

**Title of Investigation:** MRI: Development of Thermal Infrared Spectrograph 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 through 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) AO-76 systems for the now retired BBSO 0.6 m telescope and the NSO 0.7 m Dunn Solar Telescope, respectively. At first light, BBSO staff will implement the re-designed optical setup for 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 ( $\geq 1 \mu\text{m}$ ) under nominal median BBSO seeing. But diffraction limited observations would be very rare indeed at visible wavelengths, even though such observations would be an essential diagnostic for magnetic field measurements at the highest possible spatial resolution as well as for dynamic imaging of the chromosphere.

*In a BBSO/NSO collaboration, we propose for funding to implement a 308 sub-aperture (349 element Deformable Mirror) AO system for the NST to achieve diffraction limited imaging over the telescope's full range of operation.* The project is called "AO-308". A detailed AO-308 project plan for the NST has been developed (see Sections B.6 and B.7). The primary tasks include fine-tuning the optical design (which is quite close to that for AO-76 on the NST), programming of the wavefront sensor and reconstructor DSP hardware, 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 of the: (1) dynamics of kilo-Gauss magnetic flux tubes; (2) evolution of magnetic fields associated with solar activity; and (3) high cadence, high resolution studies of solar flares.

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 continues 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. Here, we propose for funding to implement a 308 sub-aperture (349 element Deformable Mirror) AO system, AO-308, for the New Solar Telescope (NST) to achieve diffraction limited imaging over the telescope's full range of operation. 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. 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 (50-70 km) 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 in-

strument 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 under exceptional seeing conditions ( $r_0 \geq 12$  cm, which is about twice BBSO's 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 (based on an available Xinetics DM with 349 actuators), 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. 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. Experience, at the National Solar Observatory at Sacramento Peak (NSO/SP) and elsewhere, from existing solar AO systems as well as detailed performance modelling of AO observations using MHD simulations of solar magnetic fields show that a Strehl of  $S \geq 0.3$  is required to perform the desired quantitative analysis of the small-scale magnetic elements.

### A.2 Science Drivers for the NST Thermal IR Spectrograph

Many fundamental properties of our dynamic star will finally come within our grasp with the tip-tilt corrected IR light feeding the NST Thermal IR Spectrograph.

### 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 alignment of the modern, off-axis 1.6 m clear aperture instrument (Goode et al., 2003) has been finished and first light has been attained at the Nasmyth focus, which will be the location of the thermal IR spectrograph proposed here. The new telescope offers a significant improvement in ground-based high angular resolution capabilities, and will substantially enhance our efforts to understand (???WHAT EVER WAS PRO-

POSED IN PREVIOUS SECTION), as sketched in Section A.2. The NST project is described in detail in <http://www.bbsso.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 PM was figured by Steward Observatory Mirror Lab. The focal ratio of the PM is  $f/2.4$ , and the final ratio is  $f/50$ . The  $180''$  circular opening in the 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. Here we are proposing for a spectrograph at the Nasmyth. 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 remove 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 (A. Coulter, 2008, private communication). In addition, we have implemented a closed cycle, chilled air knife 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. 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 ef-

