

**Title of Investigation:** MRI: Development of High-Order Adaptive Optics for the 1.6 Meter Solar Telescope in Big Bear

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### **Project Summary**

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii (UH) and the Korean National Observatory (KAO), is building its 1.6 m aperture, off-axis, New Solar Telescope (NST). It will replace Big Bear Solar Observatory (BBSO)'s principal telescope, which has an 0.6 m aperture. The NST will be the largest aperture solar telescope, and it will play a leading role in solar physics research and education. The project is funded and is well underway; first-light is anticipated early in 2007. 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 0.6 m telescope and the NSO 0.7 m Dunn Telescope, respectively.

An AO system to match the 1.6 m aperture is essential to achieve the scientific goals of the NST. AO-76 is a high-order system for the 0.6 m BBSO telescope, which is successfully operating in both the visible and near infrared (NIR) ranges. AO-76 is insufficient for reliable correction in the visible for the NST. This proposal seeks funding to build a 349 sub-aperture AO system for the NST. We have carefully estimated that under median seeing conditions at BBSO, the predicted Strehl ratio at  $0.5 \mu\text{m}$  will be above 0.6 with AO-349. The key tasks in this proposal include the optical design, the building of the electronics system and the subsequent setup/testing of the AO system utilizing the NST. Our benchmark is a design that will be as reflective as possible to make the system as achromatic as it can be. The specific scientific objectives for the AO equipped NST are campaign observations in: (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. Our campaigns will often be in collaboration with NASA Missions to maximize scientific advances to better understand our star. In sum, we directly address the two criteria required in any NSF proposal:

(1) Intellectual merit: NSO is planning to build its flagship telescope for the community: the 4 m Advanced Technology Solar Telescope (ATST). Until the ATST is built, several years from now, 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 the solar corona, the NST with BBSO's unique seeing conditions, will enable new, cutting edge science in the study of solar activity. Even after the ATST is on-line, the NST will continue to be an essential telescope in making campaign-style observations. We have in place the same core team used in the AO-76 project for AO-349, and in this we have already demonstrated our abilities by developing these two most successful solar AO systems. The tasks of the NST and AO teams are clearly defined, delineated and separated, although two teams work closely.

(2) Broad Impact: The development of the proposed AO system will enable us to further explore Multi-Conjugate Adaptive Optics (MCAO) by combining the hardware from AO-76 and AO-349. This effort is highly relevant to the development of MCAO systems for 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. As well, our effort in collaboration with NSO will be of benefit to the ATST project. Further, our 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, an undergraduate and a post-doc will participate in the project. The resulting data will 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 to the community.

## 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. Our campaigns are often in collaboration with NASA Missions to maximize scientific advances to better understand our star. 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 scientific and instrumental accomplishments that position us to advance to the next level of our scientific objectives, which will center on understanding energy release and transport on various 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, a project that is well on its way, is a crucial step toward this goal.

The Advanced Technology Solar Telescope (ATST) site survey was initiated in 2000 and 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 Adaptive Optics (AO) correctable, seeing conditions with extended periods of excellent seeing from sunrise to sunset (see Figure 1). For any modern, ground-based solar telescope, an AO system is required to correct seeing induced image smearing and distortions. A minimum Fried parameter of about 6 cm is required for AO correctability. Obviously, BBSO is a unique site for locating a large aperture solar telescope because it achieves diffraction limited resolution with AO for many consecutive hours, day after day. 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. However, if the telescope were placed very much higher than the site survey tower (as for ATST, but NST is only about twice as high as the tower), all sites would improve and the BBSO advantage would shrink. Haleakala was selected as the ATST site because of the ATST's primary scientific objectives: studying the physics of the solar corona and detecting the extreme fine structure of magnetic fields, which can be usefully studied with exceptional seeing for short periods of time. The lake at BBSO provides a natural inversion, which effectively suppresses the boundary layer and makes the observatory ideally suited for sustained, high-resolution and synoptic observing programs, and the 1.6 m New Solar Telescope (NST) is being built for these purposes, and more.

We now review our 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 completed 76-element AO project.

#### 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 0.6 m 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. The NST is a whole new system starting with being the largest aperture off-axis telescope. We have

made great strides in implementing this project, including the figuring of the largest aperture, off-axis primary mirror, the ongoing construction of the optical support structure with active optics, a new dome to house the larger telescope, and a whole new control system.

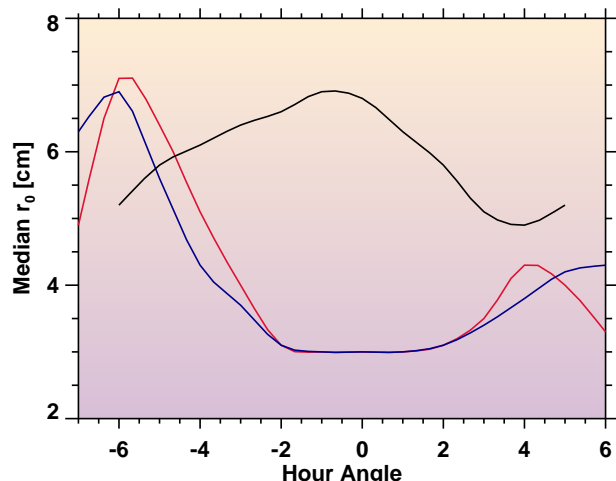
The project is described in detail in <http://www.bbso.njit.edu/newtelescope>. To minimize risk, we borrowed from the design of existing telescopes as much as possible. For example, the new, larger dome follows the SOAR design using the same vendor, with minimal, but required modification: the NST dome has louvers to ensure proper airflow inside the dome, and so this and other improved thermal properties of the new dome will solve the long-standing dome-seeing problem at BBSO. 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 and being implemented. The telescope has a 1.7 m primary mirror with the 1.6 m clear aperture. It has an 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 range will cover from 0.39 to  $1.7 \mu\text{m}$  in the Coude Room one floor beneath the telescope and all wavelengths including far infrared 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 is the thermal control system to keep the temperature of the mirrors very close to, or below that of the ambient air. We are using a wind-gate system in the new dome (discussed below) to control the airflow from the wind and help maintain the same temperature inside and as outside the dome. In addition, we will implement an airknife system to limit so-called "mirror seeing".

