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Scientific instrumentation for the 1.6 m New Solar Telescope in Big Bear

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The NST (New Solar Telescope), a 1.6 m clear aperture, off-axis telescope, is in its commissioning phase at Big Bear Solar Observatory (BBSO). It will be the most capable, largest aperture solar telescope in the US until the 4 m ATST (Advanced Technology Solar Telescope) comes on-line late in the next decade. The NST will be outfitted with state-of-the-art scientific instruments at the Nasmyth focus on the telescope floor and in the Coudé Lab beneath the telescope. At the Nasmyth focus, several filtergraphs already in routine operation have offered high spatial resolution photometry in TiO 706 nm, Hα 656 nm, G-band 430 nm and the near infrared (NIR), with the aid of a correlation tracker and image reconstruction system. Also, a Cryogenic Infrared Spectrograph (CYRA) is being developed to supply high signal-to-noise-ratio spectrometry and polarimetry spanning 1.0 to 5.0 μm. The Coudé Lab instrumentation will include Adaptive Optics (AO), InfraRed Imaging Magnetograph (IRIM), Visible Imaging Magnetograph (VIM), and Fast Imaging Solar Spectrograph (FISS). A 308 sub-aperture (349-actuator deformable mirror) AO system will enable nearly diffraction limited observations over the NST's principal operating wavelengths from 0.4 μm through 1.7 μm. IRIM and VIM are Fabry-Pérot based narrow-band tunable filters, which provide high resolution two-dimensional spectroscopic and polarimetric imaging in the NIR and visible respectively. FISS is a collaboration between BBSO and Seoul National University focussing on chromosphere dynamics. This paper reports the up-to-date progress on these instruments including an overview of each instrument and details of the current state of design, integration, calibration and setup/testing on the NST.

1 Introduction

More and more evidence indicate that magneto-convection, with an intrinsic scales of $\leq$100 km at the base of photosphere, are the sources of solar activity and variability. The dynamic studies of these fine structures drive us to build large-aperture solar telescopes and state-of-the-art facility-class instruments. Over the past decade, with the rapid development and maturity of adaptive optics (AO), the time has come for building meters-class solar telescopes.

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

Benefitting from its large aperture, and the long periods of excellent seeing at Big Bear Lake, the NST aims at high spatial and temporal resolution, campaign-style observations of the Sun. As a result, six facility-class scientific instruments have been designed and will be installed at several telescope foci, which serve as high-resolution photometry, spectrometry, and polarimetry in the visible and near infrared (NIR) wavelengths. This paper reports the up-to-date progress on these instruments including an overview of each facility and details of the current state of design, system integration, calibration and setup/testing on the NST.

2 Instruments

The NST (Goode et al. 2003) is an all reflecting, off-axis Gregorian system consisting of a parabolic primary mirror (PM), prime focus field stop and heat reflector (heat-stop), elliptical secondary mirror (SM) and diagonal flats (M3, M4, M5). Figure 1 shows a cutaway sketch of the NST with respect to the locations of six equipped scientific instruments. The NST is located on the top-floor telescope deck. The final f-ratio is 52. A $100''$ circular opening on the heat stop defines an $70'' \times 70''$ square field-of-view (FOV) on the focal planes. On the east side of the telescope structure is the Nasmyth Bench. Solar light is imaged by PM and SM, then folded through the declination axis by M3 and M5 to the Nasmyth bench. The first instrument, Nasmyth focus broad-band filtergraphs are mounted here. If a folding mir-

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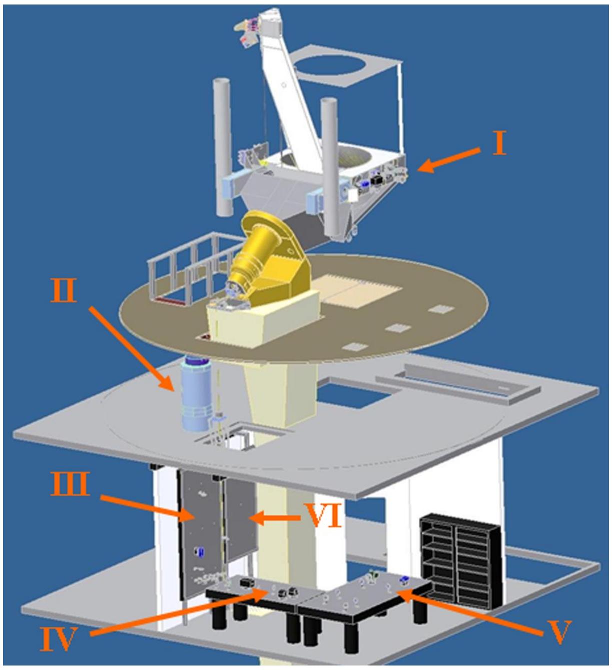

