

**Title of Investigation:** MRI: Development of High-Order 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 1.6-m aperture, off-axis, New Solar Telescope (NST). It will replace Big Bear Solar Observatory (BBSO)'s principal telescope with its 65-cm aperture. This largest solar telescope will play a leading role in solar physics research and education. 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.

An AO system to match the 1.6m aperture is a critical component to achieve the scientific goals of NST. 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. It is insufficient for the correction in the visible for NST. This proposal seeks funding to build the 349 sub-aperture AO for NST. We estimate that, under median seeing conditions at BBSO, the predicted Strehl ratio at  $0.5\mu\text{m}$  is above 0.6 with AO-349. The key tasks in this proposal include the optical design, building electronic system and subsequent setup/testing of the AO system under the NST. We are considering a design that will be as reflective as possible to make the system achromatic. The specific scientific objectives for the AO equipped NST 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 National Solar Observatory is building its flagship telescope: the 4-m Advanced Technology Solar Telescope (ATST). Until ATST is built, the AO equipped NST will be the largest aperture solar telescope, located in one of the best observing sites. While the ATST's primary science focus is on the physics of small scale flux tubes and solar corona, NST with its unique seeing condition, will enable new, cutting edge science in study solar activity. 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 will 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 Ph.D. student, a undergraduate and a post-doc will participate in the project. The data will likely to be used in many Ph.D. theses. Our data will be open to the scientific community and about 50% of observing time will be open for competition.

## A. Project Description

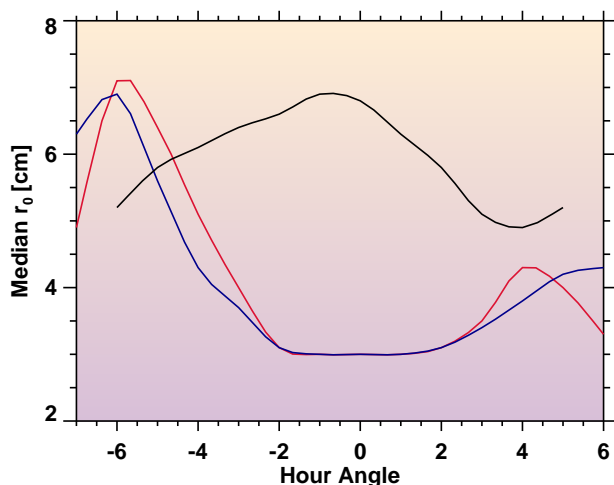
### A.1. Research Activities

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  $1.7 \mu\text{m}$  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 48 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

