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Pupil-transformation multiconjugate adaptive optics for solar high-resolution imaging

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Abstract. We propose a multiconjugate adaptive optics (MCAO) system called pupil-transformation MCAO (PT-MCAO) for solar high-angular resolution imaging over a large field of view. The PT-MCAO, consisting of two deformable mirrors (DMs), uses a Shack–Hartmann wavefront sensor located on the telescope pupil to measure the wavefront slopes from several guide stars. The average slopes are used to control the first DM conjugated on the telescope aperture by a solar ground-layer adaptive optics (AO) approach while the remaining slopes are used to control the second DM conjugated on a high altitude by a conventional solar AO via a geometric PT. The PT-MCAO uses a similar hardware configuration as the conventional star-oriented MCAO. However, a distinctive feature of our PT-MCAO is that it avoids the construction of tomography wavefront, which is a time-consuming and complex process for the solar real-time atmospheric turbulence correction. For the PT-MCAO, current widely used and fully understood conventional solar AO closed-loop control algorithms can be directly used to control the two DMs, which greatly reduces the real-time calculation power requirement and makes the PT-MCAO easy to implement. In this publication, we discuss the PT-MCAO methodology, its unique features, and compare its performance with that of the conventional solar star-oriented MCAO systems, which demonstrate that the PT-MCAO can be immediately used for solar high-resolution imaging. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.55.9.094103](https://doi.org/10.1117/1.OE.55.9.094103)]

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1 Introduction

A conventional adaptive optics (AO) with one deformable mirror (DM) can only provide a small correction FOV on the order of a few arc-seconds in the visible, which is limited by the isoplanatic patch. To achieve a large correction FOV, a MCAO system consisting of several DMs, each conjugated on a different altitude to correct the corresponding turbulence is required. Two different MCAO systems were proposed until now: star-oriented¹ and layer-oriented² approaches. Diolaiti et al.³ showed that when the FOV is discretized according to the directions of guide stars (GSs), the layer-oriented and the star-oriented correction have equivalent performances.

For the star-oriented MCAO, a wavefront sensor (WFS) conjugated on the telescope pupil is used to measure the wavefront slopes from several GSs. Atmospheric tomography is conceived as a method to measure the instantaneous three-dimensional (3-D) phase perturbations at different altitudes in the atmosphere, in order to get the control signals for MCAO.⁴ Light from several GSs are used to probe the 3-D perturbations, which are retrieved by solving an inverse equation. A star-oriented MCAO system is based on a global wavefront reconstruction and, therefore, cannot work without this tomography.⁵ Testing of the star-oriented/layer-oriented MCAO was first demonstrated by the multiconjugate adaptive optics demonstrator (MAD)—a prototype built

at the European Southern Observatory.⁶ Recently, after 10 years of development work, the Gemini MCAO System, the first star-oriented facility-class MCAO system consisting of five laser GSs and two DMs, eventually demonstrated the feasibility to deliver high-resolution imaging over a FOV of 120 arcsec.⁷

While the star-oriented MCAO is a promising technique, it is still challenging. As discussed by Ragazzoni et al.,⁸ the tomography wavefront reconstruction for the star-oriented MCAO is a complex and time-consuming process for the real-time atmospheric turbulence corrections. The solar MCAO systems that are currently being developed for the 1.6-m New Solar Telescope (NST) and the 1.5-m GREGOR or the future 4-m Daniel K Inouye Solar Telescope and European Solar Telescope are all based on star-oriented MCAO approach^{9,10} in which a Shack–Hartmann wavefront sensor (SHWFS) is used to measure and reconstruct the global tomography wavefront information at different altitudes. Compared with the nighttime MCAO system, solar MCAO is extremely time-consuming, since cross-correlation is used to calculate the vector slopes of the multiple GSs. As a result, there is no routine operational solar MCAO available now, although progresses are being made for solar MCAO developments.^{11–13}

In this publication, we propose a pupil-transformation MCAO (PT-MCAO) for solar high-resolution imaging over a large FOV. Our PT-MCAO uses a similar hardware

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configuration with that of the star-oriented MCAO. That is, it uses a SHWFS located on the telescope pupil to measure the wavefront slopes from multiple GSs. However, our PT-MCAO does not need the tomography wavefront reconstruction. Instead, it directly uses two conventional AO loops with two DMs for wavefront correction, after conducting a simple pupil coordinate transformation, which greatly reduces the required calculation time and is easy to implement.

