

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

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## Proposal Summary

In Fall-Winter 2008 at Big Bear Solar Observatory (BBSO), first light observations will be made with our 1.6 m clear aperture, off-axis telescope - the NST (New Solar Telescope). The NST will be the most capable, largest aperture solar telescope in the US until the 4 m off-axis ATST (Advance Technology Solar Telescope) comes on-line in the middle of the next decade. Here we propose, in collaboration with the National Solar Observatory (NSO), to build a high order adaptive optics (AO) system for the NST that will enable diffraction limited observations over NST's principal operating wavelength range from 0.4-1.7  $\mu\text{m}$ . This system is essential for the NST to achieve its scientific potential of probing for the first time the fundamental scale of the Sun's dynamic magnetic field, the origin of space weather, while providing valuable experience and risk reduction for the ATST project.

Earlier, BBSO and NSO collaborated in the successful implementation of two 76-element (each with a 97-element Deformable Mirror(DM)) AO-76 systems for the now retired BBSO 0.6 m telescope and the NSO 0.7 m Dunn Solar Telescope (DST), respectively. At first light, BBSO staff will implement the re-designed AO-76 on the NST. Detailed and realistic error budget analyses that include AO residuals, as well as telescope and instrument error budgets, show that AO-76 will yield diffraction limited images in the near infrared (1  $\mu\text{m}$ ) under nominal median BBSO seeing. But diffraction limited observations would be very rare indeed in the blue end of the visible spectrum, even though such observations would be an essential diagnostic for magnetic field measurements and be required for the highest possible spatial resolution.

*In a BBSO/NSO collaboration, we propose for funding to implement a 308 sub-aperture (349 element Deformable Mirror) AO system for the NST.* Few solar telescopes have AO, and none has such a high order correctability. The principal tasks for the NST high-order AO development include fine-tuning the optical design (which is quite close to that for AO-76 on the NST), operational integration of the wavefront sensor (WFS) and reconstructor electronics system, and the subsequent set-up/testing and performance characterization of the AO-308 system at the NST.

The principal scientific objectives for the AO-308

equipped NST are visible light 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.

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

(1) Intellectual merit: AO-308 will enable the NST to provide the community the highest resolution, diffraction limited data on the fundamental character of our dynamic star, while probing the origins of space weather. Over the next decade, NSO will build and begin operating the ATST, the flagship telescope for the solar community. AO-308 will be a significant testbed for the more complicated ATST AO. After the ATST is on-line, the NST will continue to be an essential telescope in making campaign-style observations.

(2) Broader Impact: The development of the proposed AO system continue our decade long tradition of training the next generation of scientists who build instruments. The resulting data will be used in many PhD theses. Our data will be open to the scientific community, and a substantial portion of observing time on the NST will be open to the community.

## A. Project Description

### A.1 Overview

High spatial and temporal resolution observations of the Sun are crucial for solving many outstanding problems in solar astronomy. In particular, high spatial resolution polarimetry is essential and requires large aperture telescopes with images corrected by high order adaptive optics. In Fall-Winter 2008 at Big Bear Solar Observatory (BBSO), first light observations will be made with the new 1.6 m clear aperture, off-axis telescope - the NST (New Solar Telescope). At this writing, observations of stars are about to commence for alignment purposes, which will be immediately followed by observations of the Sun. The NST will be used in traditional BBSO-style campaign observations to understand the dynamics of our star, but now at unprecedented spatial and temporal resolution. Such resolution will enable us to finally probe the fundamental scale of the Sun's dynamic magnetic field, which is the origin of space weather that can have appreciable terrestrial impacts. The NST will be the largest aperture solar telescope in the US, and perhaps the world, until the 4 m off-axis ATST (Advanced Technology Solar Telescope) comes on-line in the middle of the next decade. In addition to its tremendous scientific potential the NST will be the testbed for many essential components and technologies of the ATST. *Primarily we propose here, in collaboration with the National Solar Observatory (NSO), to build a high order adaptive optics system for the NST that will enable diffraction limited observations over the NST's principal operating wavelengths from 0.4  $\mu\text{m}$  through 1.7  $\mu\text{m}$ , which is essential for the NST to reach its scientific potential.*

Previously, BBSO and NSO collaborated in the successful implementation of two 76-element (each with a 97-actuator Deformable Mirror (DM)) Adaptive Optics systems (AO-76) for the now retired BBSO 0.6 m telescope and the NSO 0.7 m Dunn Solar Telescope (DST), respectively. At first light, BBSO staff will implement the re-designed AO-76 on the NST. Detailed and realistic error budget analyses that include AO residuals, as well as telescope, interface and instrument error budgets, show that AO-76 will yield a high Strehl ratio of about 0.7 in the near infrared (1  $\mu\text{m}$ ) under median BBSO seeing. However, in the visible AO-76 will deliver reasonable Strehl ( $\sim 0.3$ ) only un-

der exceptional seeing conditions ( $r_0 \geq 12$  cm, which is about twice the median Fried parameter,  $r_0 \sim 6$  cm, at 0.5  $\mu\text{m}$ ). Thus, diffraction limited observations will be rare in the visible spectrum, even though they would be an essential diagnostic for magnetic field measurements and critical for the highest possible spatial resolution. We emphasize that for AO-308, according to our error budget analysis, we realistically expect to achieve a Strehl ratio of 0.3 in the detector plane in the visible (0.5  $\mu\text{m}$ ) for median BBSO seeing conditions, which turns out to imply steady, diffraction limited data. The Strehl, generally used to quantify the performance of an AO system, is the ratio of the maximum intensity in the AO corrected image in the detector plane to that from a theoretical, perfect imaging system operating at the diffraction limit.

In 2009, the Kiepenheuer Institute (KIS, Germany) will begin operating, GREGOR, its own 1.5 m on-axis solar telescope. For the same strong scientific reasons the GREGOR project is also developing a high order AO system with order 300 degrees-of-freedom (DOF). We propose a close collaboration between NJIT, NSO and KIS in developing these high order AO systems. Combining the significant experience and expertise of these institutes will ensure that the development is achieved in the most efficient and cost effective way, while virtually guaranteeing success in this essential task.

