Nasmyth focus instrumentation of the New Solar Telescope at Big Bear Solar Observatory

Wenda Cao, Nicolas Gorceix, Roy Coulter, Friedrich Wöger, Kwangsu Ahn, Sergiy Shumko, John Varsik, Aaron Coulter, and Philip R. Goode

Center for Solar-Terrestrial Research, New Jersey Institute of Technology, 323 Martin Luther King Blvd., Newark, NJ 07102;
Big Bear Solar Observatory, 40386 North Shore Lane, Big Bear City, CA 92316
National Solar Observatory/Sacramento Peak, P. O. Box 62, Sunspot, NM 88349

ABSTRACT

The largest solar telescope, the 1.6-m New Solar Telescope (NST) has been installed and is being commissioned at Big Bear Solar Observatory (BBSO). It has an off-axis Gregorian configuration with a focal ratio of F/52. Early in 2009, first light scientific observations were successfully made at the Nasmyth focus, which is located on the east side of the telescope structure. As the first available scientific instruments for routine observation, Nasmyth focus instrumentation (NFI) consists of several filtergraphs offering high spatial resolution photometry in G-band 430 nm, Ha 656 nm, TiO 706 nm, and covering the near infrared 1083 nm, 1.6 μm, and 2.2 μm. With the assistance of a local correlation tracker system, diffraction limited images were obtained frequently over a field-of-view of 70″ by 70″ after processed using a post-facto speckle reconstruction algorithm. These data sets not only serve for scientific analysis with an unprecedented spatial resolution, but also provide engineering feedback to the NST operation, maintenance and optimization. This paper reports on the design and the implementation of NFI in detail. First light scientific observations are presented and discussed.

Keywords: Telescope, Photometry, Imaging, Solar observation

1. INTRODUCTION

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii and the Korea Astronomy & Space Science Institute, has successfully developed and installed a 1.6 m clear aperture, off-axis New Solar Telescope (NST) at the Big Bear Solar Observatory (BBSO). The NST will be the largest aperture solar telescope in the world until the 4 m Advanced Technology Solar Telescope (ATST) and 4 m European Solar Telescope (EST) begin operation late in the next decade.

The NST adopts an all reflecting, off-axis Gregorian configuration that consists of a parabolic primary mirror (PM), prime focus field stop and heat reflector (heat-stop), elliptical secondary mirror (SM) and diagonal flats. Figure 1 shows the west and east view of the NST. The PM is 1.7 m with a clear aperture of 1.6 m. The PM was figured to a final figure residual error of 16 nm rms. The focal ratio of the PM is f/2.4, and the final ratio is f/52. The 180″ circular opening in the prime focus field stop defines the maximal unvignetted field of view (FOV) of the NST. This field is re-imaged by the SM forming the Gregorian focus about 5 m distant. The light is folded by M3 and F4 through the declination axis to the Nasmyth Bench. The working wavelength range will cover all wavelengths including the far infrared at the Nasmyth focus.

The Nasmyth Bench is located on the east side of the telescope structure, as shown in the right panel of Figure 1. Because only a few reflectors (PM, SM, M3 and F4) are used to form the Nasmyth focus, the images acquired here are not only particularly suitable for first light scientific observations, but also serve for engineering feedback to the NST alignment, operation, maintenance, and optimization. The simplicity of the optical feed allows investigation of the PM-SM alignment while offering the first available scientific observations. Available Nasmyth focus instrumentation (NFI) in concert with post-facto processing provides high spatial resolution photometry across the visible and near infrared spectrum. Early in 2009, first light scientific observations were
2. OPTICAL DESIGN OF NFI

Although the NFI is a straightforward instrument, its design suffers from several constraints imposed by the telescope and surrounding environment. First, the Nasmyth Bench has dimensions of 0.6 m width and 2.4 m length only. Such limited space forces the NFI to be designed as compactly as possible. Second, the NFI is mounted on the east side of the central box and rotates with the telescope structure during daytime observations. Heavyweight instrumentation definitely affects telescope balance and accurate tracking. Third, the NFI, along with the NST, is in an open air environment in the telescope dome. Therefore, the NFI design has to rule out delicate instrumental components which are sensitive to ambient temperature and humidity variations. Considering these constraints, it is wise to design the NFI as a straightforward filtergraph system, rather than attempting complicated spectrograph or magnetograph systems.

