

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

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A. Proposal Summary

Adaptive optics (AO) has brought about a revolution in ground-based astronomy yielding diffraction limited imaging in the isoplanatic patch (typically $\leq 10''$). Multi-Conjugate Adaptive Optics (MCAO) is vital for the new generation of large-aperture, ground-based solar telescopes for which the science is driven by the quest for the highest spatial and temporal resolution observations. Powerful, dynamic, magnetically driven events on the Sun can cover a $\gtrsim 60''$ field of view (FOV) with seeming simultaneity, so measuring events requires temporal image stability over the FOV. While serving as a pathfinder for the Daniel K. Inouye Solar Telescope (DKIST) AO, strengthened motivation for MCAO now comes from our first successes using three deformable mirrors (DMs) on the 1.6 m off-axis New Solar Telescope (NST) in Big Bear Solar Observatory (BBSO) in which the diameter of the corrected field was expanded by $\sim 3\times$ over that of the isoplanatic patch from a single DM.

NST's MCAO system *Clear* is today's only operating solar MCAO system, and the first to have demonstrated obvious improvement over classical, single DM AO correction. With *Clear*, we have followed a genetic experimental approach, i. e. our philosophy has been implementing a solar MCAO system with maximal flexibility in order to try a wide range of setups, and being able to move quickly from one to the next. At least 6 different configurations (deformable mirrors sequences, and wavefront sensors locations and configurations) can be realized with *Clear*. Various wavefront sensor options are available with up to 308 subapertures, and up to a $70''$ FOV, which is split into 19 guide regions (solar analogs to guide stars). A primary goal of *Clear* is to provide a pathfinder for solar MCAO by identifying and solving open issues in MCAO. The capabilities and flexibility of *Clear* are unique.

Here we propose, primarily in collaboration with our partners of fifteen years – the National Solar Observatory (NSO) and the Kiepenheuer Institute (KIS) in Germany to utilize and improve *Clear* in order to make MCAO a mature technique for use in many observational programs. On this track, it has become critical to obtain a good characterization of the seeing during our experiments while we are trying to correct for it, but also throughout the observing season to identify the optimized potential of *Clear*. For this reason we propose to implement a dedicated, real-time turbulence profilometer that is optimized for this task and permanently available, i. e. it will be independent of the MCAO hardware and the MCAO light path. Further, we propose to cross-check our experiments with the new solar AO simulator *Blur* developed at NSO. The goal here is to make *Blur* a validated tool to help us understand the performance of *Clear*. *Blur* will also play a key role in the upcoming planning of the future DKIST MCAO system. That is, its ability to reliably model the performance of *Clear* is critical for meaningful DKIST MCAO design studies. Further, we propose to implement an advanced wavefront reconstruction scheme that has already delivered a performance boost to stellar MCAO. The solar photosphere features various structures such as sunspots, smaller and larger pores as well as granules - the latter changing quickly in time. To make MCAO a reliable tool for all kinds of solar surface structures with equal performance and to run the MCAO control loop over - in principle - unlimited periods of time without interruption, we propose to develop and test appropriate and necessary enhancements to the image-correlation based wavefront sensing. We shall also exploit the intrinsic GLAO capability of *Clear* to advance this new complementary solar AO mode of operation.

Clear expands the NST's diffraction limited FOV to cover entire active regions enabling critical spectroscopic and polarimetric observations, which include, for instance, flares that may occur at anytime and anywhere in an active region. 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. The resulting data from the upgraded NST will be used in many Ph.D. theses. Construction of the community flagship, off-axis DKIST is underway and it will be fully commissioned in late 2019. After the DKIST is on-line, the NST will continue to be a critical telescope in making campaign-style observations.

(2) Broader Impact: The development of *Clear* will be primarily a BBSO and NSO collaboration, and will continue BBSO's two decade long tradition of training the next generation of scientists who build instruments. MCAO experiments and their hardware implementation on the NST will be an essential pathfinder for the more complicated DKIST AO with MCAO and GLAO to come. 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.

B. Project Description

B.1 Broader Impacts

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 and has been in regular operation for more than six years. Like the 4 m clear aperture flagship Daniel K. Inouye Solar Telescope (DKIST) now under construction, the 1.6 m clear aperture NST is an off-axis Gregorian telescope – comparable designs have made the NST an ideal testbed for various DKIST instrumentation and technologies, especially single deformable mirror (DM) classic adaptive optics and ground-layer adaptive optics, as well as multiple DM multi-conjugate adaptive optics (MCAO). Further, the testing and development of solar MCAO systems is relevant for nighttime telescopes. NST data, and a substantial portion of NST observing are open to the community.

B.2 Overview

The advent of Adaptive Optics (AO) has revolutionized solar astronomy by enabling diffraction limited observations of our nearest star with the two most powerful telescopes (the NST and German Gregor Telescope in Tenerife) having sufficient aperture to resolve what is generally regarded as the fundamental scale of the Sun’s surface. The stunning successes of solar AO have come from systems with a single DM, so that only the isoplanatic patch (typically $\lesssim 10''$ in visible light under good seeing conditions) can be corrected to the diffraction limit with decreasing correction as distance from the patch increases. It is important to bear in mind that magnetic field dynamics are the cause of the sun’s powerful, explosive and non-local events, like flares events and coronal mass ejections (CMEs), which can cover $60''$ or more. Spectro-polarimetric measurements of magnetic fields require imaging that is temporally stable over the entire field-of-view (FOV). Furthermore, 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. Thus, 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. Further, a typical sunspot might cover $\gtrsim 60''$, which is about two-thirds the size of the FOV of the NST. If a small-scale flare were to occur somewhere in the FOV, it is not likely that the flare would occur within the isoplanatic patch. Typically, image reconstruction is used to correct the full field to the diffraction limit at the cost of temporal resolution being reduced by a factor of ~ 100 , which yields time steps of a few seconds, rather than a few tens of milliseconds (ms) because the information in a burst (~ 100) of images is combined into a single image (see Fig. 1), whereas the images input to reconstruction are regarded as having roughly the same time scale as the dynamical action, for a review see Nordlund et al. (2009). Furthermore, dynamical solar phenomena, like flares (see Fig. 1) and CMEs are quite non-local, with nearly simultaneous, somehow interconnected manifestations of the dynamics often spread over the entire FOV. Such large-scale events are tied to the origins of what is broadly called “space-weather” (for details see <http://swpc.noaa.gov>) which can impact the terrestrial environment including satellites. Since meaningful image reconstruction relies on an unchanging FOV during each burst, the reconstruction is problematic during the most scientifically significant moments of large dynamical events. Thus, wide-field, diffraction-limited correction of MCAO is the holy grail for addressing the fundamental dynamics of our star.

MCAO would provide the much needed real-time diffraction limited imaging over an extended FOV (Dicke, 1975; Beckers, 1988; Ellerbroek, 1994; Ragazzoni et al., 1999; Rigaut et al., 2000; Tokovinin et al., 2001). 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 a demonstrated technique for correcting atmospheric turbulence over a wide FOV for observations of the night sky (Marchetti et al., 2003; Rigaut et al., 2014; Neichel et al., 2014b), and the Gemini South MCAO system (GeMS) is routinely used for astronomical observations (e.g.

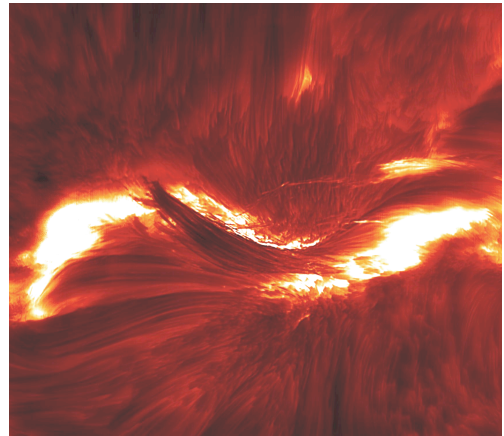


Figure 1: Flare seen in chromosphere in $H\alpha$ centerline. The NST image is for NOAA Active Region 11817 on 11 August 2013 and the FOV of $50'' \times 50''$ is spanned by the C2.1 flare’s impulsive phase. Post-flare loops can be seen running right-left covering parts of the right-left flare emissions.

