Title of Investigation: Adaptive Optics System for the 1.6 Meter Solar Telescope in Big Bear
Principal Investigator: Haimin Wang, BBSO/NJIT
Co-Principal Investigators: Phil Goode, Deqing Ren and Carsten Denker, BBSO/NJIT
Collaborator: Thomas Rimmele, National Solar Observatory

Project Summary

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii (UH) and the Korean National Observatory (KAO), is building the world's largest aperture solar telescope. The 1.6-m aperture, off-axis, New Solar Telescope (NST) will replace Big Bear Solar Observatory (BBSO)'s principal telescope with its 65-cm aperture. The project is well under way; first-light is anticipated at the end of 2006. Under prior NSF/MRI support to NJIT, in collaboration with the National Solar Observatory (NSO), we have successfully developed two 76-element Adaptive Optics systems (AO-76) for the current BBSO 65-cm telescope and the NSO 76-cm Dunn Telescope.

To fully utilize the scientific capability of NST as early as possible, we propose to transfer the AO-76 system, with modifications, to the NST immediately after it is installed. This proposal seeks funding for that task. AO-76 is a high-order system for the 65-cm BBSO telescope, which is successfully operating in both the visible and near infrared (NIR) ranges. We understand that when integrated into the NST, the AO-76 will be a lower order AO in the visible. However, we anticipate that it will have full capability of correcting the seeing in the NIR. More specifically, under median seeing conditions at BBSO, the predicted Strehl ratio at $1.6\mu m$ is above 0.8. For about 10% of the time, the predicted Strehl ratio at $0.5\mu m$ is above 0.5. Therefore, our initial scientific focus for the NST will be in NIR studies of the solar atmosphere and its activity. Diffraction limited observations will also be made during the good seeing periods in the visible. The key tasks in this proposal include the optical design and subsequent setup/testing of the AO system for the NST. Both the refractive and reflective designs will be considered.

Over the last two years, we have developed a state-of-art NIR imaging magnetograph system (IRIM) that has attained its first scientific light at BBSO. The specific scientific objectives are: (1) High cadence, high resolution studies of solar flares; (2) Evolution of magnetic fields associated with solar activity; and (3) Dynamics of Kilo-gauss magnetic flux tubes.

In sum, we directly address the two criteria required in any NSF proposal:

(1) Intellectual merit: The AO equipped NST will be the largest aperture solar telescope, located in one of the best observing sites. It will enable new, cutting edge science. We have already demonstrated our abilities by developing the two most successful solar AO systems in the world.

(2) Broad Impact: The development of the proposed AO system is the first solid step toward an even higher-order AO system for the NST, which will also enable us to further explore Multi-Conjugate Adaptive Optics (MCAO). This effort is highly relevant to the development of MCAO systems for the nighttime telescopes. The scientific results will be extremely important in the understanding of the dynamics of magnetic fields on a fine spatial scale, as well as space weather monitoring and forecasting. The scientific objectives will also be closely linked to several key research topics in nighttime astronomy: the physics of stellar coronal heating, stellar magnetic fields and stellar flares. This project has strong integrated research and education components. A post-doc, a Ph.D. student and an undergraduate will participate in the project. Our data will be open to the scientific community.

A Project Description

A.1 Results from Prior NSF Support Related to this Proposed Research

Of the two US observatories capable of making high-resolution observations of the Sun, BBSO is the one operating in a campaign mode. We believe that a more fundamental understanding of solar magnetic fields and the solar atmosphere depends on sustained, higher resolution and higher cadence observations. Over the past few years, we have substantial accomplishments that position us to advance to the next level of our scientific objectives, which will center on understanding energy release and transport on different scales in the solar atmosphere, as well as the associated evolution of magnetic fields. Our research requires a continuing effort in instrument development, and a dedicated scientific team to make and analyze new observations. Building the new off-axis 1.6-m telescope at BBSO is a crucial step toward this goal.

The Advanced Technology Solar Telescope (ATST) site survey was initiated in 2000 and has identified at the end of a four-year survey three excellent sites for solar observing: Big Bear Solar Observatory, California – Mees Solar Observatory, Haleakala, Maui, Hawaii – Observatorio Roque de los Muchachos, La Palma, Canary Islands, Spain (Hill et al. 2004). All three sites are suitable for high-spatial resolution observations. Haleakala and La Palma have strong advantages for coronal science. However, only BBSO – the mountain-lake site – provides consistent seeing conditions with extended periods of excellent seeing from sunrise to sunset (see Figure 1). For any ground-based modern solar telescope, an Adaptive Optics (AO) system is required to correct seeing induced image smearing and distortions. A minimum Fried parameter, 6 cm, is required for AO correctibility. Obviously, BBSO is uniquely qualified to be a site for building a large aperture solar telescope and achieving diffraction limited resolution with AO for long periods of time. Periods of excellent seeing (sufficient to be corrected by AO) are limited to one or two hours in the early morning for the Pacific/Atlantic mountain-island sites, Haleakala/La Palma, where the seeing deteriorates once the ground heats up and a turbulent boundary layer has been established. Haleakala was selected as the ATST site to achieve its primary scientific objectives: extreme fine structure of magnetic fields that can be studied with exceptional seeing for short periods of time and physics of solar corona. The lake at BBSO effectively suppresses the boundary layer and makes the observatory ideally suited for sustained high-resolution and synoptic observing programs, and the 1.6-m NST is being built for this purpose.

We now report on the significant progress on two major instrumentation projects that are relevant to the development of the proposed AO system: the on-going NST project and the finished 76-element AO project.

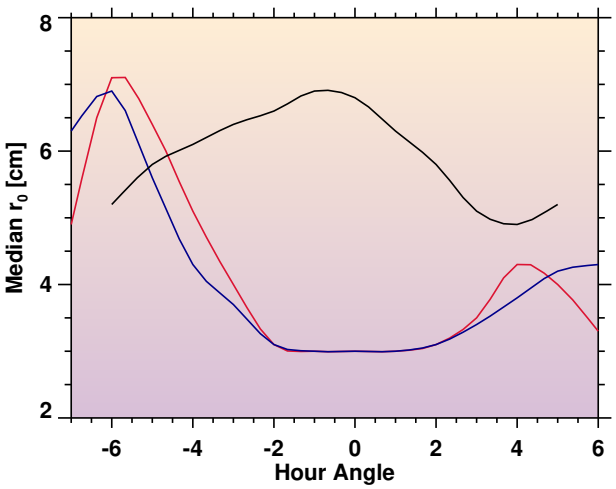

Figure 1: The median value of the r_0 (Fried parameter, a rough measure of the diffraction limit, $r_0 \geq 5.5$ cm is required for correction by AO) measurements from the S-DIMM instrument (principal ATST site survey instrument, see http://atst.nso.edu/site/ for details) for the three finalists to be the ATST site (**Big Bear**, **Haleakala**, and **La Palma**) as a function of hour angle (adapted from Figure 10.13 in Hill et al. 2004, ATST Site Survey Report).

A.1.1 New Solar Telescope at BBSO

Supported primarily by a current NSF MRI grant (ATM-0320540), BBSO/NJIT, in collaboration with the University of Hawaii (UH) and Korean National Observatory (KAO), have formed a team to upgrade BBSO by replacing its principal 65-cm aperture telescope with a modern, off-axis 1.6-m clear aperture instrument with a $180'' \times 180''$ field of view (FOV) (Goode et al., 2003). The new telescope offers a significant improvement in ground-based high angular resolution capabilities, and enhances our continuing program to understand photospheric magneto-convection and chromospheric dynamics. These are the drivers for what is broadly called space weather – an important problem, which impacts human technologies and life on Earth. This New Solar Telescope (NST) is a whole new system starting with being the largest aperture off-axis telescope. We have made strides in implementing this project, including the design of the optical support structure with active optics, a new dome to house the larger telescope, and a whole new control system.

