

Title of Investigation: Solar Multi-Conjugate Adaptive Optics Experiments on the 1.6 Meter Solar Telescope in Big Bear

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Project Summary

Adaptive optics (AO) is essential for the new generation of ground-based solar telescopes because the science is driven by the quest for the highest spatial resolution observations. This quest is made possible by continuing advances in adaptive optics. Second generation solar adaptive optics hardware sufficient to correct the bluest wavelengths for the 1.6 m off-axis New Solar Telescope (NST) is now in regular operation at Big Bear Solar Observatory (BBSO). Continuing a decade long collaboration in AO with the National Solar Observatory (NSO) and the Kiepenheuer Institute (KIS) in Germany, we have had on-sky, engineering first light observations with our third generation AO hardware—multi-conjugate AO (MCAO) on the NST. (HOPEFULLY???)

NST's MCAO system is not only today's most powerful solar MCAO system, but it is purposely flexible. It features three deformable mirrors, each having 357 actuators with 19 guide regions spanning 85". The design offers two pupils in which one of the deformable mirrors can be placed. One position is upstream of both high-altitude deformable mirrors (DMs), whereas the other position is downstream of them. The high-altitude DMs are arranged in a "stacked double Z" configuration to enable individual tuning of their conjugate positions without affecting the rest of the light path or needing to change anything downstream. A primary goal of NST's current solar MCAO system is to provide an experimental platform to advance the development in this field.

Here we propose, in collaboration with NSO (and KIS???), to experimentally investigate the impact of the orders of placement of the deformable mirrors and wavefront sensors in all their multiplicity of permutations. This option is unique, no other current solar MCAO system installed at a telescope provides this option. The option to widely vary the conjugate positions of the high-altitude DMs in a pathfinder system like NST's MCAO is worthwhile for multiple reasons: First, it allows for an experimental study of the impact of "mis-conjugation". Second, the configuration can be tuned to seasonal changes of the turbulence profile over Big Bear. Third, the very demanding option is opened to keep the DMs conjugated to the turbulent layers as the telescope elevation changes with the Sun's diurnal motion on the sky. The proposed ex-

perimental studies to be made with NST's MCAO system will deliver answers to open solar MCAO questions and will enable us to cross-check new simulation tools. The optimized MCAO hardware will enable the NST to achieve its full scientific potential, while also serving as a pathfinder for the Advanced Technology Solar Telescope (ATST) AO and MCAO projects. Construction of the off-axis ATST is underway and will be fully commissioned in 2019.

MCAO expands the diffraction limited field of view (FOV) to cover entire active regions enabling critical spectroscopic and polarimetric observations, which include, for instance, flares that may occur at any time and anywhere in an active region. MCAO eliminates a major limitation of conventional AO systems, the small isoplanatic patch, and, thus provide the tool to effectively study, with unprecedented spatial resolution, fundamental scientific questions like the onset and evolution of flares, flare triggering mechanisms, magnetic reconnection events and many other dynamic solar phenomena that require diffraction limited observations over an extended FOV with the requisite high temporal cadence. In sum, we address two required criteria:

(1) Intellectual merit: Optimized MCAO will enable the NST to provide the community the highest resolution, diffraction limited data over a large FOV to probe the fundamental character of the extended object that is our dynamic star. Over this decade, NSO will build and begin operating the ATST, the flagship telescope for the solar community. MCAO experiments and their hardware implementation on the NST will be an essential pathfinder for the more complicated ATST MCAO. After the ATST is on-line, the NST will continue to be a critical telescope in making campaign-style observations.

(2) Broader Impact: The development of the proposed MCAO system will be a BBSO and NSO (and KIS???) collaboration, and will continue BBSO's decade long tradition of training the next generation of scientists who build instruments. The resulting data from the upgraded NST will be used in many Ph.D. theses. Further, the testing and development of solar MCAO systems is relevant for nighttime telescopes. Our data, and a substantial portion of NST observing will be open to the community.

A. Project Description

A.1 Overview

Adaptive Optics (AO) is revolutionizing solar astronomy by enabling diffraction limited observations of our nearest star with more powerful telescopes having sufficient aperture to resolve what is regarded as the fundamental scale of the Sun. The stunning successes of solar AO have come from systems with a single deformable mirror (DM), so that only the isoplanatic patch (typically $\lesssim 10''$ in visible light under good seeing conditions) can be fully corrected. However, dynamical solar phenomena, like flares and coronal mass ejections (CMEs) are quite non-local, with nearly simultaneous, somehow interconnected manifestations of the dynamics spread over the entire field-of-view (FOV), which is typically an order of magnitude larger in angular extent than the isoplanatic patch. Of course, image reconstruction may expand the region of diffraction limited observation, but at the price of being limited to timesteps of a few seconds, rather than a few tens of milliseconds (ms) where the images that are input to reconstruction have the same time scale as the dynamical action. Further, spectropolarimetry requires imaging that is stable over several seconds over the entire FOV to measure the Sun's dynamical magnetic field. Thus, multi-conjugate AO (MCAO) is the holy grail for understanding the fundamental dynamics of our star.

The Sun is an ideal target for research on, and development of MCAO technology. While stellar MCAO systems need either multiple bright natural guide stars or artificial high-power laser guide stars for wavefront tomography, the Sun offers enough information to reconstruct the optical turbulence in Earth's atmosphere even though it is a single star. This is due to proximity of the Sun to the Earth, which makes the Sun an extended observational target in contrast to a point-source like distant star. Further, since the Sun is not a uniform radiator but exhibits a fine structure—its ubiquitous granular field—that offers sufficient information to reconstruct the requisite wavefront information with necessary speed.

Big Bear Solar Observatory (BBSO) has built, and now operates the highest resolution solar telescope ever built – the NST (New Solar Telescope). The NST is the first facility-class solar telescope built in the U.S. in a generation. The NST is an off-

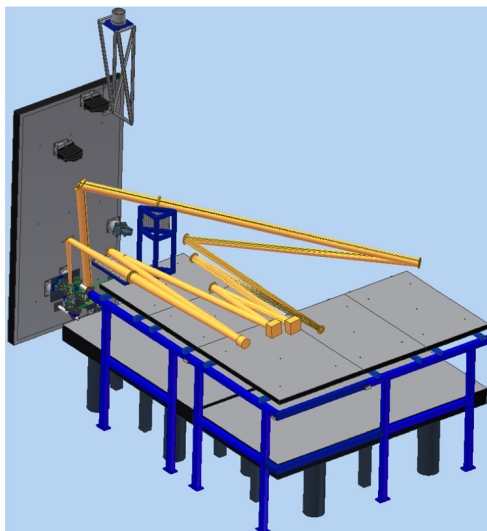


Figure 1: Opto-mechanical design of NST MCAO system. The ground layer DM is on the vertical bench, while the two DMs conjugated to higher altitudes are on the horizontal bench. The latter two DMs are shown as rectangular shapes in cross-section, and a linear translation of them changes their conjugation altitudes without requiring any other optical changes. This is a key strength of the “double z” design.

axis, 1.6 m clear aperture telescope that has been in operation for more than four years. Its third generation AO system has been deployed and it is today's most powerful and most flexible solar MCAO system. In detail, under NSF-MRI-0959187 support, the MCAO system on the NST was built in a close collaboration with our partners in that proposal — the National Solar Observatory (NSO), and the German Kiepenheuer-Institute für Sonnenphysik (KIS). NST's MCAO is strongly based on the concepts of the MCAO system of the German GREGOR telescope which are the results of the pioneering and continuous solar MCAO research at KIS and NSO. In particular, NST's MCAO uses the KAOS Evo 2 control software that has been developed at KIS, and their verified hardware. **add bunch of references**