(b) From the outset, the central and risky part of the NST project was the figuring of the off-axis, primary mirror to high optical quality. However, the figuring of the Zerodur primary mirror is nearing completion at Steward Observatory Mirror Lab, University of Arizona (UA Mirror Lab), as part of their 20/20 project (<http://www.optics2001.com/telescope.htm>). We believe this was the optimal facility for figuring the NST primary mirror. The lab was 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 telescopes. 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 rms.

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).



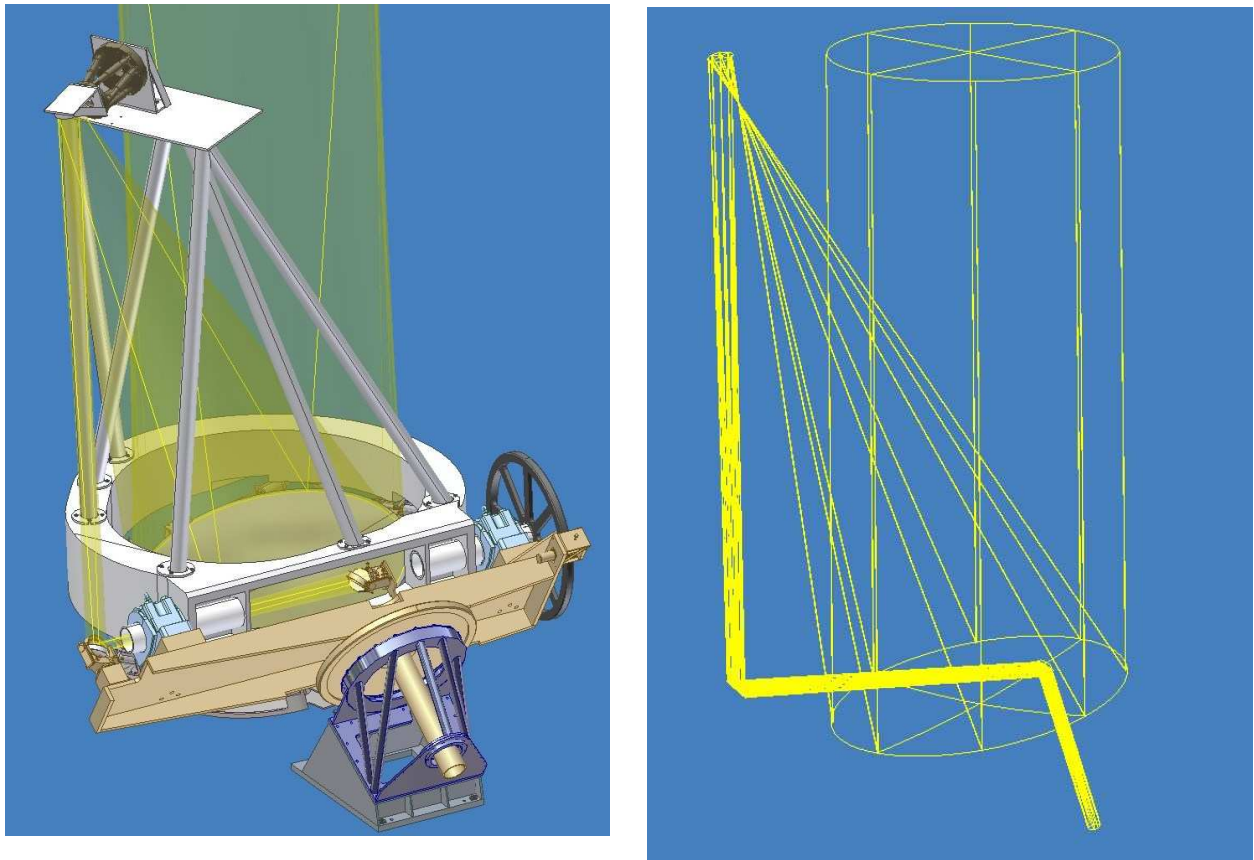


Figure 2: Schematic of the 1.6 m off-axis, open NST and its optical layout.