Table 1. Available observing wavelengths of interest of the NFI

<table>
<thead>
<tr>
<th>Wavelengths</th>
<th>Filter type</th>
<th>Bandpass</th>
<th>Diffraction limit</th>
<th>Scientific motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>430.5 nm</td>
<td>interference</td>
<td>5.0 Å</td>
<td>0.068”</td>
<td>G-band bright points</td>
</tr>
<tr>
<td>656.3 nm</td>
<td>tunable Lyot</td>
<td>0.25/0.5 Å</td>
<td>0.103”</td>
<td>filaments, spicules, jets, flares ...</td>
</tr>
<tr>
<td>705.7 nm</td>
<td>interference</td>
<td>10.0 Å</td>
<td>0.111”</td>
<td>granulations, sunspots ...</td>
</tr>
<tr>
<td>1.083 μm</td>
<td>tunable Lyot</td>
<td>0.25 Å</td>
<td>0.170”</td>
<td>coronal holes, upper chromosphere</td>
</tr>
<tr>
<td>1.6 μm</td>
<td>tunable Lyot</td>
<td>2.5 Å</td>
<td>0.252”</td>
<td>the deepest photosphere</td>
</tr>
<tr>
<td>2.2 μm</td>
<td>interference</td>
<td>5.0 Å</td>
<td>0.346”</td>
<td>cold clouds in the chromosphere</td>
</tr>
</tbody>
</table>

Benefitting from powerful photon collecting capability (over 2 m² area) and unprecedented diffraction limited resolution (~ 0.07” in the visible) of the NST, the filtergraph system focuses on narrow-band photometric observations with high temporal and spatial resolution. In order to minimize seeing-induced image degradation, a correlation tracker (CT) system and speckle reconstruction techniques have been developed and applied to the system. Driven by intrinsic scientific motivations, multiple narrow-band interference filters and Lyot filters can be deployed in the NFI. Table 1 lists available observing wavelengths of interest and their scientific motivations.
Figure 2 depicts the optical layout of the NFI consisting of the main scientific imaging system and the auxiliary CT system. The main and auxiliary optical paths are drawn with red arrows and green arrows, respectively. The focal length of the PM is 3.85 m leading to a f-ratio of $f/2.4$. The heat-stop is a prime focus field stop and is tilted. The currently operating heat-stop has a hole of 3.8 mm defining a unvignetted circular FOV of $180''$. The focal length of the SM is 300 mm resulting in an effective focal length of 83.2 m and a final f-ratio of $f/52$. A flat folding mirror M3 directs the light through the declination axis of the telescope. After another flat folding mirror F4, a 73 mm diameter solar image is formed on the field stop (FS) on the Nasmyth Bench. The plate scale on the FS is $2.48''/mm$. The FS has a physical size of 41 mm × 41 mm allowing $\sim 100'' \times 100''$ square FOV for the NFI relay optics. The telescope pupil image is formed 322 mm after the SM. The collimator is a 108 mm diameter parabola with a focal length of 1600 mm. It on one hand collimates solar image on the FS into infinity, and on the other hand re-images a 32 mm telescope pupil onto the tip-tile mirror (TT) after a flat folding mirror. The TT has a diameter of 38 mm, which also acts as a folding mirror feeding the light onto a beamsplitter (BS). The BS is used to direct 95% of the light to the main scientific imaging system and the rest of 5% to the auxiliary CT. The imaging lens behind the BS has a focal length of 800 mm, which provides a f-ratio of $f/26$ to the camera and a plate scale of 4.96''/mm. Meanwhile, the pupil image on the TT is collimated into infinity. The PCO-2000 cooled digital 14-bit camera system is responsible for acquisition of scientific data. This 2048 × 2048 camera has a pixel size of 7.4 μm × 7.4 μm resulting in an image scale of 0.034''/pixel and an effective FOV of $70'' \times 70''$. The NFI optics are designed to provide diffraction limited image quality for the wavelength range from 430 nm to 2.2 μm. As shown in Table 1, the shortest wavelength of interest is at G-band 430 nm. The diffraction limit at g-band is 0.068''. Therefore, the camera is set up in over-sampling configuration over most of the observational wavelength range, which offers more reliable information at high spacial frequencies. Narrow-band filter (either an interference filter or a tunable Lyot filter) and neutral density filters are placed between the imaging lens and camera. The whole system is covered with a sealed box to reduce the influences of stray light and dust. Solar heating on the FS can cause local turbulence in the box that degrade image quality. To solve this problem, a circulating cooling system was designed and attached on the back side of the metal FS to conduct the majority of solar heat out of the box.