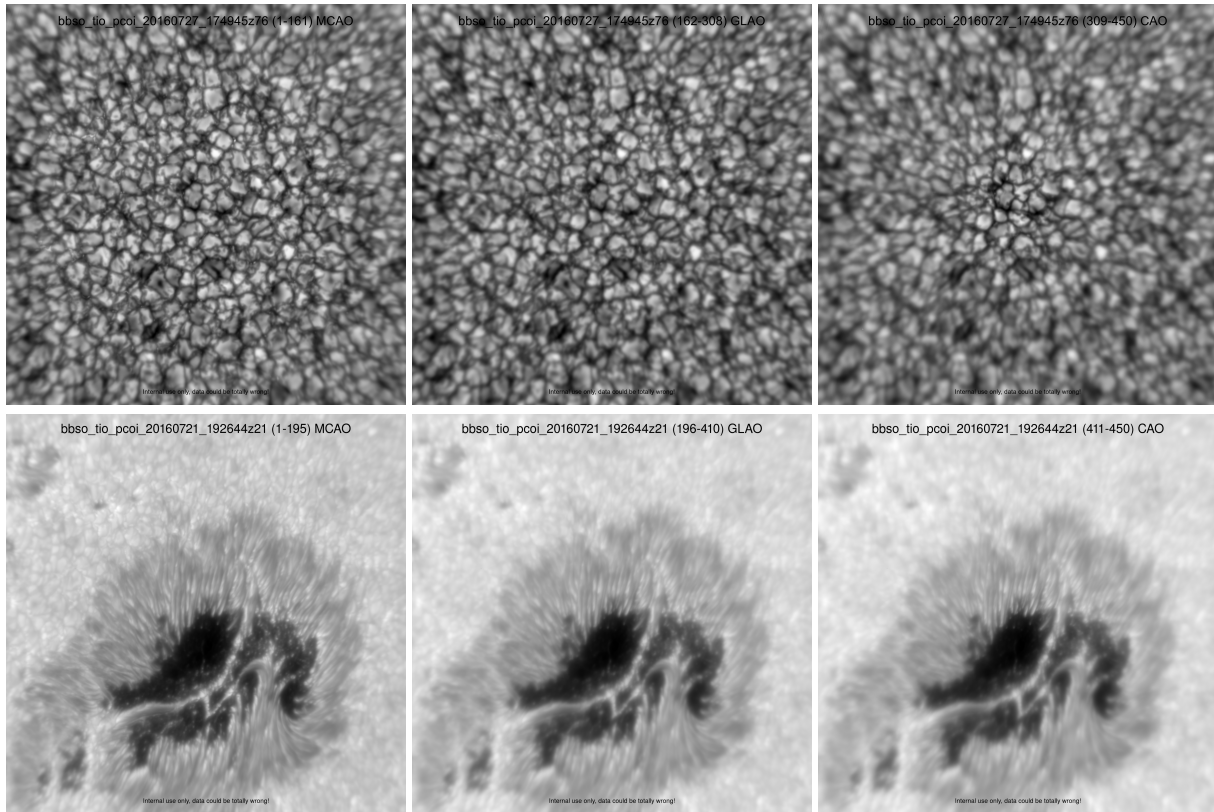


Figure 2: The Sun observed in a field of view of $53'' \times 53''$ with, left to right, MCAO, GLAO, and CAO correction with *Clear* on the NST through a filter for the titanium oxide line (705.7 ± 5 nm). The top row shows a quiet region of the Sun between 10:49:45 and 10:50:16 local time on July 27th, 2016. The bottom row shows a sunspot in active region NOAA 12567 on July 21st between 12:26:44 and 12:27:24. Each image shows the sum of the images within a block with MCAO (left), GLAO (middle), and CAO (right) correction in a continuous burst of 450 frames recorded. No image reconstruction or contrast enhancing methods were applied. Real-time movies are available online ([GIVE ONLINE LOCATIONS???](#)).

Neichel et al., 2014a). 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 (GeMS) uses five LGSs and three natural guide stars. This project was started in 1999, saw first light in 2011, and is now in regular operation. GeMS produces images close to the diffraction limit in the near infrared uniformly over a field of $2'$.

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 Kiepenheuer Institut für Sonnenphysik (KIS) and deployed in Tenerife) and ultimately the DKIST.

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.

Owing to its proximity, the Sun presents an extended FOV, and with its granular structure and various scales

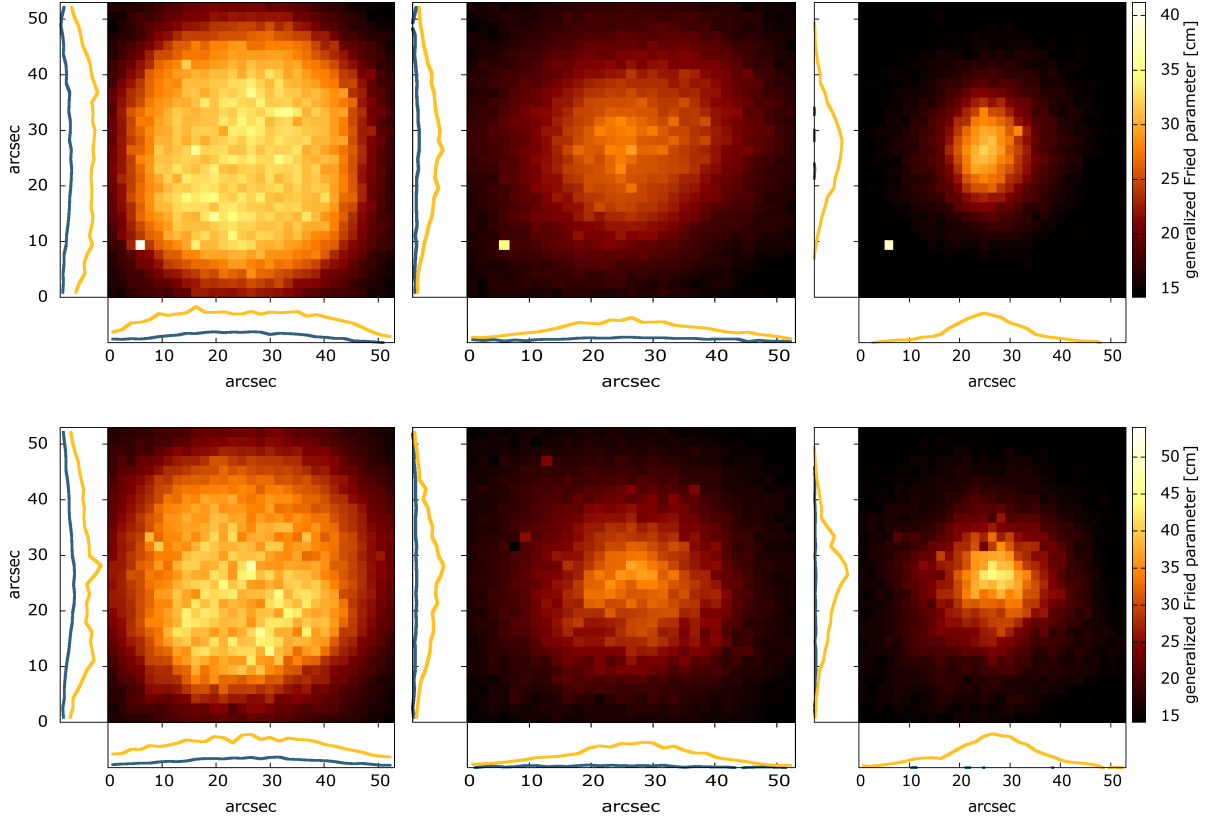


Figure 3: Generalized Fried parameter (Cagigal and Canales, 2000) across the field of view in the images shown in Fig. 2. The yellow lines along the ordinate and abscissa represent the relative intensities down and across the middle of the field, whereas the blue lines represent the corresponding relative intensities along the margins. For both rows, the full-width at half-maximum in the CAO yellow is $\sim 10''$, while that for the MCAO is $\sim 30''$.

of magnetic features (see Fig. 2), there are innumerable so-called “guide regions” (solar equivalent of guide stars, but guide regions are also extended objects, like granules, pores, etc.). Thus, the sun offers enough information to reconstruct the optical turbulence in Earth’s atmosphere even though it is a single star. The feasibility of solar MCAO was demonstrated in pioneering experiments (Berkefeld et al., 2010; Rimmele et al., 2010), which demonstrated that two DMs with up to four guide regions could reduce the residual image motion, and thus, in principal, effectively expand the FOV.