The polishing of the primary is progressing well and is scheduled for completion, including a series of final tests, no later than March 2006. The project is no longer risky because the residual error in the surface figure of the primary mirror is already very small. 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, novel holographic testing system to account for the off-axis nature of the mirror. It turns out that profilometer (most useful when the rms figure error is of order a wavelength) and holographic (most useful when rms errors are a fraction of a wavelength) testing of the primary yielded the same result over the visible, so we are confident of the testing. The polishing is nearing completion with the rms error being about 35 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 March 2006, the primary and the secondary will be tested in tandem in the UA 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

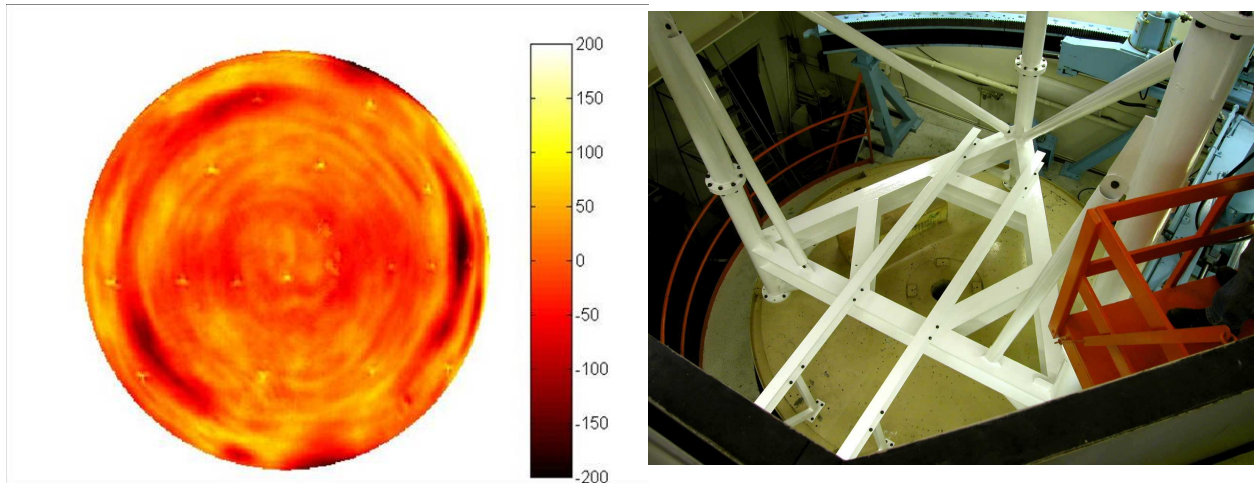


Figure 3: The left panel shows the interferometric pattern of the residual polishing error. As of this writing, the rms error is below 35 nm (less than shown in figure). On the right is the testing tower while it was being installed. At the top is the 0.5 m spherical mirror and the PM is transferred from the polishing tool to the bottom of the tower for testing. At present, testing is done after about 10 hours of polishing.

secondary optics. The heat stop will be constructed in the UH shop at the Institute for Astronomy.

(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. It will initially operate in an open loop (using a carefully constructed lookup table), and after initial testing it will operate as a closed loop system. 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).

(f) To accommodate the size of the NST and control the airflows for thermal control, a new dome was required. MFG Ratech was contracted to design, build and install the new dome. This task is now complete. 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, covering the height range of the primary mirror. The dome was installed late in 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 0.6 m telescope will continue under the new dome, and focal plane instruments and the existing AO will continue operating through the Summer of 2006. After the Summer 2006 observing season, the current telescope will be removed to make way for the NST.

(g) Development of the software for the telescope control system is more than halfway finished. The software team consists of three members from BBSO/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). Since we have a strong team for this task, different components of the software will be cross-checked, to ensure that they are working properly.

### **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 0.6 m telescope and the other for the 0.7 m 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 of 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; Rimmele, 2004; Yang et al., 2004; Tritschler et al., 2005; Xu et al., 2004, 2006). 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. The figure compares the variances of the Zernike coefficients for modes up to order 35, for AO-off and AO-on data (Tritschler et al., 2005). The Fried parameter for this particular data set is 5.4 cm, slightly lower than the value of the median seeing at BBSO. The variances are a factor of 100 smaller for the AO-corrected data. Therefore, the mean wavefront aberration is 100 times smaller after the AO-correction. The temporal variances were determined from time sequences of about 10000 AO measurements over the entire pupil.

### **A.1.3. Near Infrared and Visible Imaging Vector Magnetograph Systems**

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). The filter 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). The Lyot filter was designed as part of the Ph. D. thesis of a now graduated student, and the filter solves the longstanding problem of constructing a filter-based IR magnetograph, while avoiding the complications of using a double etalon. We have obtained and implemented a large format IR CMOS camera ( $1\text{k} \times 1\text{k}$ , 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 enables accurate measurements avoiding Zeeman saturation of the traditional filter-based magnetograph systems. Both magnetic field strength and the filling factor were derived from fitting the Stokes V profiles (Cao et al., 2006).

Although IRIM has many advantages on its own, to achieve the highest spatial resolution with NST, we must emphasize instrumentation in visible. We have developed a Visible Imaging Magnetograph system (VIM) that is tunable from 400 to 700 nm with a bandpass of 0.01nm (Denker and Tritschler, 2005). This system has also achieved its first light recently at BBSO. With AO correction, NST will achieve diffraction limited images with a spatial resolution of about 50 km, when observations are made at 500nm (better than three times the resolution possible in the near-IR with the NST).

