

# Progress on the 1.6-meter New Solar Telescope at Big Bear Solar Observatory

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## ABSTRACT

The New Solar Telescope (NST) project at Big Bear Solar Observatory (BBSO) now has all major contracts for design and fabrication in place and construction of components is well underway. NST is a collaboration between BBSO, the Korean Astronomical Observatory (KAO) and Institute for Astronomy (IfA) at the University of Hawaii. The project will install a 1.6-meter, off-axis telescope at BBSO, replacing a number of older solar telescopes. The NST will be located in a recently refurbished dome on the BBSO causeway, which projects 300 meters into the Big Bear Lake. Recent site surveys have confirmed that BBSO is one of the premier solar observing sites in the world. NST will be uniquely equipped to take advantage of the long periods of excellent seeing common at the lake site. An up-to-date progress report will be presented including an overview of the project and details on the current state of the design. The report provides a detailed description of the optical design, the thermal control of the new dome, the optical support structure, the telescope control systems, active and adaptive optics systems, and the post-focus instrumentation for high-resolution spectro-polarimetry.

**Keywords:** solar telescopes — telescope control systems — adaptive optics

## 1. INTRODUCTION

The Sun is the only star where we can observe detailed surface structure. The intrinsic scales of magneto-convection on the Sun are less than 100 km. This fine structure is one of the drivers for building solar telescopes with large apertures. Recent advances in adaptive optics (AO) make it possible to build solar telescopes in an open configuration and thus go beyond the conventional meter-class vacuum telescopes, which have been in operation at solar observatories for many decades. NST is an off-axis telescope with a 1.6-meter aperture.<sup>1</sup> NST will replace the BBSO 65 cm vacuum telescope and several small-aperture refractors. Separate facilities will be built along the causeway to replace the refractors.

NST is ideally suited for campaign-style solar observations of unprecedented spatial and temporal resolution, which are required to follow the dynamics of active regions on the Sun. NST will feed BBSO's new generation of magnetographs<sup>2,3,4</sup> and real-time image reconstruction (RTIR) system utilizing parallel processing.<sup>5,6</sup> NST will be outfitted with an AO system to serve the facility-class post-focus instruments. By the time NST's sustained observations start, there will be new assets in space (Solar-B, the Solar Dynamics Observatory (SDO) and the Solar Terrestrial Relations Observatory (STEREO)) to study the Sun. Therefore, we expect many synergies to unfold between the next generation of ground- and space-based observatories.

NST partner institutions include the Institute for Astronomy at the University of Hawaii, the Steward Observatory at the University of Arizona and the Korea Astronomy and Space Service Institute. The AO system was developed in collaboration with the National Solar Observatory.<sup>7,8</sup>



**Figure 1.** Big Bear Solar Observatory with the new 5/8-sphere dome. The small dome in front of the observatory building houses an auxiliary telescope for Earthshine observations.

## 2. SCIENTIFIC MOTIVATION

The scientific objectives of NST include (1) high-resolution, high-cadence studies of solar flares, (2) the structure and evolution of magnetic fields in flaring active regions, (3) the dynamics of kilo-Gauss flux tubes, (4) magnetoconvection in sunspots and (5) the heating mechanisms of the upper solar atmosphere.

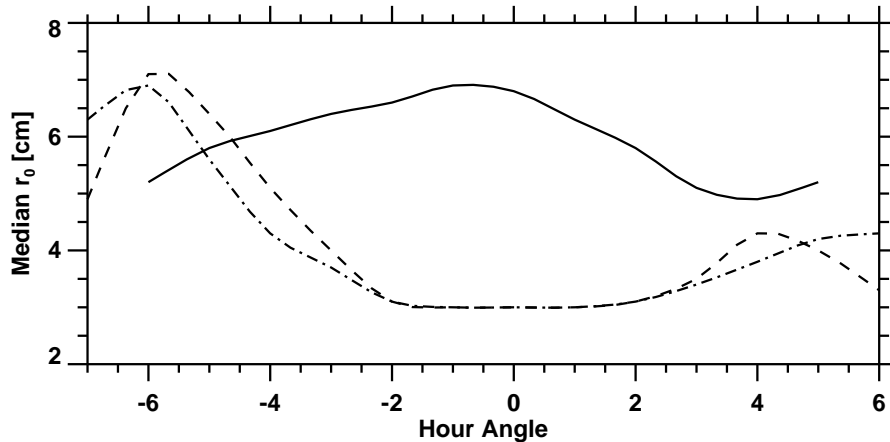
High-angular resolution is required to resolve the fundamental length and time scales (pressure scale height and photon mean free path) related to the fundamental magnetic structure size. The magnetic fields provide channels for energy and momentum transport. They couple the dynamics of the upper atmosphere to the convectively driven behavior of the magnetic field at the surface of the Sun. Understanding the dynamic interaction of photospheric flux concentrations with turbulent granulation is also essential in order to estimate the total energy flux that is transmitted or channeled by small-scale flux tubes into the higher atmosphere.