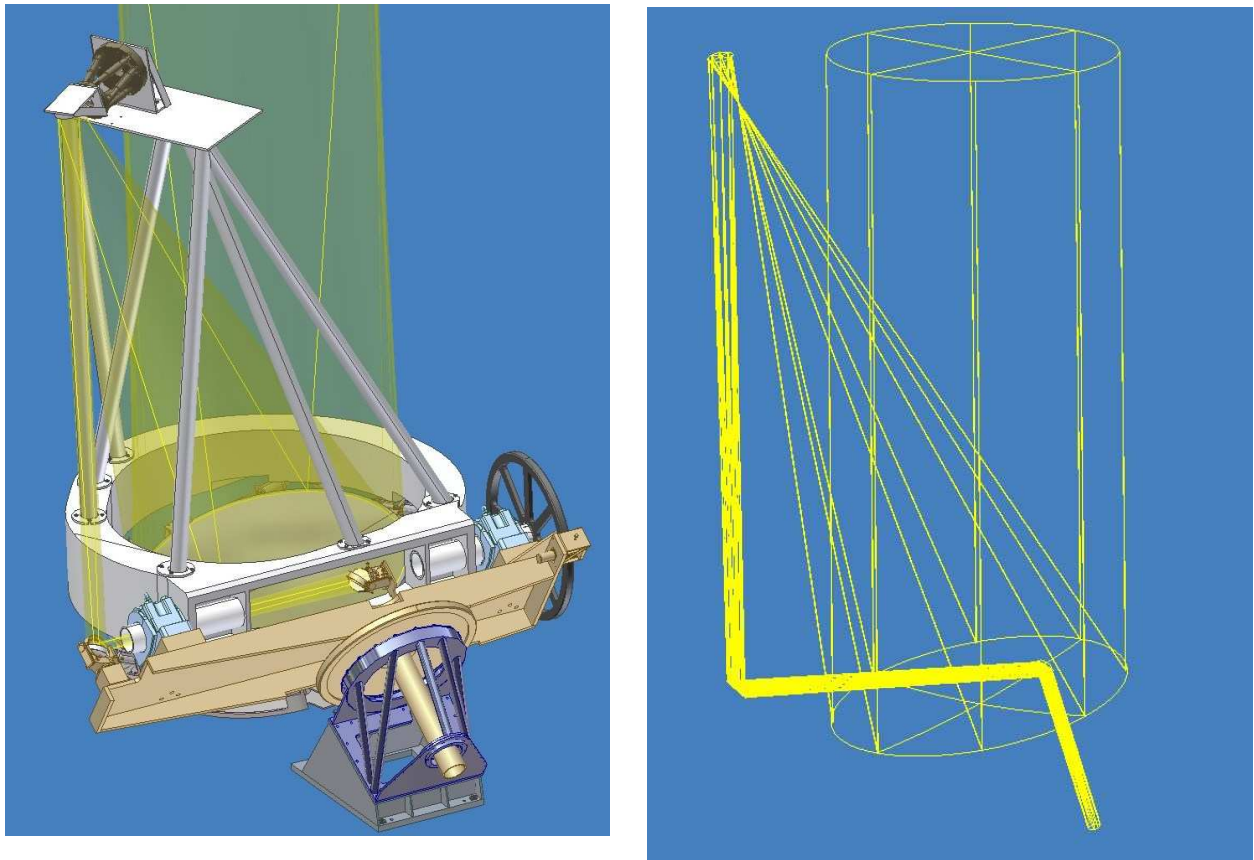


Figure 2: Schematic of the 1.6 m off-axis, open NST and its optical layout.

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).

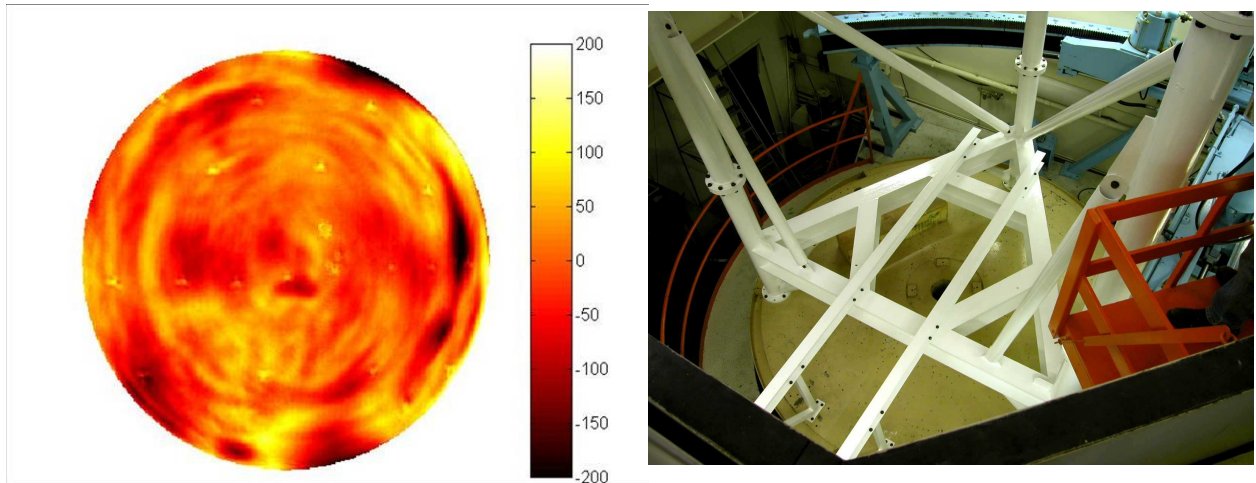


Figure 3: The left panel shows the interferometric pattern of the residual polishing error. As of this writing, the rms error is below 48 nm. On the right is the testing tower being installed. At the top is the 0.5 m spherical mirror and the PM is transferred from the polishing tool to the bottom of 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 was contracted to design and build the new dome. 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 dome was installed in 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, 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.