### A.2 Science Drivers for the AO-308 Equipped NST

Many fundamental properties of our dynamic star will finally come within our grasp with the AO-308 equipped NST feeding light to existing BBSO instrumentation. These properties are at the heart of what drives space weather. The BBSO site has been well-characterized within the ATST site survey (see <http://atst.nso.edu/site> for details). The NST will be installed in the existing telescope structure at a height of 14 m above the lake (compared to 6 m for the ATST S-DIMM survey instrument). Even at this relatively low height for a solar telescope, the lake-effect, which suppresses ground-layer seeing, produces good, and consistent seeing over long periods of time. Using the ATST site survey data and comprehensive error budget analysis we computed the normalized histogram of Strehl ratios that the AO-308 is expected to achieve. As mentioned above, under median seeing conditions

at BBSO, our analysis predicts a reasonable Strehl of about 0.3 in the detector plane at  $0.5 \mu\text{m}$ , and that will enable us to meet our scientific goals. Requirements for the AO performance and performance predictions are detailed in Section B.3. The site survey data reveal steady, AO-correctable seeing all day long, so that the NST can quite usefully operate in the traditional BBSO campaign-style observing mode and obtain long time-sequences of diffraction limited data. Such diffraction limited data in blue are essential to probe with the highest resolution of the NST those phenomena that have been tantalizingly beyond our reach with the sub-meter class solar telescopes that have been used (like NSO's DST, the German Vacuum Tower Telescope and the Swedish Vacuum Telescope). Having the extra factor of 2-3 in angular resolution will be essential in resolving features that are only smudges to us at present. With solar maximum coming in  $\sim 2011$ , and satellites like STEREO, Hinode and SDO flying then, the AO-308 equipped NST will be critical in addressing problems of long interest at BBSO and in the solar community:

(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 a review). In the bluest wavelengths, the 1.6 m telescope will obtain the highest resolution, high cadence images of flares to date. We have high temporal cadence observations of such bursts, but we can't quite tell where they are and how they move about. NST observations with  $0.06''$  resolution will aid us greatly here. Such 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. Cao et al. (2004, 2006) and 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 DST at NSO on 2003 October 29, with AO-76). The study demonstrated the potential for new scientific results when high resolution photospheric observations are combined with hard X-ray imaging and spectroscopic observations; however, even with a resolution approaching 100 km in the blue, the flare

ribbons were not resolved. Since the NST will have better than twice the spatial resolution of the DST at the same high temporal cadence, while having diffraction limited light a greater fraction of the day, we expect that the NST will provide new and basic insight into this problem.

(b) Dynamics of Kilogauss Flux Tubes

Understanding the dynamic behavior and structure of small scale kilo-Gauss fluxtubes is a primary scientific goal. 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 unsolved observational problem in solar and stellar physics. Sustained diffraction limited observations at 50 km ( $\sim 0.06''$ ) resolution with high temporal cadence, just below the putative diameter of fluxtubes, are critical to resolve this problem. Multi-wavelength investigations using NST and satellite data will advance our understanding of flux tube physics.

(c) 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. The study of energy release in stressed magnetic fields has motivated many attempts to detect flare-induced changes in the magnetic fields in active regions. Until very recently, no one had 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; Liu et al., 2005). The inconsistency among the results is due to observational limitations. One cannot get high temporal and spatial resolution, as well as high polarization accuracy at the same time with

existing telescopes/instruments. The NST equipped with AO-308 will provide much more reliable, and higher quality measurements of the always difficult vector magnetic fields (for vector fields we will compare with Hinode (Solar-B) FG, the filter-based vector system as it is now operational, as well we will compare with vector fields from the Solar Dynamics Observatory (SDO) when it is launched). A consistently sufficient Strehl ratio to deliver diffraction limited light to the focal plane instrumentation will ensure that the detected field variations will not be due to variations 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? Significant advances here require the full diffraction limit of the telescope, although we will be able to build good statistics by resolving more events in the NIR with the NST than we could with the old BBSO telescope because of the larger Zeeman splitting and larger Fried parameter in the IR.

### A.3 Schematic of the NST

BBSO has removed its old 0.6 m aperture telescope (donated to the Los Angeles Amateur Astronomy Society) and the installation of the modern, off-axis 1.6 m clear aperture instrument (Goode et al., 2003) is on-going as of this writing. The new telescope offers a significant improvement in ground-based high angular resolution capabilities, and will substantially enhance our continuing program to understand photospheric magneto-convection and chromospheric dynamics, as sketched in Section A.2. These are the drivers for what is broadly called space weather – an important problem that impacts human technologies and life on Earth. The NST project is described in detail in <http://www.bbso.njit.edu/newtelescope>.

The NST is configured as an off-axis Gregorian system consisting of a parabolic primary, prime focus field stop and heat reflector (heat-stop), elliptical secondary and diagonal flats, see Figure 1. The primary mirror (PM) is 1.7 m with a clear aperture of 1.6 m with a final figure residual error of 16 nm rms. The focal ratio of the primary mirror is  $f/2.4$ , and the final ratio is  $f/50$ . The  $180''$  circular opening in the