The intrinsic relationship between small-scale physical processes and large-scale phenomena has yet to be established. One of the most intriguing discoveries in solar physics in recent years is the presence of a local dynamo, which may produce the small-scale magnetic flux tubes covering the entire Sun. On the other side of the spatial spectrum are sunspots, where the total magnetic field is strong enough to dominate the hydrodynamic behavior of the local plasma. High-resolution observations over long periods of time will make NST an important instrument to bridge the gap between local and global phenomena on the Sun.

## 3. SITE CHARACTERISTICS

BBSO was established in 1969 by the California Institute of Technology after a comprehensive site survey in Southern California.<sup>9</sup> The observatory is located at the end of a 300 m causeway at Big Bear Lake's north shore at an elevation of about 2000 m (see Figure 1). Offices, workshops and dormitories are located in an adjacent facility on shore. The surrounding waters of Big Bear Lake effectively suppress the boundary layer seeing. Predominate south-westerly winds bring smooth air flows across the flat surface of the lake providing superb conditions for solar observing. Very good to excellent seeing are generally encountered when winds are moving over the open water to the telescope from the south and west.

The seeing characteristics at Big Bear differs markedly from the high-altitude, volcanic island sites measured in the ATST site survey.<sup>10</sup> The median  $r_0$  for BBSO is shown as a solid line in Figure 2 (Haleakala: dashed and La Palma: dashed-dotted). Observations using AO will be viable for extended periods during a typical day from sunrise to sunset. The long periods of good seeing in the middle of the observing day present observing opportunities, which are not common at other observatories. The NST primary mirror will be at nearly the same height above ground level as the detector system used to take these data.<sup>11</sup> Thus, the site survey results



**Figure 2.** Seeing characteristics at selected sites for high-resolution solar observations (BBSO: solid, La Palma, Canary Islands: dashed-dotted and Haleakala, Maui: dashed).

have direct bearing on the thermal design and control of the telescope.<sup>12</sup> The site survey instrument has been disassembled but will be relocated to an observing platform attached to the southern wall of the observatory building and its measurements will be integrated in the daily NST operations.<sup>13</sup>

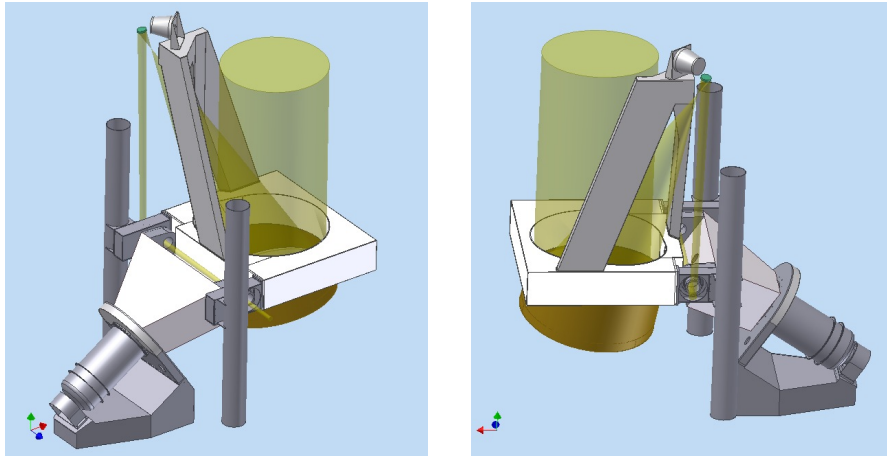
#### 4. OBSERVATORY DOME AND THERMAL CONTROL

Since the telescope structure is open, sophisticated dome ventilation and environmental controls have to be implemented. The thermal control systems include an air cooled optical support structure (OSS), a cooled primary mirror, forced air flows at primary mirror and heat stop, and liquid coolant systems to absorb rejected light at the heat stop. The light-path of the off-axis telescope and the OSS are shown in Figure 3.

