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Schmidt, Dirk, Marino, Jose, Gorceix, Nicolas, Rimmele, Thomas, Johnson, Luke, et al.

Dirk Schmidt, Jose Marino, Nicolas Gorceix, Thomas Rimmele, Luke Johnson, Thomas Berkefeld, Philip Goode, "From Clear to DKIST: advancing solar MCAO from 1.6 to 4 meters," Proc. SPIE 10703, Adaptive Optics Systems VI, 1070326 (17 July 2018); doi: 10.1117/12.2313787

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

From Clear to DKIST: advancing solar MCAO from 1.6 to 4 meters

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ABSTRACT

The MCAO pathfinder Clear on the 1.6-meter Goode Solar Telescope has been enabling us to advance solar MCAO from early conceptual demonstrations to science grade wide-field image correction. We report on recent improvements to the control loop and we comment on issues such as the co-aligning of wavefront sensors and deformable mirrors and the sensitivity of wavefront sensor gains. Further, we comment on the challenges to wavefront sensing and the control system architecture faced when scaling up to a 4-meter aperture. Finally, we present an early concept of the future MCAO upgrade for the Daniel K. Inouye Solar Telescope.

Keywords: multi-conjugate adaptive optics, Clear

1. INTRODUCTION

Clear is a pathfinder instrument to advance multi-conjugate adaptive optics (MCAO) for observations of the Sun. In July 2016, we demonstrated for the first time the superiority of MCAO over classical AO for high-resolution observations of the Sun throughout the visible light regime, and also the advantage of high-order ground-layer only correction.[1] The findings from Clear provide critical input to the design of the MCAO system for the upcoming Daniel K. Inouye Solar Telescope (DKIST). Clear is mounted on the Goode Solar Telescope (GST) of the Big Bear Solar Observatory.[2] It features three deformable mirrors (DMs), one of which is conjugate to the telescope pupil, and two are conjugate to higher altitudes that can be changed easily between about 2 and 8 km. Clear was first set up in late 2013; being purposefully designed to be very flexible, Clear has undergone major changes in the course of the years.[3,4] The most relevant change was the reduction of the field of view for the MCAO correction to about 35×35 arcsec from about 70×70 arcsec for the 2016 season. While waiving the one-arcminute goal would allow a wider range of altitudes that the DMs can effectively correct,[5] we also were able to rigorously change the wavefront sensing scheme. Instead of two separate wavefront sensors, namely a high-order Shack-Hartmann with a narrow field of view and a lower order multi-directions wide-field Shack-Hartmann, we were able to implement a high-order wide-field wavefront sensor with 8.8×8.8 cm subapertures as shown in Figure 1. Its field of view of 35×35 arcsec is subdivided into 3×3 guide regions, each of which about 12 arcsec wide.

2. IMPROVEMENTS, PROBLEMS AND SOME SOLUTIONS

2.1 Durability of the control loop

In July 2016, the MCAO control loop was only performing well for approximately 30 seconds until the correction would rapidly degrade and the loop become unstable because we did not update the correlation reference in the wavefront sensor which is needed to account for the continuously changing structure on the Sun. After the successful demonstration of solar MCAO for a short time, we refined the correlation update procedure for MCAO in 2017. We then were able to run the MCAO control loop continuously for up to 53 minutes, involving more than 310 correlation update procedures. We recorded the focal plane during that time continuously with 14 fps in the titanium-oxide line at 705.7 nm. Figure 2 shows a sequence of snapshots of this burst. Each image is the average image of 10 frames, no image reconstruction was performed. Variable seeing conditions and birds flying in front of the telescope—vignetting individual subapertures—were handled automatically and the control loop remained stable over 53 minutes until an unidentifiable event suddenly put the loop into a unstable condition from which it could not recover automatically. A more comprehensive overview of Clear and our findings shall follow in a future paper.