NST's MCAO system is not only today's most powerful solar MCAO system, but it is purposely flexible. It features three deformable mirrors, each having 357 actuators, and a total of 669 image registration fields, which are distributed to 19 guide regions spanning $85''$. NST's MCAO was designed to offer maximum flexibility for addressing the outstanding issues in maturing the MCAO technology for solar observations. The opto-mechanical design of NST's

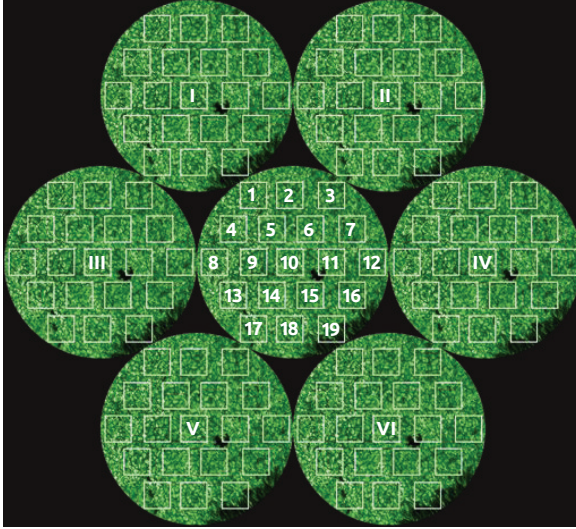


Figure 2: Illustration of the image plane of a low-order wide-field Shack Hartmann WFS with 7 sub-apertures and 19 guide regions. The guide region images in all 7 sub-apertures get correlated with each other to reconstruct the wavefront slope for each guide region. **The actual NST MCAO uses 19 sub-apertures for this WFS.**

MCAO is rendered in figure ???. Three identical deformable mirrors (DMs), made by Xinetics/Northrop Grumman, form the heart of this system. The design offers two pupils in which one of the deformable mirrors can be placed. One position is upstream of both high-altitude DMs, whereas the other position is downstream of them. The high-altitude DMs are arranged in a “stacked double Z” configuration, which allows for individual tuning of their conjugate positions without affecting the rest of the light path and needing to change anything downstream. By shifting and exchanging each DM and its dedicated flat folding mirror, a conjugation range from 2 km to 8 km can be covered almost continuously by both DMs. The low-order wide-field wavefront sensor is located next to the instrument focus downstream of all DMs. When the pupil DM is placed in the pupil image upstream of the high-altitude DMs (current setup), the high-order narrow-field wavefront sensor can be either located in between the pupil DM and the high-altitude DMs (current setup) or also downstream of the high-altitude DMs, see Figure ??. A primary goal of NST’s current MCAO system is to advance the development in this field. For this reason, a complex optical design with many mirrors was the trade-off against a simpler design.

We propose to experimentally investigate the im-

pact of the orders of placement of the deformable mirrors and wavefront sensors in all its permutations. This option is unique, no other current solar MCAO system installed at a telescope provides this. The ordering problem has been addressed theoretically **even analytically???**, but a clear result is still lacking **Flicker ref.** The latest MCAO experiments at the Dunn Solar Telescope (Sunspot, New Mexico) raised concerns whether or not a configuration A can work or if configuration B is to be preferred. It has been shown, that a system in configuration A is slightly non-linear as a “dynamic mis-registration” perturbs the wavefront sensor signals **my ref.** (DEFINE “A” and “B”???) The answer to this question is of fundamental consequences for future solar MCAO systems, like the one that yet to be designed for the 4 m Advanced Technology Solar Telescope (ATST).

We propose a series of tasks here: The option to widely vary the conjugate positions of the high-altitude DMs in a pathfinder system like NST’s MCAO is worthwhile for multiple reasons: First, it allows for an experimental study of the impact of “mis-conjugation”. Second, the configuration can be tuned to seasonal changes of the turbulence profile over Big Bear. Third, the very demanding option is opened to keep the DMs conjugated to the turbulent layers as the telescope elevation changes with the Sun’s diurnal motion on the sky. The proposed experimental studies to be made with NST’s MCAO system will deliver answers to open solar MCAO questions and will enable us to cross-check new simulation tools. Hence, NST’s MCAO constitutes an important foundation of the future MCAO system of the ATST.

Although sophisticated numerical simulations do exist, most of the simulations of solar MCAO systems are based on numerical codes and concepts that have been developed for night-time applications, and do not account for all effects. For example none of the simulations includes a realistic simulation of the camera image in a wide-field low-order SH-WFS, and none of which model the effect of dynamic mis-registration. Both modellings involve much more computational demands. NSO and KIS? are developing a realistic simulation tool that incorporates the KAOS Evo 2 control software, and which models dynamic mis-registration and solar wavefront sensors realistically.

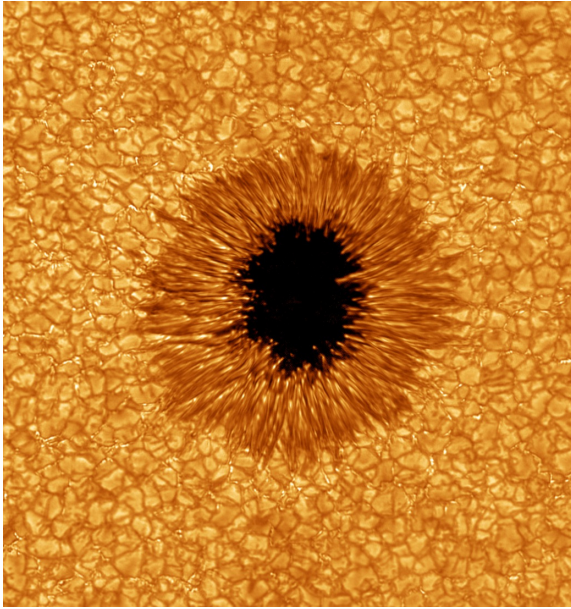


Figure 3: A small sunspot observed on 2 July 2010 using AO-76.

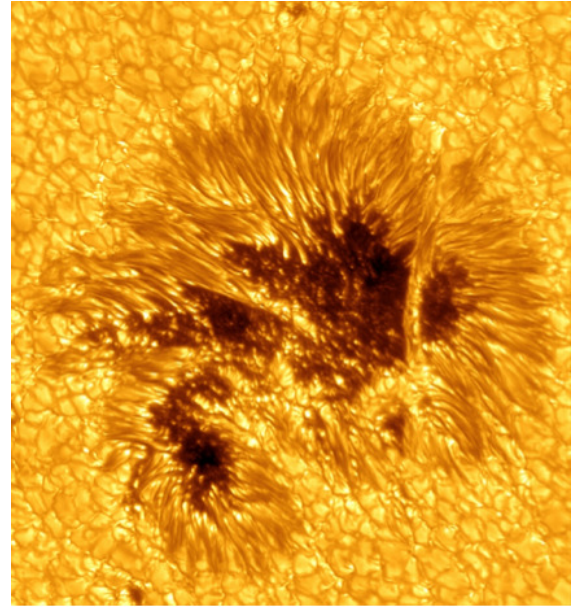


Figure 4: A sunspot image on 22 May 2013 was near disk center. Improved spatial resolution from AO-308 within the isoplanatic patch reveals a much more complex and fine structure to the magnetic field compared to Figure 1.

