRA First Light	Spectroscopy Covering 1.0- 5.0 μm	$0''.15$-$0''.80$

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

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 Figure 1. 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)[3] 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 (region of full correction by AO) for most observations.

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, r_0, 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 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-76 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 would deliver a sufficient Strehl ($\sim$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 have been 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 system is being tested in BBSO at this writing. We purchased a 357 actuator DM 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 processing (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 having provided the camera to DSP and DM to DSP interfaces. 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 early summer of 2012 and run AO-308 in parallel with AO-76 for the summer of 2012 with AO-308 being initially concentrated on G-band.

Our efforts with the NST will be directed toward high resolution NST data covering the spectral range from 0.4 to 5.0 μm to probe the solar atmosphere from the surface to the base of the corona, from the smallest scales to largest scales, and from the quietest to most active Sun.

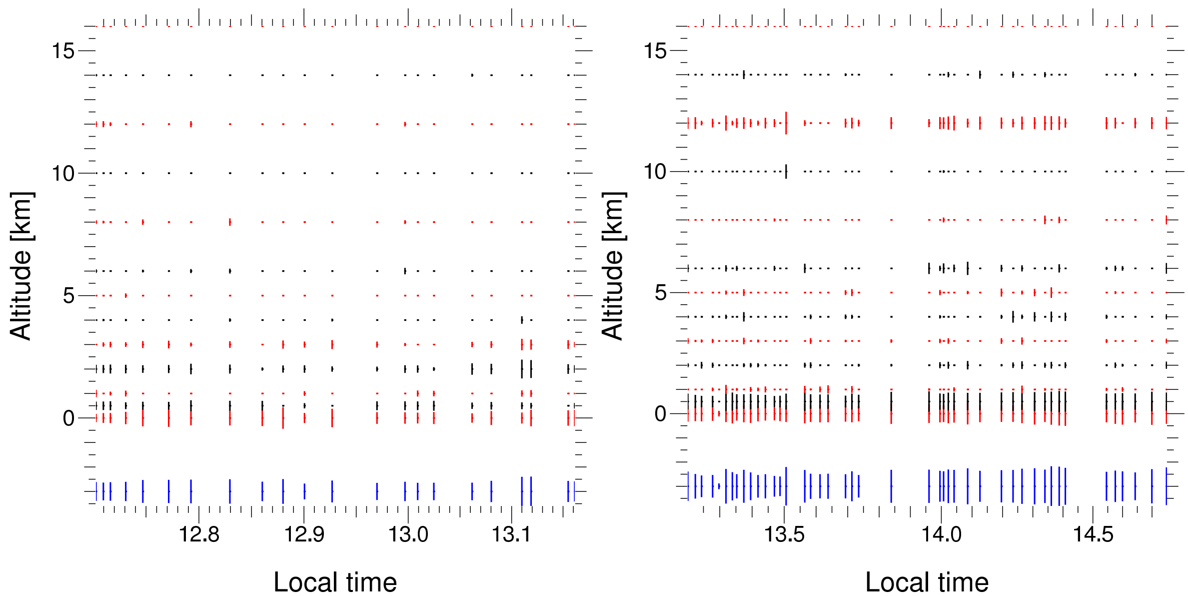

Figure 2. Atmospheric profiles for June 22$^{\text{nd}}$ (left) and 28$^{\text{th}}$, 2011 (right). The vertical extensions of the lines indicate the seeing, $\epsilon = 1.2\lambda/r_0$: an extension of 1 km corresponds to a seeing of $2''$ (the longer the bar, the larger ϵ, the stronger the turbulence). Blue lines: total integrated seeing. The average seeing (isoplanatic angle) equals $1''.6$ ($5''.5$) on June 22$^{\text{nd}}$ and $2''.0$ ($2''.5$) on June 28$^{\text{th}}$.