Adaptive Optics Systems VI, edited by Laird M. Close, Laura Schreiber, Dirk Schmidt, Proc. of SPIE Vol. 10703, 1070326 · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2313787

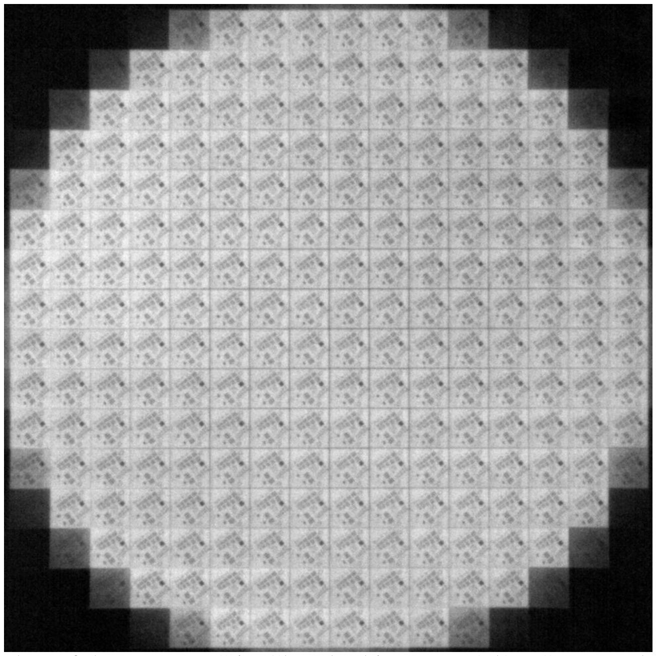


Figure 1: Snapshot of the MD-WFS in Clear looking at a 1953 USAF resolution test chart.

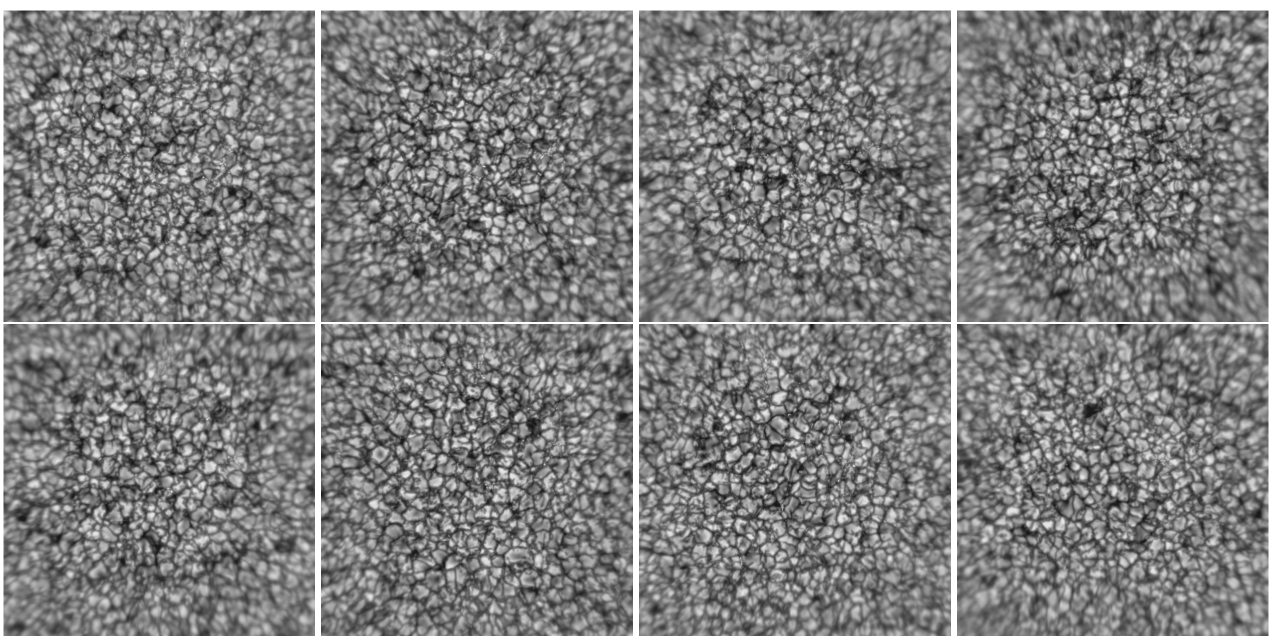


Figure 2: Examples of images in a 53 minute long sequence of continuously MCAO corrected image burst recorded at 14 fps. The time between each displayed image is about 7.5 minutes (top-left to bottom-right). Each image shown is the average of 10 frames. The field of view is about 53×53 arcsec, and the wavelength is 705.7 nm (titanium-oxide). Full movie-available at `https://cuna.nso.edu/clear`.