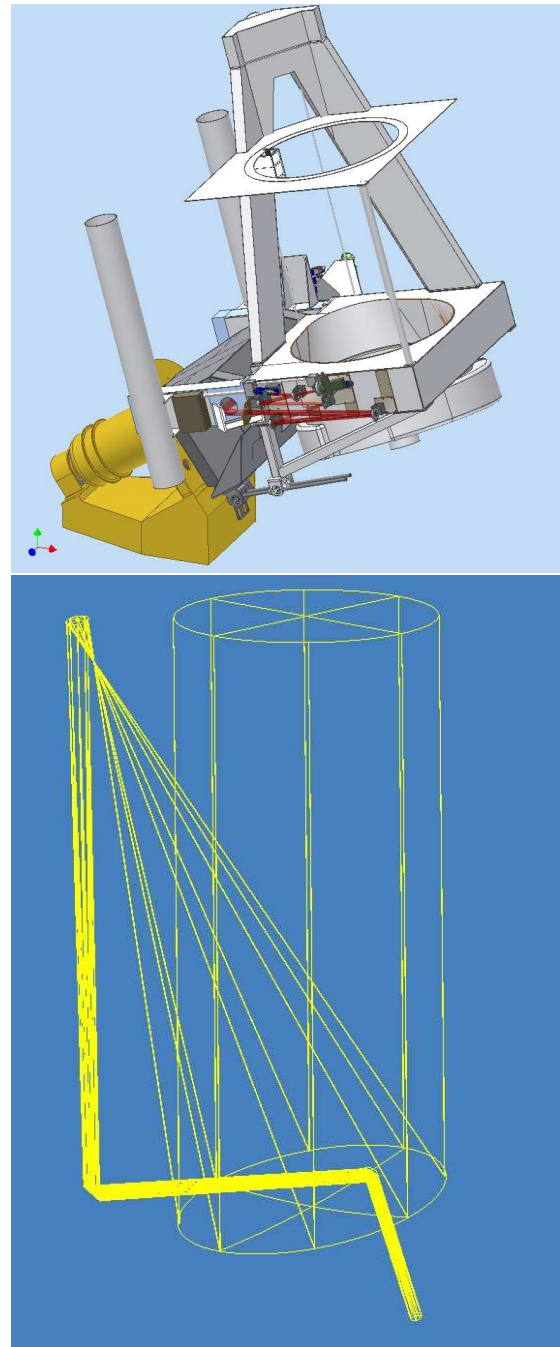


Figure 1: Schematic of the 1.6 m off-axis, open NST (top) and its optical layout (bottom). On the top part, the heat stop (HS) resides at the Gregorian focus with the SM mounted on a PI hexapod. The wavefront sensing system (WFS) resides immediately before M3 (along with the polarization optics for magnetic 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 where the spectrograph will reside (???REPLACE UPPER DRAWING WITH ONE HAVE A SCHEMATIC SPECTROGRAPH ON THE NASMYTH???) for which the light path is shown in red. This is where the first light observations occurred. The design was driven by competing needs for rigidity near the SM and an open light path. For more details, see <http://www.bbsso.njit.edu/newtelescope>.

fects. Its shape will be controlled by a wavefront sensing system (<http://www.wavefrontsciences.com>), which resides immediately before M3. First light observations of the Sun have been made at the Nasmyth focus, and image is shown in Figure 3.

The new, larger dome, required to house the NST, is fully operational and the installed telescope is shown in Figure 2. The elliptical secondary mirror (SM) was silvered, and was been tested by both SORL (Space Optics Research, which figured the SM) and Steward before its installation on the NSI PI hexapod. 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 Strehl Ratio of the Beam Feeding the Spectrograph

Ideally, we would like the Nasmyth Bench spectrograph to be fed with diffraction limited light over the entire 1.0-5.0  $\mu\text{m}$  range of operation. This spectral range does not require full adaptive optics correction because the terrestrial atmosphere is less turbulent in the IR than in the visible, so tip-tilt corrections alone are sufficient for most observations. Given the seeing at BBSO and the limitations of tip-tilt corrections, the diffraction limit will almost never be achieved

at 1.0  $\mu\text{m}$ , while for wavelengths beyond 2.5  $\mu\text{m}$ , diffraction limited observations will be the norm.

The Strehl, generally used to quantify the performance of an adaptive optics (AO) system, is the ratio of the maximum intensity in the corrected image in the detector plane to that from a theoretical, perfect imaging system operating at the diffraction limit. Experience, at the National Solar Observatory at Sacramento Peak (NSO/SP) and elsewhere, from existing solar AO systems as well as detailed performance modelling of corrected observations using MHD simulations of solar magnetic fields show that a Strehl of  $S \geq 0.3$  is required to perform the desired quantitative analysis of the small-scale magnetic elements. So, under what circumstances will this Strehl be achieved for light fed to our planned spectrograph by a tip-tilt system?