Our MCAO system on the NST is called *Clear* and features three DMs that can be conjugated to different altitudes. The control system, KAOS Evo 2, for *Clear* was originally developed by Berkefeld and Schmidt for the Gregor telescope (Berkefeld et al., 2012). Here, propose to use and advance that real-time control system KAOS Evo 2 continuing the fifteen year long collaboration in AO among the National Solar Observatory (NSO), KIS (hence KIS AO control system has the name KAOS), and BBSO of New Jersey Institute of Technology (NJIT). *Clear* includes MCAO, as well as two single DM systems, classical AO (CAO) and ground-layer GLAO (AO).

B.3 Results from Prior NSF Support

Results from the first ever clearly and easily visible successful solar MCAO imaging are shown in Fig. 2. The results are from NSF-AST-ATI-1407597 support. These first step explorative, but impressive results were obtained on the NST with the three DMs conjugated to the pupil, 3 km and 8 km, respectively, and a wavefront sensing FOV of $35''$ that utilizes a single multi-directional Shack-Hartmann wavefront sensor (MD-WFS). Initially we started with two separate wavefront sensor stages, namely an on-axis, high-order, narrow-field wavefront sensor (OA-WFS) and a low-order, wide field MD-WFS, which were built for a correctable FOV of approximately $1'$, following the MCAO approach at the German Vacuum Tower Telescope (VTT) and Gregor (Berkefeld et al., 2010) shown schematically in Configuration 1 of Fig. 4 with the idea being to add high altitude corrections to those from a single pupil conjugated

DM. While this scheme worked well in several laboratory tests with an artificial target and turbulence generated by cooktops placed in front of the DMs, the effectiveness of the wide-field correction was much less impressive when we observed the Sun, even with trying various changes in DM conjugation heights.

We realized that a very spread out turbulence distribution would not fit well to our three DMs at the AO4ELT4 meeting in Fall 2015, when we were advised by F. Rigaut to reduce the targeted corrected FOV in order to reduce the generalized fitting error by making the each high altitude DM effective over a wider (deeper) range in height. Concurrently, we had already planned to upgrade our low-order MD-WFS with a faster camera that would allow us to use more subapertures while preserving the FOV. With this camera, and the advised reduction of the FOV, we were able to design a medium to high-order MD-WFS that enabled us to eliminate the separate high-order narrow-field WFS that was required until then to appropriately cover the FOV. For the 2016 season, we implemented the new MD-WFS designs with 112 (11.8 cm) and 208 (8.8 cm) subapertures and a FOV of $35'' \times 35''$ that was divided among 7 or 9 guide regions. Our new wavefront sensing scheme is very similar to the laser-guide-star scheme of the Gemini South MCAO System, which offers an equally high wavefront sampling for all 5 laser-guide-stars. The reconfigured MD-WFS also allows us to operate the control loop in a medium- to high-order GLAO manner similar to that proposed by Rigaut (2002). The new wavefront sensor camera is able to read the 992×992 px needed for the 208 subaperture configuration at 1000 fps, as well as the real-time control computer that needs to process up to $208 \cdot 9 = 1872$ image correlations per loop cycle that limits our control loop frequency, and thus the control bandwidth.

(Highest-performing classical solar AO systems are designed to operate at least as fast as about 2000 Hz for acceptable time delay error). From the beginning, *Clear* was designed to have great opto-mechanical and real-time control system flexibilities to enable us to test various approaches that have been used, proposed, or could be adopted for solar MCAO, and to investigate the importance of the position of the pupil DM (before or after the high-altitude DMs, (Flicker, 2001)) for our wavelength ranges and turbulence profiles (see Configuration 3). For *Clear*, we use and advance the real-time control system KAOS Evo 2 to have the flexibility requirements implicit in Fig. 4. KAOS Evo 2 was initially developed by Berkefeld and Schmidt for the Gregor telescope. A schematic overview of all configurations that are available in *Clear* is shown in Fig. 4. For the NST, it was rather easy to add an update to include our new wavefront sensing scheme, Configuration 6, which was used when we acquired the images shown in Fig. 2.

The peculiar looking optical design seen in Fig. 5 was originally made to purposefully allow highly flexible, individual adjustments in the conjugation to localized layers for each high-altitude DM (see Fig. 6). This design was exploited in the new wavefront sensing scheme in order to determine the configuration that minimizes the generalized fitting error. According to Rigaut et al. (2000), a DM with actuators spaced by d_{act} can cover a range in height of

$$\Delta h_{\text{max}} = 1.75 d_{\text{act}} / \theta, \quad (1)$$

below and above the DM, with θ being the FOV to which the correction shall be applied. In our new case with about $30''$ guide-region separation, this is approximately $1.75 \cdot 9 \text{ cm} / 30'' \approx 1 \text{ km}$ for the DM conjugate to the pupil, approximately 2 km for a DM when conjugate to 3 km, and about 3 km for a DM in 8 km, that is **we continuously cover the range from 0 to 11 km with the reduced wavefront sensing field of view.**

With a total of 1071 actuators in the DMs of which 555 are effectively used at this time, *Clear* offers the most degrees of freedom for image correction of any solar telescope today. (Each of the DMs, which were manufactured by Northrup-Grumman AOA Xinetics, has 357 actuators and shows a best flat figure error of about 4 nm rms). In order to

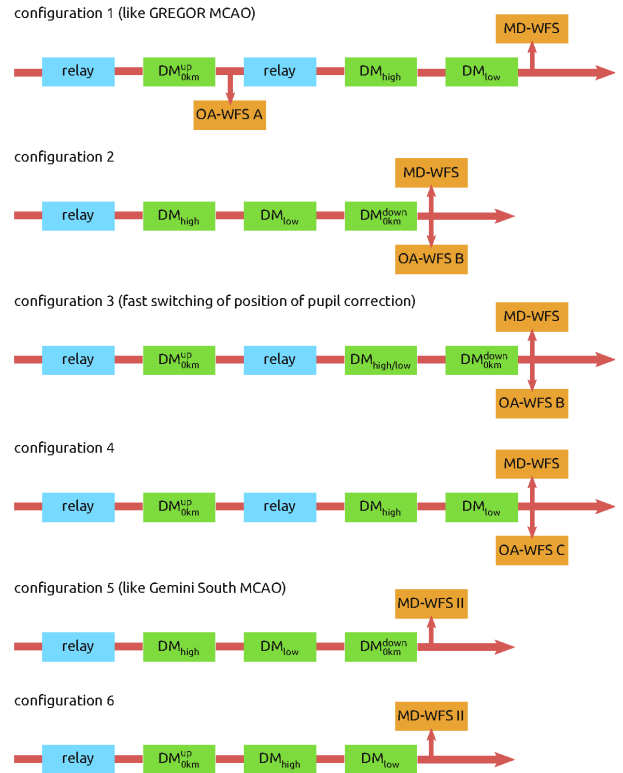


Figure 4: Schematic of the various possible DM and WFS configurations in *Clear*.

identify the wavefront modes on the DMs that are poorly reconstructed, we used a simple analysis of the system's condition number. Depending on signal to noise conditions we used typically about 150 Karhunen-Loeve modes on the pupil DM, and up to 90 and 50 modes on the DMs at 3 and 8 km, respectively, with the MD-WFS configuration having 208 subapertures and 9 guide-regions. modes on the DMs that are poorly reconstructed, we used a simple analysis of the system's condition number. Depending on signal to noise conditions we used typically about 150 Karhunen-Loeve modes on the pupil DM, and up to 90 and 50 modes on the DMs at 3 and 8 km, respectively, with the MD-WFS configuration having 208 subapertures and 9 guide-regions.

During our most successful experiments which took place in July 2016, we monitored the focal plane with a CCD camera through an interference filter for the titanium oxide line (705.7 ± 5 nm). We took numerous bursts of 450 frames with short exposures operating at 14.7 frames per second, i. e. a total time span of approximately 31 seconds. Each burst typically contains about 150 frames (10 sec) with continuous MCAO, GLAO and CAO correction. (The KAOS Evo 2 control software enables us to switch the mode of AO correction instantaneously without losing lock.) These bursts are short enough to be interpreted as *quasi-simultaneous* observations with CAO, GLAO, and MCAO correction. In order to rule out that the perceived effects are due to unnoticeable seeing changes that happen to occur co-incidentally when we switched the mode of correction, we recorded numerous of such bursts. In the CAO mode of correction, we used the pupil DM and the central guide-region only, the other DMs were at rest and off-axis guide-regions were ignored. In GLAO mode, we equally considered all guide-regions to control the pupil DM, while the higher DMs were still at rest. From simultaneously recorded control loop telemetry data,

we can identify the frames in each burst that were corrected in MCAO, GLAO, or CAO manner, respectively. Each row of Fig. 2 shows one of the 450 frame bursts, recorded on July 2016, and divided into three blocks of MCAO, GLAO, and CAO correction, where each image shows the superposed frames of each block.