We replaced the real-time computer that runs our AO control software *KAOS Evo 2* in Spring 2018 by a *TYAN Thunder HX FT77D-B7109* with two *Intel Xeon Gold 6154* (18 cores, 3.0 GHz) that is able to run the control loop at a rate of 1567 Hz, which is the maximum frame rate of the *Mikrotron EoSens 3CXP* camera that we use in the wavefront sensor for the region of interest we use. Tests with both the old and the new computer indicate that the image transfer (from end of exposure to last line transferred) takes about 100 µs longer than the theoretical transfer time with the frame grabbers we use. We are investigating an alternative model to further reduce the bandwidth error.

2.2 Alignment of deformable mirrors in MCAO

In a classical AO (CAO) setup with a Shack-Hartmann wavefront sensor, the actuators in the pupil-conjugate DM and the subapertures are often configured in the Fried geometry. That is, one actuator is placed in each corner of a square subaperture. For DMs conjugate to higher altitudes, there is no general matching pattern between subapertures and actuators. Many MCAO reconstructors, however, eventually reconstruct modal DM commands (e. g. Karhunen-Loeve modes) and it becomes important that the modal basis of the DMs is centered on the optical axis of the wavefront sensor. If this is not the case, each mode that the DM produces will be accompanied by a tip-tilt signal in the wavefront sensor. At least the tip-tilt control bandwidth will be degraded by ”unconsciously” fighting DMs that produce ”pseudo tip-tilts” but other modes might suffer from similar crosstalk, too. Further, the wavefront sensor might see areas on the DMs that are outside of the circle that defines the modal support. It is critical to realize that the optical axis of the wavefront sensor does not necessarily need to be identical with the optical axis of the telescope. Consequently, the centering of the footprint of the light beam on high-altitude DMs is in general not relevant, even though it might appear tempting to align based on the incoming light by tilting some mirrors to center the beam on the DMs. In order to align high-altitude DMs with the wavefront sensor, these DMs need to be displaced laterally after the complete light path has been aligned without tilting any optical element in the path. Consequently, the high-altitude DMs in an MCAO system are ideally mounted on *x*-*y* translation stages parallel to the mirror surfaces. While it is probably possible to define modes that are decentered on the DM but centered with the wavefront sensor at the cost of asymmetrical use of the DM, *x*-*y* stages allow to recenter the DMs in case of an emerging misalignment without needing to remodel the wavefront reconstructor and whatever consequences this would imply. The described method decouples the wavefront sensor pointing from the telescope boresight and thereby tremendously simplifies aligning and maintaining alignment in the MCAO path. In Clear, we support each high-altitude DMs with a jack and a horizontal linear stage that is parallel to the mirror surface (Figure 3). For the aligning, we oscillate the parabolic modes on each of the three DMs at different frequencies, e. g. 20, 30, and 50 Hz, and we observe the power spectra of the *x*- and *y*-tip-tilt signals seen by the wavefront sensor. Then we first minimize the peaks in the *x*- and the *y*-power spectra that correspond to the pupil conjugate DM by tuning the lateral position of the microlens array. Subsequently, we minimize the peaks associated with the high-altitude DMs by adjusting their lateral position with the *x*-*y* stages. This procedure works very well and fast and could easily be automated. Due to distinct oscillation frequencies this method is insensitive to lab seeing.