The project is described in detail in http://www.bbso.njit.edu/newtelescope. To minimize the risk to the NST project, we have borrowed on the design of existing telescopes as much as possible. For example, the new, larger dome follows the SOAR design, with minimal, but required modification: the NST dome has louvers to ensure proper airflow inside the dome, so the long-standing dome-seeing problem at BBSO can be solved. The NST optical and software control designs are similar to the existing SOLAR-C (UH) and the planned ATST facility led by NSO – all three are off-axis designs. We have full funding for the NST, except for the funding for its AO system. Figure 2 shows the mechanical schematics and optical layout of NST. Full operation is expected by the spring of 2007. The specific details of our progress are:

(a) All optical and mechanical designs are completed. The telescope has a 1.7-m primary mirror with the 1.6-m clear aperture. It has the off-axis Gregorian configuration consisting of parabolic primary, heat-stop, elliptical secondary and two diagonal flats. The focal ratio of the primary mirror is f/2.4, and the final ratio is f/50. The working wavelength will cover from 0.39 to 1.7 μm in the Coude Room one floor beneath the telescope and all infrared wavelengths at the Nasmyth focus on the dome floor. We chose an off-axis design primarily because of its vastly reduced stray light, since there is no central obscuration, which reduces the telescope's MTF (Modulation Transfer Function) at high spatial frequency.

We have designed an open telescope structure with an equatorial mount. A key design issue for a large aperture open solar telescope the thermal is the control system, including keeping the temperature of the mirrors very close that of the air. We are using the wind-gate system in the new dome (discussed below) to control the airflow from the wind and help maintain the same temperature inside and outside the dome. In addition, we will implement an airknife system to limit so-called "mirror seeing".

(b) The central and risky part of the NST project is the figuring of the primary mirror to high optical quality. The Zerodur primary mirror is being polished at Steward Observatory Mirror Lab, University of Arizona (UA Mirror Lab), as part of their 20/20 project (http://www.optics2001.com/telescope.htm). This is the optimal facility for figuring the NST primary mirror. The lab is funded to polish a fast, off-axis 1.7-m mirror as a proof-of-concept study for figuring seven 8.4-m mirrors for twin 21-m telescope. The end product of the proof-of-concept will be the primary mirror for the NST. The precision of the primary is targeted at 10 nm. The polishing of the primary is progressing well and is scheduled for completion no later than February 2006. The progress is sufficient enough that we now know that the project is no longer risky. The risk concerned the characterization of the figure of the primary. For the testing of the figure, Steward built a testing tower with a 0.5 spherical mirror at its top and a special holographic system to account for the off-axis nature of the mirror. It turns out that profilometer and holographic testing of the primary yielded the same result over the visible, so we are confident of the testing, and the polishing continues with the rms error being about 200 nm as of this writing (see Figure 3).

(c) The 145-mm concave secondary and its backup are also in the final polishing stage at Space Optics Research Lab (SORL). Shortly after February 2006, the primary and the secondary will be tested in tandem

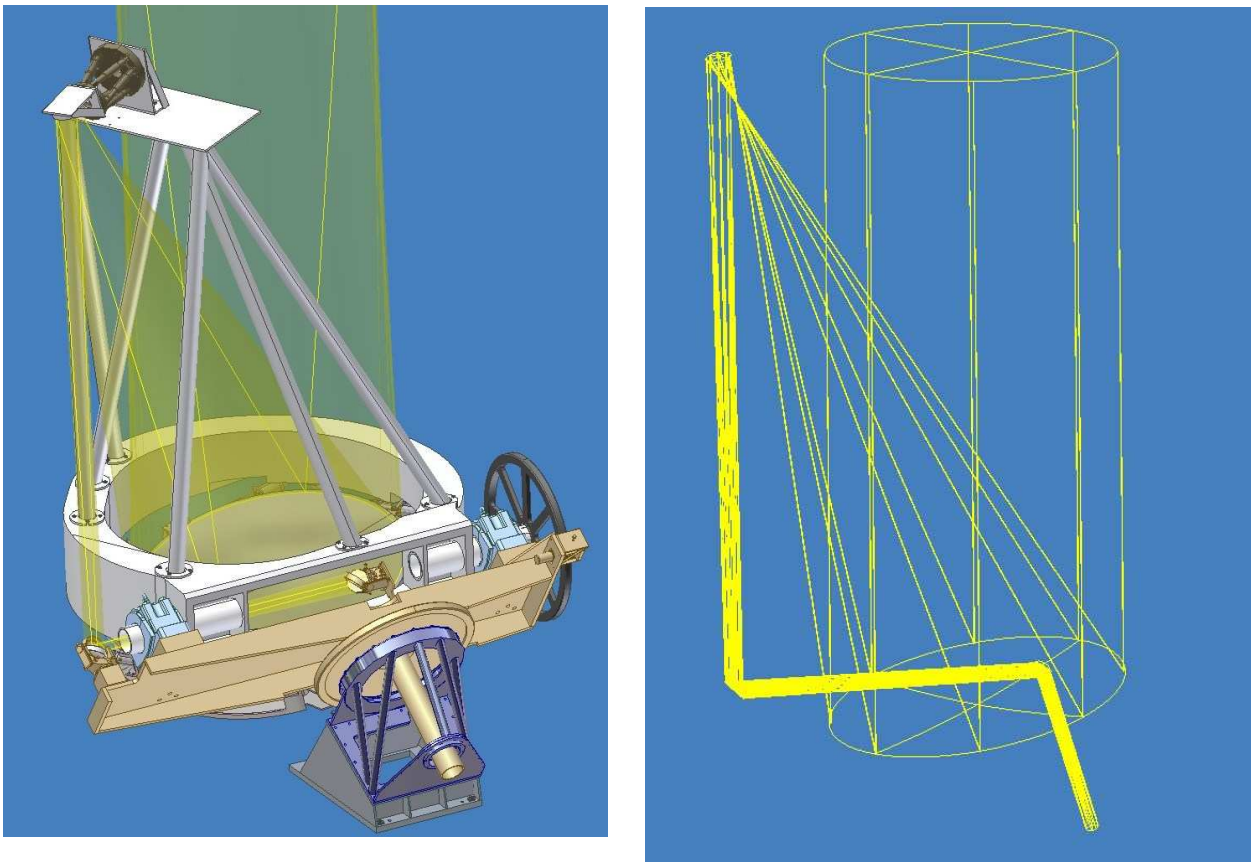

Figure 2: Schematic of the 1.6 m off-axis, open NST and its optical layout.

in the UA Mirror Lab or Optical Sciences Center. Testing equipment will be set-up for this final system test of the principal optics of the NST. The downstream mirrors of the NST are all flats.

(d) The heatstop is the responsibility of the UH part of our team, and will follow that of SOLAR-C. A reflective surface with a 3.8 mm opening is located at the prime focus of the telescope. This opening is the field stop for the system and the reflective surface rejects most of the solar image, limiting the radiation that passes on to the downstream optics. The surface will be cooled by liquid jets. The rejected light will be collected in a beam absorber. The heat load will be removed from the telescope via circulating, chilled fluid. The heat stop system will remove about 2 Kilowatts of heat, allowing less than 30 Watts to pass on to the secondary optics.