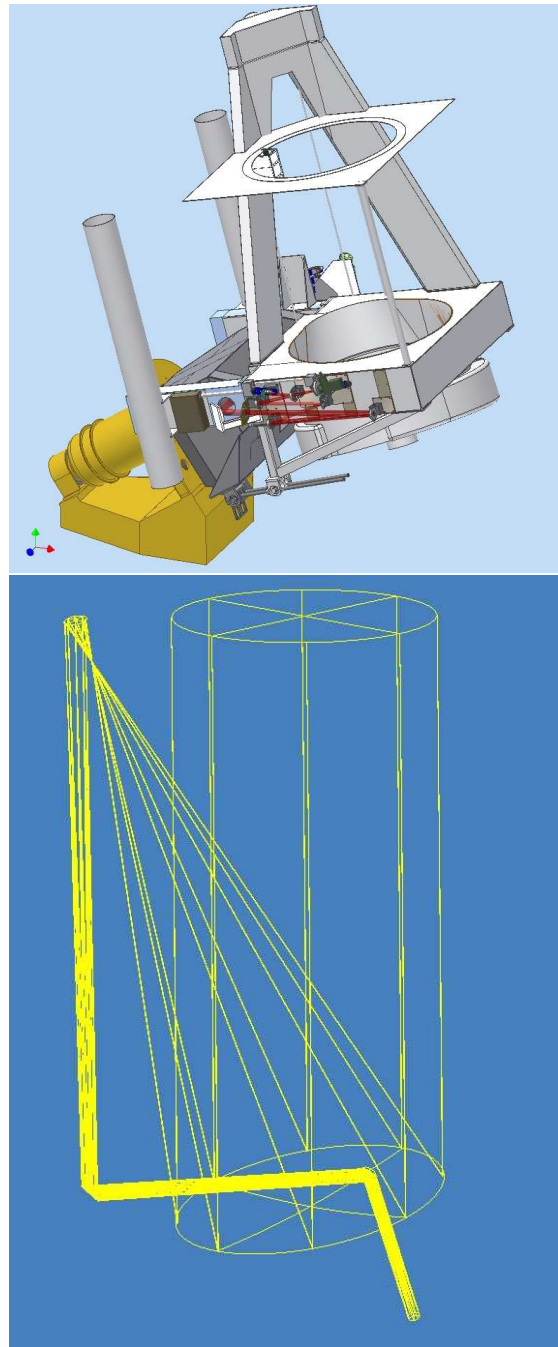


Figure 1: Schematic of the 1.6 m off-axis, open NST (top) and its optical layout (bottom). On the top part, the heat stop (HS) resides at the Gregorian focus with the SM mounted on a PI hexapod. The wavefront sensing system (WFS) resides immediately before M3 (along with the polarization optics for magnetic field measurements). M4 sends the light to the Coudé Room below. The HS, SM, M3 and M4 are not apparent in the figure. If M4 is flipped the light goes to the Nasmyth Bench for which the light path is shown in red. This is where the first light observations will occur. The design was driven by competing needs for rigidity near the SM and an open light path. For more details, please visit the BBSO website.



Figure 2: The NST equatorial mount, mirror cell, counterweights (for right ascension balance), and tower to secondary.

field stop defines a  $120'' \times 120''$  maximal square field of view (FOV) of the NST. The working wavelength range will cover 0.4 to  $1.7 \mu\text{m}$  in the Coudé Laboratory one floor beneath the telescope and all wavelengths including far infrared at the Nasmyth focus on an optical bench attached to the side of the telescope structure. An off-axis design was chosen principally 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, as illustrated in Figure 1. A key design issue for a large aperture, solar telescope is the thermal control system to keep the temperature of the mirrors very close to, or even slightly below that of the ambient air. The dome employs a wind-gate and exhaust system to control the airflow from the wind helping to maintain the same temperature inside and outside the dome, and clear concentrations of heat in and around the optical paths. In fact, we have measured the temperatures along the optical path from the telescope to the Coudé Laboratory (which is thermally controlled to 0.5 C). When the vent gates

and exhaust system are turned on, the temperature all along the optical path becomes precisely uniform. In addition, we have implemented a closed cycle, chilled air system as part of the OSS (Optical Support Structure) to limit so-called "mirror seeing" by sweeping away turbulent cells and directly cooling the PM. After each day of observations, the PM will be cooled overnight to ensure that it is cooler than ambient in the morning. The OSS and active support mirror cell were built and tested by DFM, Engineering in Longmont, CO. The PM is supported by 36 actuators that can bend out low-order aberrations, such as those due to gravity and/or thermal effects. The OSS has been installed and is being tested at this writing. Alignment and first light observations will follow immediately. These two key steps will be done in collaboration with DFM and Steward Observatory with standard alignment-laser hardware from an outside vendor (ATT). Steward figured the PM.

The new, larger dome, required to house the NST, is fully operational and all construction under the dome (such as the extension of the support pier) has been completed. The elliptical secondary mirror (SM) is finished and silvered, and has been tested



by both SORL (Space Optics Research, which figured the SM) and Steward. The PM is active, and its shape will be controlled by a wavefront sensing system (<http://www.wavefrontsciences.com>), which will reside immediately before M3. The latest version of the BBSO telescope headquarters control system software has been written in BBSO and tested at DFM. While this software is not essential for early observations, it would make them somewhat less cumbersome.

#### A.4 AO-76 at BBSO

As mentioned in Section A.1, under a prior NSF MRI grant (AST-0079482), we have successfully built two high-order AO systems (each with a 76 subaperture AO system using 97 actuator deformable mirror(DM)), 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 is also the PI in the AO-308 project. A number of papers have been published to describe these two AO-76 systems and their scientific results (Ren et al., 2003a; Didkovsky et al., 2003; Denker et al., 2005,2007; Rimmele, 2004; Yang et al., 2004; Tritschler et al., 2005; Xu et al., 2004, 2006, Cao et al., 2006). Figure 3 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 4. 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 10,000 AO measurements over the entire pupil. Often, the 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 the generally-assumed Kolmogorov turbulence). These observations were made before the new dome with vent gates was installed along with the full heat exhaust system,

which tells us that we can be assured that the Fried parameter will be sufficient to enable steady diffraction limited imaging even at the bluest wavelengths, because our temperature sensor measurements have shown a uniform temperature all along the optical path.

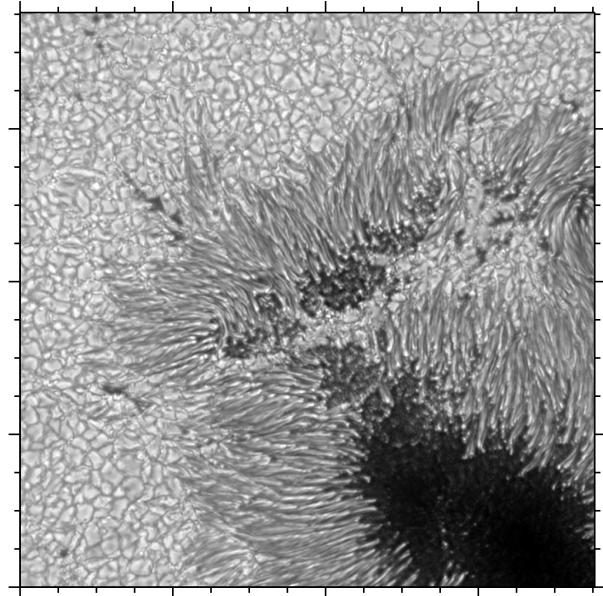


Figure 3: A diffraction-limited image obtained at BBSO on April 29, 2005 with the AO-76 system and speckle reconstruction.