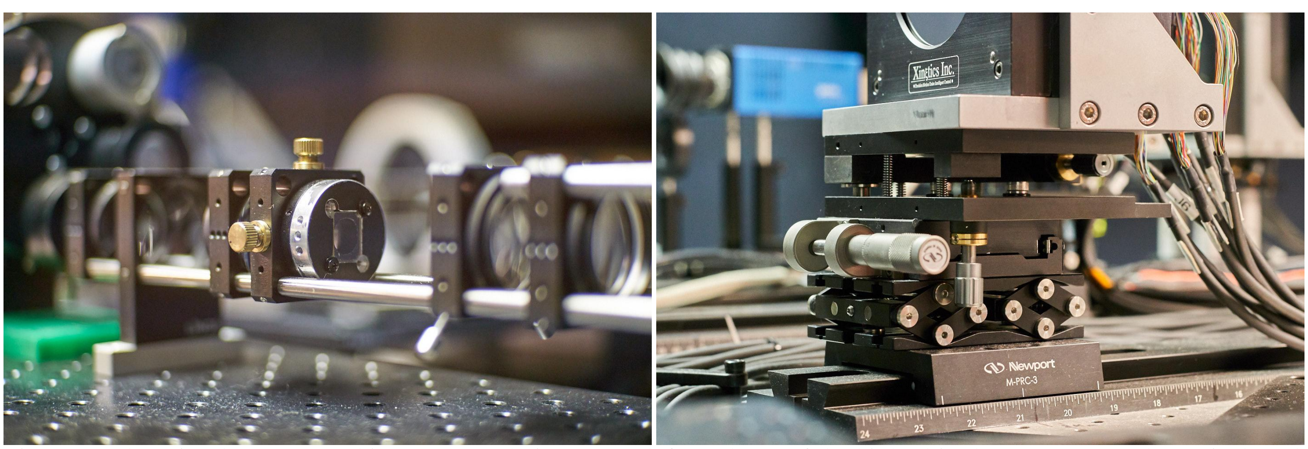


Figure 3: The microlens mounted in a *x*-*y* translation stage (left) and one of the high-altitude DMs mounted on a jack and on a linear stage (right).

2.3 Wavefront sensor gain

When we acquired the interaction matrix early in the course of the project by poking the DMs and recording the response the wavefront sensor that is looking at an artificial target—a slide displaying solar granulation—in an upstream focal plane, we noticed that the tip-tilt response is not uniform across all guide regions but depends on the very structure of the target. Figure 4 displays the effect for two different guide regions. In this example, the tip-tilt mirror was oscillating at about 91 Hz. The amplitudes of the image displacements measured by the wavefront sensor are significantly different up to about 30%. With a different slide we were able to achieve a more uniform response and to mitigate this effect in our interaction matrix. An open question is how strong this effect is for actual solar images and what the performance impacts are on the wavefront correction . In a classical AO wavefront sensor with a single guide region, the effect would be a slightly different closed loop bandwidth (if the controller remains in a stable regime). In fact, it is known that the controller parameters can be pushed higher for solar granulation than for a pore. Non-uniform measurement gains in multi-directional wavefront sensing, however, potentially introduces an error to the tomographic reconstruction. Observations with Clear indicate that this effect is not utterly critical, it should however be investigated if there is a performance penalty—in particular when aiming for the diffraction limit of a 4-meter aperture—and weather some kind of online wavefront sensor gain calibration for the ever evolving solar structure needs to be developed similar to the gain calibration of a quad-cell Shack-Hartmann.[6,7]

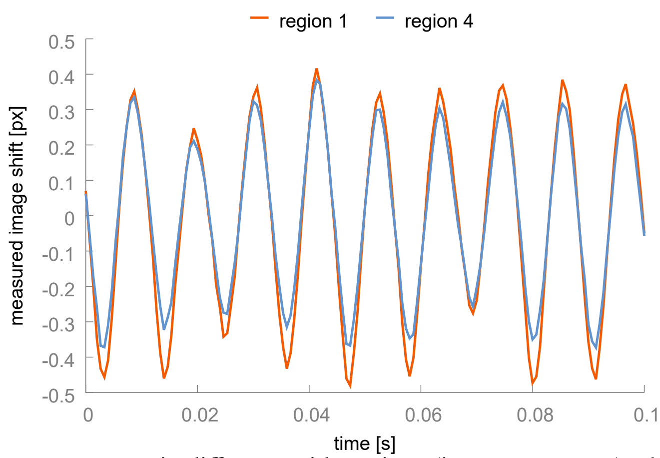


Figure 4: Image displacement measurement in different guide regions (image structures) while tip-tilt mirror is oscillating.

3. MCAO FOR DKIST

3.1 First generation high-order classical AO of DKIST

DKIST will feature a classical, high-order AO system from the very beginning;[8] this system is currently being setup and tested in the lab at NSO's headquarters in Boulder, Colorado.[9] The subapertures measure approximately 9.3×9.3 cm which also corresponds to the actuator spacing of the M10 deformable mirror that is conjugate to the pupil. This system incorporates about 1500 subapertures and 1600 actuators in the 4-meter aperture. The wavefront sensing is accomplished by a correlating Shack-Hartmann sensor with 20×20 px per subaperture requiring a 960×960 px region of interest in the wavefront sensor camera. The frame rate and the control loop frequency are close to 2000 Hz. The position of the AO image correction in the field of view (the 'lock-point') can be controlled with a field steering mirror in front of the wavefront sensor. DKIST shall be upgraded with an MCAO system a few years after commissioning. We present early concepts of a potential implementation.