A.2 First and Second Generation AO on the NST

The successes of the first generation AO on the Dunn Solar Telescope (DST) and the old 0.5 m telescope in Big Bear Solar Observatory (BBSO) has delivered the enabling technology for the development and construction of large aperture solar telescopes such as the NST and the ATST. This Shack-Hartmann AO system has a 97-actuator deformable mirror (DM), and is called “AO-76” for its 76 pupil subapertures. The 1.6 m off-axis NST enjoyed first light in January 2009 and used AO-76 for its first diffraction limited observations in 2010, see Figure ???. The 1.6 m aperture was chosen because it is the smallest that can resolve the fundamental scale of magneto-convection rooted at the base of the photosphere, which has an intrinsic scale ~ 100 km (the photon mean free path) that must be probed. Thus, studies of the dynamics of these fine structures required solar astronomy to graduate to larger than meter-class optical solar telescopes. However, without AO such efforts would not lead to significant advances in our understanding of the complex MHD processes that drive solar activity.

The NST is the first facility class solar telescope built in the U.S. for a generation and is largest aperture, highest resolution solar telescope in the world and will dominate U.S. ground-based solar observations until the end of this decade when the 4 m ATST

comes online. Since AO-76 was implemented on the NST in the Summer of 2010, diffraction limited observations have regularly been obtained in the red end of the spectrum. Figure ?? shows a typical diffraction limited image of a sunspot taken in TiO 705.7 nm. The image in Figure ?? was called the most precise image of the Sun’s surface ever taken¹ and was chosen by the science editors of National Geographic as one of the top ten space images of 2010. After three years of considerable effort there is a new AO system on the NST having 357 actuators enabling a fuller correction of atmospheric distortion. Figure ?? shows a sunspot image from 2013, after the new AO system came into regular operation. Figure ?? and Figure ?? are sunspots from comparable seeing days, the image from 2010 (with 97 actuator DM) and Summer 2013 sunspot image (with 357 actuator DM) were both taken in TiO (710 nm). The differences between the two images are stark. The 2013 image shows a much sharper central region. What is apparent in the center of the Summer 2013 image is the fine structures, which are absent in the 2010 image. For instance, in the 2013 data sequence, one can see dark centers in some umbral dots something that has been predicted (REF???) , but has never been seen be-

¹<http://www.cieletespace.fr/node/5752>

fore. Basically, the higher order AO corrects sufficiently to enable us to exploit the NST's large aperture. Thus, for a sunspot, like that in Figure ??, we resolve $<0''.1$ dark centers in umbral dots. Basically, AO-308 corrects sufficient KL modes to enable us to exploit the NST's large aperture. In detail, for granulation AO-308 corrects about 150-200 modes, while for a sunspot with its higher contrast more than 300 modes are corrected. Thus, for a sunspot, like that shown in Figure ??, we resolve $<0''.1$ dark centers in umbral dots. However, the correction by modes with respect to the field angle drops faster for high order modes than for lower order ones. For this reason, correcting very high order modes can make the Strehl for large field angles even worse, as characterized in the more rapid roll-off in the 2013 sunspot in Figure ??. Thus, the AO-76 image (correcting only about 70 KL modes) shows a more gradual roll-off in image quality because of the more gradual decline in the Strehl, meanwhile that AO-76 residual errors are larger than those for AO-308. Thus, paradoxically, the sharper roll-off in AO-308 indicates that AO-308 is successful, while providing strong motivation for solar multi-conjugate adaptive optics (MCAO). The Strehl is the ratio of the maximum intensity in the AO corrected image to that in the diffraction limited image in the focal plane. In a movie of Figure ??, one can see a clear twisting motion in the light bridge. During dynamical events, like solar flares and filament eruptions, odds are that much of the action in the FOV is typically far from the isoplanatic patch, which provides further motivation for MCAO. Further, a movie of Figure ?? has a time step of a few seconds because of the required image reconstruction. However, dynamical events certainly have significant subsecond components. MCAO provides superior temporal resolution and spatial resolution. Such image quality enables us to probe the origins of space weather on much finer spatial scales that ever before. A schematic of the NST and its instrumentation is shown in Figure ??. The MCAO setup (shown in more detail in Figure ??) is shown with the yellow optical path. The first DM is on the vertical bench and corrects the ground layer. The second and third DMs are on top of the double decker optical benches. The optical setup for the latter two DMs looks a little complicated, but it is designed so that linear displacements of either (or both) DMs changes the conjugation altitude.

We note that AO-308 as funded by NSF-AST-ATI-0905279 utilizes digital signal processors (DSPs) that were programmed in-house. AO-308 has also been controlled by the KAOS system. There is no apparent difference in image quality. Switching between the two only required a flip-mirror. Thus, we can easily change between AO-308 controlled by DSPs and MCAO experiments controlled by KAOS. The implementation of KAOS to control AO-308 was surprisingly easy with the main problem being realizing and solving its great sensitivity to rf-noise.

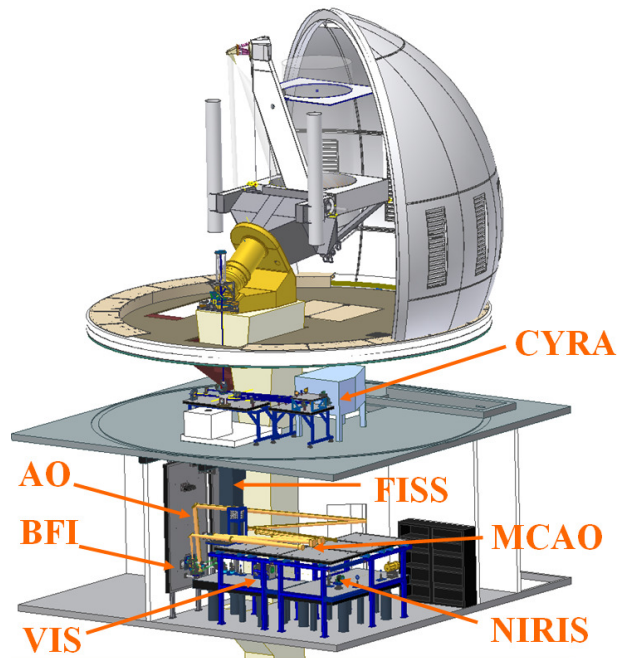


Figure 5: A schematic of the off-axis NST with its secondary mirror at the highest point. NST light is fed from the top floor to either the Coudé Lab or CYRA (CrYogenic solar spectroGRAph). CYRA precedes AO in the optical path and is fed by a tip-tilt correction, which is sufficient for most of its $1\text{-}5\ \mu\text{m}$ operating range. In the Coudé Lab, all light is first corrected by AO, then the beam is split into IR and visible light components, which are fed to one or more of the BFIs (Broadband Filter Imagers), like TiO (G-band), $H\alpha$ or $10830\ \text{\AA}$, or to FISS (Fast Imaging Solar Spectrograph), as well as to NIRIS (Near InfraRed Imaging Spectro-polarimeter) and VIS (Visible Imaging Spectro-polarimeter). CYRA will be fed by a tip-tilt correction.

