ATST AND SOLAR ADAPTIVE OPTICS STATE OF THE ART

Friedrich Wöger*, Thomas Rimmele, and Jose Marino

National Solar Observatory, ATST/SacPeak, PO Box 62, Sunspot, NM 88349, USA

Abstract. The 4 meter aperture Advanced Technology Solar Telescope (ATST) is an ELT for solar astronomy, and as such will address a broad range of science questions that require its adaptive optics (AO) system to operate in several different observing scenarios. We review the science drivers that lead to the most demanding ATST AO system requirements, such as high Strehl ratios at visible wavelengths, MCAO correction, and photon starved, extended FOV wavefront sensing using large, faint structures at the limb of the Sun. Within the context of existing high-order AO systems for solar telescopes we present an overview over the current ATST AO system design and capabilities. Finally, we will describe the widely used post-facto image processing techniques of AO corrected solar imaging and spectroscopic data that are required to achieve the desired spatial resolution especially at the short end (380 nm) of the visible spectrum over ATST’s full FOV. We will lay out how these techniques will be supported in the AO system to help ATST achieve its scientific goals.

1 Introduction

In the dawning age of large aperture solar telescopes, solar adaptive optics (AO) systems have become a mission critical tool for the scientific success of these ambitious efforts. This is as true for projects currently under construction such as the 4 m aperture Advanced Technology Solar Telescope (ATST) [16] as it is for planned ones such as the 8 m ring aperture Giant Chinese Telescope [11] or recently commissioned 1.5 m class telescopes such as NST [5] and GREGOR [30].

Solar AO shares the main concepts for wavefront control with systems developed for the use with stars during night time. However, despite these commonalities there also exist some significant differences mostly related to wavefront sensing using the structures prevailing in the solar atmosphere. The difficulties of extended source wavefront sensing in the visible light wavelength range have been described often in the past (see e.g. [20] for a summary), and have been addressed in running systems such as those located at Dunn Solar Telescope [21] operated by the National Solar Observatory (NSO), the German VTT [27], and the Swedish SST [23]. These solar AO systems – besides opening new science windows and thus improving the scientific output of the telescopes – served as path finders for the systems that are now being designed and developed as part of the large aperture projects.

However, with the new capabilities of the larger telescope apertures come challenges for solar AO systems that have to be considered to be able to achieve the high Strehl ratios often necessary to address complex scientific objectives. For example, of growing importance for the future scientific output of large aperture telescopes will be the extension of the AO correction to a larger field of view (FOV) using a solar multi-conjugate adaptive optics (MCAO) system or fast post-processing algorithms for image reconstruction, or a combination of both. The ground work provided by early versions of solar MCAO systems [19,3,22] encourages further effort in this area, while post-processing techniques combined with conventional solar AO corrected
image data have been widely researched for some time [28, 17, 13, 36, 37]. In addition, the ATST has been designed to have the ability to observe structures in the high layers of the solar atmosphere, the corona. To use this telescope feature in combination with AO correction would be highly desirable, but is extremely challenging because of the dim nature of the corona. In the following sections, we will briefly address the state-of-the-art of solar AO at the example of ATST and some of the challenges of its scientific goals, and will then describe the current efforts to analyze and overcome the most significant ones.

2 Current State-of-the-Art of Solar Adaptive Optics Systems

2.1 Some challenges of large solar telescope science

The ATST with its unobstructed 4 meter aperture will be the world’s first extremely large telescope for solar observations. It is intended to give scientist unique opportunities to gain insight into the mechanics of the smallest-scale structures in the solar atmosphere (that are believed to be about 20 milli-arcseconds in diameter, e.g. [38]) as they interact with each other over a large
range of heights. Acquiring diffraction-limited observations within a large wavelength regime – starting at around 380 nm and covering visible and infrared wavelengths – is thus the highest priority of ATST.