3.2 Wide-field wavefront sensing for DKIST

A major challenge in implementing a MCAO system for a 4-meter solar telescope is the wavefront sensing. Due to the image correlation based wavefront slope estimation, a large number of pixels is needed. Following the most recent wavefront sensing scheme of Clear, we are considering 3×3 guide regions for DKIST's MCAO implementation that span a field of view of approximately 35×35 arcsec and is sampled with 9.3 cm subapertures (corresponding to the actuator spacing in the pupil-conjugate DM). The meta-pupil for this configuration is shown in Figure 7; further is it shown that even with a field of view of 72×72 arcsec, the metapupil overlap is similar to Clear with 35 arcsec which is important to minimize the tomography error.[10]

Like in Clear, we need to dismiss the outer subapertures that are prone to being clipped randomly by the pupil edge due to the action of high-altitude DMs. Consequently, there are only 41 subapertures in diameter instead of 43. This results in a total subaperture count of approximately $3 \cdot 3 \cdot 1313 = 11817$ and 23634 wavefront slopes. If we require 60×60 px per subaperture for the 35×35 arcsec field, we would need a detector with about 2500×2500 px to accommodate 41 subapertures across. A field of view of 60×60 arcsec would require a detector well in excess of 4k×4k px. We are not aware of a commercially available image sensor that provides this pixel number at a frame rate of order 2000 fps and a charge capacity that exceeds 30,000 electrons per pixel. For this reason, we need to distribute the wavefront sensing among multiple cameras with smaller regions of interest that can run at the demanded frame rate as shown in Figure 5. There are several potential options that we investigate:

1. The wide-field light path can be split up into 9 paths by 8 beamsplitters that are located anywhere before the microlens array as shown in Figure 6a. The given reflectivities and transmissions provide the same photon flux in each path. If the beams are separated before the pupil imaging optics, this optics does not need to be optimized for the full field of view but can be optimized for the smaller guide region field of view. The downside of this approach is the large number of beam splitters that need to be added and the inefficient use of photons because all field points are distributed equally onto all sensors regardless if they will be blocked eventually by a field stop or not.

2. A very photon-efficient way is slicing the focal plane with mirrors as shown in Figure 6b, each cutting out a guide-region from the full field of view hence acting as a field stop. This approach is prone to nonuniform vignetting effects among the subaperture images if a mirror edge that is not the focal plane vignettes the beam.

3. The focal plane of a wide-field Shack-Hartmann wavefront sensor might also be subdivided and relayed onto separate cameras with fiber bundles, similar to the fiber-optic integral field unit in SPIES.[11]

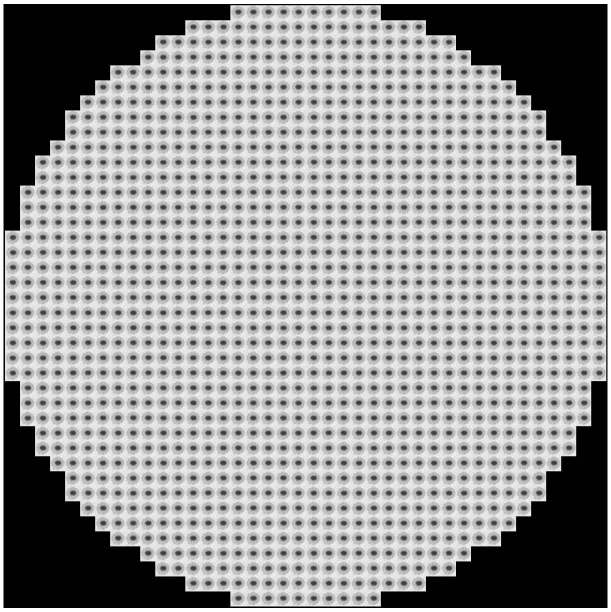
Options 1 and 2 would enable to change the spanned field of view from e. g. 35 arcsec to 60 arcsec by repositioning the boresights of the 8 off-axis sensors without the need for more pixels and higher required image data rates. By routing the fibers in option 3 such that each 10 arcsec subfield gets imaged onto one detector, the position of the 8 off-axis directions can also be changed without the need for more pixels to be read out. A trade study will need to evaluate the options for their feasibility.