A.3 Overview of MCAO on the NST

As discussed above, a severe limitation of conventional AO is its inability to fully correct the seeing

aberrations beyond the isoplanatic patch. Anisoplanatism causes the quality of the AO correction to gradually decline away from the diffraction limit with distance from the chosen lock center. As a consequence, the Strehl ratio decreases. For short exposures, i.e, broad-band imaging, post-processing such as speckle reconstruction may restore contrast to the conventional AO corrected images. Arguably, however, the most exciting science requires long exposure spectroscopy and polarimetry over an extended FOV.

In the visible, conventional AO limits the corrected FOV to about $10''$ or less. In contrast, a sunspot or active region extends typically over 1-2 arcmin. In order to capture the dynamic temporal evolution of sunspot structures on the relevant spatial scales, one requires spatial resolution of $0''.1$ or less. Flares can occur “unannounced” anywhere in the extended FOV. Flare trigger mechanisms operate rapidly and on the smallest spatial scales. Their location within the FOV is difficult, if not impossible to predict. Thus, we are led directly to a requirement for diffraction limited resolution over a FOV of 1-2 arcmin.

A single cell of supergranular convection, the convective flow pattern that reflects the organization of the magnetic network of the Sun, is of order $30''$ in diameter. In order to study dynamic, magnetic reconnection events in the network boundaries, one requires diffraction limited resolution over a FOV that covers at least 2-3 network cells, i.e., $60''$ - $90''$ in spatial extent. The vast majority of solar observing programs would benefit tremendously from diffraction limited resolution over an extended FOV.

The Sun is a natural target for extended object wavefront sensing; any number of “target stars” can be made from the 2-D structure of the Sun by using correlations from Shack-Hartmann wavefront sensing, which is the technique being used in our approach to solar AO. Implementing operational solar MCAO has been an essential, but challenging task that faces the NST, GREGOR (the 1.5 m on-axis solar telescope built by our partners at the Kiepenheuer Institute in Germany (KIS) and deployed in Tenerife, Spain) and ultimately the ATST.

MCAO provides the much needed real-time diffraction limited imaging over an extended FOV. In the simplest view of MCAO, one has two, or more, deformable mirrors (DMs) to correct anisoplanatism with each DM being conjugated to a different layer

of atmospheric turbulence. MCAO is now a demonstrated technique for correcting atmospheric turbulence over a FOV (Ragazzoni et al. 1999, Tokovinin et al. 2001, Ellerbroek et al. 2003). Wavefront sensing in nighttime MCAO is difficult because for general use, multiple laser guide stars (LGSs) are needed for tomographic wavefront reconstruction. Thus, to accurately reconstruct 3-D turbulence, generally a number of LGSs are needed. The GEMINI SOUTH MCAO system uses five LGSs and three natural guide stars (UPDATE ???).

The development of MCAO for existing solar telescopes and, in particular, for the next generation large aperture solar telescopes is stated as a top priority in the US adaptive optics roadmap (see http://aura-astronomy.org/nv/AO_Roadmap_2008_Final.pdf). The Sun is an ideal object for the development of MCAO since solar structures provides “multiple guide stars” with any desired configuration. The roadmap further states that MCAO development must progress beyond these initial proof-of-concept experiments and should include laboratory experiments and on-sky demonstrations under controlled or well-characterized conditions, as well as quantitative performance analysis and comparison to model predictions. With our proposal, we respond fully to the US AO roadmap and propose to implement its goals for studies of the Sun.

We propose to expand and characterize the high order MCAO system at BBSO 1.6 m NST to develop a well-characterized, operational MCAO that will greatly enhance the capabilities of the NST and lead to new, otherwise unobtainable discoveries. *The project is a collaboration between NJIT, NSO, and KIS and will lead to optimal MCAO systems at the currently largest aperture solar telescopes in the world, the NST, as well as its German counterpart GREGOR. This MCAO development effort is also an important pathfinder for providing the 4 m ATST with an MCAO system in the not too distant future. Although, BBSO is a university run observatory, the community will have access to the MCAO equipped NST through an open proposal process.*

Phil Goode (BBSO/NJIT), Thomas Rimmele (NSO and NJIT research professor) and Wenda Cao (BBSO/NJIT) were the PI team of NSF-AST-ATI-0905279 the successful AO project to replace our 97 actuator DM with a 357 actuator DM, so that NST

can take diffraction limited observations over a single isoplanatic patch in visible light. The 97 actuator DM was sufficient for the old BBSO telescope, but the NST has three times the aperture of the telescope it replaced. A decade ago, Rimmele (PI) and Goode were part of the PI team that built the 97 actuator AO systems on the DST and in BBSO (NSF-ATM-0079482). As well, KIS collaborated on both of these AO projects. This same team led the MCAO effort, which is the immediate predecessor of this project. A myriad of papers have been published using the DST and BBSO 97 actuator DM AO systems, as well as the 357 actuator NST system. For this proposal, the PI team is expanded to include Dirk Schmidt who is a postdoc at NSO and a recent graduate of KIS where his thesis work included development of the KAOS system software and successful laboratory MCAO experiments at KIS (DIRK HERE IS A PLACE FOR DISCUSSION OF LAB EXPERIMENTS??). He has been taking the lead in the current MCAO experiments in Big Bear with an eye toward the ATST MCAO system in the future. He is a key and welcome addition to the PI team for the work proposed here.

A.4 Background on MCAO on the NST

Before designing the MCAO setup illustrated in Figures ?? and ??, we needed to measure the altitude distribution of the atmospheric turbulence. First seeing profiles were measured using the SHAdow BAnder Ranger (SHABAR) (Beckers 2001), which are precise up to 100 m altitude. These showed that the natural inversion provided by the lake suppressed ground layer turbulence. Next, measurements of the near ground seeing were done as a part of the ATST site survey (Socas-Navarro et al. 2005; Hill et al. 2006; Denker & Verdoni 2006; Verdoni & Denker 2007). The ATST team estimated profiles up to 3.5 km from a combination of SHABAR and Solar Differential IMage Monitor (SDIMM) data. By far, the most reliable measurements were made by Aglae Kellerer (Kellerer et al. 2012) for the NST MCAO project in which she characterized the daytime atmospheric turbulence at Big Bear Lake, from the ground up to 20 km altitude, with ~ 1 km resolution using the NST for triangulation. The profiles were determined with a wide-field wavefront sensor, as suggested by Scharmer & van Werkhoven (2010). A total of 550 data sequences were collected on 26 days between June 20th and

September 28th 2011 – the height of the observing season at Big Bear Lake. Another set of 311 sequences was acquired during the winter season, between January 31st and February 23rd 2012.

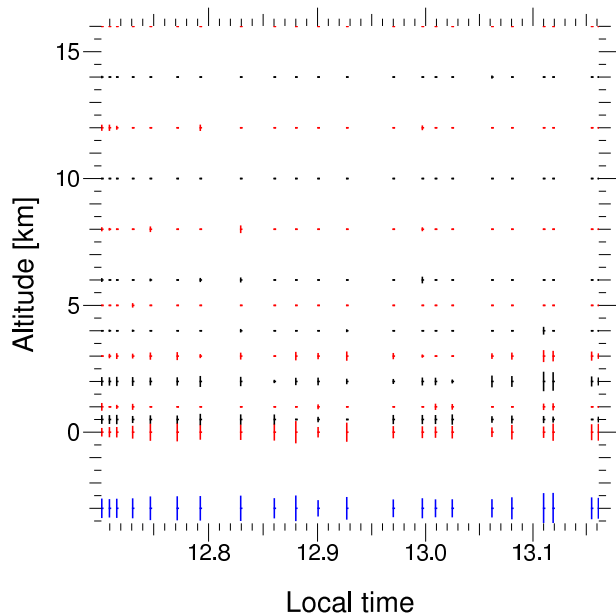


Figure 6: Atmospheric profile for June 22, 2011. The vertical extensions of the lines indicate the seeing, $\frac{1.2\lambda}{r_o}$, where an extension of 1 km corresponds to a seeing of $2''$ (the longer the bar, the larger, the stronger the turbulence). Blue lines: total integrated seeing. The average seeing (isoplanatic angle) equals $1''.6$ ($5''.5$) on June 22nd.