2 PT-MCAO Methodology

Our PT-MCAO consists of two DMs. Figure 1 shows the schematic diagram of the PT-MCAO hardware configuration. In the PT-MCAO, a SHWFS, conjugated on the telescope aperture, is used to measure the wavefront slopes from several GSs and the SHWFS information is used to control the two DMs. DM 1 is conjugated to the telescope aperture for ground turbulence correction while DM 2 is conjugated to a high altitude for the high-altitude turbulence correction. The hardware layout of our PT-MCAO is similar to that of the conventional star-oriented MCAO. For solar observation, one SHWFS can be used for wavefront measurements from several GSs.

Using the model approach, the wavefront phase ϕ can be described by the Zernike polynomial expansion of K orders as

$$\phi = \sum_{k=1}^K a_k Z_k(x, y). \quad (1)$$

Considering our PT-MCAO that is composed of two DMs, for the first DM, it is conjugated on the telescope aperture on the ground and is used to correct the low-altitude turbulences. Assume that the SHWFS has M subapertures and P GSs are used for wavefront sensing. For the i 'th GS, the slope vector is $S_i = [\Delta x_{i1} \Delta x_{i2} \cdots \Delta x_{iM} \Delta y_{i1} \Delta y_{i2} \cdots \Delta y_{iM}]^T$. For the total P GSs, the average slope S is calculated as $S = (S_1 + S_2 \cdots + S_P)/P$ and is used by the first DM to correct the associated turbulence-induced wavefront. In fact, the first DM associated AO loop in our PT-MCAO is a typical GLAO system, which is used to correct the turbulence around the ground layer. Since wavefronts from all

Fig. 1 The schematic of the PT-MCAO. In this configuration, the PT-MCAO consists of a SHWFS, two DMs and a computer (PC). Please note that the SHWFS is conjugated on the telescope pupil for wavefront sensing.

GSs are exactly overlapped on the telescope pupil, this low altitude wavefront cannot be averaged out while the high altitude wavefronts will largely be averaged out. Once the average slope S is found, we can use a conventional AO loop to correct the associated turbulence-induced wavefront, and the slope vector is associated with the corresponding wavefront A as

$$S = [B]A, \quad (2)$$

where A is the vector of Zernike polynomial coefficients of K orders:

$$A = (a_1 \ a_2 \cdots a_K)^T, \quad (3)$$

where the matrix $[B]$ is

$$[B] = \begin{pmatrix} \left. \frac{\partial Z_1(x,y)}{\partial x} \right|_1 & \left. \frac{\partial Z_2(x,y)}{\partial x} \right|_1 & \cdots & \left. \frac{\partial Z_K(x,y)}{\partial x} \right|_1 \\ \vdots & \vdots & \vdots & \vdots \\ \left. \frac{\partial Z_1(x,y)}{\partial x} \right|_M & \left. \frac{\partial Z_2(x,y)}{\partial x} \right|_M & \cdots & \left. \frac{\partial Z_K(x,y)}{\partial x} \right|_M \\ \left. \frac{\partial Z_1(x,y)}{\partial y} \right|_1 & \left. \frac{\partial Z_2(x,y)}{\partial y} \right|_1 & \cdots & \left. \frac{\partial Z_K(x,y)}{\partial y} \right|_1 \\ \vdots & \vdots & \vdots & \vdots \\ \left. \frac{\partial Z_1(x,y)}{\partial y} \right|_M & \left. \frac{\partial Z_2(x,y)}{\partial y} \right|_M & \cdots & \left. \frac{\partial Z_K(x,y)}{\partial y} \right|_M \end{pmatrix}, \quad (4)$$

and (x, y) is the coordinate of each subaperture in the SHWFS. The mode coefficient vector is found by the pseudoinverse $[B]^+$ of $[B]$, which can be solved by using singular value decomposition (SVD), minimum mean square error (MMSE), or minimum-variance reconstructor (MVR). Different algorithms used for the conventional MCAO wavefront reconstruction were studied by Lessard et al.¹⁴ They found that in the MCAO, MVRs or some other type of regularization may deliver better performance. However, in classical single-conjugate AO, there is no benefit to use the MVR, and a simple least-squares reconstructor has a virtually identical performance.¹⁴ Since our PT-MCAO is based on two classic AO loops, any above reconstructors should deliver similar performances, which is confirmed in our numerical simulations (see Sec. 3). Once the $[B]^+$ is known, the wavefront error induced by the atmospheric turbulence is

$$A = [B]^+ S. \quad (5)$$

Accordingly, the required signals (i.e., voltages) applied on the first DM for the wavefront correction can be calculated as

$$V = DA, \quad (6)$$

where D is the DM influence functions and V is the DM signals that are required to correct the wavefront error. The Zernike polynomials act as a low-bandpass filter, which is used to measure and control the actual wavefront error up to the mode number K . The choice of actual mode number that an AO system can correct should consider the system's stability, which can be determined by the condition number, as discussed by Kasper et al.¹⁵