With the support of an expiring NSF ATI grant, the AO-76 system has been redesigned to fit the NST. Figure 5 shows its final design for which the optics have been purchased. The set-up has undergone laboratory experiments in Big Bear, so that it will be ready shortly after first light of the NST. This design is simpler and more robust than that used on the old 0.6 m telescope. The design problems for the AO-76 on the NST were simpler than those for AO-76 on the old 0.6 m telescope because AO-76 was a difficult retrofit to a telescope that was never meant for AO. However, our experience with AO-76 on the old telescope should make the implementation of the AO-76 for the NST relatively straightforward. As well, the relative simplicity of the new setup helps assure us that the image quality in the Coudé Lab can only improve over that from the old setup for the 0.6 m telescope. For the new setup, only the feed optics and the reconstruction matrix for inverting the wavefront sensor output need to be changed. AO-76 on the NST will be very nearly achromatic, unlike AO-76 on the

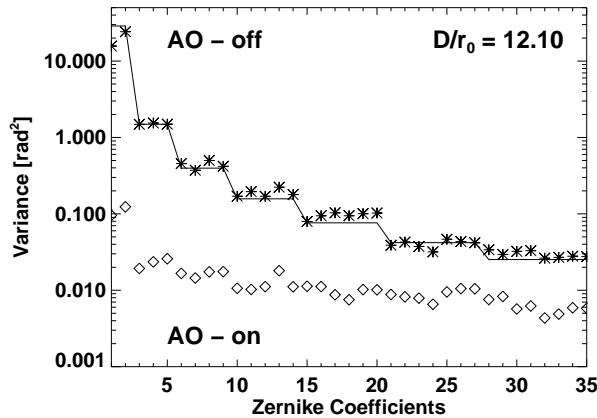


Figure 4: Comparison of the variance of the Zernike Coefficients for AO-on (carets) and AO-off (asterisks) data determined from the BBSO AO WFS. The solid curve represents a fit to the Kolmogorov spectrum of the AO-off data for  $D/r_0=12.10$  (Trischler et al., 2005), where  $D=65$  cm and  $r_0$  is the Fried parameter. The larger the ratio  $D/r_0$ , the more important AO correction becomes.

old telescope. Figure 6 shows the spot diagram for AO-76 for the NST. The Airy disk is for wavelength  $0.5 \mu\text{m}$ . The spots are not fully confined to the Airy disk, but this is not a problem since the design has been optimized over a wavelength band much broader than that of any of the instruments. Thus, we will be able to reach the diffraction limit. Any difficulties in reaching the diffraction limit is further eased by the fact that our visible and infrared polarimeters operate over a smaller field of view ( $100''$  in diameter) due to FOV limitations of the Fabry-Pérot interferometers. Thus, the polarimetric observations in all narrow-band regimes spanning  $0.4\text{-}1.7 \mu\text{m}$  will be diffraction limited.

### A.5 The Hardware: Near Infrared and Visible Imaging Vector Magnetograph Systems

The hardware needed to meet our science goals has been built and tested. It awaits AO-corrected light from the NST. In fact, BBSO has built and employed three generations of visible light and near IR (NIR) imaging systems over the last decade. Although IRIM has many advantages on its own, to achieve the highest spatial resolution with the NST, we must emphasize instrumentation in visible light. 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 sys-

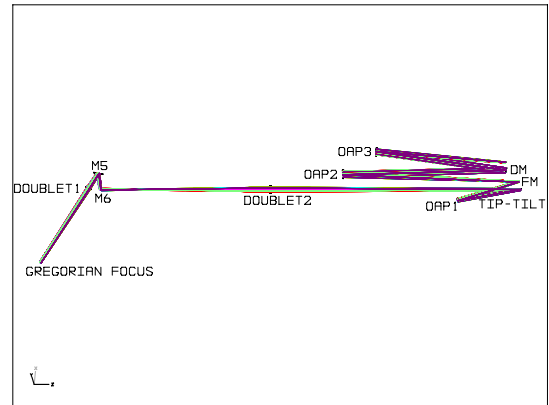


Figure 5: The design of the Coudé Laboratory optics for AO-76 for the NST. It is as achromatic as possible combination of reflective-refractive optics, while largely using off-the-shelf components. M5 and M6 are folding flats fed from the Gregorian focus beyond the folding mirror, M4, that sends the light down the coudé axis. There are two relay doublets, three OAP's (off-axis powered mirrors) and the DM.

tem has also achieved its first light on the old 0.6 m telescope at BBSO. With AO-308 correction, the NST will achieve diffraction limited images with a spatial resolution of about 50 km, when observations are made at 500 nm (better than three times the resolution possible in the NIR with the NST). Such resolution is essential to take full advantage of the capabilities of the NST. Nonetheless, observations in the NIR have advantages associated with the relatively larger Zeeman splitting in that regime.

The most recent and significant part of our NIR instrumentation was the development of a narrow band-pass filter system, which combines a Lyot filter and an IR Fabry-Pérot filter – the IR Imaging vector Magnetograph (IRIM). The IRIM design copies that of VIM, but was more difficult because VIM could use standard components or hardware (e.g., the Lyot filter) that was already on-hand. The IRIM Fabry-Pérot 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 PhD 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 a large format NIR CMOS camera ( $1\text{k}\times 1\text{k}$ , 30 frames/s) from Rockwell Scientific Imaging (now Teledyne). We enjoyed a very successful first scien-



tific light of the full IRIM hardware system in November 2004 on the DST at NSO/SP and in July 2005 at BBSO, Cao et al. (2004, 2006). 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).

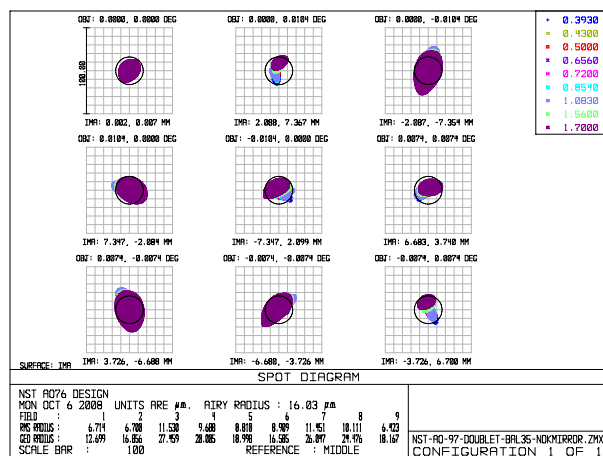


Figure 6: Spot diagram for AO-76 showing near diffraction-limited image quality for the wavelength range from 0.5 to 1.1  $\mu\text{m}$  and for a circular field of view of  $100''$ , which is appropriate for the Fabry-Pérots. The circles are the Airy disks (diffraction limit disks) of the shortest wavelength (0.5  $\mu\text{m}$ ). The spots are not fully confined to the Airy disk, but narrow-band observations, which are the norm at BBSO, will be diffraction limited.

