Ground-layer Adaptive Optics for the 2.5 m Wide-field and High-resolution Solar Telescope (Postprint)

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Abstract

The 2.5 m wide-field and high-resolution solar telescope (WeHoST) is currently under developing for solar observations. WeHoST aims to achieve high-resolution observations over a super-wide field of view (FOV) of 5’ × 5’ , and a desired resolution of 0.3’ ‘. To meet the scientific requirements of WeHoST, the ground-layer adaptive optics (GLAO) with a specially designed wave front sensing system is as the primary consideration. We introduce the GLAO configuration, particularly the wave front sensing scheme. Utilizing analytic method, we simulate the performance of both classical AO and GLAO systems, optimize the wave front sensing system, and evaluate GLAO performance in terms of PSF uniformity and correction improvement across whole FOV. The results indicate that, the classical AO will achieve diffraction-limited resolution; the suggested GLAO configuration will uniformly improve the seeing across the full 5’ × 5’ FOV, reducing the FWHM across the axis FOV to less than 0.3’ ’ ($\lambda \geq$ 705 nm, r0 $\geq$ 11 cm), which is more than two times improvement. The specially designed wave front sensor schedule offers new potential for WeHoST’ s GLAO, particularly the multi-FOV GLAO and the flexibility to select the detected area. These capabilities will significantly enhance the scientific output of the telescope.

Full Text

Preamble

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Ground-layer Adaptive Optics for the 2.5 m Wide-field and High-resolution Solar Telescope

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Abstract

The 2.5 m wide-field and high-resolution solar telescope (WeHoST) is currently under development for solar observations, aiming to achieve high-resolution imaging over a super-wide field of view (FOV) of 5 × 5 with a desired resolution of 0.3 . To meet these scientific requirements, ground-layer adaptive optics (GLAO) with a specially designed wavefront sensing system is being considered as the primary solution. We introduce the GLAO configuration, particularly the wavefront sensing scheme, and utilize analytic methods to simulate the performance of both classical AO and GLAO systems. Through optimization of the wavefront sensing system, we evaluate GLAO performance in terms of PSF uniformity and correction improvement across the entire FOV. Our results indicate that classical AO will achieve diffraction-limited resolution, while the proposed GLAO configuration will uniformly improve seeing across the full 5 × 5 FOV, reducing the FWHM across the axis FOV to less than 0.3 ($\lambda = 705$ nm, $r_0 =$ 11 cm)—representing more than a twofold improvement. The specially designed wavefront sensor schedule offers new potential for WeHoST’ s GLAO, particularly for multi-FOV GLAO and the flexibility to select the detected area, which will significantly enhance the scientific output of the telescope.

Key words: instrumentation: adaptive optics –instrumentation: detectors –instrumentation: high angular resolution –methods: numerical –telescopes –Sun: activity

1. Introduction

Ground-based telescopes are widely used for astronomical observations, with astronomers favoring large apertures for their excellent photon-gathering and imaging capabilities (λ/D, where λ is the imaging wavelength and D is the telescope aperture). However, atmospheric turbulence severely degrades image quality; even under superb seeing conditions, the achievable angular resolution of any arbitrarily large telescope operating in the visible band is limited to that of a 0.2 m telescope (Rigaut 2015). Adaptive optics (AO) was introduced to mitigate this turbulence-induced effect and improve observation image quality (Rao et al. 2016a; Wei et al. 2016; Deqing et al. 2022; Guo et al. 2022). While classical AO restores poor seeing to the diffraction limit within a narrow field of view (FOV) (Rao et al. 2016b), multi-conjugate adaptive optics (MCAO) can provide diffraction-limited imaging over an extended FOV, typically encompassing up to 1 . One of the first solar MCAO applications was performed at the Vacuum Tower Telescope, achieving an improved FOV of 30 with a sensing field of 40 . MCAO developed for GREGOR uses 19 subfields in 68 × 68 to reach a FOV of 1 (Dirk et al. 2014). MCAO at DST increases the isoplanatic patch to 40 -45 within the 1.25 full FOV, using five guide regions of 10 × 10 field in the visible light regime (Rimmele et al. 2010). More recently, NST MCAO (CLEAR) has achieved a maximum FOV of 53 utilizing 3 × 3 guide regions in 35 (Schmidt et al. 2017). Experiments with MCAO have also been performed at the 1 m New Vacuum Solar Telescope (NVST), with five selected guiding regions within a 60 × 52 field to reach an FOV of 60 (Rao et al. 2018). Theoretical simulation of the future EST MCAO system using five DMs and 19 guide stars (GS) in 70 shows a corrected FOV of 60 at 550 nm visible wavelength (Femenía-Castella et al. 2022). DKIST MCAO is expected to provide the highest spatial resolution in a FOV as large as 60 (Schmidt et al. 2022).