The wavefront sensor lock-point in DKIST's initial classical AO system can be repositioned with a field steering mirror right in front of the wavefront sensor. This feature, however, will not be practical for MCAO, because by repositioning the wavefront sensor field of view, their foot prints on the high-altitude DMs change and consequently it becomes necessary to obtain the new interaction action and to re-model the reconstructor. Since MCAO, however, is expected to provide a much larger corrected field of view this is not a significant limitation.

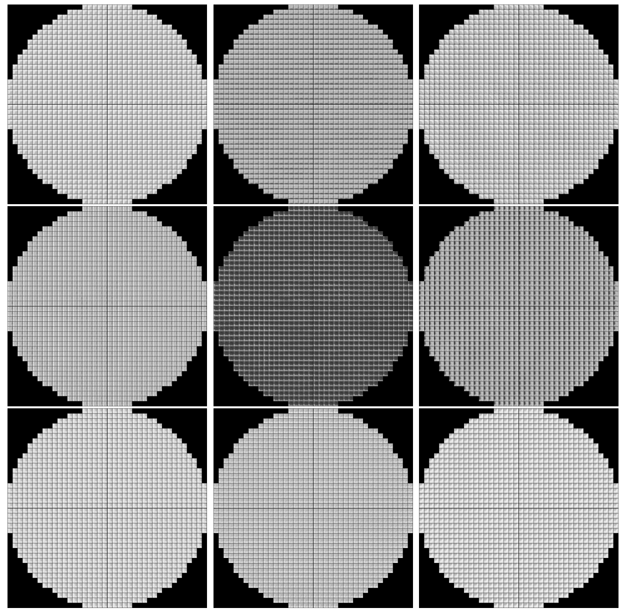
Without regarding the vignetting effects mentioned in option 3, each of the 3×3 wavefront sensors needs about 820×820 px and a camera that can be read out at about 2000 fps. These requirements are met by both the camera models used in Clear and the High-Order Wavefront Sensor in DKIST's CAO, namely the *Mikrotron EoSens 3CXP* and the *Vision Research DS-440*, respectively. The sensors in both models, however, only provide a rather low saturation charge of order 30 ke^-. The sensor in a *PCO dimax cs1* is a very attractive alternative due to its higher saturation charge that would result in an increased signal-to-noise ratio. The *PCO dimax cs1*, however, is a recording camera and a real-time streaming data interface would need to be added.

3.3 Deformable mirrors

The optical design of DKIST includes two flat mirrors that we are considering to be replaced by deformable mirrors, the M9 conjugate to 4.3 km, and the M7 at 11.2 km. The diameters of these mirrors are 400 mm and 600 mm, respectively, to transfer the 2.8 arcmin field of view of the telescope. For the 30 to 60 arcsec field that we aim to correct with MCAO, however, only a smaller parts actually need to be controlled with actuators. Monte-Carlo simulations with NSO's AO simulator Blur indicate that a good image correction can be achieved in a field of view of about 30 arcsec as shown in Figure 8. Details shall be published elsewhere. As explained in Section 2.2, the high-altitude DMs need to be mounted on translation stages that allow for lateral adjustments to keep the DMs aligned with the wavefront sensors.

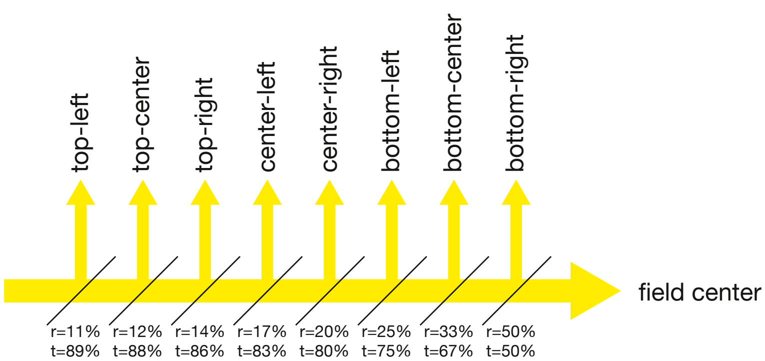


(a) A wide-field wavefront sensor for DKIST with 35×35 arcsec field of view requires about 2500×2500 px.

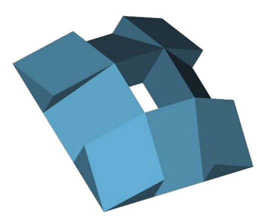


(b) 3×3 narrow field wavefront sensors pointing in different directions using separate detectors asking for much smaller detector.