A simple way of quantifying the image quality after tip-tilt correction is by computing the residual wavefront error variance,  $\sigma^2 = 0.134(D/r_0)^{\frac{5}{3}}$ . From, this we can calculate the Strehl of a long exposure image in the usual Marechal approximation (for more detailed discussion see Christou et al, 2006, and references therein), where  $S = e^{-\sigma^2}$ . Further,  $D$  and  $r_0$  are the telescope aperture diameter and  $r_0$  is the Fried parameter. 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. Without image correction, 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). The BBSO site has been well-studied within the ATST site survey (see <http://atst.nso.edu/site> for details). Over the two years of seeing measurements, BBSO has been shown to be characterized by steady seeing all day long with an average of Fried parameter of about 6.5 cm. About one-quarter of the time,  $r_0 \geq 10$  cm all day long. The origin for the steady, good seeing is the well-documented lack of ground-level atmospheric turbulence, which is the result of the NST dome being located in the middle of Big Bear Lake. The lake is almost always cooler than the air and, thus, provides a natural inversion that suppresses the turbulence during our typical observing conditions in which a constant wind comes from the west over two miles of open lake water.

Using the Marechal approximation and assuming  $r_0 \sim 10$  cm at 0.5 $\mu\text{m}$  in all cases in this paragraph, we calculate that at 1  $\mu\text{m}$   $r_0 \sim 25$  cm, and we have  $S=0.03$ ,



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

which means we are seeing limited with a seeing disk of about  $0.5''$ . At  $1.6 \mu\text{m}$ , where the Sun has its opacity minimum and there are strong magnetic lines, we have  $r_0 \sim 40 \text{ cm}$  and a tip-tilt corrected  $S=0.26$ , which is close to the 0.3 that experience has taught us is sufficient for diffraction limited imaging that would be  $0''.20$  at  $1.6 \mu\text{m}$  for the spectrograph. At  $2.5 \mu\text{m}$ ,  $r_0 \sim 70 \text{ cm}$  and  $S \sim 0.7$ . For all wavelengths red of  $2.5 \mu\text{m}$ , even the everyday seeing, after tip-tilt correction, is sufficient to feed diffraction limited light to the spectrograph. In general, we plan to use our real-time speckle reconstruction system as a daily guide on the wavelengths feeding the spectrograph.

Christou, J.C., Gladysz, S., Redfern, M., Bradford, L.W., and Roberts, L.C., 2006, *Characterization of the Variability of the Strehl Ratio of Adaptive Optics Point Spread Functions*, AMOS Technical Conference, Kihei, Maui.

### A.5 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 DM, one for BBSO's 0.6 m telescope and the other for the 0.7 m DST at NSO/SP. Dr. Thomas Rimmele of NSO, as a Research Professor at NJIT, was the PI of the project, and he is the Project Scientist for the ATST. Rimmele is the PI in the AO-308 project. Prof. Phil Goode functions as a co-PI in this project. However, to satisfy NSF requirements, he is the institutional/nominal PI at BBSO/NJIT to manage AO-308 in Big Bear. 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., 2007; Rimmele, 2004; Yang et al., 2004; Tritschler et al., 2005; Xu et al., 2004, 2006, Cao et al., 2006). Figure 4 shows a sample image obtained on April 29, 2005 with the BBSO AO-76 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 (Denker et al., 2007). 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 wave-

Table 1: IR Bands of Interest for the Nasmyth Spectrograph.

Wavelength Region	Band Properties	Science Goals
1.6 $\mu\text{m}$	Photosphere Opacity Minimum	Deepest Probing of Solar Surface
1.6 $\mu\text{m}$	Strong Magnetic Lines	Separate B-Field from Its Flux

length dependent ( $r_0 \propto \lambda^{\frac{6}{5}}$  for the generally-assumed Kolmogorov turbulence). The Fried parameter for this particular data set is 5.4 cm in the Coudé Lab, 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. These observations were made before the new dome with vent gates was installed along with the full heat exhaust system. Previous experiments using wavefront sensors clearly showed that the steady wind of several m/s at the BBSO site minimizes dome skin seeing effects, and for the old, not-sufficiently ventilated dome internal dome seeing was the dominant effect. Our temperature sensor measurements within the new dome have shown a uniform temperature all along the optical path and thus dome seeing is avoided, which tells us that the internal seeing situation is much improved and we can be assured that the combined Fried parameter (atmospheric and internal) will be sufficient to enable steady diffraction limited imaging even at visible wavelengths.

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 will make the implementation of the AO-76 for the NST relatively straightforward. As well, the relative simplicity of the new setup further assures 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

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

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 old telescope. Figure 7 shows the spot diagram for AO-76 for the NST. The optical design achieves a Strehl of  $S \geq 0.9$  across the field of the science instruments and at the relevant wavelengths.