### **A.1.4. Science Drivers for the AO Equipped NST**

As will be seen in the next section, when observing in the visible with the NST, AO-76 can achieve 50 km resolution with Strehl above 0.5 occasionally when  $r_0$  is above 12 cm. However, AO-349 can achieve 50 km resolution with Strehl above 0.5 more than half of the time. Therefore, campaigns following the evolution

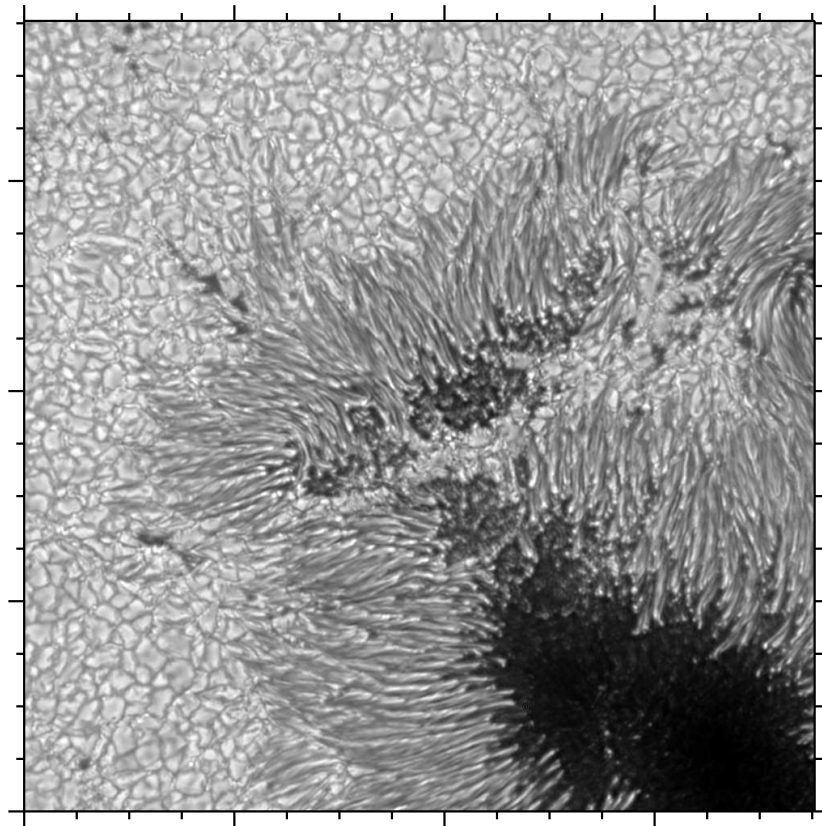


Figure 4: A recent diffraction-limited image obtained at BBSO on April 29, 2005 with the AO-76 system and speckle reconstruction.

of magnetic fields and flows for several hours continuously with such a Strehl, sub-arcsec resolution will be a unique feature of AO-349 equipped NST, even after ATST is built. The following scientific objectives reflect such a unique capability.

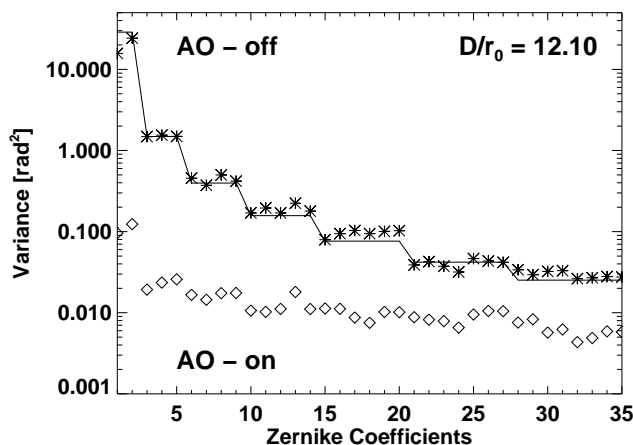
(a) High Cadence, High Resolution Studies of Solar Flares

One of the most important but not well-understood areas in flare research is the fine temporal and spatial structure of flares, so called “elementary bursts” (see Sturrock, 1989 for the review). The 1.6 m telescope will obtain high resolution, high cadence images of flares. These observations will provide details of electron precipitation on fine temporal and spatial scales. 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, 2006) presented the very first high resolution observations of an X10 white-light flare (from solar active region NOAA 10486 obtained with the Dunn Solar Telescope at NSO/SP on 2003 October 29, with AO-76). The study demonstrated the potential of obtaining the new science when the high resolution photospheric observations are combined with hard X-ray imaging and spectroscopic observations; however, even with a resolution approaching 100 km, the flare ribbons were not resolved. We anticipate that NST will provide new and basic insight into this problem.

(b) Structure and Evolution of Magnetic Fields and Flow Fields in Flaring Active Regions

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

Figure 5: Comparison of the variance of the Zernike Coefficients for AO-on (asterisks) and AO-off (carets) data determined from the BBSO AO WFS. The Solid curve represents a fit to the Kolmogorov spectrum of the AO-off data for  $D/r_0=12.10$  (Trischler et al., 2005), where  $D=65$  cm and  $r_0$  is the Fried parameter. The larger the ratio of  $D/r_0$ , the more important AO correction becomes.



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; 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. NST equipped with AO-349 will provide much more reliable and high quality measurements of vector magnetic fields. A consistently high Strehl ratio will ensure that the detected field variations will not be due to variation in seeing conditions. More specific scientific questions to be answered are: (1) 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? (2) How do electric currents evolve, and what is their relationship to particle precipitation?