In the upper left panel of Fig. 2, the great improvement is obvious with $< 0''.2$ intergranular lane bright points (Goode et al., 2010) being easily apparent even at the edge of the $\sim 35''$ diameter corrected FOV – the setup aimed for a $35''$ corrected FOV and achieved it. In the lower left panel, the fibril structure of the umbra, penumbra looks clear, as is the granular field compared to GLAO and CAO results. In these observations, nine guide regions were used. Results like those in Fig. 2 were seen many times in the ten day observing run near the end of July 2016. Another way to understand Fig. 2 is to examine the generalized Fried parameter (Cagigal and Canales, 2000), which measures the increased Fried parameter across the field due to the AO correction. We computed the generalized Fried using the KISIP image reconstruction software (Wöger et al., 2008). It is noteworthy that the FOV in the upper left panel of Fig. 2 is a granular field, which makes the results even more impressive because relatively low-contrast granulation is harder to lock-on than the rather high-contrast magnetic features like pores. The rightmost panels of Fig. 2 shows superposed images gained with CAO correction. The relatively small isoplanatic patches are apparent near the center of the FOV of each. Inspection of Figs. 2 and 3 shows the improvement of MCAO, as well as the differences between between ground-layer and classical correction. One can see advantages for both CAO and GLAO depending on the requirements of the observations with CAO providing best image detail in a small

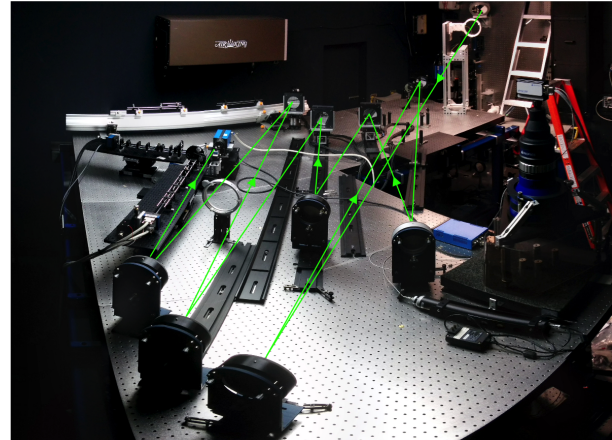


Figure 5: The MCAO bench that led to Fig. 2. The light path is sketched in green (light enters from the upper right). The black platforms on the left carry the MD-WFS and the OA-WFS (only the MD-WFS was used in the setup for Figs. 2 and 3). Feed optics are not shown in this picture. The focal plane of the MCAO path is monitored with the large blue camera (PCO2000) next to the MD-WFS. The black dovetail rails allow for quick adjustments of the high altitude DMs .

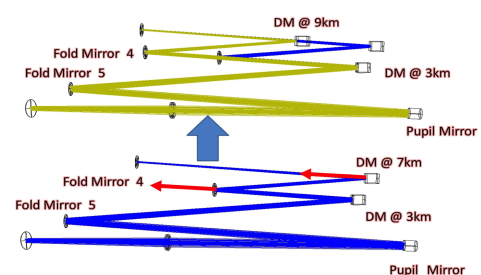


Figure 6: Top: High altitude DM is conjugated to 9 km. Below: that DM and its partner flat mirror are moved so the conjugation altitude is 7 km. No other optics need to be touched as long as the change is ± 2 km.

FOV, while ground-layer correction resulted in a lower but more homogeneous image detail over the field compared to classical correction. During our experiments, however, we found that the effect of our GLAO mode of operation was not consistent from observation to observation. We anticipate a role for variable turbulence distribution to explain this. It is apparent that the MCAO is a great improvement over CAO and GLAO. We were able to operate the MCAO control loop stably whether the pupil DM was placed before or after the high-altitude DMs. This was one of the very important questions that we needed to answer with *Clear* before planning the DKIST MCAO. However, we cannot draw conclusions yet as to which performs better, because it takes us about 2-3 hours to relocate the pupil DM, a timespan over which seeing conditions usually change completely.

The single DM system, AO-308, was supported by NSF-AST-ATI-0905279. AO-308 is the second generation AO system in BBSO. The DM has 357 actuators and 20 subapertures across a diameter of the primary mirror implying 8 cm subapertures, which is sufficient for AO-308 observations to correct the bluest of visible light under good seeing. The AO-308 system is based on digital signal processors rather than PCs, as in *Clear*, for the wavefront sensing and DM actuator control. We found that KAOS on CAO functioned as well as AO-308. So we have two separate single DM AO systems. AO-308 is used during ordinary observations and operates from a vertical bench, while the KAOS-based *Clear* system is a self-contained experimental system on a separate, horizontal optical bench. During regular observations, a single DM is used and is devoted to AO-308, but during our work on *Clear* all three DMs are devoted *Clear*. The fact that experiments with AO-308 using the BBSO system and CAO using KAOS gave similar results was comforting and demonstrated the power of PCs in AO.

The first generation AO system featured 97 actuators with 76 subapertures (10 along a diameter) with 16 cm subapertures along a diameter. This system could only correct light in the near-IR on the NST, but was sufficient for now-retired 0.5 m solar telescope in BBSO. This early AO work was supported by NSF- ATM-0079482 fifteen years ago and led to first generation AO systems in Big Bear and on the Dunn Solar Telescope (DST) of the National Solar Observatory (NSO). All three generations involved close collaboration between BBSO, NSO and KIS with Goode (BBSO) and Rimmele(NSO) being the only principals common to all AO and MCAO grants mentioned in this section.

The first MCAO setup in BBSO was built under NSF-MRI-0959187 support. The MCAO pathfinder *Clear* on the NST was built to address a multiplicity of design options with maximal flexibility because there are many outstanding issues in maturing the MCAO technology for solar observations. To our knowledge, *Clear* is not only today's most powerful solar MCAO system, but also currently the only MCAO system installed on a telescope and ready to look at the Sun. The basic system features three deformable mirrors, each having 357 actuators. Various wavefront sensor options can be implemented, ranging from narrow-field (i. e. single guide-region) on-axis sensors with about 10'' FOV and 208 or 308 subapertures, to wide-field multi-directional sensors with 19 subapertures and 19 guide regions in a 70'' FOV or 112 and 208 subapertures with 7 or 9 guide-regions in a 35'' FOV, see Fig. 4.

Our testing has been ongoing under now-expiring NSF-AST-ATI-1407597 support with first success as illustrated in Fig. 2 and Fig. 3. The MCAO work has also been done in close collaboration with our partners in those two proposals – NSO and KIS. Again, *Clear* at the NST is strongly based on the concepts of the MCAO system of the German GREGOR telescope, which are the result of the pioneering and continuous solar MCAO research at KIS and NSO. In particular, *Clear* uses the KAOS Evo 2 control software that has been developed at KIS, and their verified hardware (Berkefeld et al., 2012; Schmidt et al., 2013).