## A.6 Science Instruments: Near Infrared and Visible Imaging Vector Magnetograph Systems

The instruments needed to meet our science goals have been built and tested. These instruments await AO-corrected light from the NST. In fact, BBSO has built and employed three generations of visible light and near infrared (NIR) imaging systems over the last decade. Although IRIM (InfraRed Imaging Magnetograph) has many advantages on its own, to achieve

Figure 5: 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  $D/r_0=12.10$  (Denker et al., 2007), where  $D=65$  cm and  $r_0$  is the Fried parameter. The larger the ratio  $D/r_0$ , the more important AO correction becomes.

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 0.01 nm (Denker and Tritschler, 2005). This system has also achieved its first light on the old 0.6 m telescope at BBSO. With AO-308 correction, the NST will obtain 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 address the science questions and to take full advantage of the capabilities of the NST. Nonetheless, observations in the NIR have advantages associated with the relatively larger Zeeman splitting (Zeeman splitting increases quadratically with wavelength) in that regime and are vital for measurements of weak magnetic field strengths. In that way, visible and NIR observations complement each other.

The most recent and significant part of our NIR 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, Cao et al. 2004, 2006a). The IRIM design copies that of VIM, but was more difficult be-

Figure 6: 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.

cause VIM could use standard components or hardware that was already on-hand. The IRIM Fabry-Pérot filter has a bandpass of 0.01 nm at  $1.56 \mu\text{m}$ , giving us a 0.25 nm wide prefilter (narrower than the 0.55 nm free spectral range of the IR Fabry-Pérot). The Lyot filter was designed as part of the PhD thesis of a graduated student, and the filter solves the longstanding problem of constructing a filter-based IR magnetograph (Cao et al. 2006b), 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, Cao et al. 2005) from Rockwell Scientific Imaging (now Teledyne). We enjoyed a very successful first scientific 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. (2006a) and Xu 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., 2006a).



Figure 8: Functional block diagram of the WFS and the reconstruction unit of the AO-308 system.

generation of solar telescopes made possible by new technologies. Since AO-76 significantly corrected light from the old 0.6 m telescope at  $0.5 \mu\text{m}$ , AO-76 will significantly correct the atmospheric turbulence for the 2.6 m NST at  $1.6 \mu\text{m}$  in the NIR. The median seeing at BBSO is about  $r_0 = 6 \text{ cm}$  at  $0.5 \mu\text{m}$ , which implies it should be about  $24 \text{ cm}$  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  $50 \text{ km}$ . 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.

Figure 7: Spot diagram for AO-76 showing near diffraction-limited image quality for the wavelength range from  $0.5$  to  $1.5 \mu\text{m}$  and for a circular field of view of  $100''$ , which is appropriate for the Fabry-Pérot etalons. 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 the Strehl will be  $\geq 0.9$ .

## 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 demonstrates our team's technical abilities and give us 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

### 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 8 for AO-308. For either, a beam splitter directs a portion of the light to the wavefront sensor (WFS) that does the following: (a) 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; (b) Cross-correlations between subaperture-images and a selected reference subaperture-image are computed via a very fast computer-Digital Signal Processor (DSP); (c) Local wavefront tilts are computed by locating the maximum or centroid of the cross-correlations (CC) to subpixel precision, and (d) Drive signals for the DM are derived from the WFS 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  $135\text{Hz}$  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 has been demonstrated to be sufficient 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 DM is 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. The WFS is designed to be able to process up to 360 sub-apertures. The WFS 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. 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.

### 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 FOV for the optics must be  $100''$  in diameter, so that we realize as wide a FOV 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 modelled directly after the AO-76 WFS, and the straight-forward ZEMAX design has already been completed but is not shown here. Figure 10 shows the spot diagram for AO-308 spanning about  $0.5\text{-}1.5 \mu\text{m}$ . We will continue to optimize the design based on experience derived from implementation of AO-76 on the

Figure 9: The design of Coudé Lab optics for AO-308 of 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.

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 optical design achieves a Strehl of  $S \geq 0.9$  across the field of science instruments and at relevant wavelengths. 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-308 for the NST.