The solar magnetic field is very likely the main driver for many phenomena present in the solar atmosphere, ranging from highly dynamic small-scale features [38] to large structures such as prominences [1]. Today, many modern solar telescopes are equipped with instruments – often operating close to the telescope’s diffraction limit – that analyze the spectro-polarimetric properties of the solar light in order to remote sense parameters that allow derivation of the three dimensional solar magnetic field vector. In most cases, these measurements require the instrument to operate with extremely high spectral resolution at wavelengths that correspond to absorption lines of particular elements and molecular species, a nanometer or less in width. While the Sun provides many photons, high sensitivity spectro-polarimetric measurements become difficult when taking into account that some absorption lines can be as dim as 5%–10% of $I_c$ (the intensity at continuum wavelengths), and that a part of the polarimetric signal is typically encoded with as little as 5‰ of $I_c$ depending on the magnetic field strength. To achieve this sensitivity often requires exposure times that are of the order of seconds – long compared to the correlation time of Earth’s turbulent atmosphere – and a stable, high-Strehl PSF delivered by the AO system is required to be capable of obtaining an unbiased measurement. The ATST High-Order Adaptive Optics (HOAO) system is designed to be capable of achieving these demanding requirements in the visible light at 525 nm. Extending this capability to a larger field by means of solar MCAO is highly desirable to address several scientific questions such as the small-scale, short-lived features that can appear suddenly anywhere near an active region on the Sun (often as big as several arcminutes square) and that are thought to be connected to the trigger mechanism of solar flares. Solar MCAO systems are a field of current and intense research.

The ability to observe dim chromospheric and coronal structures at the limb of the Sun with low stray light is an ATST capability that separates it from many other current and planned high spatial resolution telescopes. Solar AO of future large aperture telescopes including ATST will be an important tool for exploring the spectro-polarimetric properties of such structures. Figure 1 shows a prominence observed with the ATST Visible Broadband Imager’s prototype $\text{H}_\alpha$ filter, that has a bandpass of 0.05 nm. The prominence which would hardly be visible at continuum wavelengths within which solar AO usually operate shows significant fine structure. Thus, a classical solar AO system would commonly not be able to use the prominence itself as reference for wavefront sensing and would have to resort to using the limb edge itself as reference, providing a correction only in the direction perpendicular to the limb. Extending wavefront sensor capability to achieve better correction at the limb of the Sun is also subject of current research [26].

2.2 ATST HOAO Design

The ATST HOAO system design is in many aspects based on concepts proven by AO systems that are in everyday use today. Nevertheless, scaling such systems up to a system adequate to meet ATST’s requirements pushes today’s technology to its limits.

The ATST HOAO (see Fig. 2) will incorporate an extended source Shack-Hartmann wavefront sensor (WFS) with a total of about 1400 subapertures, each imaging a FOV of $10 \times 10$ arc$^2$ [18]. The implementation of the WFS at ATST will involve the use of four dedicated FPGAs.
that are programmed to ingest the images of the $1k \times 1k$ px$^2$ camera sensor running at 2 kHz, segment them into $20 \times 20$ px$^2$ sub-aperture images and cross-correlate these within one frame time to find the sub-pixel shifts representing the wavefront gradient. The number of subapertures and their size projected into the pupil of the telescope is well matched to the seeing on Haleakala, the site of ATST.

Looking into the future, advances in chip technology may at some point make a solution based on CPUs more attractive because FPGAs require specialized programming knowledge, causing potential maintenance issues. Another area where future development could be beneficial is related to the low per-pixel full well capacity of $1k \times 1k$ camera sensors running at 2 kHz; higher capability would be desirable to achieve a better signal-to-noise ratio, but at this point remains to be cost prohibitive.

The ATST HOAO deformable mirror (DM) will have 1600 actuators, with the wavefront sensor subapertures being aligned to the actuator grid in a Fried geometry. Contrary to any DM of current solar telescopes, the ATST DM will have to be cooled due to some absorption of the incident light by the facesheet. This is a challenge to vendors, in particular when considering the strict environmental requirements of ATST to minimize internal seeing.

Overall, the approach of scaling up current conventional solar AO system designs to the needs of ATST has considerably reduced risk in many areas. Technological challenges continue to exist in several areas, but solutions have been found, sometimes necessarily involving detailed cost/benefit analyses.

### 2.3 Limitations of conventional solar AO

Conventional solar AO systems as they are implemented in current telescopes have had a significant impact on the science output of these telescopes – and generated the desire for even
better spatial resolution in observations. The capabilities of conventional systems, however, are limited due to design inherent issues.