The NST is situated on Big Bear Lake, 200 m from shore. The seeing at the dome characterized by a suppressed ground-layer turbulence due to the cool lake providing a natural inversion. The suppression is particularly effective for BBSO’s typical westerly winds, as the air is then cooled over 3 km of open water, and passes the NST in a cool, laminar airflow. Nonetheless, we find the ground layer to be strong. On June 22, 2011, Figure ?? indicates almost no turbulence was generated in the tropopause and the boundary layer merely extends up to 3 km. Nearly a week later on June 28, 2011 (see Figure ??) additional turbulence was generated in the tropopause at roughly 12 km altitude, and in a 5 km thick boundary layer. The results on these two days for the overall seeing were in close agreement with the observers seeing assessment notes for the days. The stronger turbulence in the tropopause on June 28th is explained by the jet stream, which was just to the North of Big Bear Lake on June 28th and farther away on June 22nd.

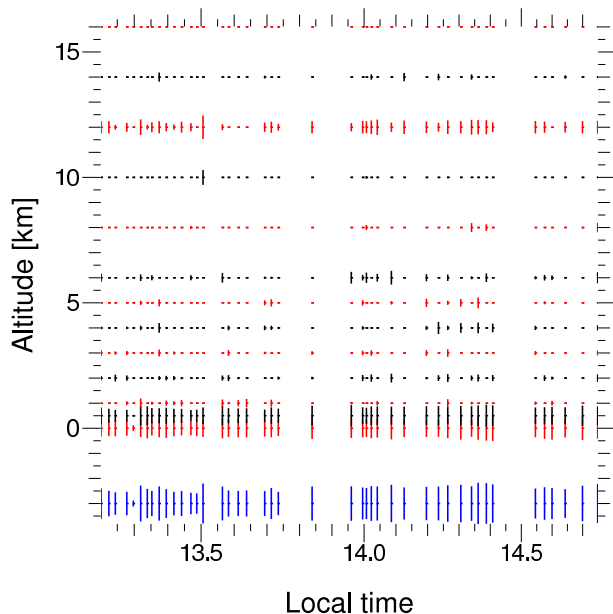


Figure 7: Same as Figure ?? except the date is June 28, 2011 where the average seeing (isoplanatic angle) equals $2''.0$ ($2''.5$) on June 28th. .

This explanation is confirmed by upper-air soundings at Vandenberg Air Force Base, 325 km due west of Big Bear on the Pacific coast. The tropopause and the jet-streams are respectively 17 km and 13 km above sea level, i.e. 15 km and 11 km above Big Bear Lake. The high wind-speeds soundings from Vandenberg on June 28th are in good agreement with the strong turbulence at 12 km in our profiles.

To decide on initial conjugations altitudes for the two horizontal bench DMs (first DM is on the vertical bench and conjugated to the ground) of the NST MCAO system, we estimate an isoplanatic angle from each profile in terms of the following relation (see the definition on page 323 of Roddiers review, 1981):

$$\theta_o = 0.31 \left(\sum_i \frac{h_i^5}{r_o(h_i)^5} \right)^{-\frac{3}{5}}.$$

The average isoplanatic angle derived from the 550 summer profiles equals $6''$ at $0.55 \mu\text{m}$ wavelength. This means that a long-exposure AO corrected image is diffraction-limited inside a $6''$ diameter FOV, on average. The current remedy for NST data consists of recording bursts of 70 short-exposure images and combining them into a single image using speckle reconstruction (Wöger et al. SHOULD PUT REFERENCE SOMEWHERE??). The resulting usable scientific field is a factor 25 larger than the isoplanatic

Atmospheric layer	Altitude range	Percentage of turbulent energy	r_o [cm]
Summer			9.1 ± 3.3
Ground	0-500 m	64%	12 ± 4
Boundary	1-6 km	31%	19 ± 7
	8-10 km	0.9%	155 ± 56
Tropopause	≥ 12 km	2.3%	88 ± 56
Winter			5.5 ± 0.8
Ground 1	0-500 m	56%	8 ± 1
Near ground	1-2 km	23%	13 ± 2
Boundary	4-7 km	15%	17 ± 2
Tropopause	≥ 8 km	5%	8 ± 1

Table 1: Average percentage of turbulent energy in different altitude-slabs and resulting Fried parameters – for the 550 summer- and 311 winter-profiles. The values refer to a wavelength of $0.55 \mu\text{m}$.

angle (see Denker et al. 2006) at the price of a much longer time step between images. Again, the long time step problem is a strong motivation for MCAO. In winter the average isoplanatic angle decreases to $2''$, so observations on better days are concentrated in the infrared, while instrumentation and telescope upgrades are done on the other days. Winter is also good for instrument experimentation.

Initially, we thought we should dedicate the MCAO observations to days in which the jetstream is not over Big Bear, which would give us the chance to test 2 and 3 DMs setups in which we would ignore high altitude corrections. Then, we would re-visit correcting the jet stream effects later.

Following Kellerer et al. (2012), we estimate isoplanatic angles after MCAO correction by setting to zero different high-altitude layers in our profiles. The turbulent layer at 500 m is likewise set to zero under the assumption that it is corrected by the ground-layer deformable mirror (DM) on the vertical bench that feeds light to the horizontal bench where the DMs conjugated to higher altitudes reside. Note that the intensity of the ground-layer ($h = 0$) does not affect the isoplanatic angle (see the equation for θ_o above). Figure ?? traces the average isoplanatic angle, without AO correction, with a ground layer AO, and with two and three DM MCAO systems. The conjugation heights of the high altitude mirrors are set to the center and to the upper limit of the boundary layer: 3 and

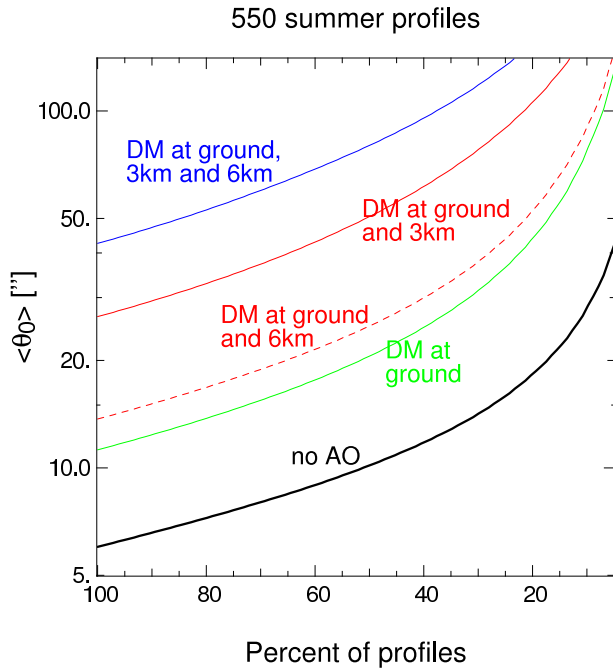


Figure 8: Average isoplanatic angle vs. the percentage of profiles with that θ_0 . The black curve is the result without AO correction. The green curve is for a ground-layer AO that corrects turbulence up to 500 m altitude, red is for a two mirror MCAO and blue for a three mirror MCAO. The conjugation heights correspond to the center and to the upper limit of the boundary layer (see Table 1).