Figure 5: Wide-field wavefront sensing options. (Note: these simulations only show 40×40 subapertures instead of 41×41.)



(a) An array of 8 beamsplitters can be placed before the entrance focus of the wavefront sensors (narrow-field optics) or before the microlens arrays (wide-field optics).



(b) 8 inclined mirrors can be placed into the focal plane to slice the image (narrow-field optics).

Figure 6: Splitting the light for 9 wavefront sensors.

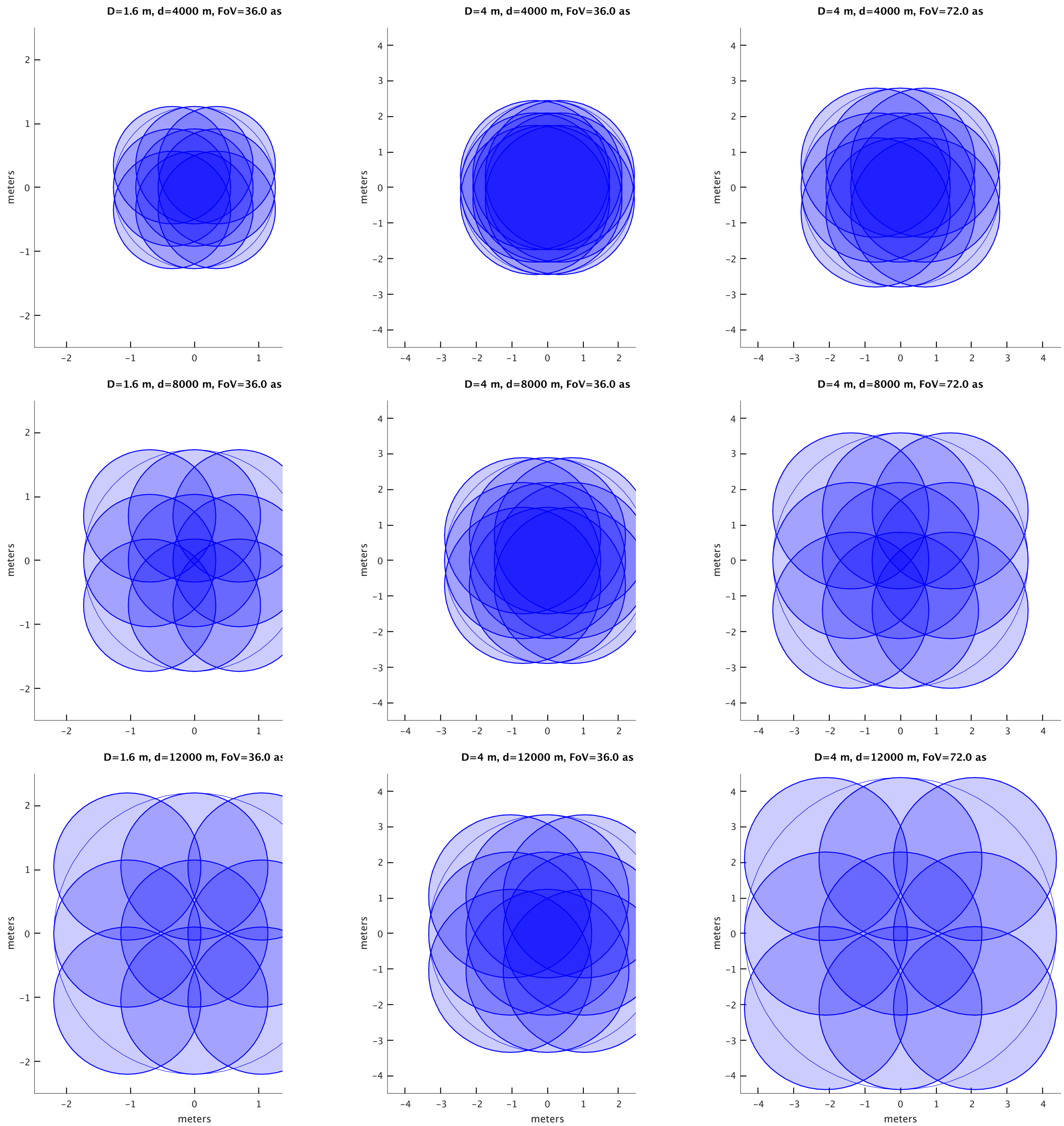


Figure 7: Footprints of 3×3 guide regions separated by 18 or 36 arcsec in different distances d from a telescope with diameter D. A field of view of 12 arcsec (round) per guide region is used in this visualization.