## B. Proposed Work

### B.1 Overview

High order AO is essential for the NST to correct the wavefront errors caused by atmospheric turbulence. We propose to develop a new, higher order AO system (AO-308) for the NST following the basic concept of our lower order AO-76 for the NST. AO-76 was originally successfully implemented on the old 0.6 m telescope, and then re-designed to be very nearly achromatic, while being appropriate for the NST light feed. The implementation of AO-76 on the NST is not part of the effort proposed here, and all development is completed and parts are in-hand for the modified AO-

76. The original BBSO AO-76 proved to be successful and has delivered diffraction-limited images in the visible and NIR with the old 0.6 m BBSO telescope (Rimmele et al. 2003, Ren et al. 2003a, Didkovsky et al. 2003, Tritschler et al., 2005). These successes demonstrate our team’s technical abilities and give us the confidence that we can upgrade to AO-308 in an optimal way, so that the NST can deliver diffraction limited observations in visible light throughout most days, which is ideal for BBSO-style campaign observations.

The NST has an aperture that is nearly three times that of the old 0.6 m telescope and represents a new generation of solar telescopes made possible by new technologies. Since AO-76 significantly corrected light from the old telescope at 0.5  $\mu\text{m}$ , AO-76 will significantly 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  $\mu\text{m}$ , which implies it should be about 24 cm at 1.6  $\mu\text{m}$  under the standard assumption of Kolmogorov turbulence. A higher order AO must be developed for the NST to make diffraction limited observations in the visible over an isoplanatic patch, while probing with spatial resolution of about 50 km. Here one should bear in mind that the spatial resolution decreases linearly with wavelength. We emphasize that AO-308 is an essential step in reaping the benefits of the investments in the NST, including its already operational downstream polarimeters.

We first consider the general design parameters of the NST.

### B.2 The AO-308 Development Plan

The conceptual operation of AO-76 or AO-308 on the NST is quite straightforward, and is illustrated in Figure 7 for AO-308. For either, a beam splitter directs a portion of the light 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 better than 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 wave-

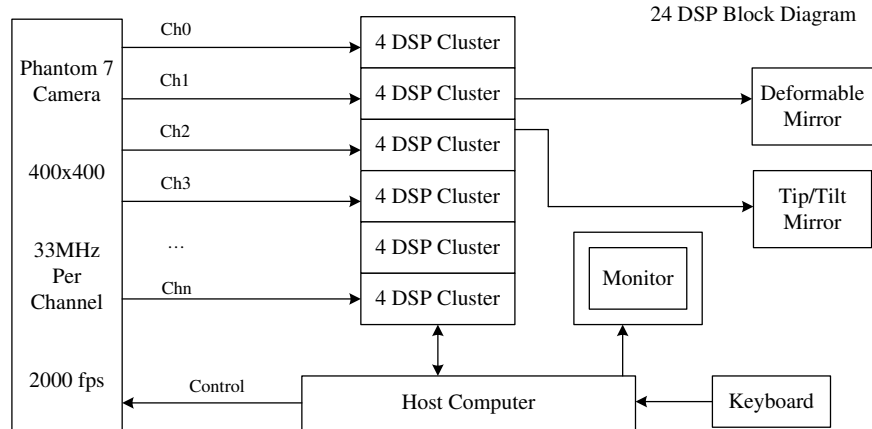


Figure 7: Functional block diagram of the WFS and the reconstruction unit of the AO-308 system.

front 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 relatively slowly varying, low contrast, spatially extended targets to measure the wavefront aberrations. The bandwidth of the correction for AO-76 was 135Hz in its closed-loop mode. With much improved computing speed now available and a newly developed DM, we expect to achieve a similar bandwidth for AO-308, which is good enough to yield diffraction limited correction of  $0.5 \mu\text{m}$  light. Of course, experience with AO-76 adapted to the NST will guide the detailed implementation of AO-308. As will be seen, the optical design of AO-308 is closely patterned after that of AO-76 (shown in Figure 5) for the NST.

For AO-308, 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 will be a Phantom V7.3 camera that has  $800 \times 600$  pixels ( $400 \times 400$  to be used to start). It has a frame rate over 6000 fps, but we will only utilize 2000 fps. Each of the nearly  $20 \times 20$  sub-apertures will be characterized by a minimum of  $20 \times 20$  pixels. The tip/tilt mirror has been mounted on a Polytec PI S-340 piezo tilt platform, and the DM will be manufactured by Xinetics, Inc. The new high density DM (5 mm spacing) just became a standard item, and the reduced spacing facilitates an optical design of AO-308 that is close to that of AO-76 for the NST. The WFS has 308 effective elements, while the DM has

349 actuators. The largest Xinetics DM at present has 941 actuators. We will consider the Cilas-416 (416 actuators) DM as well, because the GREGOR team plans to use that DM. However, this choice is not essential to our collaboration. With either choice of DM the proposed work with KIS team would be the same.

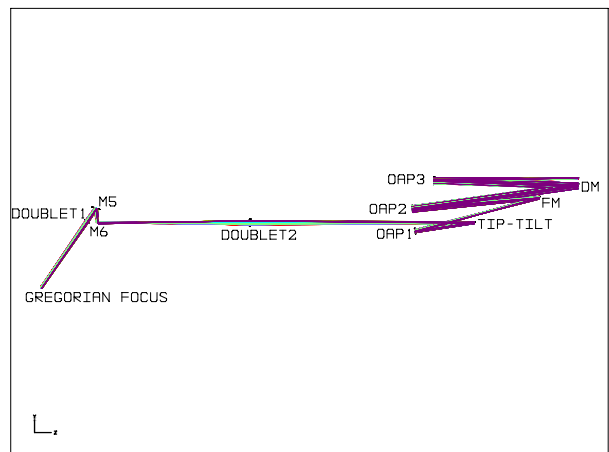


Figure 8: The design of Coudé Room optics for AO-308 for the NST. It is as achromatic as possible combination of reflective-refractive optics, while largely using off-the-shelf components. M5 and M6 are folding flats fed from the Gregorian focus beyond the folding mirror, M4, that sends the light down the coudé axis. There are two relay doublets, three OAP's (off-axis powered mirrors) and the DM. The basic similarities for AO-76 and AO-309 on the NST is apparent when comparing this figure to Figure 5

## B.2.1 The Optical Design of AO-308

The optical design of AO-308 ultimately requires replacing two doublet lenses and one powered mirror (OAP2 of AO-76 becomes OAP3 of AO-308 and a new OAP2 is required for AO-308) in AO-76 for the NST. The optical feed must relay the NST focal plane image to the Coudé Laboratory (beneath the telescope), which is about 3 m beneath the NST’s Gregorian focal plane; the field-of-view for the optics must be 100'' in diameter, so that we realize as wide a field of view as is consistent with the downstream, Fabry-Pérot based polarimeters.