### 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 Rimele of NSO, as a research professor at NJIT, was the PI for the project. He will participate in this proposed project as a 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; Rimele, 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



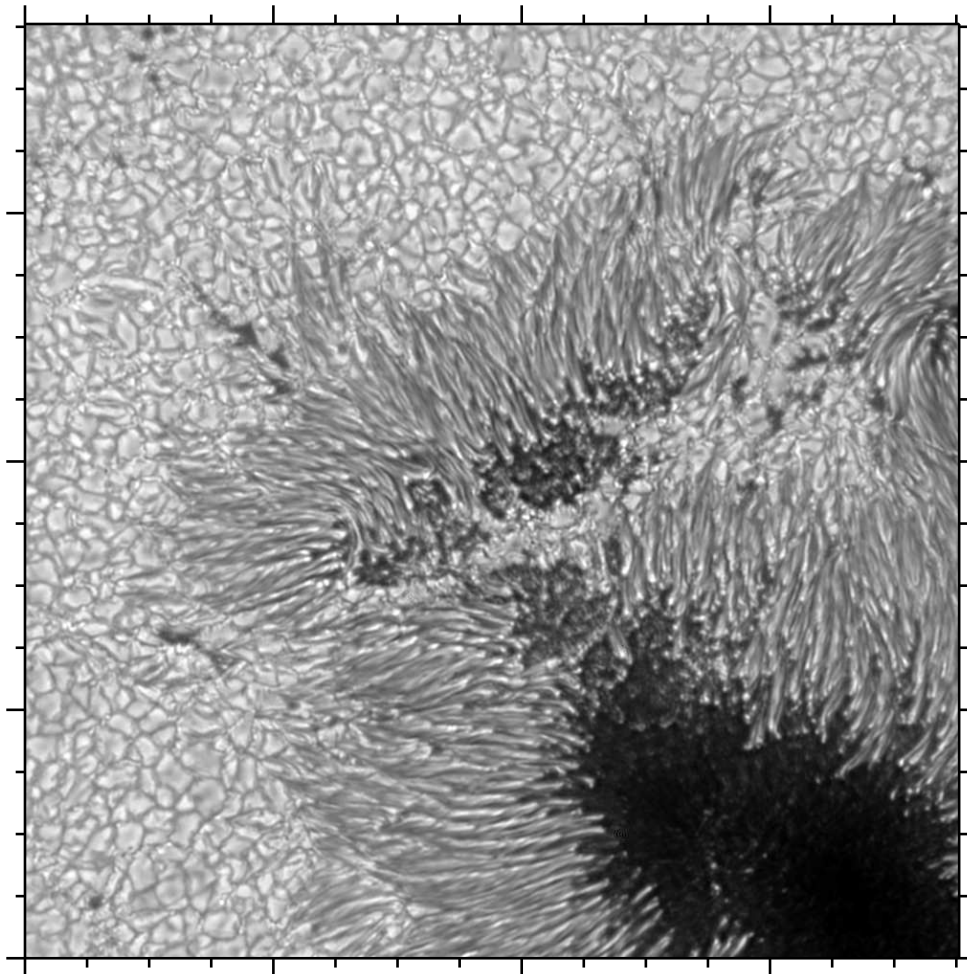


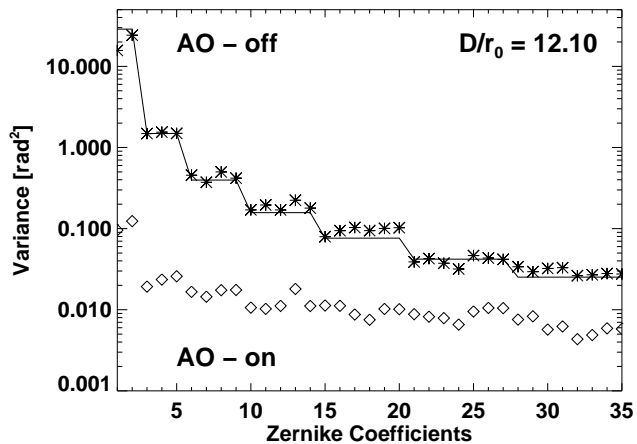
Figure 4: A recent diffraction-limited image obtained at BBSO on April 29, 2005 with the AO-76 system and speckle reconstruction.

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.

### **A.1.3. Near Infrared Imaging Vector Magnetograph System**

BBSO has built and employed several generations of near IR imaging systems. The most recent and 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  $2.5 \text{ \AA}$  at  $1.56 \mu\text{m}$ , giving us a  $2.5 \text{ \AA}$  wide prefilter (narrower than the  $5 \text{ \AA}$  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,

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).