B.4 Proposed Work

Even though we already have been able to obtain impressive images with MCAO correction, we are still in an experimental stage. At this time we cannot predict the degree of correction MCAO will provide at any particular moment. Rather, we have to try and see what happens – which is clearly not suitable for efficient observing. Further, our control loop is not yet able to handle the continuously developing image structure of the Sun, i. e. we cannot provide stable MCAO corrected imaging for longer than about 1 or 2 minutes – which is not long enough to capture dynamic solar processes. **We propose to optimize the system's performance so that it is able to provide useful image correction for a significant fraction of seeing conditions and observational programs such that *Clear* can evolve from the most successful solar MCAO demonstrator into an everyday instrument, rather than not knowing when *Clear* will be useful.** The keys to accomplishing these goals are (1) building a turbulence characterizing instrument that will enable us to understand both the momentary and the prevalent seeing conditions and to model the achievable degree of correction, (2) to upgrade the performance of the critical hardware of *Clear*, and (3) to improve our algorithms and to test them in on-sky experiments. In detail, what we propose breaks down into 9 parts:

1. Turbulence Profiler We propose to develop and implement a near real-time turbulence profiler for the NST to be connected to *Clear*. Understanding the momentary altitude dependence of the optical turbulence profile is critical in various aspects of adaptive optics (not only for MCAO and GLAO):

- During the experiments: (1) Advanced tomographic reconstruction schemes that reconstruct the wavefront in several layers (more layers than DMs) depend crucially on the turbulence profile. (2) Precise knowledge of the turbulence profile enables us to move the high-altitude DMs to their optimal positions
- After the experiments, we will be able to cross-check our experimental findings with simulations of image correction. Monitoring over long periods will enable us to identify the prevalent turbulence profile in Big Bear. A better knowledge of the typical turbulence profile in Big Bear will allow us to study the feasibility of deploying additional DMs to *Clear* to further widen the corrected field of view.
- With the advent of alternative AO modes of operation, we need to understand what performance can be expected from the AO modes under what seeing conditions. While this is obviously essential for the development and implementation of MCAO and GLAO, once fully commissioned, the person in charge, e. g. the Resident Astronomer or Duty Scientist, needs to be able to utilize the profiler data to decide the observational program and what AO flavor fits best to the momentary conditions.

In 2015, we got in contact with B. Neichel (former adaptive optics scientist at Gemini South, now Aix-Marseille University) at the European Week for Astronomy and Space Science held on Tenerife, who connected us to A. Guesalaga who works on turbulence profiling for the Gemini South MCAO (Guesalaga et al., 2014). We have established a collaboration with Guesalaga in order to install a turbulence profiling system using the SLODAR technique (Wilson, 2002) for the NST. This profiler shall be based on the Matlab implementation of the profiler of the Gemini South MCAO (Cortés et al., 2012). During all our experiments in 2016, we took several wavefront sensor datasets for turbulence profile reconstruction. Analysis on those data is pending. We have done initial cross-checking of the setup of the SLODAR algorithm and the NSO AO simulation tool. This was the initial step in our proposed effort to implement a near-realtime profiler on the NST. We used the MD-WFS for collection of data for the profiling. This WFS, however, is optimized for the MCAO control loop. Its Mikrotron EoSens 3CXP camera, which was chosen in a compromise between speed and signal-to-noise ratio for application in closed loop, is not a good option for turbulence profiling. The EoSens 3CXP camera saturates at only 27k photoelectrons. While this number is barely sufficient to lock the control loop on weak contrast solar granulation under good seeing conditions, it is not enough to detect granulation under worse seeing conditions. However, it is these seeing conditions that we want to be able to analyze with the profiler with reasonable signal-to-noise ratios. We therefore propose to install a dedicated wavefront sensor that is optimized for this task and which can be used in a variety of seeing conditions. In contrast to the wavefront sensor of the MCAO control loop, the profiling sensor shall have a fixed geometry that we do not change to ensure a consistent monitoring. An Adimec Q-2HFW-CXP camera with 1440×1440 pixels saturates at 1.6 million electrons, which allows for extremely low shot noise. With this camera, that is able to deliver 550 frames per second, we could realize a profiling wavefront sensor with e. g. a full field of view of $91''$ (maximum guide region separation $80''$ and 10 cm sub-apertures (1 m overall diameter)). This configuration should allow a vertical resolution of about 260 m. The 208 subapertures, $35''$ MD-WFS should allow for only 600 m, however, the finer we resolve in particular turbulence near the telescope, the better we shall be able to understand our GLAO experiments. In conjunction with the high-frame rate of the Adimec camera, we should be able to get an excellent signal-to-noise ratio even within quite short time interval (~ 10 s). That is important because the solar structure changes on this time scale, and we can thus avoid updating of the reference image in the digital image correlation. Another advantage of a separate profiling wavefront is that we can place it before the MCAO corrected focus, thus we would not need to account for the DMs' figures in the profiling. This is, neither do we need to interface the profiling wavefront sensor with the control loop, nor do we need to preserve a very tight alignment tolerances for this wavefront sensor.

We plan to use KAOS (in an adapted version), on a dedicated computer, for image acquisition and computation of the image shifts (wavefront slopes) in real time. The image shifts shall be analyzed with the profiling tool provided by A. Guesalaga. In order to realize the profiler, we propose for the wavefront sensor camera, a computer, and the related opto-mechanics.

2. End-to-End simulations We propose to utilize, and to refine numerical Monte-Carlo simulations to cross-check our experimental MCAO loop findings, to validate the implementation of the turbulence profiler and the tomographic minimum mean square error (MMSE) reconstructor, and to further improve the performance and stability of the control loop. Marino and Schmidt have been developing *Blur*, a numerical simulation tool that interfaces seamlessly with the

KAOS Evo 2 control software (the very same software we use in *Clear* for the real-time control) and presents it with a simulated observation. *Blur* computes realistic images in the Shack-Hartmann wavefront sensor in a geometrical approach. In a highly parallelized process, *Blur* applies optical turbulence located in a number of layers and the correction by DMs to an object structure (e. g. solar features like granulation, pores, or sunspots) over a wide field. That is, both image blurring and image distortion are modeled by a point-spread function that varies inside the field of view of the wavefront sensor. After characteristics of the camera exposure (e. g. noise sources, pixel scale) have been added, the final image is placed into the camera frame buffer of KAOS. KAOS then runs a control loop cycle as it would for an image acquired by a real camera, and eventually outputs mirror commands to *Blur*, which in turn computes a new wavefront sensor camera image with updated atmospheric turbulence, mirror figures and object structure. A simple system like AO-76 on the Dunn Solar Telescope with one turbulent layer can be simulated with over 100 iterations per second (simulator and control loop) on a 2013 MacBook Pro laptop. A computer with four Xeon E5-4650 CPUs is able to simulate about up to 5 iterations per second of the 208 subapertures 9 guide regions configuration of *Clear*. *Blur* is able to output various diagnostics such as the corrected and uncorrected wavefront for arbitrary field points in the image, which can be used for direct benchmarking and to model a high-resolution image in the science focus. We will also use *Blur* for developing and testing of KAOS without a laboratory test bench or the system at the telescope. For the design of the DKIST MCAO, it is extremely important to thoroughly understand our experimental findings from *Clear*, and be able to model them with *Blur*. This way, we ensure that our simulations for DKIST will be dependable. [SIMULATIONS CRITICAL, NEED REFERENCES & FIG TO SHOW WORK DONE](#)

3. Faster real-time control computer Our current real-time control computer was scaled such that the camera is the bottleneck (read-out and transfer) in any of Configurations 1-4 in Figure 4, rather than the processing power of the computer. In the new Configurations 5 and 6 with 208 subapertures and 9 guide regions, the number of image correlations is almost three times as big, as in our initial configurations. Our control computer constitutes the bottleneck in these configurations - which have provided the best results so far (see Figs. 2 and 3), i. e. they certainly deserve to be optimized for performance. The processing capacity of our computer limits the control loop frequency to about 1000 Hz, however, the camera would be able to deliver almost 1600 frames per second for the read-out window we use. With a faster, modern control computer, we shall be able to reach the limit of the camera and to reduce the latency in our control loop by about 400 μ s, and hence minimizing the bandwidth error. (At this time, the bandwidth error in our July experiments has not been determined, thus we cannot give a precise estimate of the decrease of the bandwidth error.) However, solar AO systems should aim for at least about 2000 Hz loop frequency in order to realize closed loop bandwidths greater than 100 Hz, which is needed because the temporal power spectrum contains signal up to at least 200 Hz (Rimmele and Marino, 2011). Much to our regret, an adequate faster camera that would allow us to reach at least 2000 Hz does not seem to be commercially available at this time. We also need a more powerful real-time control computer for more complex reconstruction schemes like the one we propose to implement in the next section.