Compared to MCAO, ground-layer AO (GLAO) achieves lower resolution but provides larger fields and greater uniformity, rather than complete compensation within small regions (Rigaut 2002; Kovadlo et al. 2020; Zhong et al 2020; Yang et al. 2023). GLAO uses a single deformable mirror (DM) conjugated to the most intense near-ground turbulence layer. Since the turbulent regions experienced by different lines of sight almost overlap at low altitudes, GLAO extracts wavefront error arising from the near-ground turbulence layer by averaging wavefront aberrations across multiple lines of sight, thereby achieving wide-field and uniform correction. For solar observations, the near-ground turbulence layer is much stronger during the day due to ground heating by direct sunlight. At typical telescope heights of 20–40 m above ground, Fried parameters are of order 10 cm (at 500 nm) even at excellent sites (Rimmele & Marino 2011), making GLAO highly attractive. GLAO has gradually evolved into an independent technology rather than a byproduct of MCAO, aiming to uniformly improve image quality over the largest possible working FOV. Nighttime GLAO provides partial correction over FOVs up to 10 (Jia & Zhang 2013). Unlike night astronomy, where most GLAO systems under development require laser GSs, the Sun—as an extended object—provides an infinite number of guide references, facilitating solar GLAO development. However, these extended sources necessitate large-format wavefront sensor (WFS) cameras and impose much higher computational loads. Due to limitations imposed by commercial cameras and hardware, the FOV for solar GLAO typically ranges from 1 to 2 . The GLAO system at DST averages wavefront distortions over 42 × 42 , with good correction extending to about 1.5 in the visible band, though uniformity degrades and FOV corners at 2 display significantly lower resolution (Rimmele et al. 2010). The NST GLAO has achieved high-resolution imaging over a 53 × 53 field at 705.7 nm (Schmidt et al. 2017), with experiments showing that GLAO correction is affected by variable vertical turbulence distribution. The tested GLAO of the 1.8 m Chinese Large Solar Telescope provides homogeneous image detail of the solar photosphere and chromosphere with a corrected FOV of 110 in three wavelength channels (G-band, Hα line, and TiO band) (Rao et al. 2020). To date, only one professional and dedicated solar GLAO system—NVST—operates regularly for scientific observations, using 3 × 3 guide regions in 42 × 37 to achieve high-resolution and uniform correction in 80 at the TiO band (Zhang et al. 2023). Their experimental results show that correction is obviously related to the detected guide region in the WFS, whereas the effect in areas outside the detecting FOV is inconspicuous, indicating that correction uniformity closely depends on the layout of guide regions.

Solar physics research requires observations of magnetic features over wide FOVs, as typical scales of solar active regions range from 1 to 3 , and even approximately 6 for sigmoids and large filaments (Aulanier & Schmieder 2002; Masson et al. 2009; Canou & Amari 2010). GLAO offers the possibility of improving seeing for large ground-based telescopes and increasing the efficiency and uniformity of observations over wide FOVs. However, the current FOV of existing GLAO systems—covering only 1 -2 —is far from sufficient for observing multiscale structures in the solar atmosphere.