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  $1.7\mu m$ . 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.1.4. Science Drivers for the AO Equipped NST

##### (a) 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 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  $1.56\mu m$ . 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.

### (b) 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.

### (c) 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.

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.2. Description of Research Instrument and Needs

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 follows the concept of the current AO system of the 65-cm telescope, but with significantly improved optical design and hardware upgrade. 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). These give us the technical ability and confidence to build the AO-349.



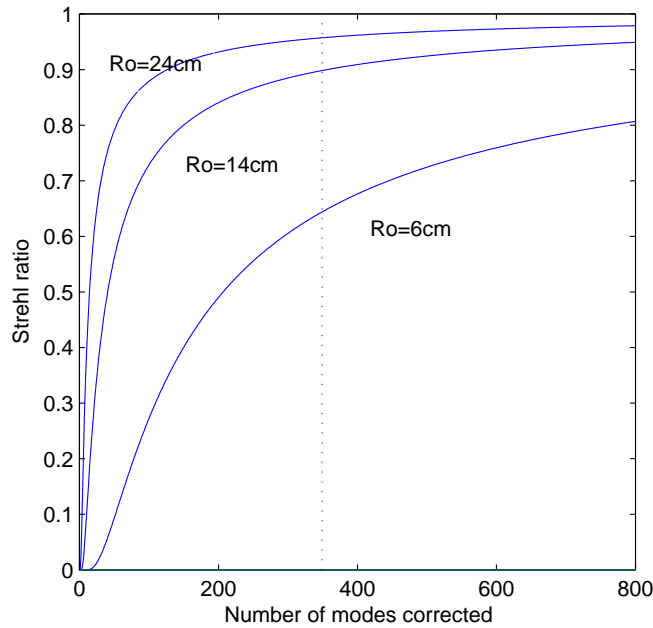


Figure 6: Theoretical Strehl ratio as a function of the corrected modes at three different seeing conditions:  $r_0=6, 14,$  and  $24\text{cm}$  are the BBSO median seeing at  $0.5, 1.0$  and  $1.6\mu\text{m}$  respectively. The dotted line indicates the maximum modes of correction of the proposed new AO system.

### A.2.1. 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 ( $r_0 \propto \lambda^{5/3}$  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-76 system could fully correct the atmospheric turbulence at  $1.6\mu\text{m}$  in the NIR. The median seeing at BBSO is about  $r_0=6\text{ cm}$  at  $0.5\mu\text{m}$ , while it is  $24\text{ cm}$  at  $1.6\mu\text{m}$ . A higher order AO must be developed for NST to observe in the visible.

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 6 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 6 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.

At  $1.6\mu\text{m}$ , when the median  $r_0$  is  $24\text{cm}$ , 76-mode correction would achieve a median Strehl ratio of 0.84. While in visible at  $0.5\mu\text{m}$ , the median  $r_0$  is  $6\text{cm}$ , the corresponding Strehl ratio is 0.18. If the correction order is increased to 349, the Strehl ratio will be 0.64 for the visible, reaching a satisfactory correction level.

### A.2.2. 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. With much improved computing speed and newly developed DM, we anticipate to achieve the similar bandwidth for AO-349.

The wave-front sensor is a correlation Shack-Hartmann WFS. The WFS is designed to be able to process up to 360 sub-apertures. The wave-front sensor detector is a Baja CMOS 10-bit camera which has  $1280 \times 1024$  pixels. We will achieve a frame rate of 1100 fps, using a  $300 \times 300$  sub-array. Therefore, each sub-aperture uses 15 by 15 pixels. The tip/tilt mirror is mounted on a Polytec PI S-340 piezo tilt platform, and the DM will be manufactured by Xinetics, Inc. The WFS has 349 effective elements while the DM has 349 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.

### A.2.3. Optical Design

Our proposed 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.

To deliver excellent optical performance, some of the optical components in the AO relay path will likely be custom-designed and made. Figure 7 is the optical layout of the initial design for the new AO main optical path, which does not include the WFS. There are two serious problems for the design on the current AO-76 system: (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 a more reflective design. In Figure 7, we show a preliminary design to overcome most of the chromatism. We understand that a purely reflective system, which deployed only mirrors, is attractive for 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. A fast lens is needed to compress the telescope focal plane image to 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. Obviously these two lenses cannot be replaced by mirrors. This initial optical design which deploys more mirrors than the refractive design still needs four lenses.