The second DM is conjugated to a high altitude. For this DM, a pupil coordinate transformation is needed for each GS, before a conventional AO closed-loop can be applied in the PT-MCAO. Figure 2 shows how the footprints of 5 GSs are projected from the telescope aperture onto a high altitude, where the second DM is conjugated. In reality, one can use any number and geometrical orientations of GSs on a specific altitude, where most high-altitude turbulence is located. For clarity, the beams from these GSs are shown evenly filling the metapupil without overlap, although this is not necessary for our PT-MCAO in real applications. Let us assume that the first DM is located on the telescope aperture/pupil plane with a coordinate system of the (x, y) plane while the second DM is located on a high altitude with a corresponding coordinate system of the (u, v) plane. The altitude is characterized by H along the positive z axis direction. For each GS i , it forms an offaxis angle θ_i with the z axis and an azimuth angle α_i with x axis in the $x-y$ plane (see Fig. 3). Since the SHWFS is measured on the telescope pupil of the (x, y) plane, not on the (u, v) plane, the corresponding coordinates on the (u, v) metapupil for each GS can be calculated based on the so-called PT as

$$u_{ij} = x_{ij} + [H \tan(\theta_i)] \cos(\alpha_i), \quad (7)$$

$$v_{ij} = y_{ij} + [H \tan(\theta_i)] \sin(\alpha_i), \quad (8)$$

where i and j represent i 'th GS and j 'th SHWFS subaperture, respectively. For the i 'th GS on the metapupil, the slope vector that used to control the second DM is measured on the telescope pupil by the SHWFS and is calculated as the slope difference of this GS with the average slope S :

$$S'_i = S_i - S. \quad (9)$$

The beams on the metapupil where the second DM is conjugated can be viewed as a resultant beam S' that consists of the P beams with: $S'(x, y) = (S'_1, S'_2, \dots, S'_P)$ (in Fig. 2, P is equal to 5). Please note that here (x, y) is the SHWFS subaperture center coordinates on the telescope pupil plane. The slope $S'(x, y)$ on the pupil plane for each GS must be converted to the resultant slope $S'(u, v)$ on the metaplane by using Eqs. (7) and (8) via the PT. On the metapupil adopted with the (u, v) coordinates, for the second DM, one can

Fig. 2 GS footprints on the pupil (left) and metapupil (right). The footprints of GSs are exactly overlapped on the telescope pupil [centered on the origin of the (x, y) coordinate system], which is transferred to a large metapupil [centered on the origin of the (u, v) coordinate system], because of the coordinate transformations of the GSs.

Fig. 3 The schematic of the images of two GSs formed on the SHWFS focal plane (represented by two star symbols). The two GSs on the $x-y$ plane are shown in the right panel. For clarity, only one SHWFS lenslet is shown.

repeat the same correction procedure as we did for the first DM.

The wavefront corresponding to the resultant slope $S'(u, v)$ of P beams is calculated on the high-altitude metapupil, where the DM 2 is conjugated and is calculated as

$$S' = [B']A', \quad (10)$$

where A' is the vector of Zernike polynomial coefficients of order K' :

$$A' = (a'_1 \ a'_2 \ \dots \ a'_{K'})^T. \quad (11)$$

The matrix $[B']$ on the metapupil is

$$[B'] = \begin{pmatrix} \left. \frac{\partial Z_1(u, u)}{\partial u} \right|_1 & \left. \frac{\partial Z_2(u, u)}{\partial u} \right|_1 & \dots & \left. \frac{\partial Z_{K'}(u, u)}{\partial u} \right|_1 \\ \vdots & & & \\ \left. \frac{\partial Z_1(u, v)}{\partial u} \right|_M & \left. \frac{\partial Z_2(u, v)}{\partial u} \right|_M & \dots & \left. \frac{\partial Z_{K'}(u, v)}{\partial u} \right|_M \\ \left. \frac{\partial Z_1(u, v)}{\partial v} \right|_1 & \left. \frac{\partial Z_2(u, v)}{\partial v} \right|_1 & \dots & \left. \frac{\partial Z_{K'}(u, v)}{\partial v} \right|_1 \\ \vdots & & & \\ \left. \frac{\partial Z_1(u, v)}{\partial v} \right|_M & \left. \frac{\partial Z_2(u, v)}{\partial v} \right|_M & \dots & \left. \frac{\partial Z_{K'}(u, v)}{\partial v} \right|_M \end{pmatrix}. \quad (12)$$

