

Title of Investigation: Observations with the 1.6 Meter Clear Aperture Solar Telescope in Big Bear: Origins of Space Weather

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A. Project Summary

Overview:

The 1.6 m clear aperture, off-axis solar telescope at Big Bear Solar Observatory (BBSO) has today's only operating multi-conjugate adaptive optics (MCAO) system, and it is called *Clear*. *Clear* is the first ever to have demonstrated obvious improvement over classical, single deformable mirror (DM) AO correction. *Clear* expands the telescope's 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 anytime and anywhere in an active region. These expanded capabilities are essential for a fundamental probe of the origins of space weather events.

Our data, and a substantial portion of GST observing will be open to the community.

B. Project Description

B.1 Adaptive Optics

The stunning successes of solar adaptive optics (AO) have come from systems with a single DM, configured 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 flaring and coronal mass ejections (CMEs), which can cover upwards of $\sim 50''$ and occasionally 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 $\sim 30''$ in diameter. Thus, to study dynamic, magnetic reconnection events in the network boundaries, it would be invaluable to have diffraction limited resolution over a FOV that covers two network cells 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 (see Fig. 1) might cover $\sim 50''$, which is about two-thirds the size of the FOV of the GST. 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, like speckle, 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, 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 and CMEs, as mentioned, 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. MCAO requires more than a single DM, and in our system, called *Clear*, we have three DMs with each being conjugated to a different altitude. This is technically difficult, but wide-field, diffraction-limited correction of multi-conjugate AO (MCAO) is the holy grail for addressing the fundamental dynamics of our star, but we have enjoyed noteworthy successes. Further motivation comes from the fact that the 1.6 m clear aperture, off-axis Goode Solar Telescope (GST) is the only solar telescope in the U.S. having sufficient aperture and modulation transfer function to resolve what is generally regarded as the fundamental scale of the Sun’s surface. This will remain true until the advent of the 4 m aperture telescope currently under construction in Maui, and due for first light in 2020, even then only the GST can be devoted to extended space weather studies.

In the simplest view of MCAO, the setup 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 the nighttime system routinely used for astronomical observations (e. g. Neichel et al., 2014a), and *Clear* is the first solar MCAO system to significantly improve (triple) the corrected FOV. 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) operates in the near-infrared and 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. Owing to its proximity, the Sun presents an extended FOV, and with its granular structure and various scales of magnetic features (see lower panel of Fig. 1), 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. In the current setup of *Clear* on the GST, we use nine guide regions (divide the FOV into nine regions and take whatever is present to guide the reconstruction). The control system, KAOS Evo 2, for *Clear* was originally developed by Berkefeld and Schmidt for the Gregor telescope (Berkefeld et al., 2012). In the current setup, the three DMs are conjugated to the

pupil with a depth of field (DoF) of ~ 1 km, an approximately 2 km DoF for the DM conjugated to 3 km, and a DoF of about 3 km for the DM conjugated to 8 km, that is with these specific conjugation altitudes of the three DMs **we continuously cover the range from 0 to 11 km with the reduced wavefront sensing field of view**. Attempting a wider FOV than $35''$, would lead to a reduced DoF and, thus, a break in correction in some place(s) between the ground and 11 km above the telescope. So for now, we need to be satisfied to MCAO trebling the corrected FOV over single DM AO and without loss of temporal cadence that comes with image reconstruction (Schmidt et al., 2017).

Results from the **first ever clearly and easily visible successful solar MCAO imaging are shown in Fig. 1 (Schmidt et al., 2017)**. As mentioned, *Clear* employs 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), and nine guide regions over the FOV to be corrected on the Sun. The DM conjugation altitudes provides corrections at all altitudes from the ground to an altitude of 11 km above Big Bear (Schmidt et al., 2017).

In the Gemini South MCAO system, GeMS, they have two DMs with starlight first striking the high altitude DM and then the one conjugate to the pupil and then the WFS. In *Clear*, the sunlight first strikes the DM conjugated to 8 km, then the one at 5 km and then the one conjugated to ground (lastly to the WFS).

For some details, during our first truly 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, ground-layer AO (GLAO) and single DM Classic AO (CAO) correction. The 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 nine 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. 1 shows one of the 450 frame bursts, recorded in July 2016, and divided into three blocks of MCAO, GLAO, and CAO correction, where each image shows the superposed frames of each block without any post-processing.