The 2.5 m wide-field and high-resolution solar telescope (WeHoST) is currently under manufacturing. The scientific requirement for WeHoST is to obtain high-resolution solar images within a large FOV of 5 × 5 with a desired resolution of 0.3 (Fang et al. 2019). This unprecedented FOV introduces novel opportunities and challenges. Based on the desired super-wide FOV and resolution below the diffraction limit, GLAO is the primary consideration. Although MCAO can provide higher resolution, the FOV size corrected by current MCAO systems makes it difficult to meet WeHoST' s scientific requirements, as capturing such a large FOV of 5 for solar observations remains a significant challenge. Compared to MCAO, GLAO achieves lower resolution but provides larger fields. The excellent results from previous GLAO systems (Chuna et al. 2017; Zhang et al. 2023) make GLAO particularly attractive for WeHoST, and it has been selected as the final preliminary optical instrument consideration.

Nighttime astronomical observations are performed in the NIR band, whereas solar observations are conducted in the VIS band with higher system requirements. Meeting the desired FOV of 5 × 5 is not an easy task for solar GLAO observations. The maximum FOV for GLAO-corrected observations depends on the detected FOV; however, there are no commercially available detectors capable of detecting within such a super-wide scientific FOV. The primary task for WeHoST' s GLAO is addressing this super-wide scientific FOV.

Secondly, the size of the effective corrected FOV is sensitive to the thickness of the compensated turbulence layer in GLAO. A thin ground layer allows a larger FOV to be corrected. However, when the target FOV is too large, the wavefront in the direction of each GS will be more effectively compensated due to atmospheric anisoplanatism, leading to nonuniform correction over the whole field. With a finite number of guide areas and limited WFS FOV, optimizing the guide areas for better detection accuracy and correction consistency is crucial. Homogeneously improved image quality over a wide field is required, particularly for accurate magnetic field topology studies (Molodij & Aulanier 2012). Accordingly, solar observations with WeHoST also need spatial uniformity correction.

In this paper, we discuss key issues for the wide-field GLAO system configuration and provide a prediction of WeHoST' s solar GLAO performance. Section 2 discusses GLAO components for WeHoST, particularly the wavefront sensing system and atmospheric turbulence parameters. Section 3 briefly describes PSF estimation based on spatial filtering analytic theory. In Section 4, we optimize the wavefront sensing system and analyze the relationship between GLAO performance and key system specifications, including the position and size of detected subfields, the position and number of GSs, the number of DM actuators, and the imaging wavelength, ultimately suggesting a final GLAO configuration. Section 5 presents our conclusions.

2.1. Preliminary Considerations of GLAO for WeHoST

WeHoST has many scientific objectives, including direct imaging of solar active regions, wide-field observation of large-scale solar eruptions such as solar flares and coronal mass ejections, and high-accuracy surveys of brightness fields, vector velocity fields, and magnetic fields in the solar atmosphere. These scientific missions determine the performance requirements of the GLAO system. The full width at half maximum (FWHM), defined as the width of the celestial coordinate range where less than half of the optical power from the star is attenuated, is commonly employed to evaluate the residual PSF delivered by GLAO. According to scientific requirements, WeHoST plans to achieve an FWHM of 0.3 across a 5 × 5 field with GLAO assistance (Fang et al. 2019). Additionally, since GLAO may suffer from spatial nonuniformity of correction when imaging over large fields, another requirement is that the FWHM difference across spatial fields should be minimized.

GLAO with a new WFS schedule has been proposed to achieve high-resolution imaging over the super-large FOV of 5 square arcminutes for WeHoST. Due to the narrow field of commercially available sensors, WeHoST considers using several small-area sensors to cover a wide FOV for wavefront sensing. While too few sensors are insufficient to cover a wide field, too many sensors may cause unnecessary problems such as optical system complexity. Additionally, extended sources on the Sun necessitate large-format sensors and much higher computational loads compared to point sources. Thus, the initial GLAO design for WeHoST accommodates up to five WFSs for wavefront sensing. As shown in Figure 1 [Figure 1: see original paper], the full-field beam can be split into five subfields (Subfields 1-5), corresponding to five sensors (WFS1-5). Considering imaging uniformity, the positions of Subfields 1-5 are symmetrically arranged within the scientific FOV. The beam splitting will be accomplished using a custom optical structure placed at the focal plane. The planned WFS schedule offers WeHoST several unique advantages, particularly changeable AO modes and flexibility in selecting the detected area.