It is a commonly known fact that conventional AO systems, with the correcting DM optically conjugated to the telescope pupil, are capable only of correcting the wavefront within a very limited FOV defined by the diameter of the isoplanatic patch [20]. For solar observations, this diameter is typically in the range between 8–10 arcs. While many science objectives can be reached with this type of correction, there are several important science use cases where it is not sufficient.

In addition, the dominating contribution to the atmospheric seeing is usually generated by turbulent air motion near the ground which is weakest in the morning for many – if not all – solar telescope sites. For solar observations, this means that the target – the Sun – is at low elevation angles when the ground layer seeing is most favorable. In these situations, however, turbulent layers located higher up in Earth’s atmosphere are geometrically further away and thus can, depending on the strength of their turbulence, cause severe anisoplanatism in observed data.

The effects of anisoplanatism on the noise of extended source Shack-Hartmann WFS measurements have been analyzed in the past [33], but did not include the effect of elevation angles. Recently, a further study based on a detailed simulation of a conventional solar AO system has shown that operating at low elevations can indeed severely reduce their Strehl ratios solely due to anisoplanatism – the effect of increased airmass was ignored – within each individual sub-aperture image of the WFS [12]. The same study demonstrates clearly that this would not be the case if no anisoplanatism was present, or the FOV in each subaperture was not extended.

In summary, the selection of the subaperture images’ FOV is a trade-off between capturing enough structure in order to achieve a well defined cross-correlation function, and reducing the measurement noise of the WFS due to anisoplanatism to achieve the highest possible Strehl ratio.

3 Current and Future Research

3.1 Solar Multi-Conjugate Adaptive Optics

As already mentioned in the sections above, there are compelling scientific questions that, in order to be addressed, require observational data that contain high spatial resolution over a large FOV.

Two experimental solar MCAO systems have been implemented, since their inception by [2], with remarkable success at NSO’s DST[19] and the German VTT[3]. Both of these systems, even though certain aspects of the implementation differed significantly, were based on the same approach for wavefront sensing: A Shack-Hartmann WFS with a reduced number of subapertures of larger diameter (projected into the telescope pupil) creates images of the extended solar surface covering a large FOV. These large FOV Shack-Hartmann images are segmented further to provide the different off-axis sensing angles needed to profile the turbulence adequately. The number of off-axis angles can vary between 3 to about 20 for these systems, but is not limited per se and only depends on the resources available. In order to maintain on-axis performance of the system, a high-order Shack-Hartmann WFS incorporating a large number of subapertures senses wavefront aberrations on-axis. Typically, the calibration procedure of the systems involves measuring the response of the WFSs to movement of multiple DMs, one of which is conjugated to the telescope pupil, and the others to a predefined geometrical height above the telescope.
There are currently efforts under way to implement two systems based on these concepts for regular use at the GREGOR telescope [30] on Tenerife, Spain, and the New Solar Telescope [5] at Big Bear Lake, USA. Both systems will incorporate three DMs, two of which will be conjugated to the strongest turbulent layers located in the upper atmosphere. These systems have shown very good performance in the lab in the past [24], and are being deployed to the telescopes now. However, from Fig. 3 it becomes obvious that there are trade-offs when following this ‘star-oriented’ approach.