MFG Ratech has replaced the old metal dome at BBSO with a larger 10 m diameter, 5/8 sphere in March 2006 (see Figure 1). The new dome is a smaller version of the dome for the Southern Astrophysical Research (SOAR) telescope.<sup>14</sup> The dome structure consists of a steel frame with a shell of fiberglass panels. The fiberglass panels have a structural foam core, which serves to stiffen the shell and insulate the dome. Modifications to the telescope pier and observing floor will follow in the second half of 2006. Limiting sunlight exposure and good dome ventilation are considered paramount for good internal seeing conditions. The dome will have a small (2 m), circular aperture to limit sunlight entry into the dome. There are 14 (0.6 m  $\times$  1.8 m) vent gates with automated, proportional positioned dampers spaced around the equator of the dome. The dampers will be controlled by the telescope pointing and tracking (TPT) subsystem. Vent gates will be selected based on wind direction to maximize ventilation. Wind speeds through the dome will be limited to about 5 m s<sup>-1</sup> by the dampers. In addition, a forced air system for low wind conditions can be used to exchange about 30 dome volumes per hour. A low thermal mass work deck will be built level with the dome support ring to facilitate access to the telescope and dome walls using standard lift equipment (see Figure 4).

#### 5. OPTICAL DESIGN

The primary mirror has a 1.6 m clear aperture (1.7 m blank). The  $f$ -ratio of the 5.3-meter parent is  $f/0.73$ . The telescope optics are based on a Gregorian design with two additional flat mirrors to direct the light into the declination and Coudé axes, respectively. The diffraction limit of the telescope at 500 nm is 0.065'' and the corresponding value for near-infrared observations at 1600 nm amounts to 0.21''. The  $f$ -number of the primary mirror is 2.4 corresponding to a focal length of 4.1 m. The primary mirror blank consists of Zerodur with coefficient of thermal expansion (CTE) of  $0.1 \pm 1.0 \times 10^{-7}$  K<sup>-1</sup>. The design specification for the surface quality of the primary mirror is  $\lambda/30$  with a  $\mu$ -roughness of better than 1.0 nm.



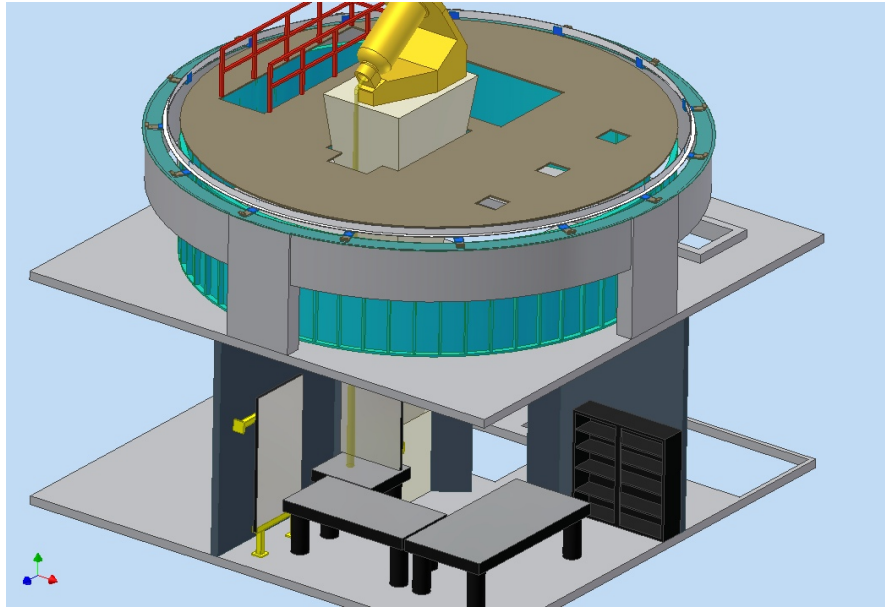
**Figure 3.** Optical path through the off-axis system and optical support structure.

The field-of-view (FOV) is 180'' in the optical laboratory. The final focal ratio in the Gregorian focus is  $f/52$  and the effective focal length of the telescope is 83.2 m, i.e., the 3' FOV produces a 73 mm diameter image. The corresponding plate scale is  $2.48'' \text{ mm}^{-1}$ . A spot diagram is provided in Figure 5 to illustrate the optical performance of NST. Since the Coudé feed includes refractive optics, the wavelength coverage for the high-resolution post-focus instruments is 390 nm to 1700 nm. Removing the flat Coudé mirror M4 provides access to an instrument station at the Nasmyth focus, where the entire visible and infrared wavelength region is accessible. The polarization and calibration optics are located between the secondary mirror M2 and the flat folding mirror M3. M2 produces a pupil image before M3, which can serve as a Lyot stop further reducing straylight in the Coudé feed. The thermal control of the mirrors is essential for the NST performance. Air-knives and other active and passive measures will be used to keep the mirror temperatures within  $\pm 0.3$  K of the ambient temperature.