Fig. 1 (online colour at: www.an-journal.org) Cutaway sketch of the NST showing six scientific instruments: I. Nasmyth Focus Filtergraph; II. Cryogenic Infrared Spectrograph (CYRA); III. Adaptive Optics (AO); IV. InfraRed Imaging Magnetograph (IRIM); V. Visible Imaging Magnetograph (VIM); VI. Fast Imaging Solar Spectrograph (FISS).

ror M4 is moved in, the solar beam will be directed along the polar axis down to an observing platform, one floor below the telescope deck. The second instrument, a Cryogenic Infrared Spectrograph (CYRA) will be built there. Relay optics can further feed light down to the Coudé Lab, two floors beneath the telescope deck. Four instruments including the Adaptive Optics (AO), the InfraRed Imaging Magnetograph (IRIM), the Visible Imaging Magnetograph (VIM), and the Fast Imaging Solar Spectrograph (FISS), will be mounted on the vertical or horizontal optical benches in this Lab.

2.1 Nasmyth focus filtergraphs

At present, Nasmyth focus filtergraphs are the only available scientific instruments for routine observation. Data acquired here serves two primary purposes: one is for scientific analysis; another is to provide feedback aiding the NST commissioning. Current efforts focus on high spatial resolution broad/narrow band photometric observations in the visible and NIR. Table 1 lists currently available wavelength of interest. With the aid of a correlation tracker system and the speckle reconstruction technique (Wöger & von der Lühe 2008), unprecedented high spatial resolution images have been acquired (see the Figs. 3 and 4 of Goode 2010).

2.2 Cryogenic Infrared Spectrograph (CYRA)

NIR observations have proven to be a promising tool to probe small-scale solar magnetic features. However, thermal background emission is a formidable obstacle in the NIR observations, especially with wavelengths above 3 μm. In contrast to traditional solar NIR spectrographs, CYRA is based on cold optics and will be the first fully cryogenic solar spectrograph. All components including the slit, grating, collimator/imager, order sorting filters, and InSb detector are placed in a dewar, which is cooled to a very low temperature ($\sim$77 K) so as to tremendously minimize thermal background emission. The NIR bands of interest include a couple of high Zeeman sensitivity photospheric lines and several promising chromospheric lines, shown in Table 2. Benefitting from the large Zeeman sensitivity in the IR, high spatial resolution and high photon flux with the NST, we expect to solve long-standing problems in solar astronomy, especially the disparity among magnetic field measurements in the visible and NIR lines and the origin of the solar chromosphere. At present, CYRA is in its initial design. It will operate over a wavelength range of 1–5 μm. Spectral resolving power is larger than 10^5. Slit length covers 70$''$ on the Sun. Dual-beam polarimetry is required to minimize seeing-caused spurious polarization. In addition, the hardware outside dewar include a correlation tracker, image de-rotator and scanner, slit-jaw imaging and guiding system.

Table 1 Available observing wavelength of interest.

Wavelengths	Bandpass	Solar Features
430 nm	5 Å	G-band bright points
656 nm	0.25 Å	Filaments, spicules, jets, flares ...
706 nm	10 Å	Granulations, sunspots ...
1.083 μm	0.25 Å	Coronal holes ...
1.6 μm	2.5 Å	The deepest photosphere
2.2 μm	5 Å	Cold clouds in the chromosphere

Table 2 NIR bands of interest for CYRA.

Spectral Lines	Magn. Sensitivity ($\lambda g_{\rm eff}$)	Region
Ti I 2.231 μm	5578 nm	Photosphere
Fe I 4.064 μm	5080 nm	Photosphere
Si I 4.143 μm	9321 nm	Photosphere
Ca I 3.697 μm	4067 nm	Chromosphere
Mg I 3.682 μm	4307 nm	Chromosphere
CO 4.6 μm	Molecular band	Chromosphere

2.3 Adaptive Optics (AO)

AO has become indispensable for modern large telescopes. Previously, BBSO and NSO collaborated in the successful implementation of two AO systems (AO-76) for the BBSO now-retired 0.65 m telescope and the NSO 0.76 m Dunn Solar Telescope, respectively (Rimmele 2004). AO-76 employs a Shack-Hartmann wavefront sensor (WFS) with 76 sub-apertures. High speed Baja camera with a frame rate of 2500 frame/s and digital signal processors (DSPs) are responsible for wavefront data acquisition, computation and reconstruction. The deformable mirror (DM) has a diam-

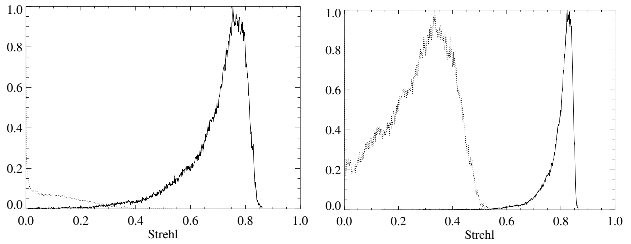

Fig. 2 Histogram (normalized to unity) of Strehl ratios in the detector plane that we expect to achieve from AO-76 (*left panel*) and AO-308 (*right panel*) as derived from comprehensive error budget analysis, and assuming the measured distribution of BBSO seeing. The grey line is for visible (0.5 μm) and the black line for NIR (1.6 μm) wavelengths.