In the upper left panel of Fig. 1, 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, as mentioned, nine guide regions were used. Results like those in Fig. 1 were seen many times in the ten day observing run near the end of July 2016 and during all three of the Summer of 2017 MCAO observations. Another way to understand Fig. 1 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. 1 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. 1 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. 1 and 2 shows the improvement of MCAO, as well as the differences 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 better image detail in a small 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. We propose to use GLAO and CAO from the outset of the work proposed here. GLAO is also an operational instrument on the GST vertical bench. It is apparent that MCAO is a great improvement over CAO and GLAO.

Even though we already have been able to obtain impressive images with MCAO correction, we are still in an experimental stage. GLAO is ready now, but MCAO will not be a regular instrument until the second year of the proposed work. We have had runs in which lock has been held for nearly two hours. However, we have nine guide-regions to update every minute, or so, and we have to eliminate the slight distortion that occurs with each update because of the relative motion of the nine guide regions. As is easy to imagine, solving this problem is straightforward, but requires some programming effort on the control software. This programming is already underway at this writing,

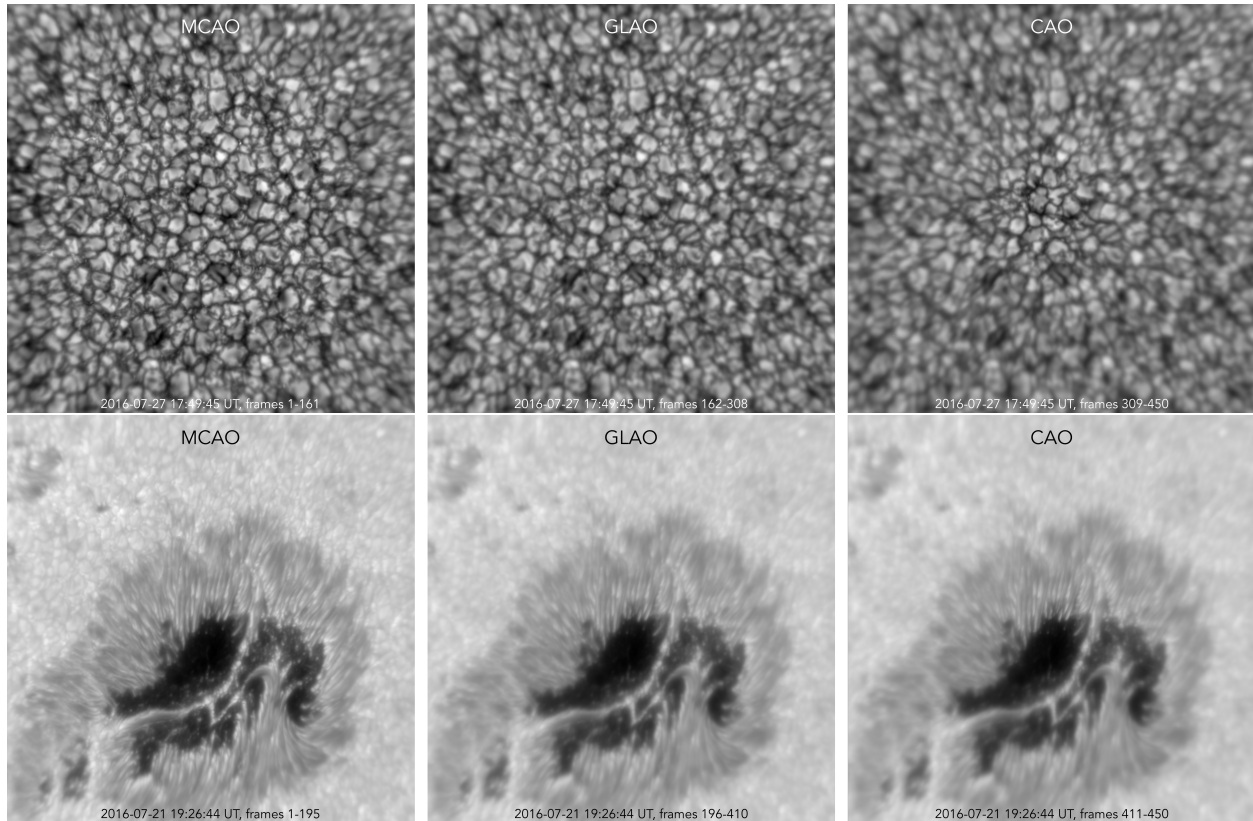


Figure 1: The Sun observed in a field of view of $53'' \times 53''$ with MCAO, GLAO, and CAO correction with *Clear* on the GST (see B.3). The top row shows a quiet region of the Sun between 10:49:45 and 10:50:16 PDT on July 27th, 2016. The bottom row shows a sunspot in active region NOAA 12567 on July 21st, 2016 between 12:26:44 and 12:27:24. Both bursts were taken with a TiO filter (705.7 nm). Each image shows the sum of the frames within a block with MCAO (left), GLAO (middle), and CAO (right) correction in a continuous burst of 450 frames recorded. Exposure time for was 1.6 ms for the granulation bursts and 11 ms for the sunspot. Real-time movies are available online at <https://cuna.nso.edu/clear-preview>.