Table 2: 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

Figure 10: Spot diagram for AO-308 showing near diffraction-limited image quality for the wavelength range from 0.5 to 1.5  $\mu\text{m}$  and for a circular field of view of 100", which is appropriate for the Fabry-Pérot etalons. 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 the Strehl will be  $\geq 0.9$ .

### 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 8 shows a block diagram of the AO-308 hardware. The processor of choice is the TigerSHARC DSP, which has also been selected by the ATST AO project and the TMT (Thirty Meter Telescope) project. Initial benchmarking of the chosen TigerSHARC DSP shows that 20 subapertures can be processed by a single DSP within less than 250 microsec leaving sufficient performance

margin and room for the implementation of telemetry data collection and potentially online PSF estimation (Richards and Rimmele 2008). Consequently, AO-308 requires only 4 clusters of DSPs with 4 processors each. The subaperture images from the WFS camera will be sorted and distributed to the DSP processors by an interface that utilizes an additional set of 8 DSPs. Programming of the DSPs is one of the main software development tasks and will be performed by Kit Richards, who has a vast amount of experience with these processors in particular, and solar AO systems development in general. *For performance reasons the programming will be done in assembly. The DSP developed for AO-308 will be to a large extent directly portable to the ATST AO system. The hardware approach was chosen for its scalability to the ATST AO system.*

There are other software development tasks, including user interface and development of the optimized reconstruction matrices (to convert from wavefront information to the movements of the actuators). Here we will work closely with the GREGOR team and J. Marino at the University of Florida, who is an ATST fellow. Both T. Berkefeld at KIS and J. Marino have extensive experience in developing reconstructors for solar AO systems. We will exchange algorithms (e.g., reconstruction algorithms) and software, and work closely together on the performance evaluation of the systems.

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.

### 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 because of the extended nature of the observed object. 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. Forward modelling using MHD simulations combined with radiative transfer and modelled AO Point-Spread-Functions provide simulated observations have been used to determine the “ground truth” of such MHD simulations.

As a first step to quantifying the AO-308 performance, we show in Figure 11 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 the 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 11, 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, high order AO is needed.

According to Figure 11, 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

Figure 11: 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.

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, and 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 limit the realistically achievable Strehl.

To obtain meaningful predictions of the Strehl ratio, we performed extensive performance modelling 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 AO residuals (e.g., fitting/aliasing, bandwidth, and WFS 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 modelling that was done for the ATST. It is fair to use this mod-

Figure 12: 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.

elling 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 12 clearly demonstrate the need for a high order AO for the highest resolution observations, which are essential to get the 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 multi-

Figure 13: 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  $>0.8$ .

ple 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, BBSO typically has 1-2 undergraduates who spend the summer at BBSO, as well as working on BBSO projects during the school year. 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.

## B.6 Hardware and Personnel Budget

*The requested budget for the project is \$895 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, about \$30 K of the hardware that we already have in hand for AO-76 that will be directly transferable 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/BBSO and NSO personnel will be working part-time on the AO-308 Project with no charge to the project. The contribution 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 8. 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 BBSO's backbone NSF 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 AO-308. The travel budget is primarily for collaborating personnel travel between BBSO and NSO/SP.

## B.7 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 proposed work and we risk losing essential BBSO staff and our momentum by delaying the start of the AO-308 project.

In the Gantt chart in Figure 14 and in Table 2, we show the major proposed tasks of the AO-308 project with timelines, as well as key personnel associated with the tasks. The Gantt chart sketches the AO-308 tasks (the detailed chart and vertical flow versions are shown in the "Supplemental Documents" Section). Before the start of AO-308, the NST observations at the Nasmyth focus will be on-going, and light will

Figure 14: The Gantt Chart shows the AO-308 project schedule. The chart is “rolled-up” because it is so detailed and would be hard to read. A complete version showing the tasks with each summary unrolled appears in the “Supplementary Documents” section, along with a vertical flow version of the full Gantt chart that is shown there.

