

MULTI-CONJUGATE ADAPTIVE OPTICS WIDENS THE FIELD FOR OBSERVATIONS OF THE SUN

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Classical adaptive optics (CAO) correction of atmospheric image aberrations using a single deformable mirror (DM) has become standard for ground-based telescopes used for high angular resolution observations of the Sun. While CAO systems are able to provide diffraction limited imaging, the effective field of view (FOV) is typically rather small when compared to the scale of solar dynamical events. Turbulence distributed in altitude cannot be corrected over a wide field with only one DM. Airflows are the cause of the aberrations and arise in multiple, diffuse layers, *e. g.* in thermals from the ground, in wind shears in the boundary layer where clouds form, and in the jet stream. Measuring the rapid and large scale changes in the sun's magnetic field underlies any effort to understand the dynamics of large flares and coronal mass ejections (CMEs). Such measurements require temporal and spatial stability over a much larger FOV than can be corrected by a single DM. For many years, it has been realized that an AO system with multiple DMs, each conjugated to a different turbulent layer could correct a much wider field and enable us to probe fundamental, but currently unaddressable problems about solar dynamics. We report here the first multi-conjugate AO (MCAO) observations of the Sun that substantially widened the corrected field of view compared to quasi-simultaneous observations single DM CAO correction. With three DMs, conjugate to the ground, 3 km, and 8 km, respectively, we obtained a corrected field, in visible light, that was about three times wider. Further, we report on the ground layer AO (GLAO) mode of operation of our MCAO system, which uses a single DM conjugated to the telescope aperture, and achieves the expected inferior results near the center of the FOV, but with smoother image correction across the field than CAO.

Adaptive optics for solar observations was originally developed as an upgrade to the evacuated sub-1-meter class telescopes of the past century, like the Dunn Solar Telescope of the National Solar Observatory, the retired 0.6 m telescope in Big Bear, and others (Berkefeld et al., 2010; ?, ?). AO was considered to be the enabling technology for today's open structure 1.5-meter class solar telescopes such as GREGOR and the New Solar Telescope (NST) of the Big Bear Solar Observatory (BBSO), and even more so for the upcoming 4-meter class telescopes such as the Daniel K. Inouye Solar Telescope (DKIST) under construction and the proposed European Solar Telescope (EST).

Here, we present observations with the NST in July 2016 using advanced AO schemes referred to as MCAO and GLAO. Figure 1 compares images obtained of the Sun corrected with MCAO, GLAO, and CAO. At the time of recording, the turbulence distribution was such that CAO correction resulted in the typical, small corrected field angle with a fast roll-off in image quality around the active (central) guide region. With MCAO correction, image detail was restored over a much wider angle. In GLAO mode, the image quality was more homogeneous than CAO but not as good in the image centre. The visual impression is supported by the analysis of the generalized Fried parameter, shown in Figure 2, which is a measure of the effectiveness of the correction over the FOV provided by adaptive optics.

Today's facility class AO systems at major solar telescopes utilize one DM, which is conjugate to the telescope pupil, and one correlating Shack-Hartmann wavefront sensor (SH-WFS) with a FOV of order 10'' (Berkefeld et al., 2010; Shumko et al., 2014). These CAO systems with its DM conjugated to the pupil