so we conservatively hold back promising use of MCAO in the first year of the work proposed here.

B.2 GST 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 GST 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. More than 100 requests for GST data were filled in 2016.

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/GST_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 GST, is always oversubscribed, and will remain so ultimately utilizing *Clear*, and as DKIST comes online because the GST has a unique role of observing in extended campaigns. We will continue our open open data policy, while also making observing time available to

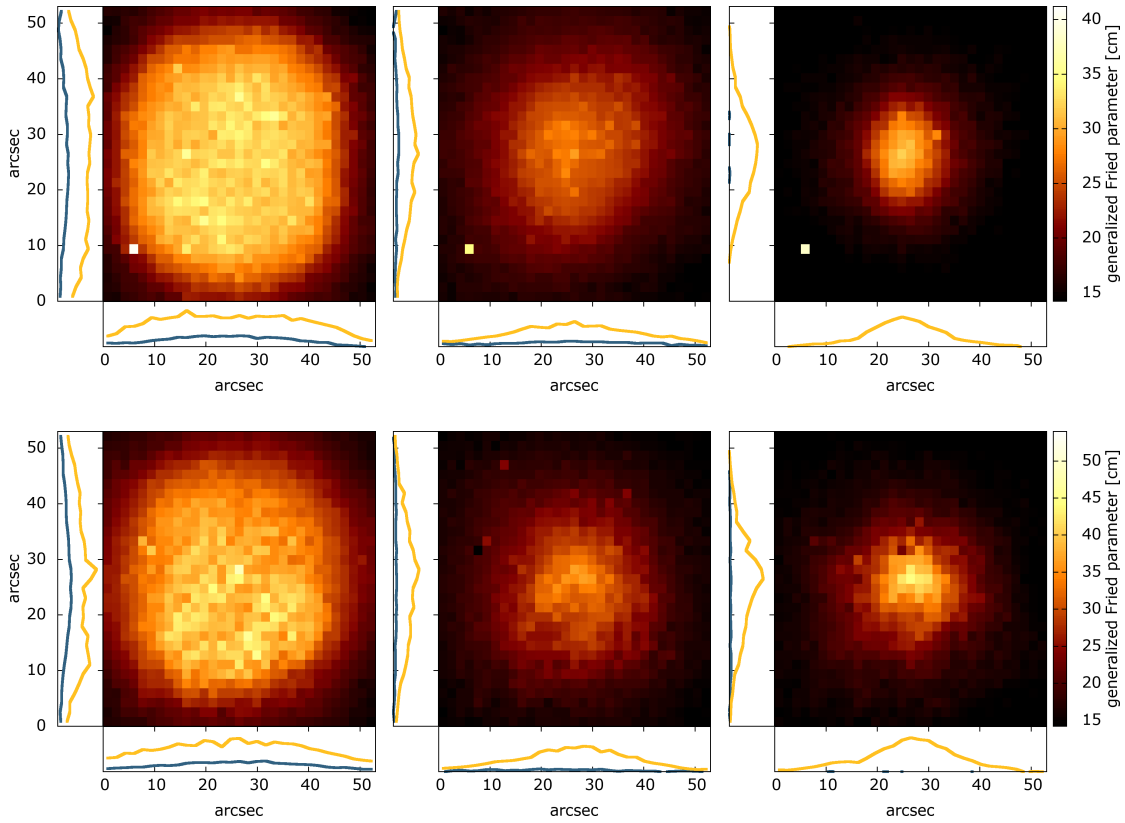


Figure 2: Generalized Fried parameter (Cagigal and Canales, 2000) across the field of view in the images shown in Fig. 1. The yellow lines along the ordinate and abscissa represent the relative intensities down and across the middle of the field, whereas the blue lines represent the corresponding relative 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 $\sim 30''$.

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.

C. References

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