6 km (see Table 1). The mirrors are assumed to correct the turbulence in a 2 km wide interval centered around the conjugation height. In Figure ??, we show the counterpart to Figure ?? for the 311 winter days.

With a two mirror MCAO system that corrects the ground and the center of the boundary layer, the isoplanatic angle gets extremely large if the turbulence is confined to the ground. The reverse — a high-altitude layer with no turbulence close to the ground rarely happens. Accordingly, correcting the center of the boundary layer secures excellent isoplanatic angles on days without high-altitude turbulence: 20% of our summer profiles yield $\theta_0 > 100''$. With a three mirror MCAO system the average isoplanatic-angle equals $43''$ in summer (blue curve in Figure ??). Note that these values are obviously optimistic since they assume a perfect MCAO correction. In summer, the average Fried parameters measured in the ground layer (0-500 m), the extended ground layer (1-2 km) and the boundary layer (3-7 km) equal 12, 23 and 32 cm, respectively. These values reduce to

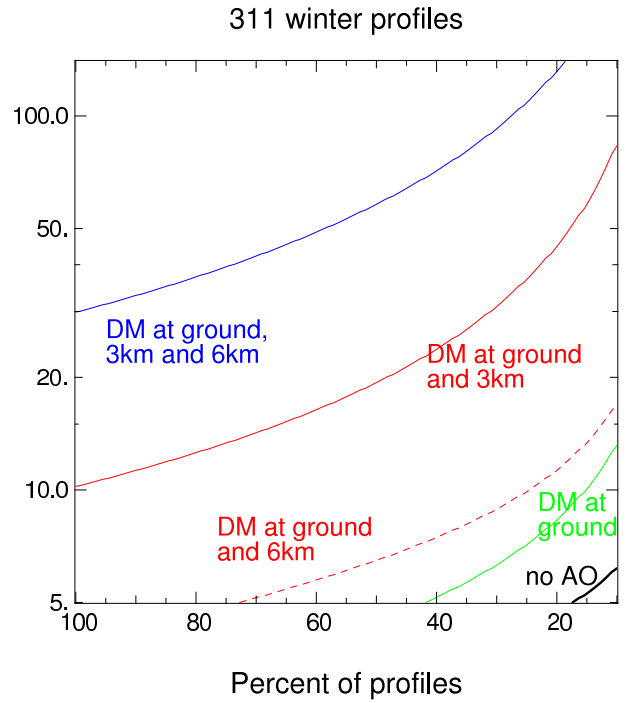


Figure 9: Same as Figure ?? except the figure is for the 311 winter measurements.

10, 20 and 27 cm in the G-band, around $0.40 \mu\text{m}$. At a 3 km altitude, the meta-pupil (the surface that contains all wavefront-footprints inside the FOV) of a $\alpha = 90\sqrt{2} \sim 130''$ diameter field equals $D_m = (D + h \times \alpha) = 3.5$ m. It equals 5.4 m at 6 km. The deformable mirrors of an MCAO system should thus have of the order of $\frac{D_m}{r_o} = 16, 18, \text{ and } 20$ actuators, respectively, per diameter at conjugation heights 0, 3, and 6 km, respectively. At BBSO, our optical setup allows us to experiment with two or three DMs and change the conjugation altitudes of the two DMs on the horizontal bench (ground layer DM is on the vertical bench) with a linear translation. We believe that the conjugation heights of the initial (WHAT WE SHOW???) two-mirror system should be 0 and 3 km the ground and the center of the boundary layer. This will ensure excellent isoplanatic angles on days without a local jet-stream (DROP THIS SENTENCE???). In Figure ??, we see that experiments with conjugation at the jet stream are also justified and will be performed. (WHAT ABOUT CHANGES TO THE OPTICAL DESIGN TO TRY CONJUGATING TO THE JET STREAM???)

One essential issue in operation of the horizontal bench, altitude conjugated DMs is how the signals

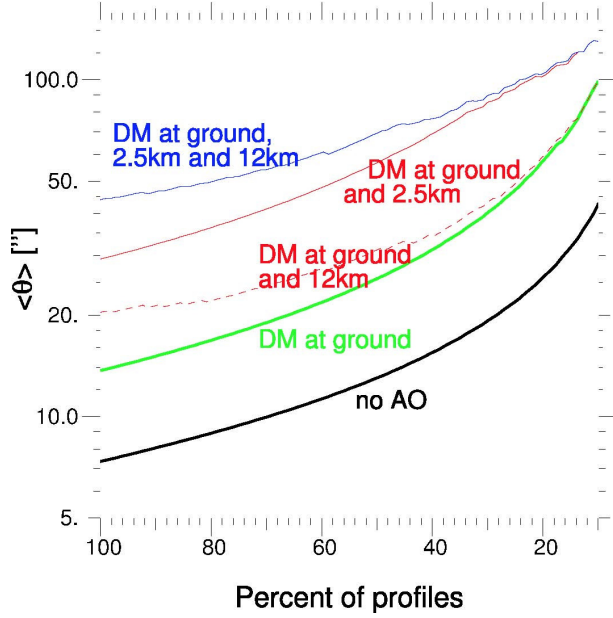


Figure 10: Same 511 profiles as in Figure ??, except conjugation at the jetstream layer is included .

are sent to each. A control matrix is used to determine the signals for correction sent to the second and third DMs, which are fed corrected light from the first DM, which resides on the vertical bench. The implemented control matrix \mathbf{SM} , converting wavefront sensor image shifts into deformable mirror modes, reads (FIX????)

$$\mathbf{SM} = \begin{pmatrix} \text{pinv}(\mathbf{MS}_{\text{TT}, \text{MD-WFS}}) \\ \text{pinv} \begin{pmatrix} \mathbf{MS}_{\text{DM}_{\text{pupil}}, \text{MD-WFS}} \\ \mathbf{MS}_{\text{DM}_{\text{low}}, \text{MD-WFS}} \\ \mathbf{MS}_{\text{DM}_{\text{high}}, \text{MD-WFS}} \end{pmatrix} \end{pmatrix}_{\text{DM}_{\text{pupil}}^{\text{low}}} \begin{pmatrix} \text{pinv}(\mathbf{MS}_{\text{DM}_{\text{pupil}}, \text{OA-WFS}}) \\ \text{pinv}(\mathbf{MS}_{\text{DM}_{\text{high}}, \text{OA-WFS}}) \end{pmatrix} \quad (1)$$

where, for example, $\mathbf{MS}_{\text{DM}_{\text{pupil}}, \text{OA-WFS}} = \mathbf{AS}_{\text{DM}_{\text{pupil}}, \text{OA-WFS}} \mathbf{MA}_{\text{DM}_{\text{pupil}}}$ denotes the modes-to-shifts matrix for the deformable mirror in the pupil (DM_{pupil}) with respect to the high-order, narrow-on-axis-field wavefront sensor (OA-WFS). MD-WFS refers to the low-order wide-field wavefront sensor, which monitors the wavefront in multiple directions. DM_{low} and DM_{high} refer to the two deformable mirrors conjugate to turbulent layers above the telescope. The matrix $\mathbf{AS}_{\text{DM}_{\text{pupil}}, \text{OA-WFS}}$ transforms actuator commands of DM_{pupil} to signals in the OA-WFS, and is gained during the system calibration. The matrix $\mathbf{MA}_{\text{DM}_{\text{pupil}}}$ decomposes modes of DM_{pupil} into corresponding actuator commands. The subscript $\text{DM}_{\text{pupil}}^{\text{low}}$