(e) The last piece of hardware needed for the NST is the Optical Support Structure and its Equatorial Mount. DFM (of Longmont, Colorado) has been contracted to build the system 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. An important part of the system is the primary mirror cell. The primary mirror is supported by 36 axial and 6 tangential actuators. These force based servos will compensate for gravity and thermally induced errors in the mirror figure. The secondary mirror will be mounted on an agile hexapod. The M850 system made by PI (Physik Instrumente of Germany) has been purchased and tested. A wavefront sensing system is being developed to control the active optics components. This system will be placed immediately before M3 (first flat mirror, which directly feeds the Nasmyth focus, or feeds flip mirror M4 that in turn feeds light to the Coude Room beneath, where the adaptive optics system resides).

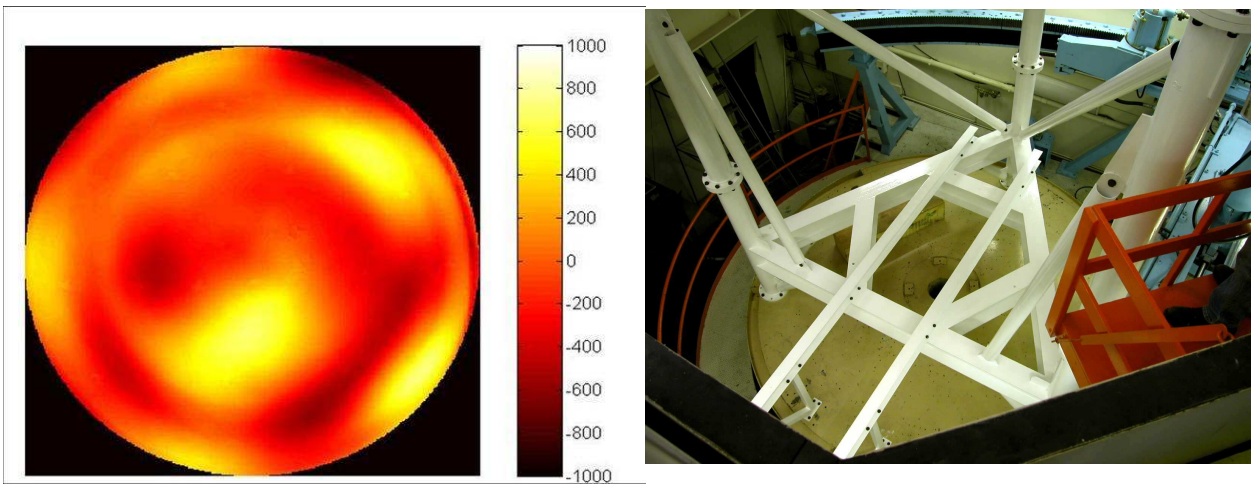

Figure 3: The left panel shows the interferometric pattern of the residual polishing error (about 300 nm at that moment). As of this writing, the rms error is below 200 nm. On the right is the testing tower being installed. At the top is the 0.5 m spherical mirror and the PM is transferred from the polishing tool to the bottom of the tower for testing. Testing is done after about 10 hours of polishing.

(f) To accommodate the size of the NST and control the airflows for thermal control, a new dome is required. MFG Ratech has been contracted to design and build the new dome. The design has been finished and constructed. It is a 34-ft 5/8 sphere dome with a retractable shutter that is similar to the SOAR dome, also designed by Ratech. The dome structure consists of a steel frame with a shell of fiberglass panels. The air circulation will be controlled by 14 windgates around the dome, at the height of the primary mirror. The installation of the dome is scheduled for November 2005. We will have a full year to test the control systems for the new dome, and our new thermal systems, before the NST is installed. Observations with the 65-cm telescope will continue under the new dome (after a two month downtime), and focal plane instruments and the existing AO can continue their testing and development through the summer of 2006.
(g) Development of the software for the telescope control system is about halfway finished. The software team consists of three members at NJIT and two members from KAO. The central computer (Headquarters) controls the following subsystems: telescope pointing and tracking; active mirror control; adaptive optics system and thermal control system. The communication links between software modules have been written and tested, and the development continues on the various subsystem control segments. The entire system will be done before Summer 2006, and will be ready for further development in the commissioning phase of the NST (beginning with first light near the end of 2006). As we have a strong team for this task, different components of the software will be cross-checked, to ensure that they are working properly.
(h) Focal plane instruments for NST are in the commissioning phase of development. These include visible and near infrared magnetograph and real time speckle imaging systems. They are presently being used to observe with the existing 65-cm telescope. The details of the infrared system will be discussed in section A.2.

A.1.2 Adaptive Optics

Under a prior NSF MRI grant (AST-0079482), we have successfully built two high-order AO systems (76 element deformable mirror AO systems), one for BBSO's 65 cm telescope and the other for the 76 cm Dunn Solar Telescope at National Solar Observatory/Sacramento Peak (NSO/SP). Dr. Thomas Rimmele of NSO, as a research professor at NJIT, was the PI for the project. He will participate in this proposed project as a

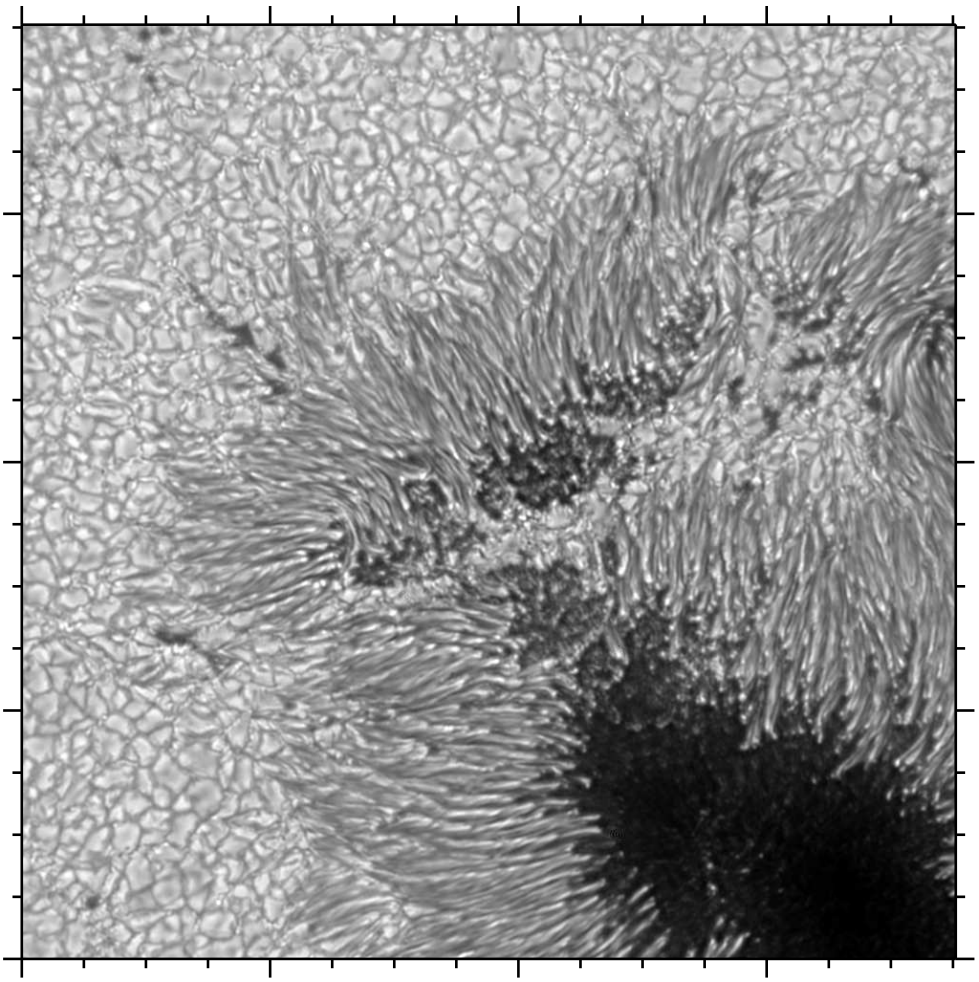

Figure 4: A recent diffraction-limited image obtained at BBSO on April 29, 2005 with the AO-76 system and speckle reconstruction.

collaborator. A number of papers have been published to describe these two AO systems and the scientific results (Ren et al., 2003a; Didkovsky et al., 2003; Denker et al., 2005; Rimmele, 2004; Yang et al., 2004; Tritschler et al., 2005; Xu et al., 2004, 2005). Figure 4 shows a sample image obtained on April 29, 2005 with the BBSO AO system. The performance of the BBSO AO system is evaluated in Figure 5. It compares the variances of the Zernike coefficients for modes up to order 35, for open- and closed-loop data (Tritschler et al., 2005). The variances are a factor of 100 smaller for the AO-corrected data. Some other AO corrected images will be presented in the next section, when we discuss science drivers of this project.