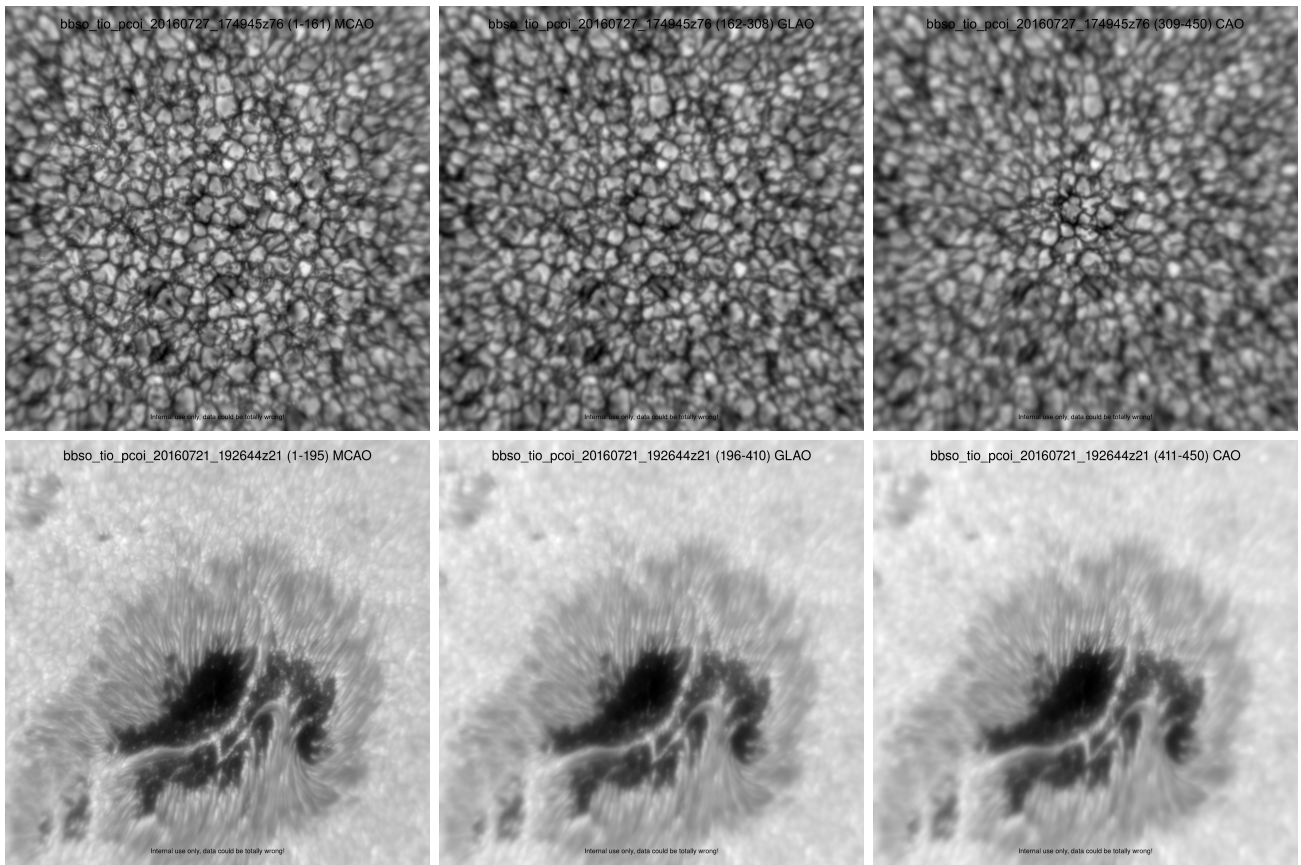


FIGURE 1. The Sun observed in a field of view of $53'' \times 53''$ with MCAO, GLAO, and CAO correction with *CLEAR* on the NST through a filter for the titanium oxide line (705.7 ± 5 nm). The top row shows a quiet region of the Sun between 10:49:45 and 10:50:16 local time on July 27th, 2016. The bottom 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.

applies the same wavefront modification equally to all directions in the FOV of the telescope. Optical aberrations due to turbulent airflows, however, can be introduced at any distance from the telescope within the troposphere, and thus can strongly vary with viewing direction. Consequently, the correction of a DM conjugate to the telescope pupil may only be valid within a limited viewing angle, which is called the isoplanatic angle. While CAO systems can provide diffraction limited images of the Sun within the isoplanatic angle, the image quality may roll off quickly — depending on the instantaneous distribution of the atmospheric turbulence in altitude. The isoplanatic angle is typically of order $5''$ to $15''$ for observations in the visible light regime at good telescope sites.