3. ADAPTIVE OPTICS

The NST has a fully operational, nearly acromatic adaptive optics (AO) system in the Coudé Lab (beneath the telescope) for diffraction limited imaging. At present the NST operates best in the near infrared (NIR). The AO system incorporates a 97 actuator deformable mirror (DM), a Shack-Hartmann wave front sensor with 76 subapertures (AO-76), and a digital signal processor system. NST images also routinely undergo post-facto speckle image reconstruction using the code developed by Wöger et al. (2008), which allows one to achieve the diffraction limit of the telescope over a larger field of view (FOV) than the AO alone allows. However, under nominal BBSO seeing conditions, AO-76 is inadequate for observations in the blue end of the solar spectrum, like G-band. But AO-308 (357 actuator DM) will be sufficient to perform diffraction limited photometry and polarimetry at all visible (and NIR) wavelengths on the NST under nominal BBSO seeing conditions.[4] At this writing, AO-308 has undergone successful bench testing (see Table 1) and for final testing, it will be run side-by-side with AO-76 beginning about mid-summer 2012. Image reconstruction, which requires a burst of AO corrected images to construct a single, full-field diffraction limited image has the consequence that the time cadence for NST diffraction limited imaging is about 5 s. Of course, sub-second cadence observations could be made, but diffraction limit data would be confined to the isoplanatic patch (several arcseconds) with a gradual roll-off away from the patch. We further note that 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. However, sub-second cadence, diffraction limited observations over the entire field can only be enabled by multi-conjugate AO.

For MCAO, one must know the seeing profile. In Figure 2, we show the profile for two days a week apart during the Summer of 2012. On June 22nd, the jet stream was well north of BBSO, while on June 28th the jet stream was over BBSO. The correlation between the jet stream, the local tropopause (seen from Vandenburg AFB ~300 km due west of BBSO), and seeing is a typical result for BBSO. Thus, the location of the jet stream can be used to determine which days are most appropriate for the highest possible resolution observations. Kellerer et al. (2012) also report that the seeing is much better in the summer ($r_0 = 9.1 \pm 3.3$ cm) than the winter ($r_0 = 5.5 \pm 0.8$ cm). The key question for MCAO is the altitudes to which one should conjugate the DMs. In Figure 3, we show the result (assuming DM fully corrects a narrow local altitude range) from modeling the measured C_n^2 results for winter and summer. It is clear that the biggest gain is to conjugate on DM to the ground layer. Then the second DM is best conjugated to about 3 km. After some experimentation in the modeling of the conjugation heights, it made more sense to use the third mirror for the upper part of the boundary layer (6 km), than for rather than the high (but weak) tropopause.