For "changeable AO modes," if one sensor in the WFS schedule provides a sufficient number of subapertures, WeHoST can achieve diffraction-limited imaging corresponding to classical AO correction. In this mode, WFS1 should point toward the central FOV, while the other four off-axis sensors (WFS2–5) use a relatively small number of subapertures in exchange for averaging the wavefront from a larger FOV. In this configuration, multiple lines of sight sense only the ground-layer turbulence, corresponding to GLAO correction. WFS1 has a maximum detected field of up to 15 × 15 and senses turbulence in all layers with high spatial resolution, while WFS2–5 have a maximum detected field of up to 40 × 40 and sense turbulence in the ground layer only, utilizing up to 21 GSs even at relatively low spatial resolution but over a wide FOV.

For "flexibility to select the detected area," the operating sensors in the WFS schedule are adjustable according to the scientific objectives of interest. In GLAO mode, at least one off-axis sensor must work to ensure wavefront detection from multiple directions; the central sensor may operate or not, and the positions of Subfields 2–5 are also adjustable.

Solar AO systems commonly use solar granulations or sunspots as GSs. Since WeHoST's solar GLAO receives wavefronts from multiple WFSs, it is reasonable to assume that the WFS layout positively impacts GLAO correction. The relationship between correction performance and WFS layout should be analyzed. Additionally, each off-axis WFS2–5 will contain several GSs from different lines of sight, and the GS layout will also affect GLAO performance.

The DM is another fundamental component of the GLAO system, and the number of actuators determines the correction order. Actuator spacing is related to the turbulence Fried parameter r_0. Since solar AO systems normally operate at r_0 larger than 8 cm—otherwise the WFS would not have sufficient contrast from granulation for wavefront sensing (Rimmele & Marino 2011)—a simple calculation yields the required number of actuators for classical AO as D/r_0, which determines that classical AO requires a 31 × 31 actuator DM. Incidentally, the number of subapertures for WFS1 is set equal to the number of DM actuators, whereas for WFS2–5, a relatively small number of subapertures is traded for a large detected FOV.

This design will allow WeHoST to operate in both classical AO mode and wide-field GLAO mode, achieving either diffraction-limited observation or wide-field high-resolution observation. The limitation of GLAO performance will not be the correction capability of the DM but may be the detection capability of WFS2–5. DM actuators should be studied according to scientific requirements, with clear recommendations provided.

It is well known that ground-based solar telescopes should cover different heights of the solar atmosphere with observational spectral lines. In WeHoST, six spectral lines are selected to image the solar atmosphere at the photosphere and chromosphere layers. The candidate spectral lines cover two white-light bands (360 and 425 nm), Hα line (656.3 nm), TiO band (705.7 nm), Ca II IR line (854.2 nm), and He I IR line (1083 nm). The resolution of different imaging channels may vary significantly, and GLAO should focus more on improvement relative to the uncorrected atmosphere.

2.2. Parameters Describing the Atmospheric Turbulence

The performance of the AO system strongly depends on the structure and distribution of atmospheric turbulence. The WeHoST project will be mounted at the Mt. Wumingshan (WMS) site. From initial surveys in 2012 through fixed-point monitoring in 2014 to current routine observations, the high-quality and continuous data provide a scientific, objective, and quantitative basis for comprehensive evaluation of Mt. Wumingshan as a candidate site for day and night astronomical observations (Song et al. 2019).

However, available data for measuring the layered turbulence profile at this site are limited. In 2020, Song et al. (2020) built a profiler using differential solar limb fluctuations to determine the turbulence profile, with the extended solar limb expanding the range of separation angles for higher resolution of the height profile. They presented daytime C ^{2}(h) measurement results for Mt. Wumingshan on 2019 November 3, showing that the strongest turbulence is mostly concentrated in the near-ground layer. We use these measurement results as our turbulence parameters. The data consist of 2184 frames of C ^{2}(h) continuously distributed from 0 to 20 km. After removing frames with obvious measurement errors, we retain 1681 frames as the final average C ^{2}(h) profile. The turbulence parameters may be limited in representativeness due to insufficient monitoring time but still hold reference value for performance analysis. Considering that turbulence volume can be modeled with a sequence of phase screens distributed along the optical axis, we discretize the continuous C ^{2}(h) profile using the optimal method proposed by Wallner et al. (1994) and Paxman et al. (1999). The altitudes and relative values of C ^{2} are listed in Table 1 .