#### (c) Dynamics of Kilogauss Flux Tubes

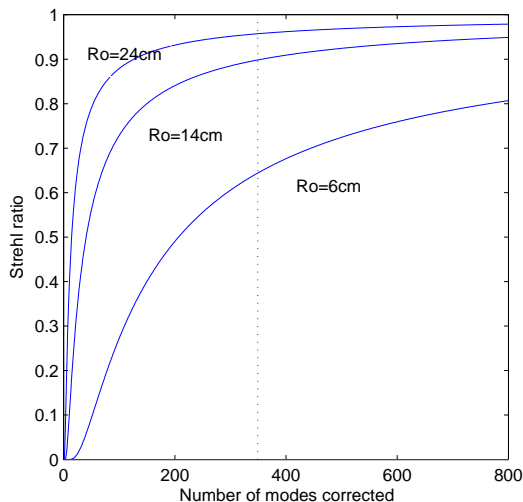
Understanding the dynamic behavior and structure of small scale kilo-Gauss fluxtubes is a primary scientific goal of the ATST. Since the NST will commence observations at least 6 or 7 years before the ATST, we will certainly heartily attack this problem with the AO-quipped NST. The key issues are the formation of photospheric flux concentrations having 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 fluxtubes interact with the turbulent flows in the photosphere? The observational determination 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.

## 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 propose to develop a new AO system for the NST, which follows the concept of the current AO system of the 0.6 m telescope, but with significantly improved optical design and hardware upgrades. 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 0.6 m telescope (Rimmele et al. 2003, Ren et al. 2003a, Didkovsky et al.



Figure 6: Theoretical Strehl ratio as a function of the corrected modes under three different seeing conditions:  $r_0=6$ , 14, and 24 cm are the BBSO median seeing at 0.5, 1.0 and 1.6  $\mu\text{m}$  respectively. The dotted line indicates the maximum number of modes that could be corrected by AO-349.



2003, Tritschler et al., 2005). These demonstrate our technical ability and give us the confidence that we will build the AO-349 system in an optimal way. We emphasize that AO-349 is essential to reap the full benefits of the investments in the NST.

### 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  $r_0$ , resolution is seeing limited. 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 0.6 m 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  $r_0=6$  cm at 0.5  $\mu\text{m}$ , while it is 24 cm at 1.6  $\mu\text{m}$ . A higher order AO must be developed for NST to observe in the visible in campaigns, while probing with spatial resolution of about 50 km. One must bear in mind that spatial resolution decreases linearly with wavelength.

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 performance of the AO system. Figure 6 plots the expected Strehl ratio vs. the 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, even moderate variations in  $r_0$  will result in large variations in the 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. Therefore, in order to minimize seeing induced variation in image contrast, high order AO is needed.

At 1.6  $\mu\text{m}$ , when the median  $r_0$  is 24 cm, a 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 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 above 0.5 (Wizinowich et al., 2004).

Anisoplanatism causes the quality of the AO correction to gradually decline with distance from the chosen isoplanatic patch. This dropoff will become more appreciable as the Strehl decreases. One may argue that post-processing such as speckle reconstruction may restore contrast of AO corrected, but low Strehl ratio

images. However, speckle requires multiple input images to construct one output image, therefore, one cannot expect to achieve our essential goal of sub-second cadence with post-processing.

### A.2.2. Overview of the AO Development Effort

The conceptual design of the operating BBSO AO system is quite straightforward. A beam splitter directs a light beam to the wavefront sensor (WFS) that does 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 a 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 now available and a newly developed DM, we anticipate achieving a similar bandwidth for AO-349, which is good enough for  $0.5 \mu$  light.

For AO-349, the wavefront sensor will be a correlation Shack-Hartmann WFS. The WFS is designed to be able to process up to 360 sub-apertures. The wavefront sensor detector is a Baja CMOS 10-bit camera, which has  $1280 \times 1024$  pixels. It has a frame rate of 1100 fps, using a  $300 \times 300$  sub-array. Therefore, each sub-aperture will be characterized by  $15 \times 15$  pixels. The tip/tilt mirror will be mounted on a Polytec PI S-340 piezo tilt platform (or a faster one if available), and the DM will be manufactured by Xinetics, Inc. The WFS has 349 effective elements, while the DM also has 349 actuators.

Due to the vastly different image scales of the 1.6 m NST and the current 0.6 m 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 effort involves the design and assembly of a new optical system for AO-349. We are very confident about the AO design, since Co-PI Ren designed the both the BBSO and NSO AO systems. These two AO-76 systems have the same hardware, but quite distinct optics. Ren will be in charge of this new design work. There are some requirements for the optics of the new NST AO-349 system: the optics must relay the NST focal plane image to the Coude room (a room one floor beneath the telescope), which is about 3 m below the NST's Gregorian focal plane; the field-of-view for the optics must be 180" in diameter, so that wide field observations will be possible. We emphasize that the optical design of the NST is final, and, as such, may be regarded as providing a well-defined light input to the downstream optics.

To deliver excellent optical performance, some of the optical components in the AO relay path will have to be custom-designed and manufactured. Figure 7 is the optical layout of the initial design for the new AO main optical path, which does not include the WFS.