4. Fully tomographic wavefront reconstruction We propose to implement in KAOS Evo 2 a tomographic minimum mean square error (MMSE) reconstructor. Such an approach is optimal because it considers a posteriori knowledge of the turbulence statistics for regularization (Fusco et al., 2001). Our current reconstruction strategy is a classical least-squares estimator (LSE), which only considers the interaction of the DMs with the wavefront sensors, i. e. we reconstruct only as many layers as we have DMs. Further, no information about the (instantaneous) optical turbulence profile and the measurement noise is utilized at this time. The MMSE reconstructor, which is successfully used in GeMS, first reconstructs the optical turbulence in many layers (more than DMs), using both an appropriate (ideally instantaneous) turbulence profile and the measurement noise for regularization. The reconstructed turbulence is then projected onto the DMs. The MMSE reconstructor was found to improve the performance of GeMS (Neichel et al., 2010), and we likewise anticipate benefit to our application. The implementation in KAOS Evo 2 requires significant modifications. Before the regularized reconstruction of the layers can be applied, the current figure of the DMs needs to be disentangled from the wavefront sensor measurements to model pseudo-open-loop measurements. This step requires inclusion of an extra matrix multiplication in KAOS. Further, from discussions with M. van Dam (Flat Wavefronts), we understand that it is advisable to implement the MMSE reconstructor in actuator space. KAOS Evo 2 currently first reconstructs modes in the DM space (arbitrary modal sets, but usually KL modes). The proportional-integral-derivative (PID) controller then operates in the mode space before the projection onto the actuator space is performed. Applying the PID algorithm on the actuators instead of DM modes requires additional modifications to KAOS. Due to the modeling of pseudo-open-loop wavefront measurements and the reconstruction of more layers than available DMs, the MMSE reconstructor requires significantly more computing power than our current control scheme. Our current control computer constitutes the bottle-neck when we use 208 subapertures and 9 guide-regions with our

classical LSE reconstructor. For this reason, we need a significantly faster real-time control computer to implement the MMSE reconstructor. The MMSE reconstructor shall be used for both, on-sky experiments and simulations. We believe that building practical know-how in on-sky experiments and numerical analysis with this reconstructor is also of great importance for the planning of DKIST MCAO.

5. Impact of image structure on image displacement estimation During our experiments we found to our surprise that the image displacement estimation on the sub-pixel level (parabolic fit of the correlation peak following up the image cross-correlation) seems to be significantly affected by the actual image structure. We noticed this while we used a slide showing realistic solar scenery as an artificial target during the measuring of the interaction matrix. To our knowledge, this has not been discussed in the literature. For CAO, this effect is not critical because it affects all measurements equally, thus it only impacts the general gain and should only affect the closed loop bandwidth (if the controller remains within stable limits). In MCAO, however, measurements in different guide-regions could be affected differently, with potentially critical consequences to the 3D wavefront reconstruction, not only in the MCAO control loop, but also for the turbulence profiler. We propose to characterize this problem with simulations and experiments using both *Blur* and *Clear*, and to implement an appropriate learn-and-apply algorithm in KAOS to correct for this effect, as needed, and to test it in observations.

6. Ground-layer only correction We propose to investigate GLAO further. GLAO has great potential to become a complementary AO operation mode to CAO and MCAO and it should help to improve the efficient use of the telescope. While the image correction performance of GLAO correction greatly varied in our experiments, we found our GLAO mode of operation often remaining more stable than the CAO mode in high-noise situations (e. g. observing granulation under less than ideal seeing). GLAO, as a seeing improver, might become interesting for high-cadence polarimetric observation programs, which require high flux but not diffraction limited resolution. For small synoptic solar telescopes, as e. g. in the future SPRING network of telescopes, GLAO might be able to provide near diffraction limited resolution for the full solar disk. Solar GLAO can be realized in two ways with a wide-field Shack-Hartmann sensor. In one approach, the Shack-Hartmann WFS is used as a multi-directional sensor just like in MCAO, i. e. the field of view is subdivided into multiple guide regions, and the reconstruction matrix applies the average wavefront of all guide regions for the ground-layer correction. In another approach, the full field of view in the wavefront sensor is used as one large guide-region, i. e. the averaging of the wavefront across the field of view is done in the image correlation, and the reconstruction matrix becomes identical to a single guide-region CAO correction. From the control point of view, the latter method is simply an instantiation of CAO. The former method is how we use the wavefront sensor in MCAO. Both methods are readily available in *Clear* and have already been tried in on-sky experiments. However, we did not take dedicated datasets to compare both approaches, which is why we propose to do so.

7. Position of pupil DM Our experiments showed that a high order MCAO control loop can be operated stably if the high-altitude DMs follow the DM conjugate to the pupil and that “dynamic misregistration” is not disruptive. Dynamic misregistration is the effect of high-altitude DMs, when located between the pupil DM and the wavefront sensor, disturbing the registration of a high-order pupil DM with a high-order wavefront sensor. However, because we had to relocate a DM from one pupil image to the other, we were not able to compare the performance impact of the location under the very same seeing conditions. It has been shown in open-loop simulations (Flicker, 2001) that it is preferable to place the pupil DM first in case of short wavelengths, strong groundlayer turbulence and low elevation angles - typical parameters for observations of the Sun. Nevertheless, the performance penalty of such a configuration to closed loop operation due to dynamical misregistration has not yet been analyzed in the literature. Understanding the performance impact, however, is important to the planning of DKIST MCAO, because seeing at that site is expected to be best early in the morning at low elevation of the Sun. With an additional DM, we can occupy both pupils in *Clear* with a DM at the same time. With our control software, we can switch during MCAO control loop operation from one pupil DM to the other instantaneously (i. e. only one pupil DM controlled at a time), and monitor the effect directly. Northrop Grumman AOA Xinetics, the maker of our three DMs, has agreed to loan us a DM system for this purpose. **JEFF CAVACO - NOT REPLIED YET - 4 DM system, not given in Fig. 4? Configuration 3?**

8. Correlation reference image update strategies In a correlating Shack-Hartmann wavefront sensor used with a continuously evolving target like the Sun, the correlation reference image needs to be updated constantly - about at least once per minute in the case of solar granulation. Update procedures used in CAO systems are well-established

and can be considered mature. For MCAO, however, a much more complex procedure is needed, which requires thorough testing. We propose to do the testing and improvement, which requires on-Sun experiments.

9. Increase of corrected field of view The main aim of our proposal is to stabilize MCAO operation. This means we expect to understand how to continuously operate MCAO, along with having a precise understanding of the instantaneous and prevalent turbulence profile, and along with being able to model and predict MCAO performance. We then expect that increasing the corrected field will be a straightforward technological challenge. We anticipate the possibility that we may need additional DMs and wavefront sensor camera hardware, so as to provide more pixels per second, but that would be a downstream endeavor. Here we propose to take measures – depending on the results of the turbulence profiling and corresponding simulations – to achieve a corrected field of view that is larger than 35'' with our present hardware after modifying only the optics in the wavefront sensors for a wider field of view (and adapting the control loop speed accordingly). For example, if a relatively common turbulence profile would allow for a 60'' corrected field of view with 3 DMs, we will redesign the MD-WFS for this field, and make a new trade-off between the subaperture size and control loop speed in recognition of the actual profile, utilizing our Mirkotron EoSens 3CXP camera that was used in Configurations 5 and 6 and the new control computer that we already require for Task (3.) above. As an example, we could realize 11.85 cm subapertures (12 across, which is one of the numbers we used in our successful runs in July 2016) and a control loop speed of almost 1100 Hz. Of course the exact specification of the wavefront sensor, and whether to use e. g. Configuration 2 instead depends on our findings. As an example, perhaps the simplest motivation to expand the corrected field would be two relatively steady non-turbulent layers between the altitudes to which we conjugate the three DMs, so that we could usefully expand the field of view by reducing the depth of field of the DMs. Only the proposed experimentation will tell us how to proceed here. In order to have a variety of options, we require support for three different microlens arrays and corresponding sets aspheric lenses, which will allow us to realize three design options. We believe that three is the optimal number that we can use in our experiments over the course of the next two years. **PARAGRAPH NEEDS MORE WORK**

10. Equipment purchases

Turbulence profilometer

wavefront sensor camera	Adimec Q-2HFW-CXP	\$10,000
computer	Server with 2 Intel Xeon E5-2699 v4 CPUs	\$13,500
frame grabber	Active Silicon Firebird Quad CXP-6	\$3,000
camera cabling		\$700
beam splitter		\$5,000
wavefront sensor optics		\$5,000
wavefront sensor mechanics		\$5,000
total		\$37,700