CAO has revitalized ground-based solar observations, however, many scientific problems require a much larger corrected FOV than CAO systems can provide. Magnetic field dynamics are at the heart of the sun's powerful, explosive and non-local events, like flares events and CMEs, which can cover $60''$ or more. Spectro-polarimetry requires imaging that is stable over several seconds over the entire FOV to measure a single realization of the magnetic field. Even if a small-scale flare were to occur somewhere in the FOV, it is not likely that the flare would occur where CAO has corrected. 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. Moreover, dynamic, magnetic reconnection events in the network boundaries, one requires diffraction limited resolution over a field that covers least 2-3 network cells, *i. e.*, $60'' - 90''$. Thus, the wide-field, diffraction-limited correction of MCAO is the holy grail for addressing the fundamental dynamics of our star. (REFS???)

In order to enlarge the FOV that it is fully correctable by AO, the third spatial dimension needs to be incorporated into wavefront correction. Additional DMs can be placed into positions that are optically conjugate to greater distances from the pupil in recognition of the actual distribution of turbulence.

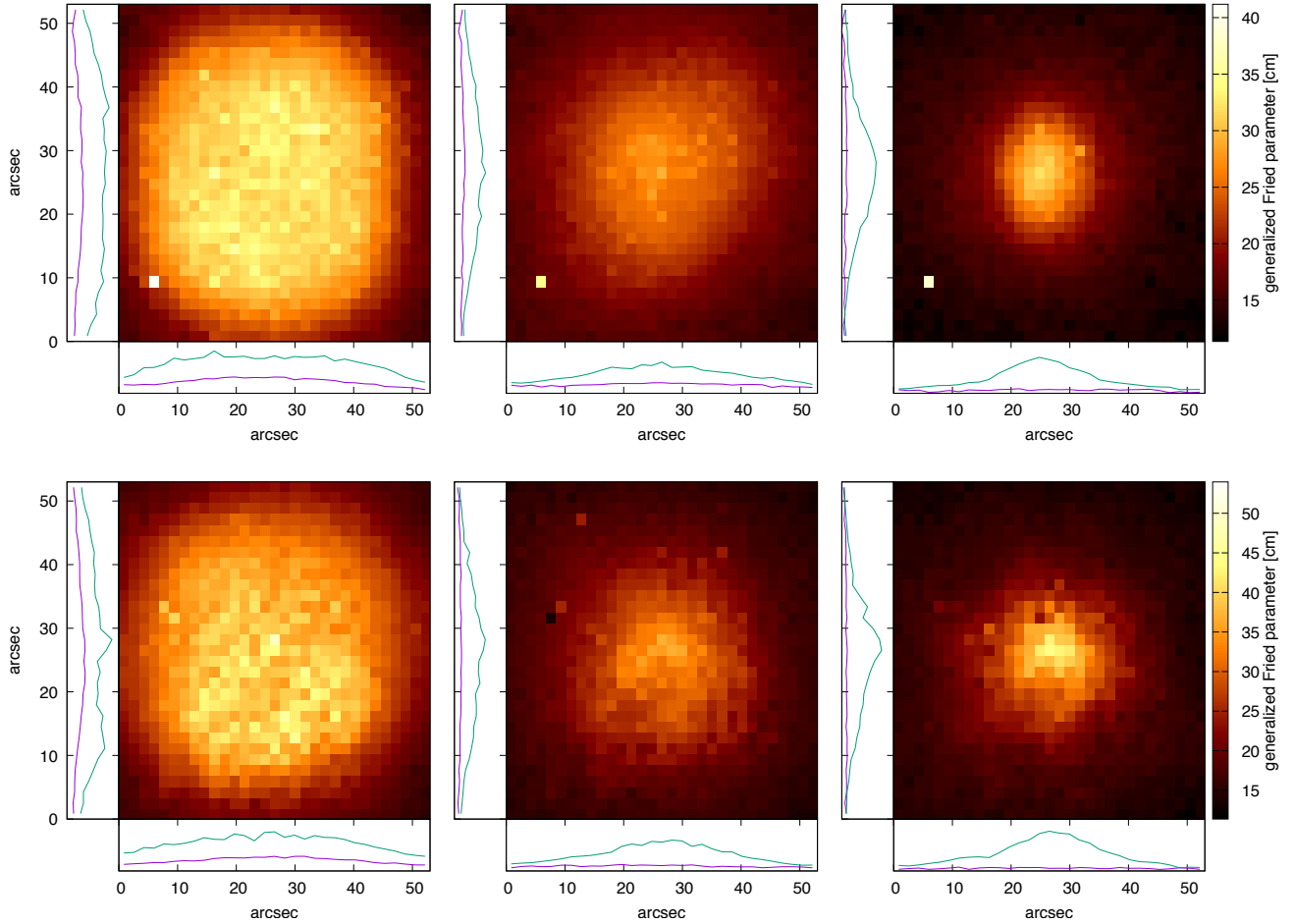


FIGURE 2. Generalized Fried parameter across the field of view in the images shown in Fig. 1. The green lines along the ordinate and abscissa represent the relative intensities down and across the middle of the field, whereas the purple lines represent the corresponding relative intensities along the margins. The full-width at half-maximum in the CAO green is about $10''$, while that for the MCAO is about $30''$.

Supplemental wavefront sensors must be deployed to probe the optical aberrations over the targeted FOV in order to steer the DMs. This concept is known as *multi-conjugate adaptive optics* (MCAO) (Beckers, 1988; Rigaut et al., 2000). Stellar observations with MCAO were first carried out by the MCAO Demonstrator *MAD* at the Unit Telescope 3 of the Very Large Telescope (Marchetti et al., 2007). The MCAO System *GeMS* of the 8-meter Gemini South Telescope operates in the near-infrared and constitutes the first MCAO system routinely used for astronomical observations (Rigaut et al., 2014). Pioneering experiments with MCAO for solar observations were performed at the Vacuum Tower Telescope (Berkefeld et al., 2010) and at the Dunn Solar Telescope (Rimmele et al., 2010). An advanced solar MCAO system was developed for the GREGOR telescope (Berkefeld et al., 2010; Schmidt et al., 2013, 2014). Despite the progress that has been made, no substantial gain in solar observations with MCAO over those from CAO has been shown until now. Ground-layer AO aims to correct for the ground-layer only by