The current AO-76 only corrects the chromatism at one wavelength and therefore cannot simultaneously work over the entire wavelength range of the visible and NIR, while the new design corrects this problem. The chromatic aberration is well-corrected by using a BK7/FK51/SK2 triplet (L2/L3 and L4/L5 lens pairs in Figure 7), in which all the glass material has excellent transmission over the visible ( $0.38 - 0.9 \mu$ ), and the NIR ( $0.9 - 1.6 \mu$ ). We understand that a purely reflective system, which deploys only mirrors, is another attractive for broadband imaging. Unfortunately such a system may not be possible for our AO system because both the tip/tilt and DM mirrors need to be located at a pupil image. A fast lens (L1 Figure 7) is needed to compress the telescope focal plane image to a small enough beam size on the tip/tilt. After the tip/tilt mirror, a re-imaging lens is needed to create a solar image before the collimator.

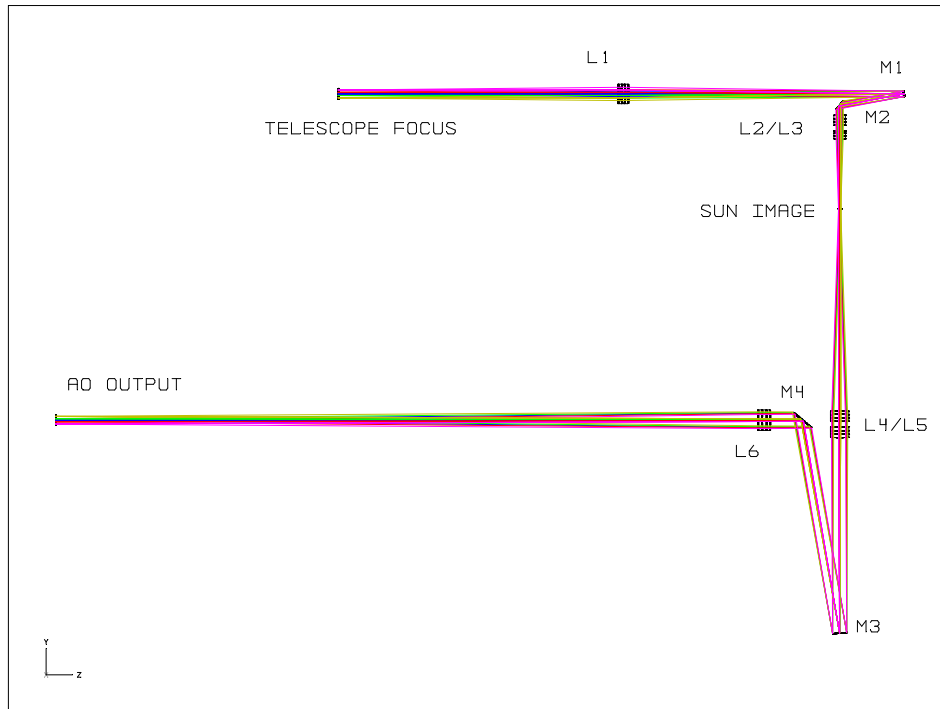


Figure 7: One of possible designs for the new AO system, i.e., a combined reflective-refractive system. M1 is the tip/tilt mirror and M3 is DM. M2 and M4 are flats. Lens L1 forms a pupil image to the tip/tilt. L2/L3 and L4/L5 are two triplet pairs. The AO output beam is  $f/50$  that is achieved through L6.

To make the reflective design more feasible, we plan to develop a larger tip/tilt mirror system. This larger tip-tilt will also solve the problem arising from a large photo-power density at the pupil plane (power six times larger than the current value for the 0.6 m telescope). We are investigating the Polytec PI S-340 system, which allows a mirror up to an aperture of 10 cm to be mounted, while the AO-76 tip/tilt has 1.5 cm. We understand that the larger tip/tilt system will suffer a reduction in the correction frequency. If we mount a 5 cm mirror to the PI-340 platform (as the design in Figure 7 uses for M1), 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. We are being very careful in this development, and the PI S-340 may not be our final choice.

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 wavefront sensing. Since the 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. Table 1 compares the essential hardware components of the old AO for the 0.6 m telescope and the new AO for the NST. Again, we emphasize that the optical design will be a major effort in this proposed project. What we have demonstrated here is that we have the expertise to conduct the design work, and know how to proceed.

Clearly, the AO design presented is a strawman that we will fully develop once this proposal is funded. We will certainly consider a more reflective system as mirrors have no chromatism. As part of our design effort, we will develop a few designs for 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 illustrate in Figure 7. Figure 8 shows the spot-diagram in the visible range for the design in Figure 7. They are the geometrical spots of the PSF (point spread function). The circles are the Airy disks (diffraction