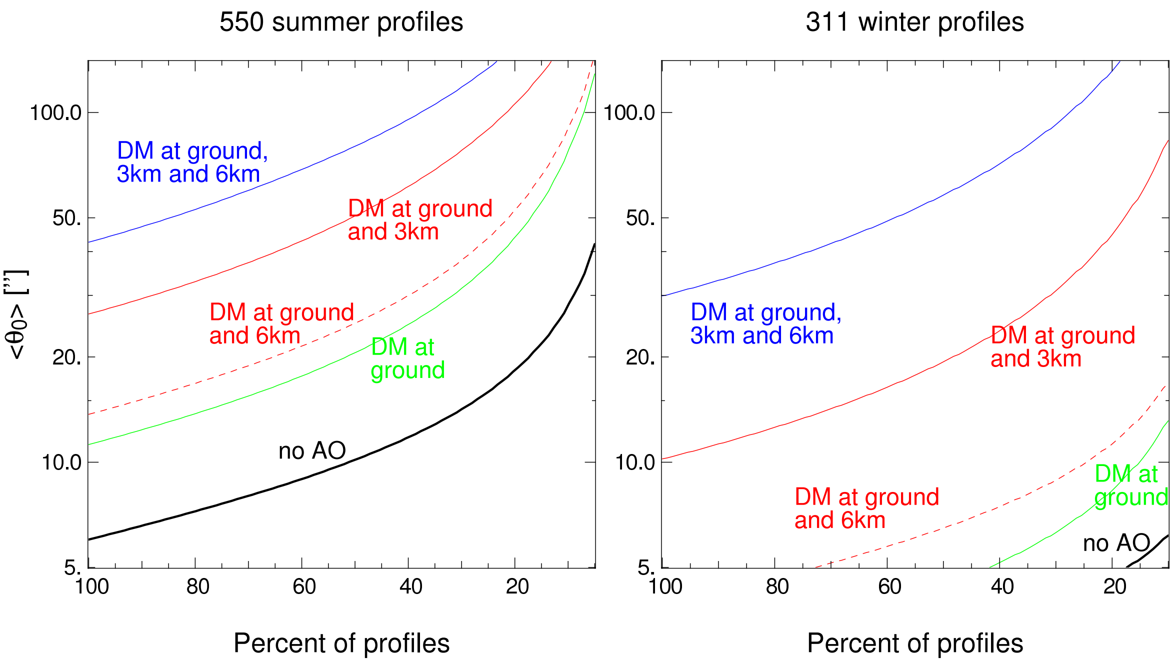

Figure 3. Average isoplanatic angle without AO correction (black), with a ground-layer AO that corrects turbulence up to 500 m altitude (green), a two mirror MCAO (red) and a three mirror MCAO (blue). We consider subsets of profiles with best isoplanatic angles in the absence of AO correction: the x-axis indicates the percentage of profiles considered, out of the total 550.

4. KEY FOCAL PLANE INSTRUMENTATION

Considering AO-76 was designed for a sub-meter class solar telescope, we have concentrated on observations red of 600 nm where we can can typically attain diffraction limited data. Thus, our workhorse instrument is the IRIM (InfraRed Imaging vector Magnetograph, see *http://www.bbso.njit.edu/projects/IRIM_Summary.pdf*, for details including facility other BBSO instruments in Table 1 replace "IRIM", by "AO" or "NIRIS" or "CYRA" or "VIM", etc. Thus IRIM is in regular operation[5] on the NST using light fed from AO-76. In Figure 4, we show