shall express, that only the lowest K (DEFINE K ???) modes of DM_{pupil} enter the inversion and that the higher modes in the inverse matrix are padded with zeros to restore it with full size. $\text{DM}_{\text{pupil}}^{\text{high}}$ means that modes higher than K are used while padding the lowest modes after inversion. Thus, the tip-tilt mirror and the lowest K modes of DM_{pupil} are controlled by the MD-WFS. At least focus and astigmatism are included in K for the current 6 sub-apertures. The OA-WFS is used to control the higher modes of DM_{pupil} . The reconstruction scheme in equation (??) means moreover that the lowest K modes of DM_{pupil} do not reflect the on-axis wavefront error but the average error of all guide regions. Hence, the on-axis guide region is not privileged but given the same weight as the other 18 regions. This shall help to get a more uniformly corrected field of view—deliberately at the cost of peak performance. This reconstruction scheme has been successfully operated in the KIS lab, but we propose to try other schemes to be used for comparison.

(PLACE FOR MCAO RESULTS???)

A.5 Proposed Work

We propose a series of tasks that benefit from the NST MCAO system taking advantage of the robustness of the NST MCAO setup. These experiments will optimize the NST MCAO and provide input to the ATST AO feed to its focal plane instrumentation. Both the NST and the ATST have off-axis designs and then there is the similarity of the NST focal plane instrumentation and the first light focal plane instrumentation of the ATST.

ATST first light scientific instruments include a 2-channel visible broad-band imager, a visible light spectrograph, a visible light tunable filter (VTF), a NIR spectro-polarimeter (NIRSP), and a NIR cryogenic spectrograph. Also, ATST 2010 SWG Meeting has emphasized the role of infrared tunable filter (NIRTF) and suggested it be the first ATST second generation instrument. NIRTF will use the same design concept as NST's NIRIS. Given the off-axis nature of both the NST and ATST, undoubtedly, NIRIS and VIS fed AO light will an excellent testbed and pathfinder for the development of these ATST spectro-polarimeters including the NIRSP, NIRTF and VTF. As well, NIRIS's operation will provide these ATST instruments with valuable experience.

The option of widely varying the conjugate positions of the high-altitude DMs in a pathfinder system like NST's MCAO is allows us to propose several tasks: First, it enables us to perform an experimental study of the impact of "mis-conjugation". Second, we propose to tune the configuration for daily and seasonal changes of the turbulence profile over Big Bear. Third, we propose to probe the very demanding option of keeping the DMs conjugated to the turbulent layers as the telescope elevation changes with the Sun's diurnal motion on the sky. The proposed experimental studies to be made with NST's MCAO system will deliver answers to open solar MCAO questions and will enable us to cross-check new simulation tools. Hence, NST's MCAO constitutes an important foundation of the future MCAO system of the ATST.

In detail, we propose to The MCAO optical setup was designed to allow many configuration to be tested.

1- Conjugate the DMs to different layers: The first high altitude DM (HA DM) can be adjusted to any altitude between 6 and 11 km. The other high Altitude DM can be located anywhere between 2 and 3.2 km. By swapping 2 mirrors (1 DM and 1 fold mirror) , we are able to push the other DM's upper limit conjugation to 5 km. This flexibility in the DM conjugations permits us to accommodate the setup to changing seeing conditions. With this, there are many studies that can be done: The first study assumes that we do not have any feedback on where the turbulent layers are. One can study how the different DMs conjugations can influence image quality. At a specific times of the day, with the DMs located at specific layers, we take some data. Then we adjust the conjugations, do a new calibration and take new data. Hopefully, the seeing conditions do not evolve much between the different configurations so that the data sets can be inter-compared. This should be done over many days, over many seasons to create statistics and understand what is the optimal configuration(s). We can also measure the impact of two DMs vs. 3 DMs.

If we assume that we know where the turbulent layers are, we would conjugate the DMs to those altitudes. With that, we can resuscitate the wide-field WFS (WFWFS) to measure the turbulence and determine the most turbulent layers. The DMs could then be conjugated to the most turbulent layers. We could study the sensitivity of the DMs conjugations,

how close do they need to be to the turbulent layers. Note that the WFWFS data reduction program was not made for fast results, and we propose to fix that. Also, we propose to determine how accurate are the WFWFS results?

2- The optical setup also creates a 90 mm diameter pupil image after the two high altitude DMs: This is an important feature not available in any other solar MCAO setup. In normal operation, the pupil DM is located before the high altitude DMs and the on-axis WFS is located before the high altitude DMs. There are advantages and disadvantages to either (WHAT ARE THEY???) . The other method is to put the pupil DM after the high altitude DMs and locate both WFS after all the DMs. The comparison of both setup should enable us to determine which method is the best in term of image quality and stability.

3- Next generation cameras to improve bandwidth:???

4- The current double-Z design does not allow conjugation into the jetstream layer: We require a modified design (???) in which two OAPs are replaced to realize an equivalent MCAO system that probes the jetstream (NEED MORE-THIS IS OUR EQUIPMENT PART???) . Also, later generation Miktronix cameras to increase the bandwidth (???) .

5- Experimentation with changes in the KAOS software: to accomodate for new hardware, new control algorithms... For that we need a licence agreement with KIS that should allow us to modify the software. Othe software, programming/modeling issues???

A.6 Science Drivers for the MCAO Equipped NST

Below we briefly describe some of the science goals that we can only meet with MCAO corrected light, which would feed our existing hardware:

(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). The 1.6 m telescope will obtain high resolution, high cadence images of flares. 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. Xu and Cao (2006) presented the very first high resolution observations of an X10 white-light flare (from solar active region NOAA 10486 obtained with the DST 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, the flare ribbons were not resolved. We anticipate that NST with MCAO will provide new and basic insight into this problem because, in part, we will be able to observe, at the diffraction limit remote, but correlated events in the FOV that precede and/or follow the flare.(UPDATE TO SHOW AO-308 TWO RIBBON FLARE???)

(b) Structure and evolution of magnetic fields and flow fields in flaring active regions

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. So, the study of magnetic fields is a very important component of flare science. This concept of energy release has motivated many attempts to detect flare-induced changes in the magnetic fields of active regions. Until very recently, no one has detected, in any consistent way, the changes in magnetic fields associated with solar flares. The BBSO group first saw signs of these changes using the old 0.5 aperture BBSO telescope, 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 was due to observational limitations. We cannot get high temporal and spatial resolution and high polarization accuracy at the same time, with existing telescopes/instruments. NST equipped with MCAO feeding NIRIS and VIS (near-IR and visible light spectro-polarimeters) will provide much more reliable, and higher quality measurements of vector magnetic fields. A consistently high Strehl ratio over the extended FOV will ensure that the detected field variations will not be due to variation in seeing conditions. More specific scientific questions to be answered are: (1) What are the relative and absolute roles of the evolution of the local and nearby photospheric magnetic fields in triggering solar flares, and what is the relationship between the evolving magnetic configuration and the properties of flares? (2) How do electric currents, derived from the field, evolve, and what is their relationship to particle

precipitation?