The Steward Observatory at the University of Arizona is polishing the primary mirror and is developing computer generated hologram (CGH) techniques required to produce 8-meter aperture, off-axis mirrors. Production of the NST primary is a 1/5 scale test project.<sup>15</sup> The surface error of the primary mirror is shown in Figure 6. The rms-surface error is 35 nm and was measured in February 2006. We expect that the final value of 10 nm will be reached after hand polishing and removal of a few “high spots”. The CGH technique is not required for the NST project, since the short focal length would allow standard null lens testing, but will have to work for the 8-meter project. Space Optics Research Labs (SORL) are figuring the parent optics of the secondary mirror. Two 145 mm diameter concave secondary mirrors will be produced from the same parent. One of them will serve as backup.

The off-axis configuration of the NST offers an unobstructed pupil allowing superior adaptive optics performance and low scattered light. The prime focus, where most of the solar radiation must be absorbed, is accessible without obstructing the light path. The secondary mirror M2 is mounted on a M-850 hexapod system manufactured by Physik Instrumente, Germany. The control software for the hexapod has been completed and the system was tested in an optical laboratory in 2005/2006.<sup>16</sup> M2 can be positioned with a linear and rotational accuracy of  $\pm 2 \mu\text{m}$  and  $\pm 10 \mu\text{rad}$ , respectively. The relative alignment of primary and secondary mirrors will be measured by a dedicated wavefront sensor to keep the telescope aligned under a variety of observing and environmental conditions.

The wavefront sensor and other calibration optics (including polarization calibration) will be located between M2 and the flat folding mirror M3. The beam has a 98 mm to 96 mm diameter in the range from 400 mm to 200 mm before M3. This requires relatively large optical elements (for example linear polarizers and retarders) with diameter of up to 120 mm. The optics will be mounted in dual wheels with four slots each. This calibration unit precedes the wavefront sensor for the active optics.



**Figure 4.** Coudé feed, observing floor and optical laboratory.

## 6. HEAT STOP ASSEMBLY

The heat stop will be designed and built in-house by the Institute for Astronomy, who developed a similar heat stop for their 0.5-meter aperture SOLAR-C telescope. The off-axis design also makes the NST ideally suited for night-time observations requiring low stray-light and a well-known telescope modulation transfer function.

NST will deliver about 2500 W to the prime focal plane. The irradiance is about  $2.5 \text{ W mm}^{-2}$  or  $2.5 \text{ MW m}^{-2}$ . This can be easily controlled by a fluid cooled, reflective surface called the heat stop. Heat stops have been used in many solar telescopes and become a necessity as the apertures increase. Mitigation of internal seeing requires minimal thermal gradients in the reflector and surface temperatures within about 1 K of ambient – making the problem more difficult. Typically, the waste beam is dumped into the environment around the telescope but this does not fit the NST philosophy of minimizing the solar radiation allowed into the dome. The waste beam reflected from the heat stop would add most of that 2500 W to the dome environment. To avoid this, the radiation is captured in a beam absorber and transferred out of the dome via circulating, chilled fluid.

While off-axis systems allow access to the prime focal plane without obstructing the entrance aperture, the region near prime focus is still quite close to the return path from the secondary. The prime focus geometry is defined by the folded light paths at M2 and the pointing range desired for the telescope. NST is designed for pointing up to  $8'$  beyond the solar limb.

Figure 8 shows the prime focal surface and defines the pointing range. The largest circle is the allowable area, where the full disk solar image can lie. The intermediate circles represent the full solar image and the small (3.8 mm) field stop is at the center. The reflecting surface of the heat stop will be slightly larger providing a buffer of about 1 cm around the image zone. Sunlight outside that area will trigger safety measures.

The base components of the heat stop and secondary mirror assembly are shown in Figure 7, which also depicts the geometry of the light paths around the prime focus region. The heat stop's reflecting surface contains the field stop, which limits the energy that reaches the secondary optics. The waste light is reflected out of the system. The geometry of the intersecting beams at prime focus limits the size of the assembly. There is a mechanical and thermodynamic advantage to keeping the incident angle small since a sealed cone must pass through the coolant volume. At large angles this cone increases the size of the heat stop and interferes with uniform coolant flows.