A.2 Science Drivers for the AO Equipped NST

As we stated above, our initial scientific objectives for the AO Equipped NST will be based on achieving full seeing correction in the NIR. In addition, partial correction in the visible will be implemented under good seeing conditions. We therefore emphasize our scientific goals based on continuous NIR observations and periods of visible observations.

BBSO has built and employed several generations of near IR imaging systems. The most recent and

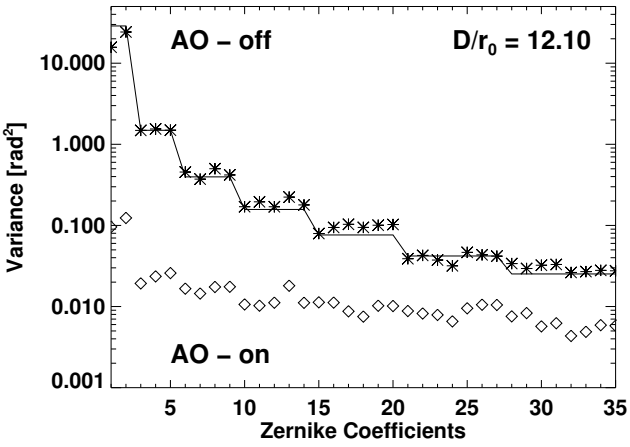

Figure 5: Comparison of the variance of the Zernike Coefficients for open (asterisks) and closed-loop (carets) data determined from the AO WFS data. The Solid curve represents a fit to Kolmogorov spectrum of the open-loop data for D/r_0=12.10 (Trischler et al., 2005).

significant part of our IR instrumentation was the development of a narrow bandpass filter system, which combines a Lyot filter and an IR Fabry-Pérot filter – the IR Imaging vector Magnetograph (IRIM). Our one-of-a-kind Lyot filter, designed by one of our former Ph.D. students, has a bandpass of 2.5 Å at 1.56 μm, giving us a 2.5 Å wide prefilter (narrower than the 5 Å free spectral range of the IR Fabry-Pérot). This solves the longstanding problem of constructing a filter-based IR magnetograph, while avoiding the complications of using a double etalon. The new and unique Lyot prefilter is being used in conjunction with our IR Fabry-Pérot filter. With this, polarimetry in the near IR has the same reliability and stability that it has for visible light. Note that the IR Lyot filter system has about 20% transmission. IRIM's total transmission is about a factor of two less than that of a dual Fabry-Pérot instrument. However, unlike a dual Fabry-Pérot system, with its instability (requires very accurate tuning that is hard to maintain) and its typically quite restricted FOV for magnetograms, our system is stable and can utilize larger FOV. Finally, a new detector technology (CMOS devices) offers high quantum efficiency, so that we can take individual exposures well within the atmosphere's correlation time in the near IR ($\sim$ 100 ms). We have obtained and implemented a large format IR CMOS camera (1k$\times$1k, 30 frames/s) from Rockwell Scientific Imaging. We enjoyed a very successful first scientific light of the full IRIM hardware system in November 2004 at NSO/SP and in July 2005 at BBSO. The strength of the IRIM is its extreme sensitivity and high spatial resolution, which allows us to study weak and small-scale magnetic fields in the quiet Sun. In active regions, it allows accurate measurements to avoid Zeeman saturation of the traditional filter-based magnetograph systems. Both magnetic field strength and the filling factor were derived from the fitting of Stokes V profiles (Cao et al., 2005).

We are in the process of further upgrading the IRIM system. A second Lyot filter has been built with the capability of tuning from 1 to 1.7μm. Therefore, we can study the solar upper atmosphere with the chromospheric (HeI 1083nm) and coronal (e.g. Fe XIII 1075nm) lines (Lin et al., 2004).

A.2.1 High Cadence, High Resolution Studies of Solar Flares

The 1.6-m telescope can obtain high resolution, high cadence images of flares in visible and NIR. These observations will provide details of electron precipitation on fine temporal and spatial scales. By combining high cadence optical imaging with hard X-ray imaging from missions such as the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), as well as with high resolution magnetograms, we expect to learn if and how the individual sub-second peaks in the hard X-ray and microwave time profiles correlate with the rapid precipitation along various flux loops. Xu et al. (2004, 2005) presented high resolution observations

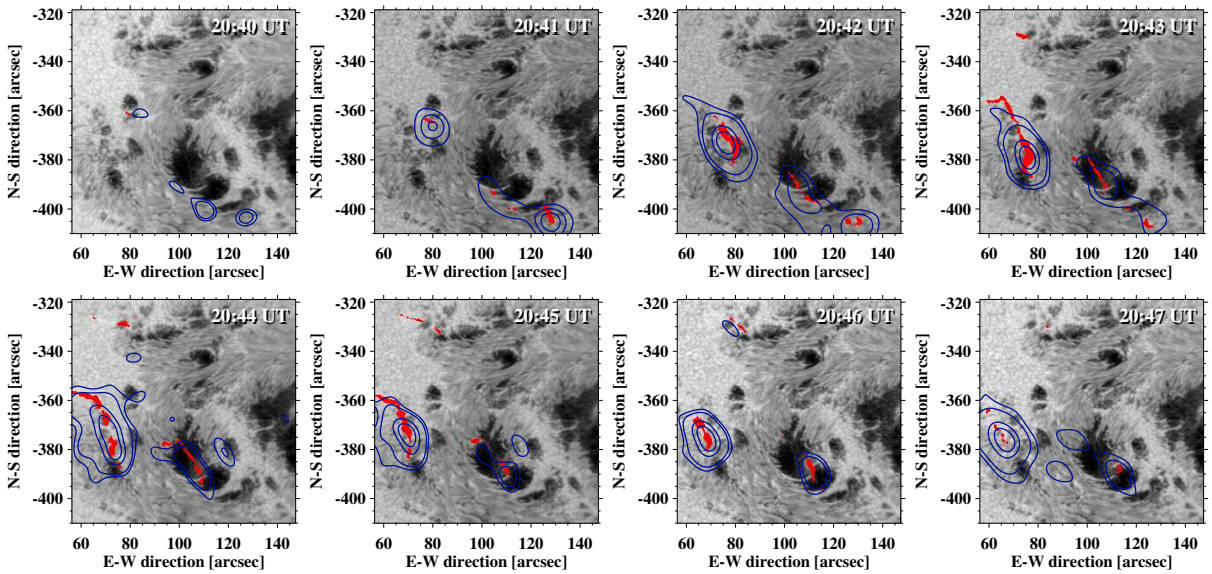

Figure 6: NIR time sequence of the X10 flare from 20:40 UT to 20:47 UT on 2003 October 29, observed with the AO-76 at NSO/SP. RHESSI HXR contours (blue) correspond to the 50 - 100 keV channel with 60 integrations. The local NIR intensity maxima are shown in red. Two flare ribbons are correlated with strong HXR kernels.

of an X10 white-light flare in solar active region NOAA 10486 obtained with the Dunn Solar Telescope at NSO/SP on 2003 October 29. The investigation focused on flare dynamics observed in the NIR continuum at 1.56 μm. This is the first report of a white-light flare observed at the opacity minimum. The spatial resolution was close to the diffraction limit of the 76 cm aperture DST. The data benefited from the newly developed AO system and the NIR CMOS camera. In addition, we compared hard X-ray (HXR) data of the RHESSI. Although it is still possible that some high energy electrons penetrate deep to this layer, a more likely explanation of the observed emission is back-warming. During the impulsive phase of the flare, two major flare ribbons moved apart, which were both temporally and spatially correlated with RHESSI HXR ribbons. Figure 6 shows the comparison of NIR flare image and the RHESSI HXR emission contours. It is clear that NIR emissions coincide well with HXR foot point emissions, but NIR observations have much better spatial ($0.6''$) and temporal (30ms) resolutions to understand the fine scale structure of flare footpoints.