To make the reflective design more feasible, we plan to develop consider a larger tip-tilt mirror system. 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 (as the design in Figure 7 uses), the working

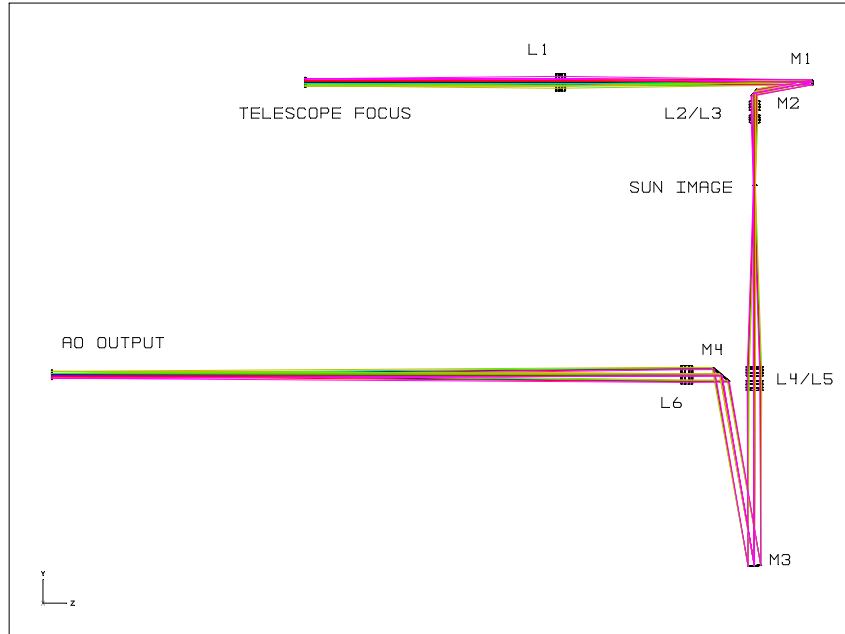


Figure 7: The new AO design, i.e., a combined reflective-refractive system. M1 is the tip/tilt and M3 is DM.

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	50mm aperture
WFS (Camera, Baja 1280 by 1200)	200 by 200 sub-array	300 by 300 sub-array
WFS (Lenslet)	10 by 10	20 by 20
WFS (Bittware DSP)	ADSP-21160	ADSP-TS201
DM (Xinetics)	96-elements 7-mm spacing	349-elements 5-mm spacing

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

Clearly, the AO design presented is only one of the options that we will develop once this proposal is funded. We will certainly consider a more 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 still need to construct a system with a combination of lenses and mirrors to optimize the performance, as we show in Figure 7. Figure 8 shows the spot-diagrams in the