have been fed to the Coudé Laboratory. When there is light in the Coudé Laboratory, AO-76 will be used to feed light to fast cameras that will record data to characterize the wavefront for use downstream in AO-308. The AO-76 light will also be fed to the IRIM and VIM systems for observations. Technically, these latter two tasks are not part of the AO-308 project, so they are denoted by asterisks in Table 2 (the last task in Table 2 is similarly noted). We remark that the AO-76 implementation will have some small overlap with the final design review and the purchase of the remaining AO-308 hardware. The NST will begin its commissioning phase about nine months before first year funding. 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 PDR followed by a careful consideration of alternative hardware, which is followed by the final, external design review. Then comes 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 in the second year. This timing will leave the BBSO staff in a good position to undertake AO-308, as a follow-up to the implementation of AO-76 for the NST (not part of this proposal). The main tasks in the second year will be development, including programming the DSPs and making the reconstruction algorithms to control the DM actuators. The tasks for the



Table 3: 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 Control Software	Richards and Varsik
	NST Wavefront Data Analysis for AO-76*	Gorceix and Cao
	VIM and IRIM on NST with AO-76*	Cao and Graduate Student
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
	Reconstruction Matrices	Rimmele and Marino
	Wavefront Data Analysis for AO-308	Gorceix 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	Rimmele, Gorceix and Cao
	Software and Electronics	Varsik and Richards
	Wavefront Data Analysis for AO-308	Gorceix and Cao
	Regular Observations with AO-308*	Team

third year are to set-up and test the AO system in its regular operating mode, use the analysis of the WFS data to sharpen AO-308, and ultimately observe with the new focal plane instruments.

PI Rimmele (he is also Project Scientist on the ATST) and Goode (institutional PI for BBSO) will manage and coordinate the diverse elements of the project. Goode is in BBSO about 50% of the time, so he will provide hands-on leadership, and coordinate the joint efforts between NSO and BBSO. Rimmele will oversee the optical and interface designs of the system, which is the most difficult part of the project. Nicolas Gorceix, the BBSO optical engineer, has completed the optical AO-308 design, which has been reviewed by Rimmele. As mentioned above, more formal review processes will occur when the project is funded. Goode will oversee the integration of the AO system and the NST, as well as the work of Jeff Nenow (mechanical engineer) and Vlad Abramenko (electronics engineer) in this integration process. Rimmele will closely work with Kit Richards on the interfacing of the WFS camera, the DSP's and

DM control. Kit Richards at NSO and John Varsik at BBSO will be in charge of the software development, which is primarily DSP control with Varsik helping to test and implement Richards' code in BBSO. A key component in the AO development is to convert from wavefront information to the movements of the actuators (reconstruction matrices). Rimmele will lead José Marino in this wavefront analysis, as Rimmele has significant experience in handling wavefront analysis for AO-76. Marino did such work when he was Rimmele's Ph.D. student at NJIT. Co-PI and NJIT Assistant Professor, Wenda Cao, is well-experienced in the BBSO AO-76 system and was a key developer of the IRIM and VIM. He will be responsible for integrating these instruments into AO-308. Aleksandra Andic, a new postdoc in BBSO, is an expert in image reconstruction, and she will see that speckle and phase diversity software is implemented into the data stream. BBSO had NSF-ITR funding in which this software was developed. Rimmele, Goode and Cao will also ensure that the AO-308 design will match the scientific requirements as sketched in Section A.2.

The Fabry-Pérot systems will be our primary science instruments. Prof. Wenda Cao has brought IRIM on-line and will utilize the work of 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 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 one semester without teaching plus a summer to bring IRIM and VIM on-line.