To deliver optimal optical performance, one of the off-axis powered mirrors for AO-308 will have to be custom-designed and manufactured. Figure 8 shows the optical layout of the design for the new AO-308 main optical path. The tip/tilt and DM mirrors are both located at pupil images. The WFS path is modeled directly after the AO-76 WFS and the straightforward ZEMAX design has already been completed but is not shown here. Figure 9 shows the spot diagram for AO-308 spanning 0.4-1.0  $\mu\text{m}$ . We will continue to review the design based on experience derived from implementation of AO-76 on the NST, which precedes the AO-308 Project. The final design of AO-308 will be reviewed by the team as well as external reviewers, once this proposal is funded. The calculated performance is close to diffraction-limited over the entire FOV and wavelength range. The design has an even better performance in the NIR. Like our current hardware set-up for measuring magnetic fields (see Section A.5), NIR and visible will have their current two separate CCD systems fed by separate camera lenses. As with AO-76 for the NST, we will not need to adjust focus for either of the two benches when we switch the AO-308 corrected light feed from one bench to the other.

Since the WFS works in a very narrow passband ( $\sim 10\%$  of the wavelength band) in the visible, commercial in-stock lenses can be used, and the chromatism would not be a concern. Table 1 compares the essential hardware components of AO-76 for the NST and the new AO for the NST. We emphasize again that the optical design of AO-308 is close to that of AO-76 for the NST.

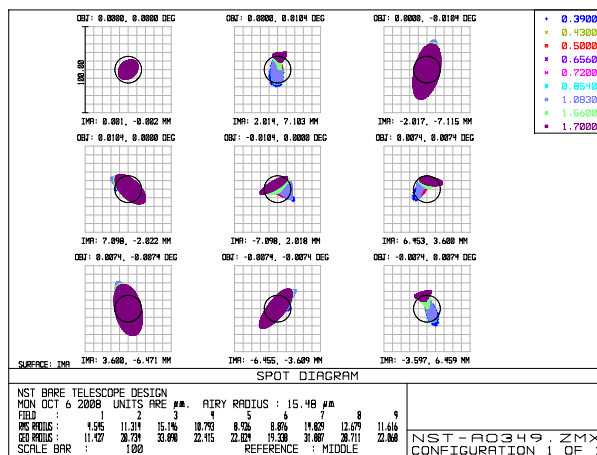


Figure 9: Spot diagram for AO-308 showing near diffraction-limited image quality for the wavelength range from 0.5 to 1.1  $\mu\text{m}$  and for a circular field of view of 100'', which is appropriate for the Fabry-Pérots. The circles are the Airy disks (diffraction limit disks) of the shortest wavelength (0.5  $\mu\text{m}$ ). The spots are not fully confined to the Airy disk, but narrow-band observations, which are the norm at BBSO, will be diffraction limited.

## B.2.2 Electronic, Computational and Mechanical Systems

Again, the principal system components for the AO system are: a correlating Shack-Hartmann WFS; a wavefront reconstructor and a DM. Figure 7 shows a block diagram of the hardware that is basically applicable to AO-308. There are many software development issues, including definition of the reconstruction matrix (to convert from wavefront information to the movements of the actuators). Here we will work closely with the GREGOR team on component development. We will exchange algorithms (e.g. reconstruction algorithms) and software. For electronics development, Bittware, the vendor for the DSPs will perform additional tasks: (1) design and construct an interface to connect the WFS camera and the DSP boards; (2) design and construct an interface to connect the DSPs and tip/tilt; (3) design and construct an interface to connect the DSPs and the DM. Bittware will tailor these links to fit our needs, and this effort will be coordinated with the AO-308 team. Nonetheless, our efforts to program, control and use the linked hardware components will be very time-consuming tasks requiring great care. Our experience with the two generations of AO-76 systems, along with the broad experience of our full team will be a great benefit here.

Table 1: Comparison of hardware components of old (AO-76) and new (AO-308) AO systems.

Hardware Components	AO-76 for the NST	AO-308 for the NST
Optical Design	Achromatic	Achromatic
Tip/tilt System	30 mm aperture	30 mm aperture
WFS Camera	Baja 200 by 200 sub-array	Phantom 7 400 by 400 sub-array
WFS (Lenslet)	10×10	20×20
WFS (Bittware DSP)	ADSP-21160	ADSP-TS201
DM (Xinetics)	97-elements 7-mm spacing	349-elements 5-mm spacing

### B.3 Performance Predictions

The AO design parameters, as detailed in Section B.2, were driven by the science requirements, the telescope properties, as well as the seeing conditions at BBSO. The practical experience from the DST, BBSO and other adaptive optics solar telescopes shows that Strehl ratios of  $S \geq 0.3$  are required in the detector plane to obtain reliable quantitative results from spectroscopic and polarimetric AO corrected observations. Forward modeling using MHD simulations combined with radiative transfer and modeled AO Point-Spread-Functions provide simulated observations that can be used to determine the “ground truth” of the MHD simulations. Such comparisons also indicate that, in particular, because of the extended nature of the observed object, high Strehl ratios ( $S \geq 0.3$ ) are required to obtain reliable quantitative measurements of the solar structure. In particular, polarimetric observations with low Strehl are from difficult to impossible to interpret. The problem here is that the requisite opposite polarity measurements are often closely (tenths of arcsecs) spaced.

As a first step to quantifying the AO-308 performance, we show in Figure 10 the “idealized” (read overly optimistic) Strehl ratio that results from considering the fitting error only vs. the number of corrected modes, using  $r_0$  as a parameter. The Strehl is idealized because it is that ratio at PM, even though it is clear that it would be smaller at the focal plane. Nonetheless, as can be inferred from the Strehl ratios in Figure 10, even moderate variations in  $r_0$ , which are common for day-time seeing, will result in undesired large variations in the Strehl, if only a small number of Zernike modes are corrected. This is due to uncorrected aberrations in the higher order Zernike modes, which increase as  $r_0$  decreases. Therefore, in order to minimize seeing induced variations in image contrast,