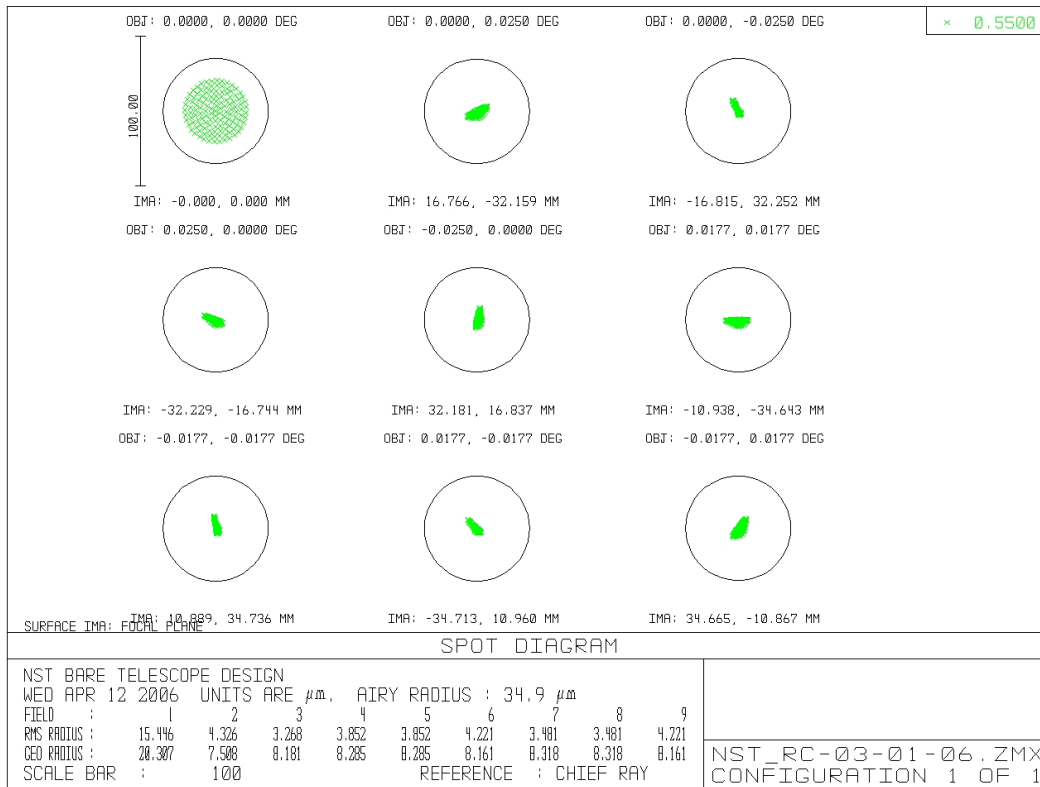
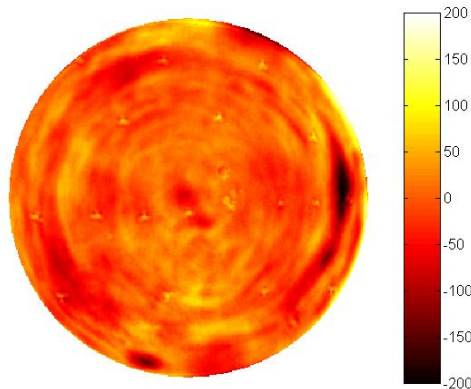


Figure 5. Spot diagram of NST optical configuration at 550 nm.

The return beam from the secondary limits the vertical extent of the heat stop. The interior cone grows as the reflecting angle increases and the tilted sides of the cone make it more difficult to get coolant directed into the area near the field stop.

## 7. OPTICAL SUPPORT STRUCTURE

DFM Engineering Inc. supplies the equatorial mount, telescope tube, primary mirror cell, positioning actuators and mirror supports for M1, the OSS pointing control system, mounts and mirrors for M3 through M5, and the primary mirror handling equipment. The system is based on their standard designs, which they have successfully implemented for many telescopes with pointing and stability specifications equivalent to those required for the NST. The standard DFM CCT 1.3 EQ mount is shown in Figure 9, which will be used with a modified, shortened fork. All major components of the OSS, including the telescope tube will be lightweight, monocoque structures. DFM Engineering proposed an unbalanced system to meet the overall mass requirement imposed by BBSO's existing pier. Studies of balanced designs produced telescopes weighing from 13 to 18 tons since the extreme cantilever of the mirror cell and telescope tube required extensive counter-weight. DFM's system will mass only 8.5 tons with the unbalanced moments taken up by the Declination (DEC) drive system. The DEC drive will be a tangent arm system capable of supporting large loads. The center of gravity (CoG) about the Right Ascension (RA) axis will vary with RA position and a pair of moving 1/2 ton counter-weights located in tubes near the DEC axis will compensate (see Figure 3). DFM's telescope software will be modified to calculate the moving CoG and control the counter-weight motions. The open telescope design requires a stiff construction of the optical support structure. Care will be taken to protect the telescope from dust and to enable it to withstand strong winds. Typical winds at BBSO are from the south-west at speeds of  $5 \text{ m s}^{-1}$ . These are also the conditions under which we have the best seeing.<sup>13</sup>



**Figure 6.** Surface error of the primary mirror.

The primary mirror structure includes a 36 point axial support and a six point tangential support for the primary mirror. Three of the axial and three of the tangential actuators are used to fix the M1 position. The remaining 33 axial force supports control the mirror figure and three tangential supports provide small rotational corrections to the primary mirror. These force based servos will compensate for gravity and thermally induced errors in the mirror figure.