The wavefront error on the high-altitude plane can be calculated as

$$A' = [B']^+ S', \quad (13)$$

where $[B']^+$ is the pseudoinverse B' . For the second DM with the influent function D' , the required voltages applied on the second DM for the wavefront correction are

$$V' = D'A'. \quad (14)$$

Solar AO uses a small region on the order of $6'' \times 6'' \sim 20'' \times 20''$ as a GS, and a SHWFS can measure the slopes from each GS on its focal plane. In this case, the GSs, shown in Figs. 2 and 3, are viewed as point source GSs. That is, it uses the point located in the center of each small GS region as a GS for the above calculations.

Table 1 The Strehl ratio comparisons between PT-MCAO and conventional star-oriented MCAO.

Second DM conjugated height (km)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
PT-MCAO Strehl ratio	0.28	0.35	0.36	0.36	0.35	0.35	0.31	0.29	0.27
MCAO Strehl ratio	0.21	0.28	0.30	0.32	0.35	0.35	0.32	0.29	0.26

3 Numerical Simulations

In order to verify the PT-MCAO's performance, we compare it with the conventional star-oriented MCAO. In this comparison, both systems have identical parameters. Two DMs, each with 23 actuators across its diameter, are used. One is conjugated on the ground telescope aperture while the other is conjugated to a high altitude above the telescope. The telescope aperture has an aperture diameter of 1.6 m, which is the same with that of the NST located on the Big Bear Solar Observatory (BBSO). We use the seeing profile measured data from the BBSO, with the seeing Fried parameter of 160, 310, 480, and 1260 mm at the height of 0.2, 1.0, 3.0, and 8.0 km, respectively, at good seeing condition,¹⁶ and this is the only available daytime seeing profile measurement data on a major solar observatory.

We use the end-to-end simulation software Yao¹⁷ to simulate both the PT-MCAO and the conventional MCAO performances. Yao can be directly used to simulate the conventional star-oriented MCAO, and it is open code-based software, which makes it possible for users to modify the software codes for specific applications. The SHWFS code is modified according to our PT-MCAO algorithm discussed in Sec. 2. Five GSs are used, in which four are located on the corners of a $30'' \times 30''$ square FOV while one is located on the FOV center. In fact, increasing the GS number may increase wavefront sensing accuracy over a fixed FOV for all MCAO systems including the star-oriented MCAO and the PT-MCAO but at a cost of reducing possible closed loop correction speed or bandwidth because of the required computation power. The square FOV is uniformly sampled by a grid of 5×5 point spread functions that are used for performance evaluations in terms of average Strehl ratio over the entire FOV. Each Strehl ratio is calculated as a result of average over the $30'' \times 30''$ FOV and average over 400 AO closed loop corrections. Wind speed is assumed to be 10 m/s for each atmospheric turbulence layer, and AO correction speed is 1500 Hz (open loop). We assume that a sCMOS SHWFS camera is used, which delivers a readout noise of $1 e^-$. To reduce the fitting error, 22 subapertures are used to sample the 1.6-m telescope diameter and both DMs have 23 actuators across its diameter. The simulation Strehl ratios at $0.60\text{-}\mu\text{m}$ wavelength for both the PT-MCAO and the conventional star-oriented MCAO are summarized in Table 1.

The simulation results in Table 1 show the average Strehl ratios as a function of the secondary DM conjugated height. It can be seen that the best conjugated height for the PT-MCAO and the conventional MCAO is in the range of 1.0 to 3.0 km. It is clear that the PT-MCAO delivers a better performance, since we found during the variable-turbulence corrections in the simulations, the PT-MCAO close loop is much more stable and robust than that of the conventional MCAO, which explains why the PT-MCAO has a better

performance than that of the conventional MCAO, and this is more significant for a telescope with a large aperture size; although, in theory, both systems should be an optimal resolution for the 2-DM correction case. It must be noted that, in these simulations, the footprints of GSs are overlapped on the second DM, which indicates that our PT-MCAO can be used for any GS geometric asterism, with and without GS footprint overlap on the metapupil.

In the above simulations, the MMSE was used for both the conventional star-oriented MCAO and the PT-MCAO. We also used SVD reconstructor for these simulations and found that while the PT-MCAO delivered identical results, the conventional MCAO delivered worse results because of the problem of the close loop instability, which further indicates that the PT-MCAO closed-loop is more robust and stable than that of the conventional MCAO.