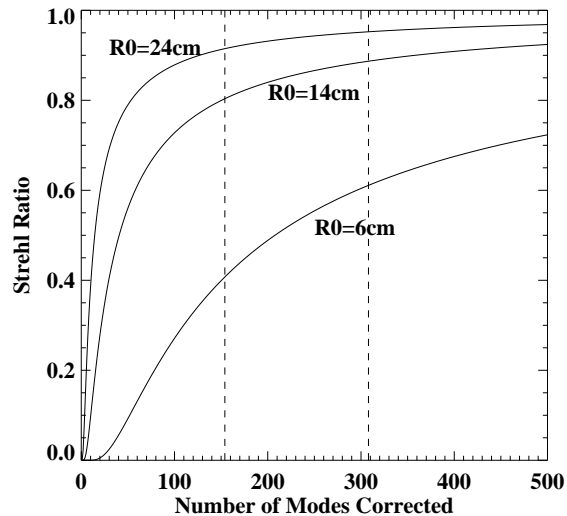


Figure 10: Theoretical Strehl ratio *at the primary mirror* as a function of the number of corrected modes under three different seeing conditions:  $r_0=6, 14,$  and  $24$  cm, which are the expected median seeing at BBSO at  $0.5, 1.0$  and  $1.6 \mu\text{m}$  respectively. The vertical dashed line on the right indicates the maximum number of modes that could be corrected by AO-308. The vertical dashed line on the left indicates the anticipated performance with half of the maximum number of modes being corrected.

high order AO is needed.

According to Figure 10, at  $1.6 \mu\text{m}$ , when the median  $r_0$  should be about  $24$  cm, a  $76$ -mode correction would achieve an idealized, median Strehl ratio of about  $0.8$ . While in visible at  $0.5 \mu\text{m}$ , the median  $r_0$  is  $6$  cm, the corresponding, idealized Strehl ratio would be  $0.2$ . If the correction order is increased to  $308$ , the idealized Strehl ratio would be  $0.60$  for the visible, reaching a satisfactory, idealized correction level above  $0.5$  (Wizinowich et al., 2004). Unfortunately, these results are only intuitively instructional, this level of correction is not germane because it does not apply to the detector plane, since many other error sources contribute to the error budget and ultimately

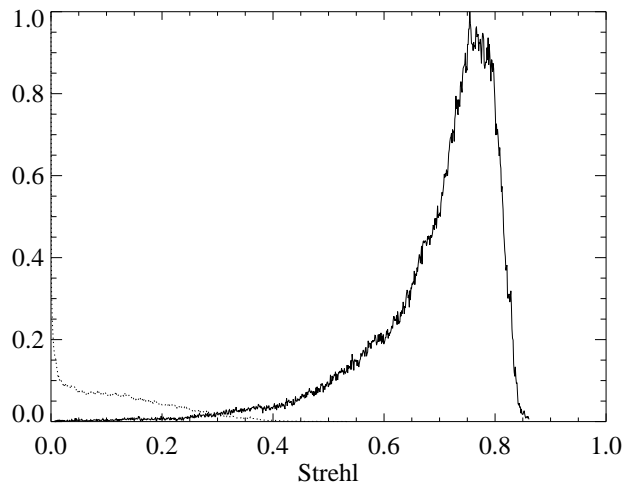


Figure 11: Histogram (normalized to unity) of Strehl ratios in the detector plane that we expect to achieve from AO-76 as derived from comprehensive error budget analysis, and assuming the measured distribution of BBSO seeing. The dotted line is for visible ( $0.5 \mu\text{m}$ ) and the solid line for NIR ( $1.6 \mu\text{m}$ ) wavelengths. For the visible, the lack of a peak indicates that diffraction limited corrections would rarely occur.

limit the realistically achievable Strehl.

To obtain meaningful predictions of the Strehl ratio, we performed extensive performance modeling in order to estimate the expected performance, quantified by the Strehl ratio in the detector plane of the post-focus instruments. This comprehensive analysis includes adaptive optics residuals (e.g., fitting/aliasing, bandwidth, and wavefront sensor noise) as well as realistic estimates of uncorrectable wavefront error contributions from the telescope (e.g., mirror seeing, interfaces and dome seeing) and the instrument(s) (e.g., non-common path errors). The analysis uses the ATST site survey data and is partially based on the extensive error budget modeling that was done for the ATST. It is fair to use this modeling for the NST because both NST and ATST are off-axis, using similar designs, have well-ventilated domes, air knives, etc. The results are shown in the form of histograms of the predicted Strehl that we expect to obtain with AO-308 at visible and NIR wavelengths. For comparison we show the expected AO-76 performance in Figure 11, which is to be compared with that for AO-308 shown in Figure 12. While for AO-308, the Strehl for the visible ( $0.5 \mu\text{m}$ ) peaks around 0.3, for AO-76 that Strehl shows no peak. This implies AO-76 will not enable observations in visible except under the most extraordinary seeing conditions. Thus, Figures 11 and

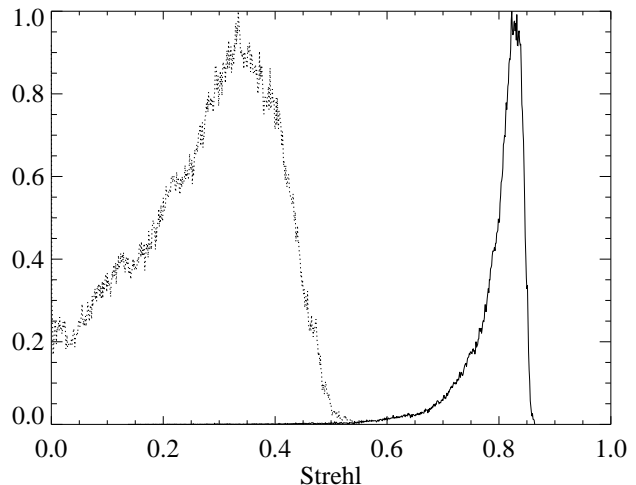


Figure 12: Histogram (normalized to unity) of Strehl ratios in the detector plane that we expect to achieve from AO-308 as derived from comprehensive error budget analysis, and assuming the measured distribution of BBSO seeing. The dotted line is for visible ( $0.5 \mu\text{m}$ ) and the solid line for NIR ( $1.6 \mu\text{m}$ ) wavelengths. For the visible, the predicted focal plane Strehl has a satisfactory value of about 0.3, while for the NIR it is somewhat  $>0.8$ .

12 clearly demonstrate the need for a high order AO for the highest resolution observations, which are essential to get full benefit of the 1.6 m clear aperture and all the effort to make the telescope off-axis.

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 to the 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 scientific goals that all are tied, one way or another, to having diffraction limited images with a sub-second cadence.

## B.4 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 six PhD students, including 2 US citizens, who will receive PhD's from NJIT in various fields: applied physics, electrical and computer engineering, and 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 PhD measurements in BBSO, although this is not possible for the AO-308 Project.