A.2.2 Structure and Evolution of Magnetic Fields and Flow Fields in Flaring Active Regions

Research using the NST will answer the following questions: (a) What is the role of the evolution of the photospheric magnetic field in triggering solar flares, and what is the relationship between the magnetic configuration and the properties of flares? (b) How do electric currents evolve, and what is their relationship to particle precipitation?

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. So, the study of magnetic fields is a very important component of flare science. This concept of energy release has motivated many attempts to detect flare-induced changes in the magnetic fields of active regions. Until very recently, no one has detected, in any consistent way, the changes in magnetic fields associated with solar flares. The BBSO group first saw signs of these changes using BBSO, TRACE and MDI one-minute cadence data (Spirock et al., 2002; Wang et al., 2002, 2004, 2005; Liu et al., 2005). The inconsistency

among the results is due to observational limitations. We cannot get high temporal and spatial resolution and high polarization accuracy at the same time, with existing telescopes/instruments. Our new, large telescope will provide much more reliable and high quality measurements of vector magnetic fields. A lot of the questions discussed above will be resolved with the new higher resolution, higher cadence data. In addition to the temporal and spatial resolution mentioned earlier, the precision of the polarimetry will be on the order of 10^{-4} for the IRIM. With the improved accuracy of our vector magnetograph system, studies of more examples of evolving magnetic fields in active regions, and changes due to flares will provide the evidence needed to lead us to understanding the process of flare energy release, and the role of photospheric magnetic fields therein.

A.2.3 Dynamics of Kilogauss Flux Tubes

The main questions about the dynamic behavior and structure of small scale kilo-Gauss fluxtubes, which need to be addressed with the 1.6-m telescope, concern the formation of photospheric flux concentrations with field strength above the equipartition field strength, and the dynamic interaction with the turbulent photospheric atmosphere. 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/channelled by small-scale fluxtubes into the higher atmosphere. The key questions are: How are fluxtubes formed and how do they evolve? What is the lifetime of a fluxtube? How do the fluxtubes interact with turbulent flows in the photosphere? The observational verification of the process(es) that leads to kilo-Gauss flux concentration in the solar photosphere, where the equipartition field strength is only about 500 G, is a fundamental problem in solar and stellar physics that needs to be solved, and 50 to 100 km resolution is critical to resolve this problem. Although the AO supported observations in NIR cannot achieve highest resolution of NST in visible, NIR observations do have a prominent advantage over the visible: the seeing conditions are more stable, therefore, the evolution of fluxtubes can be studied more accurately, with a resolution of 150km.

The final remarks about the scientific objectives are: 1) The scientific results will be extremely important to the understanding of dynamics of magnetic fields in the fine spatial scale, as well as space weather monitoring and forecasting, and 2) The research will be closely linked into several key research topics in nighttime astronomy – the physics of stellar coronal heating, stellar magnetic fields and stellar flares, as the sun is the only star that its detailed structure can be revealed.

A.3 The Technical Detail of the AO project for the 1.6-m NST

As discussed above, with its 1.6-m aperture, the performance of the NST will be significantly improved if AO is available to correct the wavefront errors caused by atmospheric turbulence. We will develop a new AO system for the NST, which is re-tailored from the current AO system of the 65-cm telescope. The current AO-76 is one of the most successful solar AO systems in the world and is delivering excellent diffraction-limited images in the visible and NIR with the BBSO 65-cm telescope (Rimmele et al. 2003, Ren et al. 2003a, Didkovsky et al. 2003, Tritschler et al., 2005). Previous experience plus crucial hardware and software components that are in hand give us enough confidence and ability to transfer it to the NST.

A.3.1 Evaluation of the Strehl Ratio

The AO design parameters are driven by the telescope properties as well as the seeing conditions at the site. In general, the seeing (Fried) parameter r_0 is used to quantify the seeing conditions at a site. r_0 is the coherence length of the atmospheric turbulence. For telescope apertures larger than r_0, the resolution is limited by seeing. The Fried parameter is wavelength dependent($r_0 \propto \lambda^{\frac{6}{5}}$ for Kolmogorov turbulence).

As stated above, the NST has an aperture that is about three times that of the current 65-cm telescope. Thus the AO system could fully correct the atmospheric turbulence at $1.6\mu m$ in the NIR. Meanwhile, for

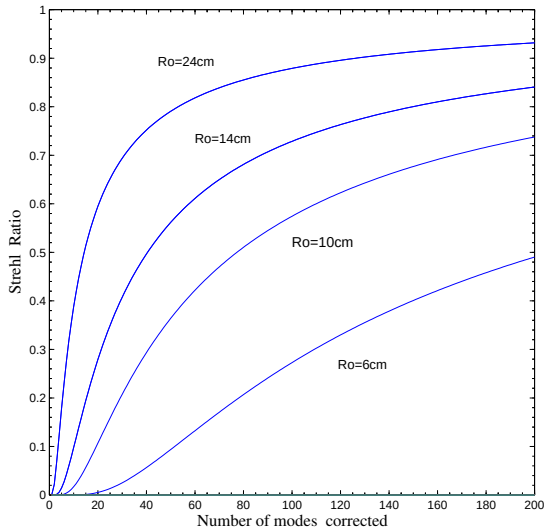

Figure 7: Theoretical Strehl ratio as a function of the corrected modes at different seeing conditions: r_0=6 cm, 14 cm and 24 cm are the BBSO median seeing at 0.5, 1.0 and 1.6μm respectively. In addition, a curve for r_0=10 cm is included for the discussion in the proposal.

visible wavelengths, it could partially correct the turbulence under good seeing condition. The median seeing at BBSO is about r_0= 6 cm at 0.5μm, while it is 24 cm at 1.6μm. The 24 cm seeing is well-sampled by the Deformable Mirror (DM) and Wave-Front Sensor (WFS) lenslet array, both of which have 10 elements across the pupil. Let us examine the details.

The Strehl (S) ratio, which is the ratio of the maximum intensity in the AO corrected image to that in the diffraction limited image, is generally used to quantify the AO system performance. Figure 7 plots the expected Strehl ratio vs. number of corrected modes, using r_0 as a parameter. It does not consider the noise the WFS images. As can be inferred from the theoretical Strehl ratios in Figure 7 that even moderate variations in r_0 will result in large variations in Strehl, if only a small number of Zernike modes are corrected. This is mostly due to additional aberrations in higher order Zernike modes, which increases as r_0 decreases.