3. PSF Estimation by Analytic Method

Predicting GLAO performance is crucial for designing large-aperture solar telescopes, as reliable prediction of image quality delivered by GLAO facilitates easier design. AO simulations are typically divided into two categories: analytic calculations (Tokovinin 2004; Ellerbroek 2005; Jolissaint et al. 2006) and full-wave propagation Monte Carlo simulations (Lloyd-Hart & Milton 2003; Basden & Morris 2016). Compared to the intensive computation of Monte Carlo models, analytic models require less computation, run faster, and are generally used to explore large parameter spaces and study various performance trade-offs.

In this paper, we use an analytic model developed by Tokovinin (2004), which provides reliable prediction of GLAO performance (Andersen et al. 2006). The residual phase fluctuation in the telescope aperture is Gaussian, thus the long-exposure PSF is directly related to the aperture-averaged structure function. The long-exposure optical transfer function of the PSF is given by:

$$T(f) = T_0(f) \exp\left[-\frac{1}{2} D_\phi(f)\right]$$

where $T_0(f)$ is the optical transfer function of an ideal telescope, f is the frequency in image space, and λ is the imaging wavelength.

Based on the Wiener-Khinchin theorem, the structure function can be acquired from the phase power spectrum. In the GLAO filter model, the power spectra of residual and atmospheric phase are related by a multiplicative factor $|G(f)|^2$. Since turbulence layers are mutually independent, the resulting power spectrum is the sum of power spectra from all layers. For each layer, the residual phase power spectrum is:

$$W_{\mathrm{res},i}(f) = W_{\mathrm{atm},i}(f)|G_i(f)|^2$$

The atmospheric phase power spectrum of the i-th turbulent layer is:

$$W_{\mathrm{atm},i}(f) = 0.0229 r_{0,i}^{-5/3} f^{-11/3} \exp\left[-\left(\frac{f}{f_0}\right)^2\right]$$

where $r_{0,i}$ is the Fried radius for layer i and L_0 is the outer scale of turbulence. $|G_i(f)|^2$ describes the portion of the atmospheric spectrum left uncorrected by GLAO, which depends on many factors such as the number of DM actuators and the guide star layout. For the i-th layer at altitude h with K guide stars located at field angles $\mathbf{a}_k$:

$$|G_i(f)|^2 = \left|1 - \frac{1}{K}\sum_{k=1}^{K} \exp\left[-2\pi i \mathbf{f} \cdot \mathbf{a}_k h\right] A(f) \mathrm{sinc}(\pi d f)\right|^2$$

where $d = D/(n-1)$ (n being the number of DM actuators). The Airy function $A(f)$ describes the shape of the telescope aperture. Finally, GLAO-corrected PSFs from different lines of sight are obtained. Although the temporal behavior of the GLAO system and wavefront sensing errors are ignored, this analytic simulation provides reliable prediction of GLAO performance (Andersen et al. 2006).

Generally, GLAO provides relatively modest image quality enhancement across a wide field. The FWHM is the most practical measure of GLAO performance, and GLAO' s effect on image quality can be equivalent to that obtained under better seeing conditions. The FWHM ratio before and after GLAO reveals seeing improvement and correction gain. It is worth highlighting that both resolution and spatial uniformity are required for solar GLAO performance evaluation. However, improving spatial uniformity of correction usually comes at the cost of resolution. Although these two performance metrics cannot be optimized simultaneously, understanding their characteristics is meaningful. Thus, we employ FWHM and FWHM ratio to reveal image quality and improvement, where smaller values indicate better resolution and gain. The difference between best and worst FWHM across the whole FOV, denoted FWHMR, extracts spatial uniformity, with smaller values indicating higher spatial uniformity.