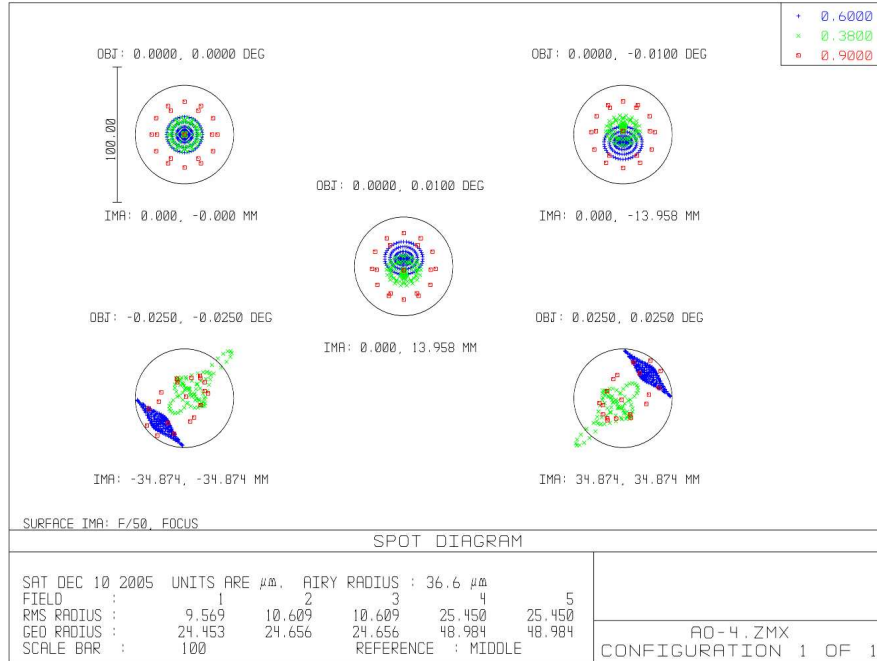


Figure 8: Spot diagram showing near diffraction-limited image quality for the wavelength range from 0.39 to 0.90  $\mu$ . The circles are the Airy disks (diffraction limit disks) of the designed wavelength (0.6  $\mu$ ), and clearly shows that except at the corners of the field of view (FOV), the spots of the geometric rays are within the Airy disk. Therefore the performance is diffraction-limited over most of FOV, while it is close-diffraction-limited at the corners of the FOV.

disks). The performance is close to diffraction-limited over the entire FOV and wavelength range. The design has even better performance in NIR. Like our current hardware setup for measuring magnetic fields (VIM and IRIM), NIR and visible will have two separate CCD systems with separate camera lenses. We do not need to adjust focus for either of the two benches when we switch wavelengths with AO-349. This is the major improvement over the current AO design for the 0.6 m telescope.

Hardware Components	AO for 0.6 m Telescope	AO for 1.6 m NST
Optical Design	Not Achromatic	Achromatic
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 (AO-76) and new (AO-439) AO systems.

Finally, the wavefront 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 wavefront error test will also be done by using the fiber interferometer, so that the alignment error is minimized. We will also use the interferometer to calibrate the WFS.

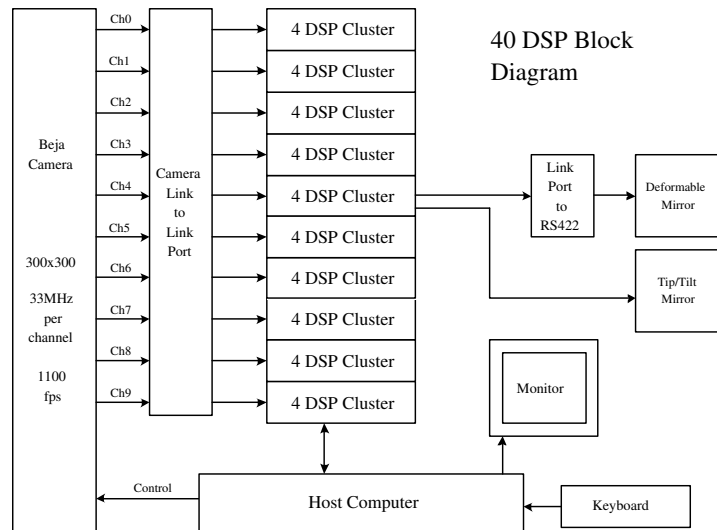


Figure 9: Functional block diagram of WFS and the reconstruction unit of the AO-349 system.

#### A.2.4. Electronic, Computing and Mechanical Systems

Again, the principal 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. Spirock has a Ph. D. in Electrical and Computer Engineering and is an accomplished instrument designer and builder at BBSO. 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 calculate the matrix, which will be implemented by Dr. Varsik. For the electronics 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 connect the DSP and the DM.

### A.3. Broader Impacts of AO-439 Project

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

This 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, in which corrections are made by more than one DM. Each is conjugated to a different altitude, while with a single DM, a single isoplanatic patch is fully corrected (anisoplanatism). While MCAO is a promising technique for correction of 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 wavefront sensing, since multiple laser guide stars are needed for the tomographic wavefront reconstruction. To accurately reconstruct 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 currently in operation. The Sun is a natural target for extended object wavefront sensing; any number of “target stars” could be made from the 2-D structure of the Sun by using correlations from Shack-Hartmann wavefront sensing – the technique being using in our solar AO system. This provides an excellent opportunity to develop MCAO. Once this proposal is funded, downstream we plan to build a dedicated WFS, which would

allow wavefront sensing over a large field of view. The large field could be further divided into many sub-field for tomographic wavefront sensing. Data from such a wide field WFS would be collected and the 3-D tomographic wavefront turbulence would be constructed, which would eventually allow us to simulate and estimate the possible performance that would be achieved for an MCAO system. Constructing MCAO is not part of our proposed task, however, some testing data can be obtained with the proposed AO that may provide important information to build the MCAO in the future.