From Figure 7, at 1.6μm, when the median r_0 is 24cm, 76-mode correction would achieve a median Strehl ratio of 0.84. While in visible at 0.5μm, the median r_0 is 6cm, the corresponding Strehl ratio is 0.18. However, r_0 above 10 cm is quite common at BBSO. Under the latter conditions, we can achieve a Strehl ratio above 0.5. In summary, at least 50% of observing time, the achieved AO correction Strehl ratio at 1.6μm is above 0.84; at 0.5μm, 10% of observing time will have a sustained Strehl ratio above 0.5.

A.3.2 Overview of the AO Development Effort

The conceptual design of the operating BBSO AO is very straightforward. A beam splitter directs a light beam to the wavefront sensor (WFS) that will do the following: 1) The telescope aperture is sampled by a lenslet array, which in turn forms an array of images of the object (e.g. granulation) to be imaged by a camera with kHz frame rate. 2) Cross-correlations between subaperture-images and a selected reference subaperture-image are computed via a very fast computer-Digital Signal Processor (DSP). 3) Local wavefront tilts are computed by locating the maximum or centroid of the cross-correlations (CC) to subpixel precision, and 4) Drive signals for the Deformable Mirror (DM) are derived from the wavefront sensor data using a modal wavefront reconstruction algorithm (e.g., Madec 1999). With sufficiently good seeing, the WFS is capable of using solar granulation, or other time varying, low contrast, spatially extended targets to measure the wavefront aberrations. The current bandwidth of the correction is 135Hz in its closed-loop mode.

The wave-front sensor is a correlation Shack-Hartmann WFS. The WFS is designed to be able to process up to 80 sub-apertures. The wave-front sensor detector is a Baja CMOS 10-bit camera which has 1280$\times$1024 pixels. We achieve a frame rate of 2487 fps, using a 200$\times$200 sub-array. The small (D=15mm) tip/tilt mirror

is mounted on a Polytec PI S-330.30 piezo tilt platform, and the DM was manufactured by Xinetics, Inc. The WFS has 76 effective elements while the DM has 96 actuators.

Due to the vastly different image scales of the 1.6-m NST and the current 65-cm telescope, the optics will have to be re-designed to ensure that the pupil of the NST is correctly imaged onto the DM and the WFS lenslet with the correct size. This will also give us the opportunity to apply some lessons learned. Furthermore, the new optics would also be needed to relay the NST image from the telescope focal plane at the dome to the observing room 5-m below where the the scientific instruments are located. The WFS optics will also be re-designed to reflect the change in the image scale. The rest of the current AO-76 system, such as the electronics (including DSPs), WFS (except for wave-front optics), and some of the mechanical mounts could be used for the new AO system. The current tip/tilt mirror will be used in our initial operation, and we will develop a larger aperture tip/tilt system in parallel (see the following section).

A.3.3 Optical Design

Since the current AO system needs to be transferred to the new NST, the major work involves a re-design and construction of the optics. We are very confident about the AO design, as Co-PI Ren designed both working BBSO and NSO AO systems. He will be in charge of this new design work. There are some requirements for the optics of the new NST AO system: the optics must relay the NST focal plane image to the Coude room (a room one floor beneath the telescope) that is about 5-m below the NST focal plane; the field-of-view for the optics must be 180" in diameter, so that wide field observations will be possible. The initial design will be optimized in the near infrared wavelength range of 0.9 to 1.6μm, but will have acceptable results in the visible.

To deliver excellent optical performance, some of the optical components in the AO relay path will likely be custom-designed and made. Figure 8 compares the optical layout of two possible initial designs for the new AO main optical path, which does not include the WFS.

On the left side of the figure, we show a design that closely follows the current working BBSO AO system. The NST pupil is first imaged onto the tip/tilt mirror with a small beam size of $\sim$15mm diameter by the lens L1. The small pupil size is needed so that the small fast tip/tilt mirror can be used. The $180''$ field-of-view is decided by the field stop in the telescope. However, the sun is re-imaged after the tip/tilt mirror by lens L2 where a field stop could be located to select a smaller field of view. The solar image is then collimated by lens L3 and the telescope pupil is re-imaged again onto the DM with an 80-mm beam size. Finally, at the AO output, a real solar image with f/50 focal ratio is formed by lens L4, which could be fed to the science instruments. The DM, camera (and its lens) and WFS are all located on a horizontal optical bench so that the alignment can be done conveniently.

If we use lenses in our system, they will consist of three optical materials FK51/BK7/FK51. The FK51/BK7/FK51 triplet was successfully used in our previous AO design (Ren et al. 2003a) and is a good choice to correct possible chromatic aberrations over a wide wavelength range. The triplets are commercially available from vendors such as Optical Components Inc. There are two serious problems for the design that is based on the current AO system (shown in the left side of Figure 8): (1) the severe optical aberration over the wide wavelength range due to the chromatism, and (2) a large photo-power density at the pupil plane that is 6 time larger than the current value for the 65-cm telescope.

To overcome problem 1, we must consider reflective design. On the right side of Figure 8, we show a modified system to overcome most of the chromatism. We understand that a purely reflective system, which deployed only mirrors, is attractive for future possible broadband imaging. Unfortunately such a system may not be possible for our current AO system due to the fact that both the tip/tilt and DM mirrors need to be located at a pupil image, and the current tip/tilt mirror has a small beam size (15mm). A fast lens with a strong optical power is needed to compress the telescope focal plane image to such a small beam size on the tip/tilt. After the tip/tilt mirror, a re-image lens is needed to create a solar image before the collimator.