4. Performance Simulation of Solar GLAO

In WeHoST, many parameters affect GLAO correction in complex ways, necessitating simulations with different configurations. Since manufacturing will take considerable time, the main GLAO parameters should be clearly recommended in the preliminary design study. We investigate the relationship between wide-field GLAO performance and the wavefront sensing system, including fundamental components such as subfield size and position, GS number and position, DM actuator count, and imaging wavelength. Specifically, five individual WFSs point to five individual subfields: the on-axis WFS uses one GS located at the subfield center, while off-axis WFSs use five GSs arranged in a circle plus the subfield center, as shown in Figure 2 [Figure 2: see original paper]. The initial system parameters (listed in Table 2) will be sequentially altered to satisfy GLAO performance requirements.

4.1. Position and Size of Subfields

WeHoST's GLAO will use five sliced subfields: one at the field center (Subfield1) and four off-axis fields (Subfields 2-5). Two issues require analysis: the size of Subfields 1-5 and the position of Subfields 2-5. We reposition the subfields and investigate the relationship between GLAO performance and subfield configuration, using the same angular distance for Subfields 2-5 to ensure correction uniformity.

For the first issue, we investigate two potential options: five narrow subfields versus one narrow Subfield1 plus four wide Subfields 2-5. The narrow Subfield1 ensures WeHoST can operate under classical AO correction. As shown in Figure 3 [Figure 3: see original paper], Option 1 shows poor correction at off-axis FOV, whereas Option 2 yields significantly higher resolution at the corners of the 5 FOV, which is attractive for solar observations. Compared to Option 1, Option

2 improves FWHM and FWHMR by 6.6% and 25.8%, respectively. A narrow central subfield plus four wide subfields enables a much larger corrected FOV with uniform correction.

We then test GLAO performance with different positions of Subfields 2–5 in angular and radial directions. Figure 4 [Figure 4: see original paper] shows FWHM distributions for Subfields 2–5 at two angular directions, with FWHM and FWHMR values of 0.3045 and 0.1992, and 0.3052 and 0.2006, respectively. Considering a square FOV, locating Subfields 2–5 on a square provides better correction and uniformity. Figure 5 [Figure 5: see original paper] shows FWHM for Subfields 2–5 at different radial positions, revealing that imaging resolution and spatial uniformity over a wide field are very sensitive to radial position. As the radial position moves outward, correction quality and uniformity improve then decrease, presumably reaching optimal correction around 235 . Notably, the GLAO system achieves similar correction when Subfields 2–5 are positioned between 200 –270 , indicating that the optimal position is relatively insensitive near the optimum, which reduces angular accuracy requirements for the wavefront slicing system. Based on these results, we propose $±$235 as the optimal position for Subfields 2–5 in WeHoST' s GLAO system.

4.2. Position and Number of Guide Stars

Solar GLAO systems use natural GSs as references for atmospheric turbulence compensation. Multiple GSs are distributed to sample ground-layer turbulence. In WeHoST, WFS1 uses one GS at the Subfield1 center, while WFS2–5 use five GSs distributed within Subfields 2–5. The position and number of GSs in Subfields 2–5 should be carefully designed to optimize GLAO performance across the wide FOV. We initially used an annular constellation with equal angular spacing and investigated the relationship between GLAO performance and GS radius, as shown in Figure 6 [Figure 6: see original paper]. Increasing GS radius within the subfield improves GLAO performance, with optimal position around 40 .

We then tested two GS layouts: five GSs with equal angular distance versus one central GS plus four GSs with equal angular distance, as shown in Figure 7 [Figure 7: see original paper]. These layouts provide similar correction, though the ring layout offers relatively better correction in the wider field. We also tested the relationship between GLAO performance and different numbers of GSs in Subfields 2–5, as shown in Figure 8 [Figure 8: see original paper]. As GS number increases, GLAO performance improves in both absolute resolution and uniformity across the whole field. Beyond 5 × 4 + 1 GSs, little gain is achieved by adding more GSs. While increasing GSs enhances performance, too many GSs cause redundant costs and complexity, so the number should be appropriate. Based on these results, we suggest locating five GSs on a ring at 40 radius within Subfields 2–5.