applying the field-averaged correction with the DM in the pupil, and is like MCAO, but without any additional DMs conjugated to higher altitudes in the atmosphere. Therefore, the scope of GLAO is to obtain a more homogenous image quality across the field than that using CAO, but at the cost of maximal image detail. The usefulness of GLAO is closely related to the instantaneous turbulence distribution in height. Dedicated solar GLAO experiments without MCAO were performed first at the 76-cm Dunn Solar Telescope (Rimmele et al., 2010) in the visible light regime and recently at the McMath-Pierce Solar Telescope and the Dunn Solar Telescope (Ren et al., 2015) in the near infrared H-band ($1.5\text{-}1.8\ \mu\text{m}$), but a side-by-side comparison of CAO and GLAO observations demonstrating the merit of GLAO is lacking.

The 1.6-meter New Solar Telescope (NST) of the Big Bear Solar Observatory (BBSO) in California is today's largest aperture solar telescope. Like the 4-meter Daniel K. Inouye Solar Telescope (DKIST) under construction, the NST features a clear aperture off-axis Gregorian design. For its similarity, we chose the NST to establish the experimental MCAO pathfinder system for DKIST, and named it *CLEAR*. A key aim of *CLEAR* is to evaluate experimentally different approaches and concepts in solar MCAO. It was designed for great flexibility to enable experimental studies of a multitude of concepts that have been tried or proposed. Owing to its flexibility, we use the AO control software KAOS, which has been developed for the GREGOR telescope, and altered it to suit our needs. Turbulence profiling experiments of the site in Big Bear revealed significant turbulence within the first 7-8 km above the telescope with relative weightings varying from day to day (Kellerer et al., 2012). The jet stream occasionally hinders observations in Big Bear. In general the BBSO system features three DMs, two of which can be flexibly conjugated to altitudes between 2 and 8 km above the telescope's line of sight, while the third is always located in an image of the telescope aperture. 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. Multiple wavefront sensor options are available. In this letter, we focus on configurations used in Summer 2016. We used a single Shack-Hartmann wavefront sensor unit with either 208 or 112 subapertures, which observed the Sun in the wavelength range 525 ± 15 nm over a FOV of about $35'' \times 35''$. For directional wavefront sensing ("star-oriented" MCAO approach(?)), this field of view was subdivided into 3×3 regions in which digital image correlation was performed to estimate wavefront slopes in the Shack-Hartmann subapertures, a method commonly used for solar Shack-Hartmann sensors. The high-altitude DMs were conjugated to 3 and 8 km beyond the telescope on the line of sight.