(c) Dynamics of Kilogauss Flux Tubes

Understanding the dynamic behavior and structure of small-scale kilo-Gauss fluxtubes is a primary scientific goal. The key issues are the formation of photospheric flux concentrations having field strength above the equipartition field strength and the dynamic interaction with the turbulent photospheric atmosphere. Understanding the dynamic interaction of photospheric flux concentrations with turbulent granulation is also essential in order to estimate the total energy flux that is transmitted/channelled by small-scale fluxtubes into the higher atmosphere. The key questions are: How are fluxtubes formed and how do they evolve? What is the lifetime of a fluxtube? How do fluxtubes interact with the turbulent flows in the photosphere? The observational determination of the process(es) that leads to kilo-Gauss flux concentration in the solar photosphere, where the equipartition field strength is only about 500 G, is a fundamental problem in solar and stellar physics that needs to be solved, and 50 to 100 km resolution is critical to resolve this problem. In the shorter term, multi-wavelength investigations ultimately using NST and satellite data to study this problem will advance our understanding of flux tube physics. Here MCAO will provide much more diffraction limited data, and thereby increasing our chances finding the odd event that facilitates new insights.

A.7 Education, Research Training and Mentoring

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 three PhD students, 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 NST MCAO Project. However, Dirk Schmidt, who is an NSO postdoc, is working on the MCAO project and is a co-PI on this project. In fact he will be taking a leadership role in the proposed work because it builds on his Ph.D. thesis work and

his work on the NST MCAO system. His work on this project is closely supervised by Rimmele and Goode to ensure he receives needed guidance and support. The second postdoc on the project is José Marino who earned his Ph.D. from NJIT in adaptive optics. He will be primarily mentored by Thomas Rimmele (his thesis advisor) who has been guiding his work in adaptive optics and MCAO, in particular, since Marino graduated. JOSE??? He has a close relation with nearly all members of the team, but is advised on a nearly daily basis by Rimmele. The mentoring of the postdoctoral associates is also discussed in the Supplemental Documents appendage to this proposal.

The resulting data from the MCAO 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.

A.8 NST Data Online 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.

On a typical observing day, the NST collects about 0.5 TB of raw data per channel (2-3 channels/day), and data from each channel are post-processed to about 5 GB for ease of use. Post-processing includes dark current and flat field corrections, as well as speckle reconstruction for photometric data and calibration for polarimetric data. A final step in data post-processing includes precise co-alignment and de-stretching of selected, excellent quality data sets, or sets that contain notable events. To save disk space and download time for “curious users”, reduced resolution quick look movies and data sets are available online (catalog at http://www.bbso.njit.edu/~vayur/NST_catalog/ and the automated data request form at <http://www.bbso.njit.edu/cgi-bin/NSTReqForm/>). The quick look web page provides detailed information about the data – pointing, observation times, etc. – as well as information on how to obtain .fts files of the data. The requested .fts files will appear automatically in an anonymous .ftp file; the requestor is emailed the file location. A catalog of interesting Summer

2011 data are already available on the BBSO website. Pre-processed Summer 2012 data will be on-line in near real-time at BBSO and SDO JSOC sites, as well as being referenced at the Virtual Solar Observatory (VSO).

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, especially after it is equipped with MCAO. 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. A web page describing all the requests will ensure that researchers will not duplicate their data analysis efforts.

A.9 Personnel Management Plan and Timelines

During the building of the NST, its focal plane instrumentation, and the AO-308 and MCAO projects, we have assembled a strong instrumentation team at BBSO. The instrumentation team now divides its attention between the focal plane instrumentation and AO projects with great effort on the latter. In AO, BBSO and NSO have a decade-long history of working together beginning with AO-76, then AO-308 and most recently MCAO. The proposal here is to continue and expand the efforts in MCAO for the NST, while performing essential experiments for the ATST. The NST is, and the ATST will be an off-axis telescope. The NST has focal plane instrumentation that is quite similar to that planned for the ATST. Thus, in the broadest sense the NST is a pathfinder for the ATST, which accounts for the strong mutual interest in MCAO.

The project here is relatively straightforward in an organizational sense. The key members of our team are in place and we risk losing momentum, and worse losing them without a continuity of funding. Goode supervises Nicolas Gorceix, Sergey Shumko and John Varsik. While, Rimmele supervises the efforts of Dirk Schmidt and José Marino. In practice, Rimmele and Goode set the overall tasks for the team. Since most of the work is done in Big Bear, when in BBSO Dirk Schmidt supervises the daily experiments in close coordination with Goode and Rimmele. Over the last decade, Goode and Rimmele have worked on AO-

Table 2: Tasks and Assignments for the MCAO Project.

Year	Task	Person(s) In Charge
Year 1	Overall Management and Coordination	Goode and Rimmele
	Project Management	Schmidt
	On-sky Experiments in Big Bear	Gorceix, Schmidt and Cao
	MCAO Control with KAOS	Schmidt and Shumko
	Control Matrices	Rimmele and Marino
	Integration Focal Plane Instrumentation with MCAO	Cao and Gorceix
	Optical Design for Jetstream Conjugation	Gorceix, Schmidt and Cao
	Review and Purchase Optical Hardware	Rimmele and Goode
Year 2	Overall Management and Coordination	Goode and Rimmele
	Project Management	Schmidt
	On-sky MCAO Observations	Schmidt, Gorceix and Cao
	System integration of MCAO on NST	Cao, Schmidt and Gorceix
	Regular Observations with MCAO	Team

76, AO-308 and MCAO with this broad organizational structure and it works well.

Dirk Schmidt (co-PI) brings his KAOS system experience and leadership to the project. Schmidt will also be the Project Manager. He already functions well in that role, while splitting his time between BBSO and NSO/SP. Nicolas Gorceix, the BBSO optical engineer, has done the double-z MCAO optical design and led its implementation. He already works closely and successfully with Schmidt. Shumko wrote the control software for the DSP-driven AO-308, and his skills will be of great value to the team. Jose Marino (NSO/SP) developed reconstruction algorithms reconstruction algorithms for AO-308 and is well-integrated into the team Co-PI and NJIT Associate Professor, Wenda Cao, is well-experienced in the BBSO AO-76 AO-308 systems and was a key developer of the IRIM, NIRIS and VIS. He will be responsible for integrating these instruments into the MCAO.

A.10 Budget

The requested two year budget for the project is \$650 K from the NSF. Even though no match is required, to show NJIT's commitment to this project, NJIT will match with \$100 K to pay half of the loaded salary of Nicolas Gorceix. As well, NJIT/BBSO (Goode and Cao) and NSO (Rimmele) personnel will be working part-time on this MCAO Project with no charge to the project. Again, Goode and Rimmele

not charging time to the project is how our all of our AO collaborations have worked over the last decade. The contribution here is difficult to know exactly, but it amounts to about 1 FTE. The \$650 K budget is \$30 K for equipment (NEW CAMERAS TO REPLACE MIKTRONIX CAMERAS-BANDWIDTH. OAPS????) with the rest going to salaries. \$410 K will pay half of Gorceix's salary, half of Shumko's salary, and one-eighth of the salaries of the observing staff (Plymate and Varsik) and on-site engineering (Nenow). The sub-award to NSO of \$210 K will pay half of Schmidt's salary and one-quarter of Marino's salary. The \$30 K in equipment money is to pay for off-axis powered mirrors required for the modified double-Z design required for conjugating to the jetstream.

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