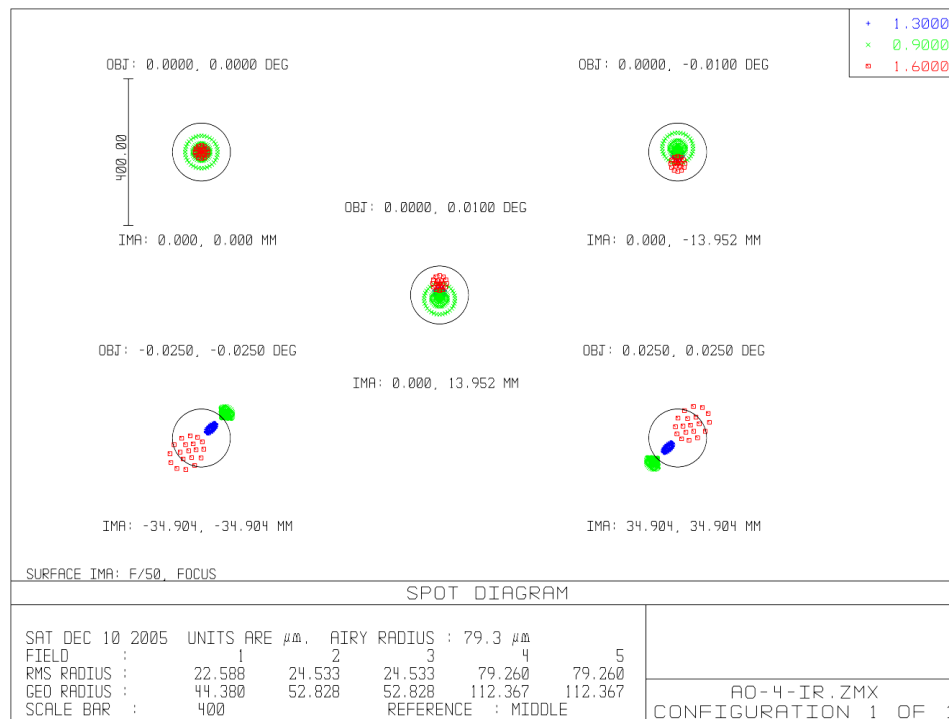
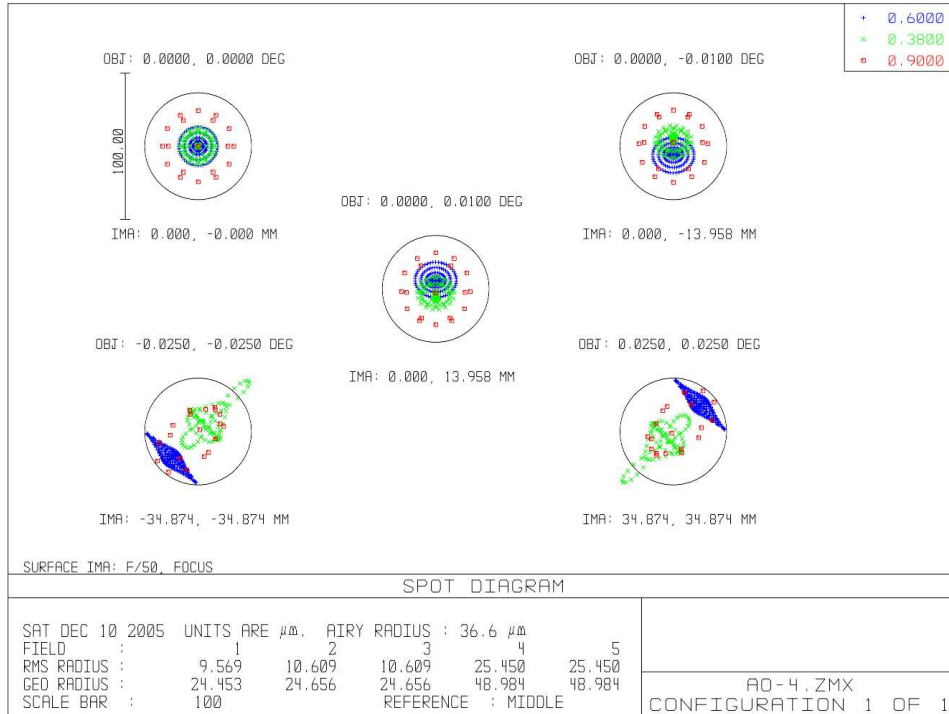


Figure 8: Spot diagrams showing near diffraction-limited image quality for the wavelength range from 0.39 to 1.60  $\mu$ . Top: visible range, bottom, NIR.

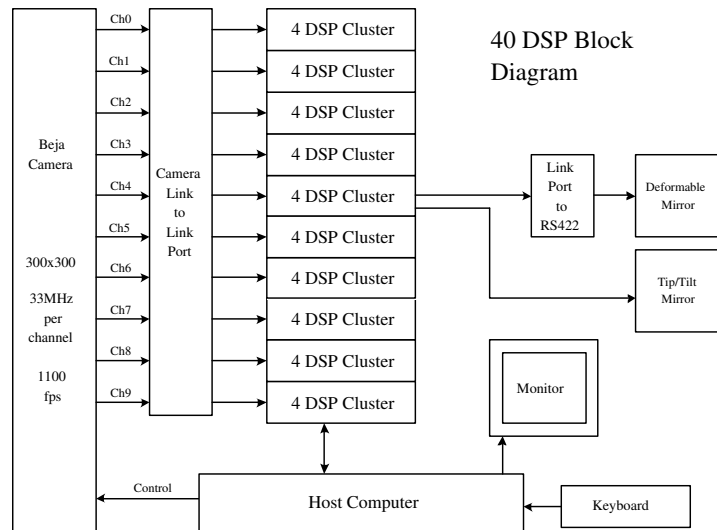


Figure 9: Functional block diagram of WFS and the reconstruction unit of the AO-76 system (Rimmele et al. 2003).

visible and NIR ranges for the design in Figure 7. They are the geometrical spots of the PSF (point spread function). The circles are the Airy disks (diffraction disks). The performance is close diffraction-limited over the entire FOV and wavelength range. NIR and visible will need two separate CCD systems with separate camera lenses, as we have planned already.