An agile hexapod supports the secondary mirror and the heat stop assembly. The flat mirror M4 can be used for automated beam switching between the Nasmyth and Coudé observing stations. Another flat folding mirror M5 feeds the vertical AO bench leading to the Coudé laboratory.

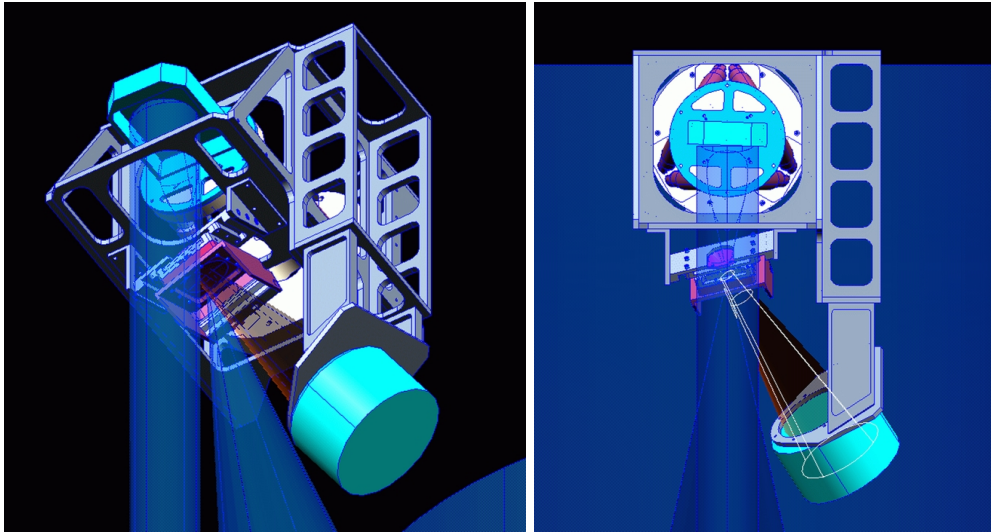
The weight of the optical support structure, at 8.5 tons, still requires that the upper portion of the telescope pier be modified to accommodate the weight increase with respect to the old vacuum telescope. In addition, the pier will be extended to bring the telescope's rotational axes to the center of the 5/8-sphere dome. NJIT's structural engineering group is developing the design for the pier extension.

A solar guider developed in-house is used for pointing control. A Sigma 70–300 mm zoom lens forms a small (4 mm) solar image on a four-quadrant sensor, which is mounted on a high-precision linear micrometer stage to allow positioning of the telescope with sub-arcsec accuracy. A Thousand Oaks solar filter protects the zoom lens and the subsequent components from exposure to too much sunlight. The system will be tested on the 65 cm telescope in mid 2006.

## 8. ACTIVE AND ADAPTIVE OPTICS

The pointing and image control systems<sup>17</sup> rely on a dedicated wavefront sensor manufactured by Adaptive Optics Associates. The DC-component of the wavefront sensor measurements provides the information for the active alignment of the primary and secondary mirrors. Active alignment includes relative orientation and spacing of M1 and M2. In addition, the figure of the primary mirror will be corrected to compensate gravitational sag and thermally induced errors. Both closed loop and open loop control (via look-up tables) will be implemented for the telescope alignment. Even though the primary is adaptive, we group those controls with the active optics section, since only slow changes due to gravity and thermal variations are corrected.

The AO system consists of three components: a wavefront sensor (distinct from the active optic wavefront sensing system), a correlation tracker-based tip/tilt platform, and a deformable mirror. The tip/tilt system is used to preserve the dynamic range of the deformable mirror. The wavefronts are measured with a Shack-Hartmann system. A duplicate version of the correlation tracker and tip/tilt platform will be implemented for the observing station in the Nasmyth focus. Initially, we will use the AO system originally developed for the 65 cm vacuum telescope at BBSO. This high-order AO system is a collaboration between BBSO and the National



**Figure 7.** Heat stop assembly.

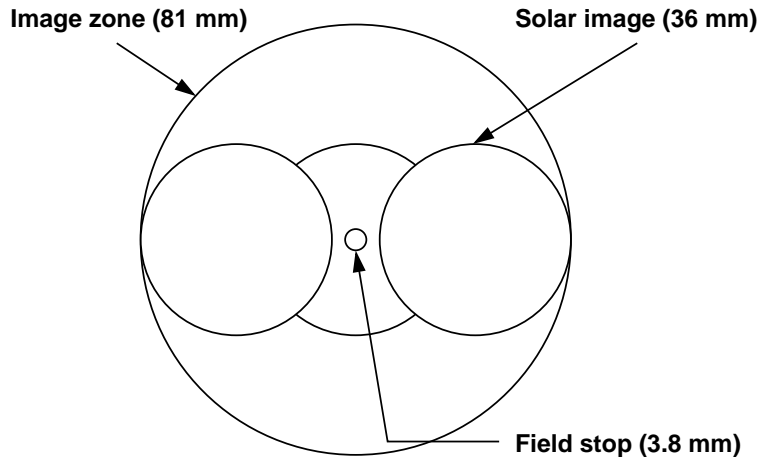
Solar Observatory (NSO). A twin system is operated at the Dunn Solar Telescope (DST) at NSO Sacramento Peak, New Mexico.<sup>8</sup>