4.3. Number of DM Actuators

The number of DM actuators determines the order of GLAO compensation. As actuator count increases, more imaging details can be obtained, albeit at higher cost. Generally, GLAO systems increase actuator pitch appropriately to trade off actuator number and cost savings. The effect of actuator number on performance should be investigated to select an appropriate count meeting scientific requirements. The requirement for diffraction-limited imaging determines that classical AO needs a DM with 31×31 actuators, as well as WFS1 with 31×31 subapertures.

As shown in Figure 9 [Figure 9: see original paper], classical AO mode can achieve diffraction-limited resolution over the FOV center. For GLAO mode, performance typically depends on turbulence strength and the proportion of ground-layer turbulence. Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show GLAO results versus actuator number for three r_0 values, leading to the following conclusions:

1. As actuator number increases, better GLAO performance is achieved, particularly in performance gain. However, the benefit diminishes beyond a certain point, with no further improvement when actuators exceed a threshold.
2. Two choices exist for actuator number: an inflection point (15×15) and an optimal point (31×31) balancing performance and actuator count.
3. Under better seeing conditions, the GLAO system obtains higher image quality, more uniform correction, and better performance gain. The performance inflection point is reached earlier, indicating that better seeing requires fewer DM actuators.

When selecting actuator number, the first consideration is the required FWHM after AO correction. Additionally, since the benefit of increasing actuator number mainly concentrates on average performance gain, selection should also consider performance improvement across the whole FOV. Worst-case seeing should be considered as it determines the boundary of turbulent conditions under which GLAO can effectively operate. Figure 11 shows that 31×31 actuators can achieve FWHM below 0.3 for GLAO correction under normal and good seeing ($r_0 \geq 11$ cm). However, FWHM is not very uniform across the FOV, possibly due to detected subfield or GS configuration—an issue discussed in the next section.

4.4. Imaging Wavelength

Imaging resolution is highly dependent on the science camera wavelength. GLAO design considers imaging quality across multiple wavelength bands: 360, 425, 656.3, 705.7, 854.2, and 1083 nm. As shown in Figure 12 [Figure 12: see original paper], after optimizing subfields and GSs, GLAO provides good gains at different wavelengths. Larger GLAO gain, higher resolution, and better uniformity are obtained at longer wavelengths. A best gain of 0.32%–0.37% is achieved at 1083 nm; as wavelength becomes shorter, resolution gradually decreases, yet the GLAO system still shows good gain. Even at 360 nm, GLAO correction improves FWHM by approximately 30%–52% across the wide FOV compared to the uncorrected atmosphere. WeHoST will achieve high-resolution observation using GLAO + speckle imaging reconstruction, and these GLAO results provide confidence for realizing the wide FOV.

4.5. Performance of GLAO

The above analysis shows that GLAO gain is mainly affected by subfield position, DM actuator number, imaging wavelength, and slightly by GS layout, while full-field PSF uniformity is primarily influenced by subfield position, GS layout, and imaging wavelength.

We optimize GLAO performance and obtain the final GLAO configuration for WeHoST, listed in Table 3 . We calculate FWHM distributions after AO and GLAO correction, as shown in Figures 13 [Figure 13: see original paper] and 14 [Figure 14: see original paper]. Classical AO achieves diffraction-limited observations at the central FOV, while wide-field GLAO achieves very homogeneous image quality over the entire 5 × 5 FOV with FWHM of 0.3 .

GLAO performance depends on variable vertical turbulence distribution because upper free-atmosphere turbulence is not corrected. We consider three possible turbulence distributions based on the typical Hufnagle-Valley model: ground layer weight at 0 km altitude is 87%, 66%, or 56% of total turbulence, with the remainder in thin layers from 1 to 10 km at 2 km intervals. The altitudes and relative C^{2} values for these layers are listed in Table 4 . We calculate FWHM distributions under these three turbulence profiles, as shown in Figure 15 [Figure 15: see original paper]. Results show that the optimized GLAO provides highly uniform correction across the whole FOV. If ground layer contribution exceeds 50% of total turbulence, FWHM is reduced by approximately half; even then, optimized GLAO achieves required resolution in good seeing. If 60% of total turbulence originates from the ground layer, GLAO can meet resolution requirements under normal seeing. If ground layer weight exceeds 87%, GLAO provides significantly good correction, enhancing imaging resolution by nearly a factor of five compared to the uncorrected atmosphere even in bad seeing. WeHoST GLAO would offer homogeneous image quality, potentially eliminating bad seeing from science observations.