A PhD student will be involved in this project. However, he/she will be funded by BBSO's five-year NSF-ATM backbone grant. 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 be trained in AO design, and will also assist with the set-up, observation and data analysis. In addition to the direct student participation in the project, these data will be important sources for graduate and undergraduate research. The NST will also become a teaching tool for optics, mechanics, computer control and solar physics.

### **B.5 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 PhD students from around the world have used BBSO data as a central part of their 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 have used our data to help plan their observing campaigns.

The observing time of the first, next generation solar telescope in the US, 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 and open data policies. We plan to make a portion of observing time available to the community. The Telescope Allocation Committee will rank the proposals and allocate time. NST data will be on line immediately, if it is not part of a special observing program. A web page describing all the requests will ensure that researchers will not duplicate their data analysis efforts.

### **B.6 Budget and Management Plan**

*The requested budget for the project is \$880 K. The budget is relatively low because the DM (\$275 K) and its controller (\$175 K) will be purchased with other funding that includes a \$100 K match from NJIT. In*

addition, there is about \$30 K of the hardware that we already have in hand for AO-76 that will be directly transferrable to AO-308. Thus, of the \$780 K in hardware required for this project, only \$ 300 K will be charged to this grant highly leveraging the NSF investment in AO-308. As well, NJIT faculty and NSO staff will be working part-time on the AO-308 Project with no charge to the project. The exact cost here is difficult to know exactly, but it amounts to about 1 FTE. Most of the key hardware items for AO-308 are shown in Figure 7. These include: 1) the Xinetics DM (\$275 K) and its Controller (\$175 K); 2) the Phantom V7.3 Camera System (\$95 K), which is the WFS camera; 3) three Bittware T26U-OU-445-306-1177 DSP boards (\$55 K); 4) integrated link from the WFS camera to the DSPs to the DM (and tip/tilt) provided by Bittware (\$120 K); 5) PI tip/tilt stage and mirror (\$15 K); 6) host computer (\$15 K); 7) lenslet array and miscellaneous hardware (\$15 K); and 8) one off-axis parabolic mirror (Optical Surfaces, \$15 K) in the AO-76 will have to be replaced. The total hardware cost for AO-308 is \$780 K. Subtracting from this items 1), 5), and 6), our equipment request is reduced to \$300 K.

The remainder of the budget is dominated by personnel costs of about 2 FTE per year over the three year project. The PhD student will be supported by a separate NST grant. The effort of these personnel will be focussed on all aspects of implementing the AO-308 system.

The main NSO task is the development of DSP code with about 20% of the support for the development of optimized control matrices for the AO-308. The travel budget is primarily for collaborating personnel travel between BBSO and NSO/SP.

### **B.7 Personnel Management Plan and Timelines**

During the building of the NST, we have assembled a strong instrumentation team at BBSO. The commissioning phase of the NST will begin during the Fall-Winter of 2008. As a part of this phase, some members of the NST team will be partly shifted to the AO project. The implementation of AO-76 is, in fact, part of the commissioning phase. AO-76 installation on the NST is not part of the work proposed here even though it is a significant precursor to AO-308. Thus, we already have our team in place to do the pro-



Table 2: Tasks and Assignments for the AO-308 Project.

Year	Task	Person In Charge
Year 1	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Optio-mechanical Design	Rimmele and Gorceix
	DSP Software	Richards and Varsik
	DSP Hardware Integration	Varsik and Richards
	NST Wavefront Data Analysis for AO-76	Andic and Cao
	VIM and IRIM on NST with AO-76	Cao and Graduate Student
	Image Reconstruction with AO-308	Andic
Year 2	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Optical Design Implementation	Gorceix
	DSP Software	Richards and Varsik
	DSP Hardware Integration	Varsik and Richards
	Wavefront Data Analysis for AO-308	Andic and Cao
	VIM and IRIM testing with AO-308 on NST	Cao and Graduate Student
	Image Reconstruction with AO-308	Andic
Year 3	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Performance Testing of AO-308	Cao, Varsik and Graduate Student
	Software and Electronics	Varsik and Richards
	Wavefront Data Analysis for AO-308	Andic and Cao
	Regular Observations with AO-308	Team

ing the purchase of the DM and its controller) on the Gantt Chart, and they will be completed with some small overlap with the final design review and the purchase of the remaining AO-308 hardware. Then, the implementation of the AO-308 hardware would begin. The main tasks in the first year of the AO-308 Project will be the immediate purchase of the AO-308 hardware. With the hardware in hand, the optical, electronic and mechanical designs of the AO-308 system will be implemented, along with its interface to the NST and the focal plane instrumentation. NST will begin its commissioning phase about nine months before first year funding. This will leave the BBSO staff in a good position to undertake AO-308, as a follow-on to the implementation of AO-76 for the NST (not part of this proposal). The main tasks in the second year will be testing and tuning, including the analysis of WFS data. The tasks for the third year are to set-up the AO system in its regular operating mode, continue the analysis of the WFS data and observe with the new focal plane instruments. Here are the detailed tasks for

the AO-308 Project:

(a) As soon as this project is funded, we will have an external review of the optical design of the AO-308 system. Then the final design will be implemented to relay the telescope’s Gregorian focal plane image to the Coudé room where most of the AO components are located on an optical bench. This includes the design of 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 (Ren et al., 2003b) 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. Rimmele and Gorceix will lead the external design review (by videocon) to ensure that the design is optimized. They have already reviewed and approved the designs pre-

sented in this proposal.

(b) 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. Rimmele will lead Aleksandra Andic and Wenda Cao in this analysis, as Rimmele has significant experience in handling wavefront analysis for AO-76.

(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 observations of large fields of view because of anisoplanatism. Absent Multi-Conjugate Adaptive Optics (MCAO), 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 has developing a Phase Diversity (PD) system under NSF-ITR support. 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 de-focus, 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. This implementation will be led by Andic and Cao who have expertise in image reconstruction (Andic) and its implementation in BBSO (Cao).

(d) The Fabry-Pérot systems will be our primary science instruments. Prof. Wenda Cao has brought IRIM on-line and will utilize the work Prof. Carsten Denker (now at AIP, Potsdam, Germany) to bring VIM to the same state of readiness. Cao will continue work on the NIR and the visible system so that both will be fully exercised with AO-76 at BBSO and be ready to be integrated into AO-308. Cao is the most experienced and expert person in the operation of AO-76 at BBSO. He will have semester without teaching plus a summer to do much of the IRIM and VIM work.

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