Figure 3 depicts the results of numerical simulations of a MCAO system that were performed with only two turbulent layers, one located in the pupil, and one located either at 3 km or 10 km above the telescope pupil. In the top row of Fig. 3, different WFS configurations are indicated: the two leftmost columns visualize the on-axis high-order WFS with $20 \times 20$ subapertures (left) together with a $12 \times 12$ subaperture WFS (right) for off-axis measurements; the two rightmost columns show the same high-order WFS for on-axis, but a low order $5 \times 5$ WFS for off-axis measurements. The row below shows the two quite different guide structure configurations. In the left column, the high-order on-axis WFS is depicted by a red dot. In this configuration, only 4 off-axis angles are measured, marked by four green squares in the graphic – with good sensitivity to aberrations containing high spatial frequencies in each off-axis direction. The configuration shown in the right column senses with far more (18) off-axis angles (purple diamonds) with low sensitivity to high spatial frequency aberrations in each off-axis direction, while using the same high-order on-axis WFS (red dot). The respective meta-pupil coverage is shown in the row below. The "4 off-axis guide region" configuration has adequate coverage at 3 km height, whereas the "18 off-axis guide region" configuration is highly redundant. However, at a geometrical height of 10 km height, it becomes clear that the meta-pupil coverage with four off-axis guide regions is sparse, while the alternate configuration shows good coverage of the meta-pupil.
This has an effect on the projected Strehl performance for each turbulence layer height scenario, which is shown in bottom row of Fig. 3. The four panels depict, on a color scale going from blue (poor Strehl) to red (high Strehl), the simulated, field-dependent performance of the two configurations, respectively for the high turbulent layer located at either 3 km or 10 km; the panels corresponding to the same turbulence layer height have been scaled to the same minimum and maximum value for both WFS configurations for better comparison. Each panel itself includes Strehl maps for different numbers of reconstructed and corrected Karhunen-Loeve modes for both the telescope pupil (low DM mode axis) and the meta-pupil (high DM mode axis). The performance of both configurations for the 3 km turbulence height scenario are quite similar, with slight advantages for the “4 off-axis guide region” configuration for uniformity of correction and Strehl ratio (in particular in the vicinity of the 4 off-axis guide regions). However, the situation is vastly different for a turbulence layer height of 10 km. The meta-pupil coverage has a significant effect on the performance of the system, in particular related to the uniformity of the correction – the “18 off-axis guide region” configuration has clear advantages here.

In summary, the results of the idealized simulation seen in Fig. 3 demonstrate qualitatively that there is very likely an optimal configuration for the number of off-axis angles in combination with the number of subapertures of the off-axis WFS, for a given turbulence layer height (and strength). This result poses a problem that is particular to solar MCAO observations as these systems will have to operate over a large range of elevation angles; new concepts for wavefront sensing are thus worthwhile exploring.

3.2 New Concepts for Extended FOV Correction

3.2.1 Layer Oriented Wavefront Sensing

An alternative to 'star-oriented' wavefront sensing is to attempt to measure the wavefront aberration contributions of each turbulent layer directly. This idea, 'layer-oriented' sensing, is attractive as it could solve many problems of MCAO systems – solar and night-time alike. Advantages of this approach include the capability to control each layer separately and independently, allowing for simple and effective optical as well as control loop optimization of the system.

In order to measure atmospheric turbulence layer-oriented for solar MCAO systems, [7] suggests to optically conjugate the lenslet arrays of typical extended source Shack-Hartmann WFSs to pre-selected turbulence layer heights. The idea is to use large FOV subaperture images for the WFSs conjugated to the high layers, and leverage the properties of the two-dimensional cross-correlation function to only keep aberrations common to each pixel (field angle) that must originate in the same turbulence layer, while suppressing the signal of non-common aberrations that are related to turbulent layer located in different heights.

This concept was showcased previously for solar ground-layer AO systems [20]. A Shack-Hartmann WFS in standard configuration (i.e. with a lenslet position that is optically conjugated to the telescope pupil), but using large FOV subimages, was used to measure aberrations introduced by ground-layer turbulence. These aberrations are common to all pixels in the image FOV; by averaging over a large subaperture FOV, the wavefront that best fits all field angles is measured and applied to the DM. The obvious advantage is that a homogeneous correction is achieved, at the cost of leaving aberrations contributed by turbulence layers located above the ground layer uncorrected. Overall, a ground layer AO will produce a Strehl homogeneously distributed over the FOV, with peak values lower than those achieved by standard high-order
AO systems, as numerical simulations show as well [12]. In [20], the corrected field was somewhat extended, however not to the expected degree. A theoretical computation shows that the 42×42 arcsec² FOV used in the experiment was not sufficient to completely remove contributions from turbulent layers above the ground layer [7], and a 5×5 arcmin² FOV is required.