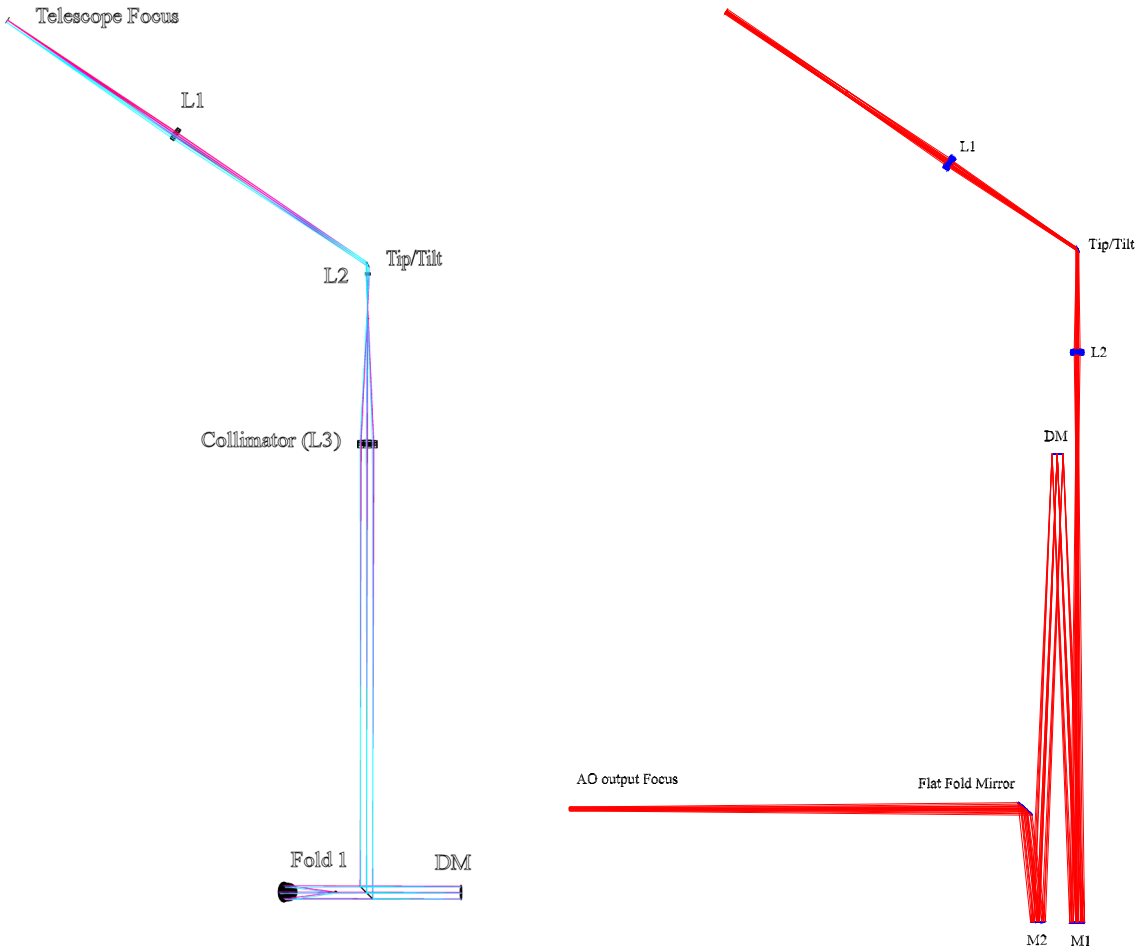

Figure 8: Comparison of the schematic conceptual optical layouts of two possible designs for the NST AO system. Left is the side view of an all-refractive system that is modified slightly from the working AO system of the current 65-cm telescope: the pupil is first imaged onto the tip/tilt mirror by the lens L1. The solar image is then collimated and the telescope pupil is re-imaged again onto the DM by Lenses L2 and L3. Finally, at the AO output, a real solar image is formed by another lens, which could be fed to science instruments. Right is a new design, i.e., a largely reflective system. Lenses after L2 are now replaced by mirrors.

Obviously these two lenses cannot be replaced by mirrors. This initial optical design which deploys more mirrors than the refractive design still needs two lenses. Both optical systems can efficiently transfer the telescope focal plane image to the Coude room where most the AO component including the WFS and all other observation instruments should be located. Comparisons of systems will be a major task in our design work.

To overcome problem (2), we must consider a larger tip-tilt mirror. Acquiring and setting up such a larger tip/tilt mirror needs time and effort. It will not be ready at the end of the first year. To make the AO ready as soon as the NST is installed, we have to plan to use the existing tip/tilt mirror to initially setup the AO. To avoid overheating in the tip/tilt mirror, we will stop down the field further to about $100''$ by $100''$. We will start to investigate a larger tip/tilt system as soon as the project is funded, and will be integrated into the system at the end of the project. Some further modification to the optical design will be made with the new tip/tilt. The proposed budget includes a Polytec PI S-340 system, which allows a mirror up to an

aperture of 10-cm to be mounted. We understand that the larger tip/tilt system will suffer a reduction in the correction frequency. If we mount the 5-cm mirror to the PI-340 platform, the working frequency will be 200Hz, instead of 800Hz for the current tip/tilt system. We will do a trade-off study to decide on the size of the tip/tilt mirror. Therefore, we are very careful in this development, and the PI S-340 may not be our final choice. After the hardware is decided, the software development will be needed to test and control the system.

A cubic beam-splitter will be located in the collimated beam after the DM, so that part of the light ($\sim$5%) is used for wave-front sensing. Since WFS works in a very narrow waveband ($\sim$10% of the wavelength) in the visible, commercial in-stock lenses could be used, and the chromatism would not be a concern. With moderate modification of the optics by changing the re-imaging lenses, the current WFS could be used for the NST's new AO system. Table 1 compares the essential hardware components of the old AO for the 65-cm telescope and the new AO for the NST.

Hardware Components	AO for 65-cm Telescope	AO for 1.6-m NST
Optical Design	All Refractive	Mostly Reflective
Tip/tilt System	15mm aperture	15mm aperture initially, at least 50mm finally
WFS (Camera, DSP, Lenslet)	Shack-Hartmann	Unchanged
DM	96-elements	Unchanged

Table 1: Comparison of hardware components of old and new AO systems.

Clearly, the AO designs presented are only two of the options that we will develop once this proposal is funded. We will certainly consider the all-reflective system. Mirrors have no chromatism and have larger transmission; however, the design with mirrors would be more complicated and instrumentation polarization is more severe. As part of our design effort, we will present a few designs for the refractive and reflective systems. We anticipate that in the end, we may construct a system with a combination of lenses and mirrors to optimize the performance, as we show on the right side of Figure 8.

Finally, the wave-front error of the entire AO system will be tested by using a single-mode fiber interferometer, which was developed by one of the Co-PIs (Ren et al. 2003b). The wave-front error test will also be done by using the fiber interferometer, so that the alignment error could be minimized. We will also use the interferometer to calibrate the WFS.

A.3.4 Electronic, Computing and Mechanics Systems

Again, the main system components for the AO system are: a correlating Shack-Hartmann WFS; a wavefront reconstructor and a deformable mirror(DM). Figure 9 shows the functional block diagram of the hardware that is basically applicable to the existing and the new AO. Although most of the electronic components will be transferred to NST, we anticipate that the software will need to be revised. Dr. John Varsik will be in charge of the software development, and the handling of the electronic system. Among many issues of software development, the reconstruction matrix (to convert from wavefront information to the movements of the actuators) needs to be modified to account for the entrance pupil difference between the 65-cm telescope and the NST. Co-PI Ren will provide the calculation of the matrix, to be implemented by Dr. Varsik. The mechanical system for the AO will be modified and fabricated by Jeff Nenow.

A.3.5 Setup, Testing and Observations of the New AO System

In Table 2, we list the major proposed tasks of this AO project. The main tasks of the first year will be the optical and mechanical designs of the AO system, and then their interface to the focal plane instruments. NST will begin its commissioning phase in the middle of the first year. The main tasks of the second year

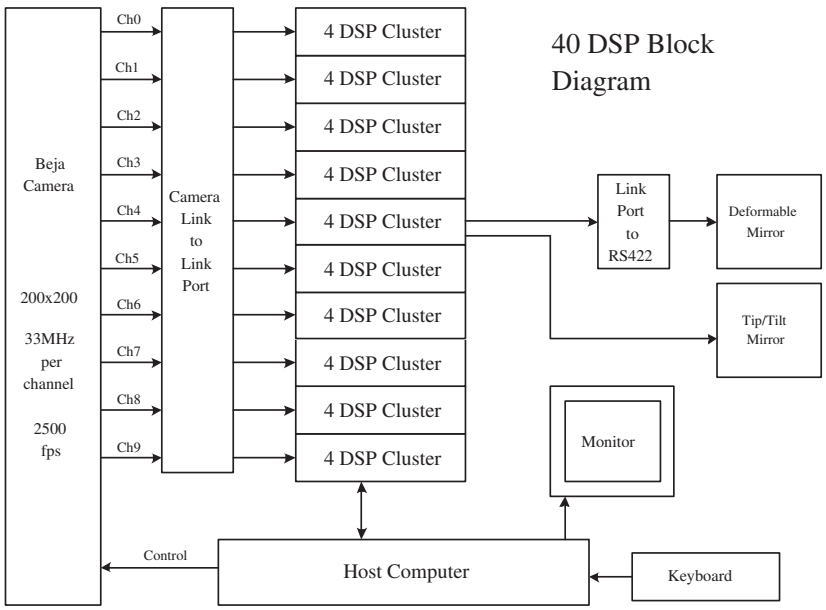

Figure 9: Functional block diagram of WFS and the reconstruction unit of the AO-76 system (Rimmele et al. 2003).