Faster real-time control computer

computer	Server with 4 Intel Xeon E5-4669 v4	\$36,000
total		\$36,000

Wavefront sensor optics for increased corrected field of view

wavefront sensor optics	\$5,000
total	\$5,000

B.5 Science Drivers for the MCAO Equipped NST

We expect that the NST with MCAO will provide new and basic insights into solar dynamics, which are driven by the sun's ever-changing magnetic field. We will be able to observe, at the diffraction limit, remote correlated events in the FOV that precede and/or follow dynamical events like flares and CMEs, as well as more subtle magnetic field effects. The MCAO corrected light will feed BBSO's two key spectro-polarimeters. The Visible Image Spectrometer (VIS) utilizes a Fabry-Pérot (FPI) etalon with a bandpass of 0.1Å and the possibility of shifting the bandpass by 2Å around the H α line center. The pixel scale is set to 0''.027. A full line scan with a 0.2Å step (11 positions)

can be performed with a cadence of about 5 s. Fig. 7 shows two images of an X-class flare $H\alpha$. The two time steps are two minutes apart in which one can see an appreciable change spread over the FOV for this rather large (X-class) flare. The dynamics shown in the two reconstructed images are too prompt over the FOV to be precisely probed without MCAO. With VIS, other spectral lines between 5500 Å and 8600 Å have their own unique uses. For instance, in Fig. 2 one can see photospheric photometric images in the TiO line, which shows the inter-granular bright points with high contrast. Other visible light lines with sufficient line depths are used for polarimetry. The VIS system is currently being upgraded to a dual FPI system like our near-infrared spectro-polarimeter. The Near InfraRed Imaging Spectro-polarimeter (NIRIS) on the NST is a dual Fabry-Pérot etalon system (FPI) that can be fine tuned to any wavelength between 1.0 and 1.7 μm . For polarimetry, the dual-beam optical design simultaneously images two different polarization states onto a 2024x2048 HgCdTe closed-cycle He cooled IR array. Some primary sets of lines of interest for NIRIS are the Fe I 15650 Å doublet, which is the most Zeeman sensitive NIR probe of the magnetic field, as well as being the deepest formed of all photospheric lines. The doublet is composed of two H-band lines at 15648 Å ($g = 3$) and 15652 Å ($g_{eff} = 1.53$). Another set of lines of interest here are the members of the He I 10830 Å multiplet that are the best currently available for diagnostics of upper chromospheric magnetic fields. In general, matters are more complicated when we move from photometry to full Stokes spectro-polarimetry in which one measures a vector magnetic field utilizing the two Zeeman components of the spectral line that are split by the magnetic field, which NIRIS partially circumvents with dual beam imaging. For NIRIS, a single realization of the vector field results from a scan cadence of $\sim 10\text{s}$ for full Stokes polarimetric measurements under stable conditions over the FOV – the stability required makes MCAO essential for systematic studies. In sum, the MCAO corrected light is fed to one of the two BBSO spectropolarimeters – with each being capable of both photometry and polarimetry.

Below we briefly describe some of the photometric and polarimetric science goals that we can only meet with MCAO corrected light feeding VIS and NIRIS:

(a) VIS Fed by MCAO

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. This concept of energy release has motivated many attempts to detect flare/CME-induced changes, especially in, or near, magnetic fields of active regions. With CAO, we have resolved previously unseen, small-scale features, but not at the diffraction limit over the FOV. Further, nearly none of them reside in, or are confined to the isoplanatic patch and image reconstruction is a compensation that has the price of limiting the time steps to $\sim 10\text{s}$, which too long a step to precisely probe the dynamics between the top and bottom panels of Fig. 7. The top and bottom images are actually 2 min apart, and are far enough separated in time to illustrate the difficulty as the signal is “traveling” about two orders of faster than the local speed of sound.

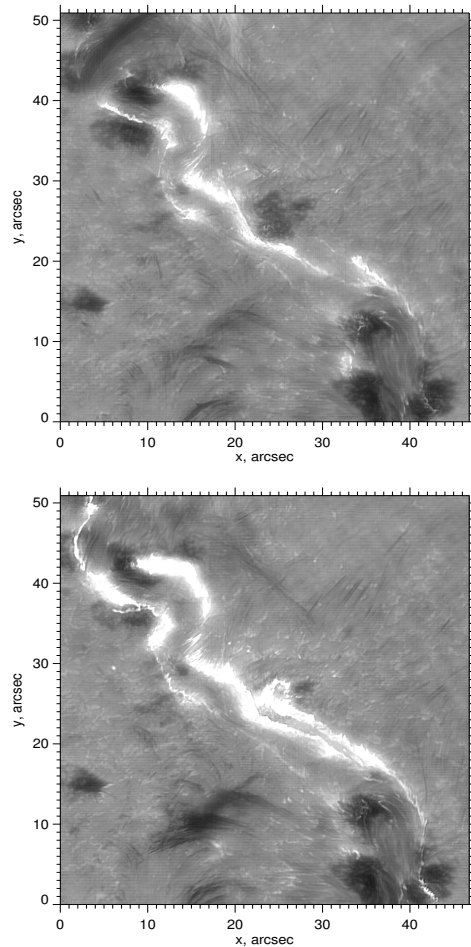


Figure 7: X1.6 fare from 7 November 2014 shown in two steps two minutes apart. The FOV is $50'' \times 50''$ and the flare is in $H\alpha$ 0.8Å off-band in the blue to show both chromosphere and photosphere. Both images were speckle reconstructed.

Without MCAO, we cannot get high temporal and spatial resolution and high polarization accuracy at the same time, with existing telescopes/instruments. The NST equipped with MCAO feeding NIRIS and VIS will provide much more reliable, and higher quality data for both photometry and 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 variations in seeing conditions. Some 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?

The larger and more stably corrected FOV with MCAO will help advance our understanding of the dynamic behavior and structure of small-scale kilo-Gauss fluxtubes, which 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 (Goode et al., 2012) 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 near term, multi-wavelength investigations using NST and satellite data to study this problem will advance our understanding of flux tube physics. As well, as can be deduced from Fig. 2, MCAO will provide much more diffraction limited data on brightpoints, and that combined with polarimetric NST observations of the sun's dynamic magnetic field, will thereby increase our chances of finding events that facilitate new insights.

(b) NIRIS Fed by MCAO

The doublet at 15650 \AA is of special interest in studies of weak magnetic features because, Zeeman splitting increases quadratically with wavelength, so NIRIS can more precisely detect magnetic flux (see Fig. 8 for a single polarimetric image with a $50'' \times 50''$ FOV). Thus, one can separate the true magnetic field strength from the filling factor for the small-scale magnetic flux elements (Cao et al., 2006; Lim et al., 2012; Yurchyshyn et al., 2013). The terrestrial atmosphere is more benign in the NIR with the mean, annualized Fried parameter at BBSO being about 25 cm at 1.5 \mu m , which is four times that at the peak in solar visible light at about 0.5 \mu m . With CAO, this larger Fried parameter is important in the observations of faint features, which otherwise would tend to drift in and out of sharpness. Thus, CAO has been helpful in the study of weak and small-scale magnetic fields. However, with MCAO we would have even greater image stability over a better corrected FOV than with CAO for sustained diffraction limited imaging over the FOV with nominal BBSO seeing. Therefore, truly reliable observations of the evolution of faint features can be performed.

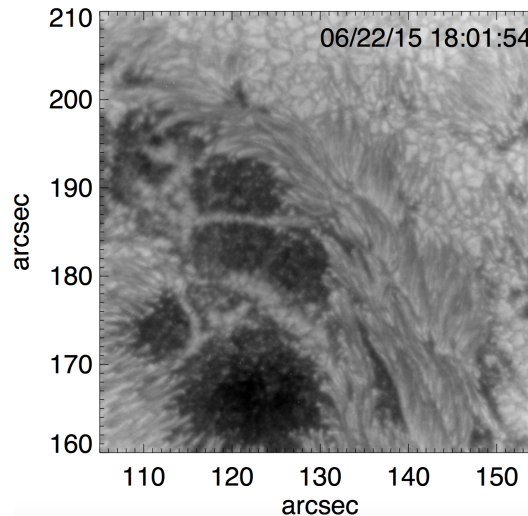


Figure 8: A single CAO image at 15650 \AA from 22 June 2015, which is one image in a polarimetric scan and is, therefore, without image reconstruction.