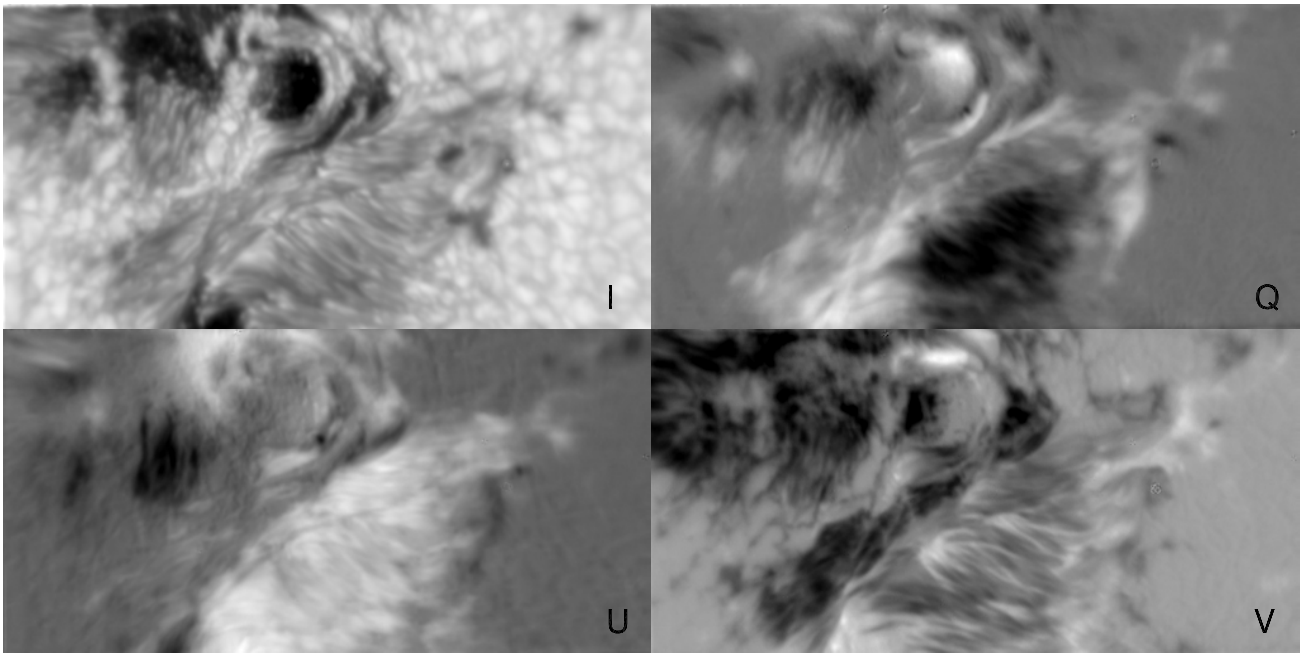

Figure 4. Calibrated IRIM vector magnetogram without any image reconstruction near AR 11283 at 463W 119M, taken on 7 Sept. 2011. Stokes I and V are sliced in the blue wing of the Fe I 1564.85 nm line while Q and U are sliced in line center. Dual-beam technology was employed to minimize seeing-induced noise. The field of view of IRIM is about $50'' \times 25''$.

the I, Q, U, and V components of a calibrated vector magnetogram without any image reconstruction. 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 Figure 4 where there is no apparent cross-talk of the line-of-sight component in the two transverse components.

The NST vector magnetogram in Figure 4 was obtained from the dual-beam IRIM, which is one of the first imaging spectropolarimeters working at 1565 nm. One might think that the quality of near infrared (NIR) 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 are now be able to separate the true magnetic field strength from the filling factor for the small-scale magnetic flux elements.[6] Additionally, the terrestrial atmosphere is more benign in the NIR with the mean, annualized Fried parameter at BBSO being about 30 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, which is an especially important consideration in the study of weak and small-scale magnetic fields. The focal plane Strehl in the NIR is sufficient to enable sustained diffraction limited imaging 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 nominal polarization accuracy is about $10^{-3}\mathrm{I}_c$. The spatial resolution will be around $0''.2$ for direct imaging and $0''.4$ for magnetograms.

We are upgrading the dual-beam IRIM to a dual FPI system (replacing Lyot filter with second FPI), so that we can fine tune to any wavelength between 1.0 and 1.7 μm (with spatial resolution increasing with wavelength from $0''.2$ to $0''.3$), rather than being confined by our Lyot filters to the 1.565 μm regime. Right now, to obtain 10830 Å