3. CORRELATION TRACKER SYSTEM

Korea Astronomy and Space Science Institute and BBSO/NJIT collaborated in the successful implementation of a CT system. The CT system is one of the critical components of the NFI, assisting in acquisition of...
high-spatial resolution data at the Nasmyth Bench by compensating image motion from low-order wavefront distortion, telescope vibration, and high frequency errors outside the correction band of the telescope guider. The CT hardware mainly includes two parts: a tip/tilt sensing system and a tip/tilt actuator. The green arrows in Figure 2 depict the light path of the tip/tilt sensing system. The imaging lens for the CT has a focal length of 600 mm forming an image of the Sun onto CT camera via a flat folding mirror. The CT camera adopts Photonfocus MV-D1024E-160-CL CMOS camera with 1024 × 1024 pixels and a frame rate of 150 fps. The image scale is about 0.23″/pixel. Typically, the CT system selects a small sub-field of 64 × 64 pixels (∼ 15″ × 15″). In this setup, the frame rate can reach 8000 fps in open loop mode. The piezo-electric tip/tilt platform S-330.30 manufactured by Physik Instrumente is chosen as the tip/tilt actuator, which provides precise angular movement of the top platform in two orthogonal axes. It has a maximum operating frequency of 2.7 kHz and the tilt range is ±1 mrad with sub-μrad resolution. With an exposure time of 1 ms, the final sampling frequency averages around 450 Hz.

The CT control software has been developed with MS Visual C++ programming language which allows flexible selection of sub-field and FOV, high-speed acquisition of live images, displacements computation with respect to reference image, as well as TT correction. Two different algorithms (SAD and 2-D FFT cross-correlation) are used to calculate relative displacement between the reference image and the live images. The reference image is updated every 10 seconds. SIMD and parallel processing technologies are adopted to expedite and improve system performance.

After a careful calibration, the CT system has been put into routine use for observations. The left panel in Figure 3 depicts the displacements in two orthogonal axes of live images with respect to a reference image when the CT is on or off. Although an obvious drift exists in the x axis, image motions in both axes drop to ±0.1″ once the CT is operational. The right panel in Figure 3 shows the power spectra of the temporal behavior of the x- (top) and y-component (bottom) of the global tilt with the CT system in open- (grey lines) and closed-loop (black lines) operation. The frequency at which the closed-loop spectrum deviates from the open-loop spectrum can be used to define the bandwidth. The close-loop bandwidth is about 120 Hz.

![Figure 3. Left panel: Temporal behavior of global tilt in two orthogonal axes when the CT is off (0-7000th frame) and on (from 7000th frame). Right panel: Power spectra of the temporal behavior of the x- (top) and y-component (bottom) of the global tilt with the CT system in open- (grey lines) and closed-loop (black lines) operation.](image-url)
4. SPECKLE RECONSTRUCTION

Although the CT system corrects image motion from telescope vibration and high frequency errors of telescope tracking system quite well, it only provides a low-order compensation to the atmospheric turbulence of the Earth, and cannot do anything about high-order corrections to the wave front deformations. As a result, to achieve diffraction limited performance of the NST, further post-processing of the observational data becomes indispensable. Among post-facto image reconstruction techniques, the speckle interferometry\textsuperscript{4} attracts our attention due to its reliable performance of phase reconstruction, near real-time data reduction, overall stability, and low requirements for optical setup. KISPI (Kiepenheuer-Institut Speckle Interferometry Package)\textsuperscript{5-7} was chosen as image reconstruction for the data set acquired with the NFI. The latest version 6 of the KISPI\textsuperscript{5} integrates two well-known reconstruction methods: the Extended Knox-Thompson algorithm and the Triple Correlation (or speckle masking) algorithm. This program has been optimized to run in multi-processor environments so as to make use of parallel computing capabilities.

Figure 4. A comparison of image of the quiet Sun region near disk center observed in TiO 706 nm before (left panel) and after (right panel) speckle reconstruction processing. KISPI v6 was employed for this speckle reconstruction. The units for the x- and y- axis are arcseconds.