Based on the WFS schedule design, detected subfields can be flexibly moved, which is necessary for observing multi-scale structures in the solar atmosphere. Figures 16 [Figure 16: see original paper] and 17 [Figure 17: see original paper] show results for five FOV sizes (1 , 2 , 3 , 4 , 5), with Subfields 2–5 pointed to positions at 46.8 , 93.6 , 140.4 , 187.2 , and 235 . These results for multiple FOVs indicate the relationship between FOV and compensated turbulence layer thickness in GLAO: a thin ground layer allows a larger FOV to be corrected, albeit with lower resolution. Additionally, we can finely adjust detected subfields within the broad FOV, focusing only on the subfield closest to the scientific target. This indicates that WeHoST' s GLAO can concentrate on interesting areas over a wide FOV. As shown in Figure 18 [Figure 18: see original paper], detected subfields can be manually adjusted radially and angularly, facilitating high-resolution imaging within specific areas. In practical observations, the detected area can be adjusted flexibly according to the scale and location of the scientific object, enabling more targeted and high-resolution observations. This flexibility allows efficient utilization of telescope time and resources, ultimately maximizing scientific outcome quality.

5. Conclusions

In this paper, we describe initial AO considerations for WeHoST. The specially designed WFS structure enables implementation of both classical AO and GLAO modes without additional AO pathways or devices, while enhancing GLAO potential, particularly for multi-field GLAO capabilities and detection region selection flexibility. We use a first-order spatial filtering analytic simulation model to analyze GLAO system performance characteristics regarding correction improvement and uniformity across the whole FOV. Simulation and analysis enable more realistic assessment of system capabilities before development.

Key GLAO specifications for WeHoST are thoroughly examined, including wavefront sensing subfield configuration, GS layout, DM actuator number, FOV, and imaging wavelength. Based on WeHoST GLAO requirements, we suggest a final GLAO configuration consisting of one DM with 31 × 31 actuators conjugated to the pupil, five combined wavefront sensors pointing to five individual subfields (one on-axis Shack-Hartmann WFS with 31 × 31 subapertures and 15 × 15 subfield, and four off-axis multi-directional WFSs with 15 × 15 subapertures and 40 × 40 subfields at 117.5 from the FOV center), and 21 GSs (one GS at the on-axis subfield center and five GSs at 20 radius from off-axis subfield centers).

Under the measured turbulence profile at the Mt. Wumingshan site, results demonstrate great potential of the wavefront sensing system for AO and GLAO applications. Classical AO mode recovers diffraction-limited resolution under normal seeing conditions ($r_0 \geq 8$ cm). The suggested GLAO configuration can uniformly improve seeing across the full 5 × 5 FOV, reducing FWHM across the axis FOV to less than 0.3 at $\lambda = 705$ nm ($r_0 \geq 11$ cm). Additionally, under different vertical turbulence distributions, the optimized GLAO achieves significantly great correction and uniformity. Our simulation results verify that this new GLAO mode can achieve WeHoST' s scientific goals. We will also typically use post-facto image-processing techniques to improve solar image quality, scientific value, and visual appeal.

The planned WFS schedule provides several unique advantages for WeHoST.

In particular, the flexibility to select the detected area enables observations of multi-scale structures and specific areas of interest. These advantages make the WeHoST GLAO system practical and unique. GLAO will be implemented on WeHoST in the coming years. In the future, we may explore achieving higher-resolution imaging within this FOV by adding a high-altitude correction loop to the GLAO system. We have also considered the feasibility of incorporating MCAO correction in the adjustable field of the WFS schedule.

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