B.6 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. In the past, our students have received 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 (holds BBSO title of MCAO Project Scientist), is working on the MCAO project and is a co-PI on this project. In fact he

has taken a leadership role as Project Scientist in the proposed work because it builds on his Ph.D. thesis work and his successful work on the NST MCAO system. He will also be key in enhancing and utilizing the KAOS Evo 2 control software of which he was one of the developers. His work on this project will be closely supervised by Goode and Rimmele to ensure he receives needed guidance and support. José Marino was a co-PI on our MCAO project as an NSO postdoc. He has been promoted to an Assistant Scientist at NSO, and he was a postdoc on the NSF-ATI grant for engineering work on the MCAO system in BBSO. Marino earned his Ph.D. from NJIT in adaptive optics. He will be primarily supervised by Thomas Rimmele (his thesis advisor) who has been guiding his work in adaptive optics and MCAO, in particular, since Marino graduated. His responsibilities in this project include modeling of AO and MCAO systems to study expected performance and optimize design and control parameters. He has developed an end-to-end solar AO simulator to produce realistic simulations of solar AO and MCAO systems. The simulator has been deployed to evaluate the future performance of high-order AO systems for large aperture telescopes, such as the NST and DKIST, which is currently under construction; and for the project here to evaluate and optimize the design of solar MCAO systems for the NST. He has a close relation with nearly all members of the team, especially Schmidt, 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 data resulting from 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.

B.7 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 1-5 TB (depending on season) of raw data per channel (2-3 channels/day), and data from each channel are post-processed to about ~100 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.

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/~vayur/nst_requests). The catalog quick look web page provides detailed information about the data – pointing, observation times, etc. – as well as links to the data request forms allowing to gain access to FITS files. The requested data will appear automatically in an anonymous FTP folder and the requester is emailed the data location. All of these software packages were prepared and written by Vasyl Yurchyshyn.

The observing time of the first, next generation solar telescope in the US, the NST, is always oversubscribed, and will remain so ultimately utilizing *Clear*, and as DKIST comes online because the NST has a unique role of observing in extended campaigns. We will continue our open open data policy, while also making observing time available to the community. The Telescope Allocation Committee ranks the proposals and allocates time. A web page describing all the requests ensures that researchers will not duplicate their data analysis efforts.

B.8 Personnel Management Plan and Timelines

The tasks and assignments of the project personnel are listed in Table 1. During the construction of the NST, its focal plane instrumentation, and the AO-308 and *Clear* projects, we have assembled a strong instrumentation team at BBSO. The instrumentation team now divides its attention between the focal plane instrumentation and *Clear* projects with great effort on the latter. In AO, BBSO and NSO have a fifteen year-long history of working together beginning with AO-76, then AO-308 and most recently *Clear*. The proposal here is to make MCAO a reliably performing, well-understood instrument that corrects a FOV $\geq 35''$ under reasonable seeing conditions, while performing essential experiments for the DKIST. NST and DKIST are off-axis telescopes. The NST has focal plane instrumentation that is quite similar to that planned for the DKIST. Thus, in the broadest sense the NST is a pathfinder for the DKIST, 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. For this project, Goode supervises Nicolas Gorceix, Sergey Shumko, Jeff Nenow, John Varsik and Vasyl Yurchyshyn. 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

Table 1: Tasks and Assignments for the MCAO Project.

Year	Task	Person(s) In Charge
Year 1	Overall Management and Coordination	Goode and Rimmele
	Project Scientist	Schmidt
	On-sky Experiments in Big Bear	Gorceix, Schmidt and Cao
	MCAO Control with KAOS Evo 2	Schmidt and Shumko
	Simulations and Control Matrices	Rimmele, Marino and Schmidt
	Profilometer Testing and Implementation	Schmidt and Guesalaga
	Integration Focal Plane Instrumentation with MCAO	Gorceix and Cao
	Initial Processing and Checking of Science Data	Yurchyshyn
	Hardware Purchases	Gorceix, Schmidt and Goode
Review and Purchase Optical Hardware	Rimmele and Goode	
Year 2	Overall Management and Coordination	Goode and Rimmele
	Project Scientist	Schmidt
	On-sky MCAO Observations	Schmidt, Gorceix and Cao
	Initial Processing and Checking of Science Data	Yurchyshyn
	Simulations and Control Matrices	Rimmele, Marino and Schmidt
	System integration of MCAO on NST	Cao, Schmidt and Gorceix
Regular Observations with MCAO	Team	

close coordination with Goode and Rimmele. Over the last fifteen years, Goode and Rimmele have worked on AO-76, AO-308 and MCAO with this broad organizational structure and it works well. **The timelines are crucial here in this two year proposal because the *Clear* project for NST needs to be finished before the start of DKIST operations. We have the team in place, but that will end in mid-2019 when DKIST will come on-line, so we have this narrow window from mid-2017 to mid-2019 to finish *Clear*.**

Dirk Schmidt (co-PI) brings his KAOS system experience and leadership to the project. He already functions well in that role, while splitting his time between BBSO and NSO/Boulder. Schmidt will spend halftime on *Clear* and halftime of DKIST AO issues. This will make for a seamless technology transfer. Thus, Dirk is the connection between the two essential U.S. solar AO projects – on the NST and DKIST, as Rimmele directs the DKIST project. It is essential that the partnership continue and that makes this proposal timely. The close NST-DKIST design similarities make the NST AO/MCAO experiments critical for a timely and optimal implementation of the DKIST AO system, as well as planned upgrades to DKIST AO. Thomas Berkefeld (KIS) co-wrote some of the KAOS software with Schmidt. Berkefeld has participated in *Clear* runs over the past two years and his participation has been beneficial because of his vast AO experience. He is a Collaborator on this proposal and will come to Summer *Clear* runs if this proposal is funded. He does not charge any of his travel or salary to this grant as he is based in Germany and is our connection to KIS. Andrés Guesalaga (Pontificia Univ Católica de Chile) is an expert on the Gemini South profilometer and a Collaborator here, and he will continue to provide his expertise and codes at no cost for the *Clear* profilometer we propose here. 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 and control matrices for AO-308 and is well-integrated into the team having the added task of simulations. Marino and Schmidt developed the simulation tool for *Clear*. BBSO mechanical engineer, Jeff Nenow will spend two months a year on the fabrication of mounts as new hardware comes for the *Clear* project. Each observing program at BBSO has a Resident Astronomer/Duty Scientist who processes the scientific data to ensure its quality. Vasyly Yurchyshyn has functioned in that role for our project and as a Collaborator on this proposal, he will continue to do so. He was the person who setup and implemented the BBSO online data archive (see Sec. B.7) and has the broadest experience in examining the quality of BBSO data of anyone at BBSO. Wenda Cao is now the Director of BBSO, and is well-experienced in the BBSO AO-76 AO-308 systems and was a key developer of NIRIS and VIS. He will be responsible for integrating these instruments into the MCAO.

BBSO commits three 10 day observing runs to the *Clear* during the best observing time, f.ex., in 2016 the project had 10 days observing slots in late May, late July and mid-September. The project will receive additional observing time in other parts of the year. For instance, GLAO system testing can be done in other seasons in which the seeing is

not as good as the Summer. As well, laboratory *Clear* experiments can be done at any time during the year and may occasionally require on-sky data.

B.9 Budget

The requested two year budget for the project is \$828 K from the NSF of which \$79 K is for equipment (see Sec. B.4 for a list).

The \$616 K to BBSO/NJIT will pay half of Gorceix's salary, one-quarter of Shumko's (system engineer) salary, and one-sixth of the salaries of Goode (PI) and Jeff Nenow (mechanical engineer) and one-twelfth the salary of John Varsik (observer and systems engineer) and one-twelfth of the salary of Vasyl Yurchyshyn (Collaborator on this proposal and resident scientist – responsible for initial processing of science data). NJIT/BBSO (Cao, co-PI), NSO (Rimmele, co-PI) and Berkefeld (Collaborator from Germany) will be working part-time on this MCAO Project with no charge to the project, as has been done for our earlier AO projects. Guesalaga (Collaborator from Chile) also will be working at no charge to the project. The budget also includes \$7 K per year for travel, which breaks down to \$5 K for 2-3 trips per year from Boulder to Big Bear for Schmidt (co-PI) and Marino (co-PI), as well as \$2 K per year for Goode to make two trips per year to Big Bear. These trips are for observing runs. BBSO provides free on-site housing for the team during observing runs. Lastly, the budget includes \$2 K per year for publication charges. We anticipate 1-2 publications per year.

The sub-award to NSO of \$212 K will pay half of Schmidt's salary and one-quarter of Marino's salary. Schmidt is the Project Scientist in the work proposed here. José Marino's responsibilities in this project include modeling and simulations of AO, GLAO and MCAO systems.

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