4 Discussion and Conclusions

The PT-MCAO we proposed is composed of two AO correction loops. The first correction loop consists of the first DM and the SHWFS, while the second correction loop consists of the second DM and the same SHWFS used in the first correction loop. While the SHWFS and the first DM are conjugated on the telescope aperture, the second DM is conjugated on a high altitude. For the first DM correction loop, the average of the wavefront slopes from all the GSs is equivalent to the average of wavefronts for a linear system, which is identical to a solar GLAO system. A recent nighttime on-sky experience demonstrated that such a GLAO correction loop is converged and can be effectively used to correct the low altitude turbulence.¹⁸ Solar GLAO was also successfully demonstrated in the NIR¹¹ as well as in the visible in our recent solar GLAO run with the Dunn solar telescope, in which a FOV on the order of $40'' \times 40''$ was used for wavefront sensing. It is highly estimated that a better performance should be achievable with an additional DM used to correct the high-altitude turbulence, which can be immediately realized by the proposed PT-MCAO. As discussed by Diolaiti et al.,³ this layer-oriented GLAO system is a linear reconstruction and its achieved correction is optimal according to the same criterion with that of the star-oriented approach. In fact, in a converging closed loop system with a sufficiently high correction bandwidth, good correction can be achieved within a few iterations.

While the low altitude is effectively corrected by the first DM loop in our PT-MCAO, the high-altitude turbulence will be corrected by the second DM loop, in which the DM is conjugated on a high altitude. Since the wavefront slope vectors for both low and high altitudes are encoded in the slope vectors measured by the SHWFS conjugated on the telescope aperture, in which the low turbulence slope vectors are represented by the average slopes of the GSs, the high-altitude associated slope vectors are decoded as the

difference of each GS slope with the average slope, which is calculated by using Eq. (9). In the extreme case that there is no high-altitude turbulence and all the turbulence is concentrated in a single ground layer on the telescopes entrance aperture, the slope difference on the high altitude will be zero, which indicates that no wavefront error needs to be corrected by the second DM loop. The differential slopes, together with the SHWFS subapertures, are projected onto the high-altitude metapupil by using the PT technique, where the second DM is conjugated. On the metaplane, each GS projects its SHWFS pattern onto this plane but located on different positions because of the different directions, as shown in Fig. 2. The multiple GSs on the metapupil can be viewed as a synthetic resultant GS whose beam on the metapupil is formed by all the beams from all the GSs. The second AO loop, based on Eqs. (10)–(14), should find the minimum of the vector slopes of the GSs (i.e., the resultant GS), which is equivalent to minimize the wavefront error of all the GSs and, therefore, is one of the optimal solutions for the high-altitude wavefront correction.

Since both DM loops are optimal solutions, the PT-MCAO should converge and provide a similar performance with that of the conventional star-oriented MCAO system, which is confirmed by our Yao-based numerical simulations.

Our current PT-MCAO is limited to two DMs. That is, the current version will not work for more than two DMs. Although the layer-oriented MCAO also does not need to reconstruct the tomography wavefronts, our PT-MCAO is different from the layer-oriented MCAO: in layer-oriented MCAO, a WFS is conjugated with each DM, in which each DM and WFS pair loop works independently to other DMs and WFS pair loops, and each loop has its own computer for wavefront measurement and AO control. In open-loop, each detector sees the proper layer and several images superimposed concerning the other layers.¹ In our PT-MCAO, a SHWFS measures the slopes of all the GSs and the DM signals are decoded, which are used to control the two DMs simultaneously. Solar layer-oriented MCAO was discussed by Kellerer.¹⁹ But such a system has not been built or tested on any solar telescope, and its potential problems regarding field vignetting and reduction with a SHWFS for high-altitude wavefront sensing with solar two-dimensional structures were described in detail by Marino and Wöger,²⁰ which needs special and dedicated solutions to address these issues.²¹ Solar MCAO systems are challenging, since the time-consuming cross-correlation based slope calculations and the real-time tomography wavefront reconstruction. While it is still a challenging task for current solar MCAO to be implemented for routine solar high-resolution imaging observations, the PT-MCAO we proposed is based on mature techniques and requires less time to calculate the control signals for the 2 DMs. Benefited from the super-stability of the closed loop correction, the PT-MCAO delivers a better performance than that of the conventional MCAO and has the potential to be immediately used for solar high-resolution imaging.

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