eter of 77 mm with 97 actuators. Closed-loop bandwidth of the whole system can reach 135 Hz. At present, AO-76 is being re-designed for the NST and will play a crucial role in early operation of the NST, especially in NIR observations. Detailed and realistic error budget analyses that include AO residuals, as well as telescope, interface and instrument error budgets, indicate that AO-76 will yield a high Strehl ratio of about 0.7 in the NIR (1.6 μm) under median BBSO seeing, as shown in Fig. 2. However, in the visible, AO-76 will deliver reasonable Strehl ($\sim$0.3) only under exceptional seeing conditions. Thus, diffraction limited observations will be rare in the visible spectrum. BBSO, in collaboration with the NSO, has been engaged in the next-generation AO system, the AO-308. It will be based on an available Xinetics DM with 349 actuators, a 308 sub-apertures WFS and the new-generation high speed DSPs and camera. According to our error budget analysis in Fig. 2, 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. In order to further expand the FOV of NST diffraction limited observation, a Multi-conjugate Adaptive Optics (MCAO) system is planned by BBSO, NSO and the Kiepenheuer Institute (KIS, Germany).

2.4 Infrared Imaging Magnetograph (IRIM)

IRIM is one of the first imaging solar spectro-polarimeters working in the NIR, which will be installed on the horizontal optical bench in the Coudé Lab. This innovative system, based on a 2.5 nm interference filter, a unique 0.25 nm birefringent Lyot filter, and a Fabry-Pérot etalon, is capable of providing a bandpass as low as 0.01 nm over a FOV of $50''$ in a telecentric configuration. A NIR achromatic rotating waveplate just ahead of M3 serves as the polarimeter modulator to reduce polarization cross-talk induced by subsequent oblique reflective mirrors. Dual-beam differential polarimetry is employed to minimize seeing-caused spurious polarization. The spectrometric and/or polarimetric data are recorded by a 1024×1024, 14 bit HgCdTe CMOS focal plane array camera. Current efforts focus on two highly Zeeman sensitive Fe I line pairs at 1564.85 nm (Landé factor g = 3) and 1565.29 nm (Landé factor g = 1.53), which are also used to probe the deepest photospheric layers due to 1.6 μm opacity minimum. Diffraction limited IRIM observations have been successfully made with BBSO's now-retired 0.65 m telescope (Cao et al. 2006). Based on the unique advantages in the NIR window, and the most capable NST equipped with AO, IRIM will provide unprecedented solar spectro-polarimetry with high Zeeman sensitivity (10^{-4}), diffraction limited resolution ($0.2''$), and high cadence (1 min for full Stokes profiles).

2.5 Visible Imaging Magnetograph (VIM)

As a twin of the IRIM, VIM is another Fabry-Pérot based spectro-polarimeter system operating in the visible wavelength range from 550 nm to 700 nm. A single Fabry-Pérot etalon is set up in a telecentric optical configuration to offer a bandpass of 0.007 nm. The FOV is $70'' \times 70''$. A couple of interference filters act as blocking side-lobe contamination. Currently available spectral lines include Hα, Fe I 630 nm and Na I D_2 line 589 nm. Considering the limited ability of AO-76 in correcting the visible image, VIM will only work as a spectrometer before the AO-308 is installed. The cadence of spectrometric measurement can reach up to 10 s.

2.6 Fast Imaging Solar Spectrograph (FISS)

FISS is a collaboration between BBSO and Korean solar community. Its purpose is to study fine structures in the chromosphere. This instrumentation consists of a field scanner, a slit, an off-axis parabolic mirror, an echelle grating, pre-filters, and two CCD cameras. The typical spectral resolution is about 1.4×10^5 and wavelength range covers from 400 nm to 1000 nm. The unique two-mirror field scanner is capable of providing fast scanning mode (8 s for $60''$ scan) for the simultaneous observations at Hα and Ca II 854 nm.

3 Conclusion

The NST has successfully worked through its installation, optical alignment, and commissioning. Nasmyth focus filtergraphs already in routine operation have offered images with unprecedented spatial resolution and high cadence. At present, we are working on the M4 alignment and relay optics which fold the solar beam along polar axis and then down to the Coudé Lab. Once we have solar light in the Coudé Lab, we will install AO-76, and subsequently the IRIM, the VIM, and the FISS. All of the scientific instruments are expected to be completely installed, tested, calibrated, and in commissioning by the end of 2010 except for the CYRA which will be implemented by 2012. Equipped with these state-of-the-art scientific instruments, the NST will provide high quality ground-base observations in the ascending and maximal phases of solar cycle 24, which will open the door to an new era in solving long-standing solar puzzles.

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