## C. References

- Cao, W., Denker, C., Wang, H., Ma, J., Qu, M., Wang, J., & Goode, P. R. 2004, *Characteristic Evaluation of a Near-Infrared Fabry-Perot Filter for the InfraRed Imaging Magnetograph (IRIM)*, SPIE, 5171, 307-315
- Cao, W., Jing, J., Ma, J., Xu, Y., Wang, H. and Goode, P.R., 2006, *Diffraction Limited Polarimetry from Infrared Imaging Magnetograph of Big Bear Solar Observatory*, PASP, 118, 838-844
- Denker, C. and Tritschler, A., *Measuring and Maintaining the Plate Parallelism of Fabry-Pérot Etalons*, 2005, PASP, 117, 1135-1444
- Denker, C., Tritschler, A., Rimmele, T., Richards, K. and Hegwer, S., 2005, *The High-Order Adaptive Optics System at the Big Bear Solar Observatory*, Solar Physics, submitted
- Denker, C., Mascarinas, D., Xu, Y. Cao, W., Yang, G., Wang, H., Goode, P. R. and Rimmele, T., 2005, *High-Spatial-Resolution Imaging Combining High-Order Adaptive Optics, Frame Selection, and Speckle Masking Reconstruction*, Solar Physics, 227, 217-230
- Didkovsky, L., Dolgushyn, A., Marquette, W., Hegwer, S., Ren, D. Fletcher, S. Richards, K., Rimmele, T. R. Denker, C. and Wang, H. 2003, *High-order Adaptive Optical System for Big-Bear Solar Observatory*, Proc. SPIE, 4853, 630-639
- Goode, P. R., Denker, C. J., Didkovsky, L. I., Kuhn, J. R. and Wang, H., 2003, *1.6 M Solar Telescope in Big Bear – The NST*, JKAS, 36, 125-133
- Liu, C., Deng, N., Liu, Y., Falconer, D., Goode, P. R., Denker, C. and Wang, H., 2005, *Rapid Change of delta Spot Structure Associated with Seven Major Flares*, Ap.J., 622, 722-736
- Madec, P.Y., 1999, in *Adaptive Optics for Astronomy*, F. Roddier ed., Cambridge University Press, 131
- Ren, D., Hegwer, S. and Rimmele, T. R. et al. 2003a, *The Optical Design of a High Order Adaptive Optics for the NSO Dunn Solar Telescope and the*

- Big Bear Solar Observatory*, Proc. SPIE, 4853, 593-599
- Ren, D., Rimmele, T., Hegwer, S. and Murray, L. 2003b, *A Single-mode Fiber Interferometer for AO Wavefront Test*, PASP, 115, 355-361
- Richards, K. and Rimmele, T.R., 2008, “*Real-time processing for the ATST AO system*”, AMOS 2008
- Rimmele, T. R., 2004 *Recent advances in solar adaptive optics*, 2004, SPIE, 5490, 34-46
- Rimmele, T. R., Richards, K., Hegwer, S. L., Ren, D., Fletcher, S., Gregory, S., Didkovsky, L. V., Denker, C. J., Marquette, W., Marino, J. and Goode, P. R. 2003, *Solar Adaptive Optics: A Progress Report*, Proc. SPIE, 4839, 635-646
- Spirock, T., Yurchyshyn, V. and Wang, H., 2002, *Rapid Changes in the Longitudinal Magnetic Field Related to the 2001 April 2 X20 Flare*, Ap.J., 572, 1072-1076
- Sturrock, P. A., 1989, Proceedings of Max’91 Workshop, p. 1
- Wang, H., Spirock, T. J., Qiu, J., Ji, H., Yurchyshyn, V., Moon, Y.-J., Denker, C. and Goode, P. R., 2002, *Rapid Changes of Magnetic Fields Associated with Six X-Class Flares*, Ap.J., 576, 497-504
- Wang, H., Liu, C., Qiu, J., Deng, N., Goode, P. R. and Denker, C., 2004, *Rapid Penumbra Decay Following Three X-Class Flares*, Ap.J. Letters, 601, L195-198
- Wizinowich, P.L. and 11 others, 2004, *Adaptive Optics Developments at Keck Observatory*, SPIE, 5490 1-11
- Xu, Y., Cao, W., Liu, C., Yang, G., Qiu, J., Jing, J., Denker, C. and Wang, H., 2004, *Near-Infrared Observations at 1.56 Microns of the 2003 October 29 X10 White-Light Flare*, 2004, Ap.J. Letter, 607, L131-134
- Xu, Y., Cao, W., Liu, C., Yang, G., Jing, J., Denker, C., and Wang, H., 2006, *High Resolution Observations of Multi-Wavelength Emissions During Two X-Class White-Light Flares*, Ap.J., 641, 1210-1216
- Yang, G., Xu, Y., Cao, W., Wang, H., Denker, C. and Rimmele, T. R., 2004, *Photospheric Shear Flows Along the Magnetic Neutral Line of Active Region 10486 Prior to An X10 Flare*, 2004, Ap. J. Letters, 617, L151-154