The KISPI v6 has successfully been operated in a parallel processing computer at BBSO (the BEEHIVE). The BEEHIVE is an symmetric multi-processing system that is equipped with 8 AMD Opteron 8350 CPUs with 2.00 GHz clock speed. Each CPU has 4 cores leading to a total number of 32 usable processing units. RAM memory has a capacity of 32 GB and four RAID 1 hard drives offer a total storage size of 3.5 TB. 64-bit Fedora 10 with linux kernel 2.6.27 is adopted as the operating system. The typical computational time is 5-6 minutes to speckle-reconstruct one $2024 \times 2024$ image from one burst with 100 frames. Figure 4 shows a comparison image of the quiet Sun region near disk center observed in TiO before (left panel) and after (right panel) speckle reconstruction processing. The bright points (BPs) in the dark intergranular lanes are clearly seen in the right panel of Figure 4. These BPs are believed to be the counterparts on photosphere of magnetic concentrations with a physical size of about 100 km. The diffraction limit at $\lambda = 706$ nm is $\theta = 1.22\lambda/D = 0.111''$, where $D$ is the NST aperture. Thus, the speckle reconstructed image is close to the diffraction limited resolution of the NST.
5. FIRST LIGHT SCIENTIFIC OBSERVATIONS

The NFI has been implemented and put into routine observation on the Nasmyth Bench. Observations and data reduction usually adhere to the following procedures: First, the exposure time used for acquisition of images should be sufficiently short to freeze the atmosphere wavefront aberrations. In G-band and TiO, typical exposure times are less than 10 ms at solar disk center. However, Hα observations are photon-starved due to the narrow passband and low transmission of the Hα Lyot filter, as well as the deep Hα spectral line profile. On-chip 2×2 binning has to be performed to provide enough photons and allow a short exposure of ≤ 30 ms. As a result, the CCD sampling is slightly lower than the Nyquist frequency of the diffraction limit in Hα. Second, a series of “Speckle bursts” are taken with a frame rate of 14.7 fps. Each “Speckle burst” consists of approximately 100 images. Thus, the typical cadence of bursts is 15 s, with a minimum cadence of 10 s. Image selection technique is an option for collecting the best 100/70 frames with the highest sub-field rms contrast out of a total of 120/100 frames. Third, each raw image in a burst is corrected with dark frame subtraction and flat fielding. The “clean” burst serves for the data input for speckle reconstruction employing the KISIP v6. Output of the KISPI code is a single speckle reconstructed image with a format of 2048 × 2048 or 1024 × 1024 depending on the data format of the input burst. Fourth, every reconstructed image is aligned to its previous one using the techniques of relative shift and de-stretching. Finally, the resulting speckle reconstructed data sequence is ready for scientific research.

First light observations taken with the NFI reveal a number of exciting scientific results. As shown in the right panel of Figure 5, Goode et al.8 observed that the smallest scale photospheric magnetic field seems to come in isolated points in the dark intergranular lanes, rather than the predicted continuous sheets confined to the lanes, and the unexpected longevity of the bright points implies a deeper anchoring than predicted. With high spatial resolution surface photometry of the quiet Sun, Andic et al.9 noted that a disproportionate fraction of the oscillatory events appear above observed bright point-like structures, implying that observed flux tubes may be the source of many observed oscillatory events. Using the NFI, Chae et al.10 investigated the morphology and dynamics of plasma visible in the Hα line, as shown in the left panel of Figure 5, and found evidence of magnetic reconnection occurring in the chromosphere of the quiet Sun. With Hα off-band observations, Cao et al.11 discovered that the dark upflows propagating along the filament channel are strongly associated with the intensity oscillations on the solar surface around the filament footpoints.

![Figure 5. Left panel: Full field-of-view NST Hα image co-aligned with the corresponding high-resolution MDI magnetogram (red contours for +10, +20, +40 G, and blue ones for -10, -20, -40 G). Right panel: Typical granular subfield observed in TiO with a field of view of 12" × 12". The nearly circular bright points in the dark lanes are horizontal cross sections of nearly vertical fibers of the intergranular magnetic field represented in intensity.](image-url)
ACKNOWLEDGMENTS

This work is supported by the NSF grants AGS-0847126 and AGS-0745744, the AirForce grant AFOSR-FA9550-09-1-0655 and by the NASA grant NASA-NNX08BA22G.

REFERENCES