### **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 have fifteen Ph. D. students (including 5 US citizens 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 assist in the AO design, the setup, observation and data analysis. The undergraduate will mainly participate in software development, and data analysis. In addition to the direct student participation in 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.

### **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 for 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 the NST will be oversubscribed because of its much improved scientific capability compared to the old 0.6 m 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 have used for the past 5 years. The Telescope Allocation Committee will rank the proposals and allocate time. 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 the data are from a special observing program, then we ask the PI of that program to coordinate with the requestor, and we would only intervene if that process were unsuccessful.

## **A.4. Management Plan**

During the building of the NST, we have assembled a strong instrumentation team. Now nearly all of the in-house design work for NST has been done, and construction of different parts has been sub-contracted to outside vendors. Part of the NST team will be shifted to the AO project. The AO work will not conflict with the NST effort. We already have our team in place to do the proposed work and we risk losing them

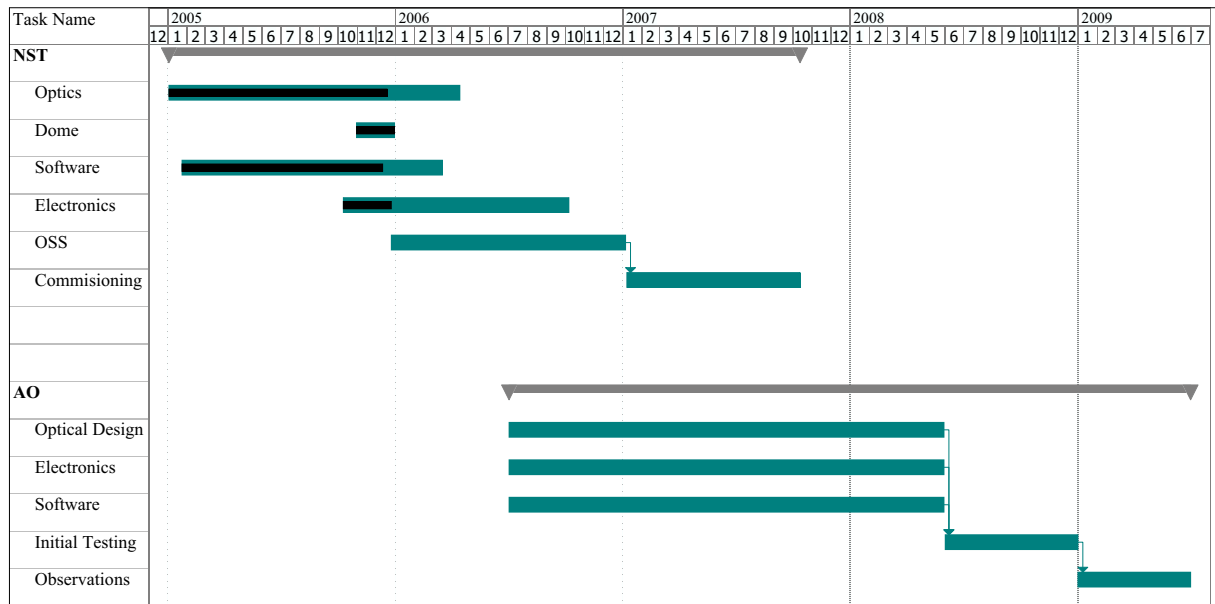


Figure 10: The Gantt Chart showing the project schedule for NST and AO.

and our momentum by delaying the start of the AO-349 project. PI Wang will manage the project and lead the science definition for the AO design. He will coordinate with the NST Project Director, 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 in the role of general advisor, and he will review the designs at each step using his extensive and profound experience in AO projects. Co-PI Ren will lead the design and setup of AO-349. Varsik will be in charge of software development, and Spirock, the electronics system. Even with the proposed effort of the AO team, NST still has sufficient technical and scientific staff lead by Goode with a team that includes Coulter, Abramenko (Electric Engineer), Yang, Shoumko (software) and Nenow (Mechanical Engineer).

In Table 2, we list the major proposed tasks of this AO project. The main tasks in 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 in the second year will be fine-tuning of design and software development. The task for 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 optical setup 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  $15'' \times 15''$  field of view will be imaged on its lenslet array and the CCD detector for wavefront sensing. The WFS will be carefully tested with our single-mode fiber interferometer to make sure that it has minimal optical aberration. In addition, we will iteratively 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. Dr. Rimmele will lead the design review to ensure that the design is optimized.

(b) A new larger tip/tilt mirror will be selected and tested, and integrated into the system in the second year.

(c) 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, when one does not require very high temporal cadence, is to post-process the data into 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. This project is funded by NSF-ITR grant (IIS-0324816). 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 wavefront information of the AO 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
	VIM and Wavefront Data Analysis for Current AO	Denker and Undergraduate Student
	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
	Optical Design Modification	Ren
	Software	Varsik and Undergraduate Student
	Electronics	Spirock
	Overall Management and Science Direction	Wang
Year 3	Interface with NST	Goode
	General Technical Advising	Rimmele
	AO setup and testing	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	Denker, Cao and Graduate Student

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

(d) Since the Fabry-Pérot systems will be our primary science instrument, they must be in a very mature stage before the end of the second year. Dr. Cao will continue work on the NIR system and Prof. Denker on the visible system, so that both will be fully exercised with the current AO at BBSO and NSO/SP and be ready to be integrated into AO-349.

(e) 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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