will be to set up the AO system, analyze WFS data and observe with the new focal plane instrument, in particular, the IRIM system. The designing, setting-up, testing and observing with the system will have the following components and will be carried out mainly by Wenda Cao, a post-doctoral associate and Dr. Ren:
(a) In the first half-year, we will design the main optics of the AO system, which must also relay the telescope's Gregorian focal plane image to the Coude room where most of the AO components are located on an optical bench. The mechanical design will be conducted in the second half-year. Concurrently, we will also design the optics for the WFS, for which a $20'' \times 20''$ field of view will be correctly imaged on the lenslet array and the CCD detector for wave-front sensing. We estimate that all the current WFS optics will be replaced by using in-stock components; in year 2, we will design the mechanical mounts for the WFS. The WFS will be carefully tested with our single-mode fiber interferometer to make sure that it has minimal optical aberrations. In addition we will test the main AO optics with the interferometer until the main optical system is well aligned. All parts will then be integrated as a whole system, and trial observations will be conducted to make sure that the whole AO system works properly.
(b) A new larger tip/tilt mirror will be investigated and tested in the first year, and integrated into the system in the second year.
(c) The NST will use 42-actuator active mirror system. If a separate WFS for the active mirrors encounters difficulty, AO-76 will be used to evaluate telescope aberrations by averaging WFS data over a set time period. This will provide an initial "lookup" table for the active mirror system, and evaluate the change of aberrations when the NST is moving to point in different directions, or under different thermal conditions. This will be done in the beginning of year 2.
(d) It is well-known that for a regular AO system, the high bandwidth correction requirement allows only partial correction. Also AO is not so effective for large fields of view because of anisoplanatism. The solution is to post-process the data in subfields smaller than the anisoplanatic patch, which for many applications is on the order of $5''$. The problem is to separate the object and the aberrations, two unknown quantities, in the images in the presence of noise, a third unknown. To obtain corrections in a larger field of view, BBSO is developing Phase Diversity (PD) system. PD utilizes a model of the image formation process to constrain

the estimation of the aberrations and the common object in two image channels with a known difference in the pupil phase, usually a focus shift. An image collected in this second optical channel will contain the effects of the unknown phase aberrations, but also will be influenced by the intentional defocus, which adds a known quadratic phase. Obviously, the phase information from a PD system will help us to analyze the wave front information of the AO system.
(e) Since the IRIM will be our initial science instrument to work with NSO and the new AO system, it must be in a very mature stage before the end of the first year. Dr. Cao will work on this system, to be tested with the current AO at BBSO and NSO/SP, then to be integrated to the new AO.
(f) A key component in the AO development is to analyze the wavefront data to evaluate the operation of the AO, and guide the modification of the system. Co-PI Prof. Denker will lead this effort, since he has gained significant experience in analyzing the current BBSO AO data (Tritschler et al., 2005).

Year	Task	Person In Charge
Year 1	Overall Management and Science Direction	Wang
	Interface with NST	Goode
	General Technical Advising and Design Review	Rimmele
	Optical Design	Ren
	Software and Electronics	Varsik
	Mechanical Design and Fabrication	Nenow
	Investigate and Build New Tip-Tilt System	Varsik, Nenow
	Wavefront Data Analysis for Current AO	Denker, and Undergraduate Student
	Finish IRIM with current BBSO and NSO AO	Cao and Graduate Student
Year 2	Overall Management and Science Direction	Wang
	Interface with NST	Goode
	General Technical Advising	Rimmele
	AO setup and test	Ren, Cao, Varsik and Graduate Student
	Optical Design Modification	Ren
	Software and Electronics	Varsik
	Build New Tip-Tilt System	Varsik, Nenow
	Mechanical Fabrication and Modification	Nenow
	Wavefront Data Analysis for New AO	Denker and Undergraduate Student
	IRIM Observation with AO	Cao and Graduate Student

Table 2: Tasks and Assignments for the Proposed AO Project.

A.4 Relationship to Future Work and Nighttime Astronomy

A.4.1 Higher Order Solar AO in the Future

After the NST is fully operational with the proposed AO-76 in 2008, we will then explore extending the full AO correction down to visible wavelengths. Obviously, there are many important spectral lines in the visible for the solar observations. In addition, the diffraction limit in the visible is three times better than that at NIR, so higher spatial resolution will be achieved if we can obtain full AO correction in the visible. We acknowledge that such an AO system would require a larger number of DM actuators, WFS sensing elements and fast DSPs, but the scientific return is also greatly enhanced. This will be a challenging task and require substantial new funding that we will seek in the future. However, working with AO-76 on NST is an essential step to help us gain the experience to upgrade the AO in the future. For example, with the proposed upgrade, we will study wavefront based on WFS data to characterize the local turbulence properties, and to decide how many elements will be needed for the higher order AO.

A.4.2 Multi-Conjugate AO

The project is also an essential step to enable us to explore Multi-Conjugate Adaptive Optics (MCAO) in the future. MCAO is a further development of the AO concept, where the correction is made by several DMs conjugated to different altitudes. While MCAO is a promising technique for atmospheric turbulence correction over a large field of view (Ragazzoni et al. 1999, Tokovinin, A. et al. 2001, Ellerbroek et al. 2003), nighttime MCAO is difficult for wave-front sensing, since multiple laser guide stars are needed for the tomographic wave-front reconstruction. To accurately reconstruct the 3-D turbulence, generally at least 3$\sim$5 laser guide stars are needed. Due to this and other difficulties, there is no nighttime MCAO that is in operation currently. The sun is a natural target for extended object wave-front sensing; any number of "target stars" could be made from the 2-dimensional structure of the sun by using correlation Shack-Hartmann wave-front sensing technique – a technique being using in our solar AO system. This provides an excellent opportunity to develop the MCAO. Once this downstream proposal is funded, we plan to build a dedicated WFS, which would allow wave-front sensing over a large field of view. The large field could be further divided into many sub-field for tomographic wave-front sensing. Data from such a wide field WFS could be collected and the 3-D tomographic wave-front turbulence could be constructed, which would eventually allow us to simulate and estimate the possible performance that is achieved for an MCAO system.

B Education and Research Training

BBSO currently has fifteen Ph.D. students (including 5 US and 3 female students) who will receive Ph.D.s from NJIT in various fields, ranging from applied physics to electrical and computer engineering to computer science. The very best NJIT students are attracted to the BBSO program. The typical student designs and builds the instruments used to make his/her Ph.D. measurements in BBSO. These students utilize the laboratories and our small observatory on campus to test the instruments for use at BBSO. BBSO also supports 2-3 undergraduate students for summer research at Big Bear.

Although we do not seek additional funding for students in this proposal, one of the Ph.D. students and an undergraduate student supported by BBSO's operation budget will be assigned to the project. We believe that this project will be a strong draw for talented NJIT students who are already interested in instrument development.

BBSO also plays an important role in training Post-docs for the solar physics community, through various instrumentation and research projects. Since NJIT took over the operation of BBSO in 1997, eight of our post-docs have obtained tenure track/tenured positions.

C Personnel and Management

As the project is relatively small, PI Wang will also act as the Project Scientist/Project Manager to monitor the progress of the project and ensure the proper connection between instrumentation and scientific return. He will coordinate with the NST Project Manager, Roy Coulter. Co-PI Goode will oversee the integration of the AO system and the NST, as he is the PI of the NST project. Co-PI Denker will participate in the design of the optical system and analyze WFS data. Wang, Denker and Goode will not charge this grant as they are paid as regular faculty members. The proposed budget will cover 50% of Co-PI Ren's salary, and 50% of the salary of a post-doc, Wenda Cao, 25% of the salary of Varsik, a research professor, plus 25% of the salary of Jeff Nenow, the mechanical engineer at BBSO. Dr. Rimmele will participate in the project under the role of general advising and reviewing of designs, using his profound experience in AO projects. The hardware cost of the project is around $50k.

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