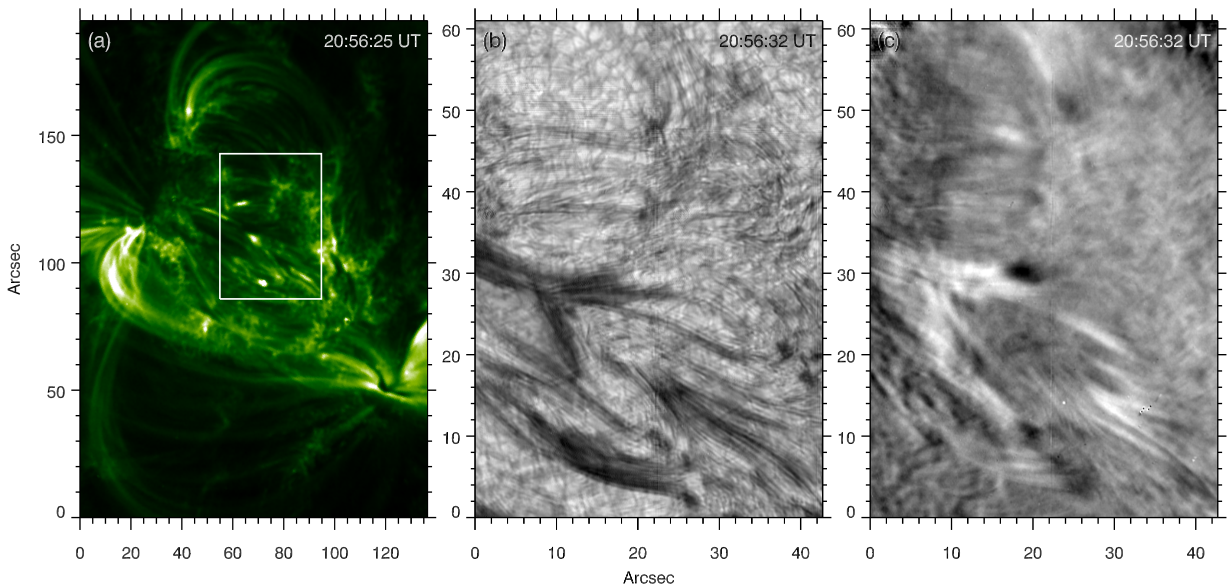

Figure 5. The left panel shows an AIA/SDO image (171 Å) of a coronal magnetic loop complex from 10 Feb 2012. The white box indicates the subfield of NST HeI 10830 A filtergram (center panel) and line-of-sight magnetogram (right panel) observations.

magnetograms we use an appropriate Lyot filter and the IRIM camera, see Figure 5. The upgraded instrument is called NIRIS[7] (NIR Imaging Spectro-polarimeter, see *http://www.bbso.njit.edu/projects/NIRIS_Summary.pdf* or see Cao et al. 2012, for details). NIRIS will have all the capabilities of IRIM with about five times the cadence, with better spatial resolution for magnetograms deriving from its various advantages, such as having about ten times the light throughput of IRIS and much more rapid line scans with each step having a narrower bandpass. Various trade-offs in performance are possible here, but we expect to perform vector polarametry at the top of the chromosphere. Until recent NIR results using a 10830 Å Lyot filter, such polarimetric measurements have only been made with spectrographs, like SOLIS. NIRIS will be on-line in Fall 2012 (see Table 1).

The weakness of IRIM/NIRIS 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. For the work planned here, we will have AO-308 and VIM for science that requires vector magnetograms of the highest spatial resolution ($0''.1$).

To better understand the fine structure of the solar chromosphere, NST is equipped with the 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 $40'' \times 60''$. 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.

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. We expect CYRA will be tested in the Summer of 2013.

ACKNOWLEDGMENTS

This work is supported by the NSF-AGS-0847126, NASA-NNX08BA22G and AFOSR-FA9550-12-1-0066.

REFERENCES

[1] Goode, P. R., Coulter, R., Gorceix, N., Yurchyshyn, V., and Cao, W., "The NST: First results and some lessons for ATST and EST," *Astron. Nachr.* **331**, 620-623 (2010).

[2] Cao, W., Gorceix, N., Coulter, R., Ahn, K., Rimmele, T. R., and Goode, P. R., "Scientific Instruments of 1.6 m New Solar Telescope in Big Bear," *Astron. Nachr.* **331**, 636-639 (2010).

[3] Wöger, F. and von der Lühe, O., "KISIP: a software package for speckle interferometry of adaptive optics corrected solar data," *Proc. SPIE* **7019**, 46-54 (2008).

[4] Kellerer, A., Gorceix, N., Marino, J., Cao, W., and Goode, P. R., "Profiles of the Daytime Atmospheric Turbulence above Big Bear Solar Observatory," *A&A* **542**, A2 (2012).

[5] Cao, W., Ahn, K., Goode, P. R., Shumko, S., Gorceix, N., and Coulter, R. "The New Solar Telescope in Big Bear: Polarimetry II," *ASP Conference Series* **437**, 345-349 (2011).

[6] Cao, W., Jing, J., Ma, J., Xu, Y., Wang, H., and Goode, P. R., "Diffraction-limited Polarimetry from the Infrared Imaging Magnetograph at Big Bear Solar Observatory," *PASP* **118**, 838-844 (2006).

[7] Cao, W., Goode, P. R., Ahn, K. Gorceix, N., Schmidt, W. & Lin, "NIRIS - the Second Generation Near-Infrared Imaging Spectro-polarimeter for the 1.6 Meter New Solar Telescope," *ASP Conference Series*, in press (2012).