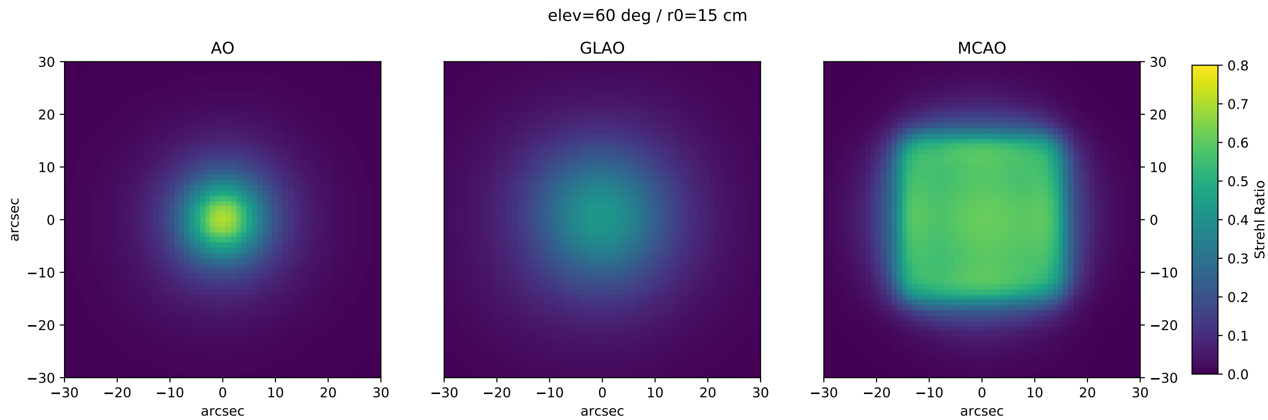


Figure 8: Simulation example of Strehl ratios across the field of view for DKIST with classical, ground-layer and multi-conjugate correction.

3.4 Real-time controller

The computational requirements for the real-time controller of DKIST's MCAO are demanding. The real-time controllers in DKIST's CAO and in Clear perform of order 1500-1900 cross-correlations per loop cycle. This can easily be done with modern CPUs at frame rates of 2000 Hz in a single computer. In fact, Clear's new dual *Intel Xeon Gold 6154* computer can compute 1872 square-difference functions over 5×5 px of 20×20 px at a rate of 1567 fps (maximum frame rate of camera) with 20 cores (maybe even less). Cross-correlations in Fourier-space require less CPU operations and can be done with less cores. For the 9 wavefront sensor cameras that we picture for DKIST's MCAO, however, a cluster of multiple computers is needed to receive and to process the images. One cluster node could maybe process the correlations for 2-3 cameras (each 1313 correlations) depending on the correlation algorithm. The memory bandwidth of one node might not be sufficient for multiple cameras, and benchmarking is needed to evaluate what cluster configuration is best. A similar approach has been chosen for the real-time controller of TMT's MCAO system NFIRAOS recently that deploys one cluster node based on x86 CPUs to each wavefront sensor and involves a 7000×32400 matrix-vector multiplication at a rate of up to 800 Hz.[12] The matrix for DKIST will be significantly smaller, comprising $2 \cdot 1313 \cdot 9 = 23634$ wavefront slopes and about 1000 to 1500 actuators per deformable mirror and we believe that a x86 cluster is a workable approach for DKIST's MCAO real-time controller.

4. CONCLUSIONS AND OUTLOOK

Clear continues to be an extremely valuable experimental platform to advance solar MCAO. While it is now able to provide high-resolution image correction in a field of view of about 30 arcsec over many tens of minutes, we will use it to further refine the algorithms to make MCAO a mature technology. The outcomes and the findings from Clear are directly applied to conception of the MCAO upgrade for DKIST. An MCAO for DKIST imposes new challenges to the wavefront sensing system and the real-time controller. We presented possible concepts for the implementation of such a system. Additional studies will need to identify the best practical approaches.

ACKNOWLEDGMENTS

Clear is sponsored by the U.S. National Science Foundation under the grant NSF-AST-1710809. The U.S. National Solar Observatory and the Daniel K. Inouye Solar Telescope are sponsored by the U.S. National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The Big Bear Solar Telescope and its Goode Solar Telescope are facilities of the New Jersey Institute of Technology.

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