During the experiments presented in this work, we monitored the focal plane with a pco.2000 CCD camera through an interference filter for the titanium oxide line (705.7 ± 5 nm). We took numerous bursts of 450 frames, each 2048×2048 pixels, with 1-2 ms exposure time at 14.7 frames per second. During the acquisition of a burst, the AO operating system KAOS recorded closed loop data of wavefront sensor measurements and other status data. Typically, we switched the AO operation mode during a burst, e.g. we started with MCAO correction and after 150 frames recorded by the pco camera we switched to GLAO, and after another 150 frames to CAO correction. The simultaneous records of the AO control loop status allow us to relate the mode of AO correction to any camera frame. We recorded bursts of 450 continuous frames and switched the mode of correction during the bursts, instead of recording separate dedicated bursts of 150 frames for each mode, in order to avoid downtimes due to data writing during which seeing conditions might change. Hence, we were able to monitor the impact of switching the mode of AO correction on the image plane from one frame to the other. By repeating this procedure, we rule out that effects could be accounted to seeing which might incidentally have changed in the same instant we switched.

We identified the three blocks of modes of correction in each 450 frames burst, and added all frames of each block (after dark and flat field calibration) to simulate long term exposures. Further, we analyzed each block with the speckle image reconstruction software *KISIP* (Wöger et al., 2008), which can compute the *generalized Fried parameter* ρ_0^{gen} across the image. The generalized Fried parameter is an estimate of the apparent Fried parameter due to the CAO, GLAO and MCAO corrections (Cagigal & Canales, 2000). The Fried parameter (Fried, 1965) is widely used to characterize strength of optical aberrations due to atmospheric turbulence. *KISIP* uses the Spectral Ratio method (von der Lühe, 1984) to estimate the generalized Fried parameter from the extended solar scenery. This method is sensitive to strong static aberrations, however, unless the static aberrations are strong enough to inhibit the transfer of spatial frequencies lower than those corresponding to $\lambda/\rho_0^{\text{gen}}$, the estimates can be used safely to gauge the effectiveness of the correction over the FOV provided by any type of AO system (Soltau et al., 2002).

Figure 1 presents the added images of each block of MCAO, GLAO, and CAO corrected frames in two 450 frames bursts, one taken around noon on July 21, and the other in the morning of July 27, 2016. At these times, the turbulence distribution was such that CAO correction resulted in the typical small corrected field of order $10''$ with a fast roll-off in image quality. With MCAO correction, image detail was restored over in much wider angle. In the GLAO mode, the image quality was more homogeneous than CAO but not as good in the image centre. The generalized Fried parameter plotted in Figure 2 illustrates the effect of the different AO modes quantitatively. While MCAO correction provided a well corrected field that is approximately three times wider than with CAO correction, MCAO correction even slightly

improved the image detail at the margin of the 53'' field. The ground-layer correction resulted in a lower but more homogeneous image detail over the field. We emphasize that we got comparable results for observations of solar granulation, and of a sunspot, two typical sceneries one finds in the photosphere of the Sun.

With *CLEAR*, we showed experimentally—for the first time—that MCAO can be used to impressively enlarge the corrected field of view for solar observations. We also showed that under some circumstances an observer might choose GLAO over CAO. After further experimentation, we plan to make *CLEAR* a regularly operating instrument on the NST and ready this technology for the 4-meter Daniel K. Inouye Solar Telescope.

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