The Shack-Hartman wavefront sensor with 76 subapertures measures the wavefront aberrations, which are corrected in a closed loop by a deformable mirror with 97 actuators manufactured by Xinetics. The wavefront sensor detector is a 10-bit CMOS camera manufactured by Baja Technologies, which has  $1280 \times 1024$  pixels. The control software was developed at NSO/SP. However, only  $200 \times 200$  pixels are read to achieve a frame rate of  $2500 \text{ frames s}^{-1}$ . Digital signal processors (DSPs) are used to compute cross-correlations between subaperture images and a pre-selected subaperture reference image. This system provides high Strehl ratios and images with diffraction-limited quality, if the seeing conditions are good and the Fried-parameter  $r_0$  exceeds 7 cm. The implementation of this system at the NST will provide full correction in the infrared under good seeing conditions. However, in the visible wavelength range only partial correction can be achieved. Ultimately, the existing AO system has to be replaced with system with sufficient degrees of correction covering the entire wavelength range from 390 nm to 1700 nm. A system with about 350 actuators is currently in the design and development phase.

## 9. CONTROL SYSTEMS

The telescope control system (TCS) is a distributed computing system with a hierarchical structure. The software development relies on an object-oriented design (OOD). A head quarter (HQ) computer maintains the communication with the subsystems.<sup>16,18,19</sup> Information exchange is standardized using forms written in the extensible markup language (XML). The internet communications engine (Ice) is used as middleware for communication between subsystems and HQ. Each subsystem is implemented as both client and server. Every subsystem registers itself with HQ upon start. TCS must control and coordinate different subsystems and keeps track of the status of the whole telescope system. Only valid commands are executed and protocols have to be implemented to protect the system from executing potentially damaging commands. The subsystems include dome control, telescope pointing and tracking, active optics, thermal control, weather and environmental parameters, and science instruments. Each major subsystem will have its own control computer. We will use a databank system to store the extensive information generated during a typical observing day. This information will be analyzed to optimize instrument performance and, in case of systems failure, provide critical details on how to prevent the occurrence of such events in the future. TCS design goals include easy operation and flexibility. Most of the low-level, hardware related details are hidden from the telescope operators, who control the telescope system by issuing high-level commands. However, for subsystem maintenance and failure recovery access to the low-level commands is still possible.





**Figure 8.** Prime focus geometry.

## 10. POST-FOCUS INSTRUMENTATION

The high-resolution instrumentation is located in a Coudé laboratory on the second floor of the observatory building. It consists of the AO system, a spectrograph, two imaging spectro-polarimeters for observations in the visible and near infrared wavelength regions,<sup>2,3,4</sup> and a fast CCD camera system for image restoration.<sup>5,6</sup> The imaging spectro-polarimeters use Fabry-Pérot etalons to restrict the bandpass to about 10 pm. The first two-dimensional spectroscopic observations with the aforementioned systems are shown in Figure 10. The spatial resolution will improve by a factor of three, once the instruments are moved to the NST, and with post-facto image correction, we expect to see even more fine structure in the spectroscopic data. Polarization optics with nematic liquid crystal variable retarders will enable us to measure the full Stokes vector in both the photosphere and chromosphere. We have modeled optical configurations based on the existing hardware that will work at the NST, however, with a reduced FOV of about  $50'' \times 50''$ . Other than this, the optical layouts, the data reduction, and the data analysis procedures basically remain the same. Assuming  $1024 \times 1024$  pixel detectors, the image scale corresponding to the aforementioned FOV will be  $0.05'' \text{ pixel}^{-1}$ .

Another option to record the three-dimensional data cube (two spatial and one spectral) is to use a grating-type spectrograph and scan one of the spatial dimensions. The Fast Imaging Solar Spectrograph (FISS) has two main objectives: One is to study the fine-scale structure and dynamics of cool plasma in the photosphere and chromosphere related to prominences/filaments, flares, surges, fibrils and spicules. The other is the calibration of narrow-band filters used in Big Bear such as visible and near-infrared Fabry-Pérot etalons and Lyot filters. The spectrograph is a fully reflecting system using mirrors and an Echelle grating. It has a focal length of about 1.5 m and a spectral resolving power of 150000 (near infrared) to 220000 (violet). It is possible to record  $H\alpha$  line and  $\text{Ca II K}$  line simultaneously in a dual-band mode. Other lines in the visible and near infrared may be recorded individually in a single-band mode.