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.2.4. 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 new AO. Dr. John Varsik will be in charge of the software development, and Dr. Thomas Spirock will design and construct 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 made. Co-PI Ren will provide the calculation of the matrix, to be implemented by Dr. Varsik. For the electronic part, the following tasks need to be finished: (1) Design and construct an interface to connect the WFS camera and the DSP board; (2) Design and construct an interface to connect the DSP and tip/tilt; (3) Design and construct an interface to connector the DSP and the DM.

### A.3. Impact of Infrastructure Projects

#### A.3.1. Relationship to Future Work and Nighttime Astronomy

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 3~5 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.

### **A.3.2. Education and Research Training**

NJIT has a diverse student body in an urban environment, with a large minority student population. BBSO highly prizes its special role in the education of the next generation of scientists who build instruments. We 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.

We seek funding for two students in this proposal: a Ph.D. student and an undergraduate student. We believe that this project will be a strong draw for talented NJIT students who are already interested in instrument development. The graduate student will play the important role in the AO design, the setup, observation and data analysis. We have recruited Patricia Jibben to fill this position. She will be located at BBSO after finishing core courses on campus in the first year. The undergraduate will mainly participate in software development, and data analysis. In addition to the direct student participation of the project, the data will be important sources for graduate and undergraduate research. The telescope will also become a teaching tool for the optics, mechanics, computer control and solar physics.

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. Dr. Cao is the post-doc involved in this project.

### **A.3.3. Data and Telescope Time**

Since NJIT began operating BBSO, its telescope time and data have been open to the community. Many scientists have had observing time. Further, several Ph. D. students from around the world are using BBSO data as a central part of the work on their theses. Data requests come to BBSO on a daily basis from around the world. We are an active participant in the Virtual Solar Observatory (VSO). Users of our telescopes and data are only asked to acknowledge BBSO in their resulting publications. Many observers use our data to help plan their observing campaigns. As of 2005, all the BBSO data from the previous twelve months, on a rolling basis, are online, supported by a search engine to aid users.

The observing time of NST will be oversubscribed because of its much improved scientific capability comparing to the old 65-cm telescope. We will continue our open observing time, open data policy. We plan to make 50% observing time available to the community. The observing proposals will be submitted through the same web page that we used in the past 5 years. Telescope Allocation Committee will rank the proposals and allocate times. For the NST data, if it is not part of a special observing program, it is open



immediately. A web page describing all the requests will ensure that researchers will not duplicate the data analysis effort. If it is from a special observing program, then we let the PI of that program to coordinate with the requestor.

#### A.4. Management Plan

PI Wang will be 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. Dr. Rimmele will participate in the project under the role of general advising and reviewing of designs, using his profound experience in AO projects. Co-PI Ren will lead the design and setup of AO. Varsik will be in charge of software development, and Spirock, the electronic system.

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 and Graduate Student
	Software	Varsik and Undergraduate Student 1
	Electronics	Spirock
	Wavefront Data Analysis for Current AO	Denker and Undergraduate Student
	Focal Plane Instruments 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
	Optical Design Modification	Ren
	Software	Varsik and Undergraduate Student
	Electronics	Spirock
Year 3	Overall Management and Science Direction	Wang
	Interface with NST	Goode
	General Technical Advising	Rimmele
	AO setup and test	Ren, Cao, Varsik, Spirock and Graduate Student
	Software and Electronics	Varsik and Spirock
	Wavefront Data Analysis for New AO	Denker and Undergraduate Student
	Observation with AO	Cao and Graduate Student

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

In Table 2, we list the major proposed tasks of this AO project. The main tasks of the first year will be the optical, electronic 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 will be fine-tuning of design and software development. The task of the third year is to set up the AO system, analyze WFS data and observe with the new focal plane instruments. Here are the detailed tasks:

(a) As soon as this project is funded, 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. Concurrently, we will also design the optics for the WFS, for which a  $30'' \times 30''$  field of view will be correctly imaged on the lenslet array and the CCD detector for wave-front sensing. 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, 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-349 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 3.

(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 Fabry Perot systems will be our main science instrument, it must be in a very mature stage before the end of the second 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).

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