First light instrumentation at the Nasmyth focus will be a simple filtergraph using a Rockwell IR camera. The wavelength coverage will be .9 to 2.5 microns and the imager is  $1024 \times 1024$  pixels. A tip/tilt system based on correlation tracking will be implemented to provide good Strehl ratios at the longer wavelengths.

## 11. CONCLUSIONS

In these proceedings, we have reported several milestones towards the completion of the NST including software development, completion of the primary and secondary mirrors, the replacement of the dome, and progress in the post-focus instrumentation. System integration of the NST is scheduled for May 2007. Telescope alignment procedures will have to be developed and tested during an interim phase and we expect to begin full operations in early 2008. NST is one of many efforts in experimental solar physics (e.g., GREGOR<sup>20</sup> and ATST<sup>21</sup>) to



**Figure 9.** Standard CCT 1.3 EQ mount manufactured by DFM Engineering. A modified version with a shortened fork will be used for the NST

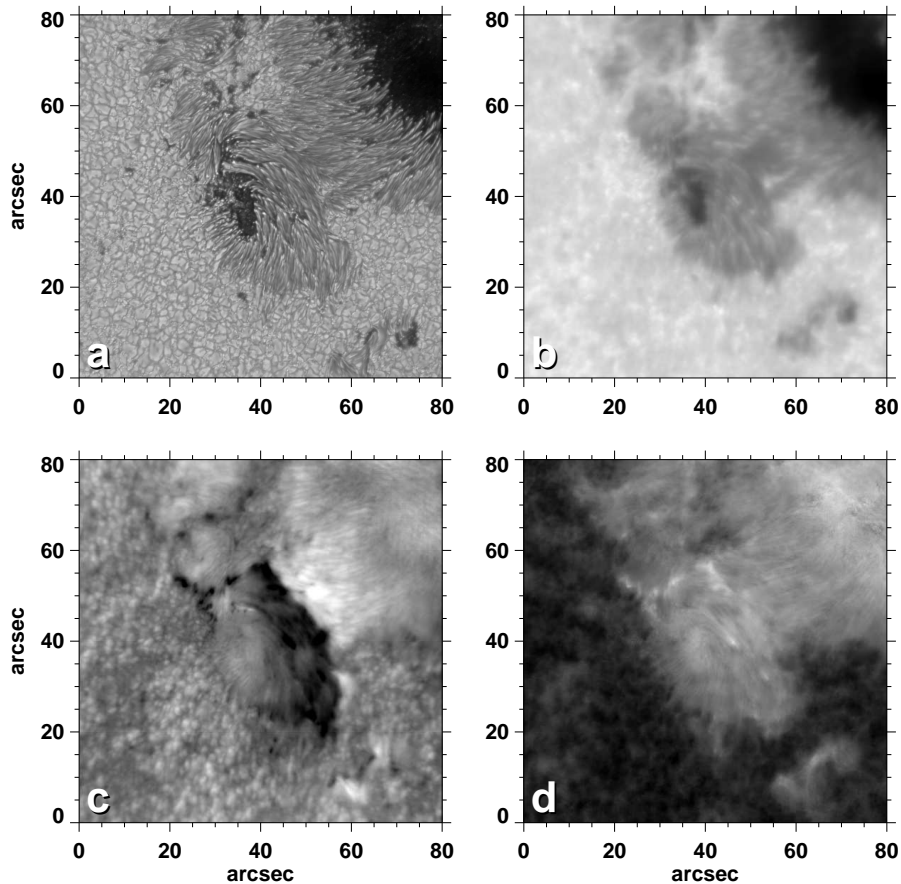
build telescopes with larger apertures and new capabilities. In combination, with existing and upcoming space missions, these telescopes will begin a new area for solar physics and bring us closer to solving the many puzzling problems in solar physics.

## 12. ACKNOWLEDGMENTS

This work was supported by NSF under grants ATM 00-342560, ATM 02-36945, IIS ITR 03-24816 and AST MRI 00-79482 and by NASA under grant NNG0-6GC81G.

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**Figure 10.** High-resolution observations of a small  $\delta$  configuration in solar active region NOAA 10756 observed with the 65 cm vacuum refractor at BBSO on 2005 May 2. (a) White-light speckle reconstruction at 600 nm, (b) Fe I 630.28 nm line core intensity, (c) dopplergram displayed between  $\pm 1 \text{ km s}^{-1}$ , and (d) FWHM of the Fe I line as a “crude” proxy of the magnetic field strength.

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