The concept of wide-field wavefront sensing, while having only limited use at high-resolution solar telescopes such as ATST, could enable ground-layer AO and thus benefit future ground-based large synoptic telescopes, e.g. 'SPRING' [6], for which homogeneous spatial resolution is usually preferred over high Strehl ratios. For example, for a telescope aperture diameter $D = 0.5\text{ m}$, a 7×7 sub-aperture geometry is sufficient for an adequate correction. In order to achieve a well defined cross-correlation function peak, the solar surface structure must be resolved; a pixel size of 1 arcsec/pixel or better must be used. With a sub-aperture FOV of 5×5 arcmin², corresponding to 300×300 pixels², a 2k×2k pixels² imager, preferably operated with 2 kHz is needed; a sensor with these specifications is not easily available yet.

When attempting to apply the layer-oriented approach to layers other than the ground layer, optical constraints are incurred that are likely to severely impact the functionality of this ‘layer-oriented’ extended source Shack-Hartmann WFS. As mentioned in [7] in a side note, when conjugating the lenslet array to an optical conjugate other than the telescope pupil, vignetting becomes an issue in each subaperture image. The sketch in Fig. 4 (left) demonstrates the severity of the problem by use of a purely geometrical argument. Rays that pass through the lenslet array (here projected into the extended meta-pupil for illustration purposes) for different field angles will be vignettet by the telescope pupil itself, and only a (lenslet position dependent) part of the original solar scene will be visible within each subaperture camera image. As shown in Fig. 4 (right) this means that computing two dimensional cross-correlation functions between a pre-selected reference subaperture image, and any other subaperture image is likely to be subject to significant noise, because there is only little overlap between the images. The effect has been verified by both further numerical evaluation and an experiment at the Dunn Solar Telescope [14].

Fig. 4. Illustration of the issues associated with attempting to use an extended source Shack-Hartmann WFS with a lenslet array conjugated to a turbulence height other than the telescope pupil (left). Many incoming rays with angles corresponding to the extended FOV are not transferred through the telescope pupil (red), for lenslets not positioned near the optical axis. The subaperture images (right), computed with ray tracing for a lenslet optically conjugated to a height 2.5 km above the telescope pupil, further demonstrates the difficulty: in addition to the fact that there is vignetting making a cross-correlation of subapertures difficult, the ‘illuminated’ parts of the FOV will show different solar structure.
Optical wavefront differentiation is a further idea for layer-oriented extended source wavefront sensing that has been put forward in [31], and has been implemented in a prototype in the recent past [25]. The design is based on a focal plane mask approach; this mask is adapted to the scenery of the solar structure in the FOV of the WFS. Similar to a pyramid sensor, the mask illuminated by the solar scenery is re-imaged to sense the aberrations in the telescope pupil, or potentially other conjugate heights. While this approach is very promising in general, it appears to suffer somewhat from signal-to-noise ratio issues that are likely related to the low contrast of the solar structure at the focal plane, which is related to the wavefront signal in the pupil image of the sensor.

3.2.2 Combining AO with Image Post-processing Techniques

Post-processing techniques have been used frequently since the advent of digital processors [9, 8, 32]. However, the development of AO system have greatly pushed these techniques as well, starting with the fact that the input images for the post-processing techniques have higher quality and thus the algorithms produce better results. In particular for solar physics, combining solar AO corrected image data with post-processing techniques have proven to be a powerful tool to extend the high-spatial resolution to a larger FOV. Today, the most commonly used techniques to enhance solar observational data are a) deconvolution with point spread functions (PSF) computed from AO telemetry data [13], b) speckle image reconstruction using AO telemetry data for correct photometry [37], and c) multi-frame blind deconvolution (and derivatives) [28]. Each of these techniques are advantageous for certain observations.

AO PSF deconvolution for solar AO corrected data is heavily based on the work done by [29], with the adjustments for solar AO described in [13]. The technique is in particular useful for situations where the data has to be gathered using long exposure times, e.g. to achieve high spectroscopic or spectro-polarimetric accuracy. ATST will provide – at the full 2 kHz rate – AO telemetry data streams during ongoing observations to support the ability to post-process any data observed with an operating AO system at an off-site location. In particular fiber spectrograph image data can potentially benefit greatly from this reconstruction technique in the future.

In addition, ATST will provide the data handling software infrastructure to support analysis of the AO telemetry data on the fly to enable near real-time or even real-time data post-processing on the summit [4]. An example for post-processing algorithms capable of near real-time processing are based on speckle image reconstruction (e.g. [32]). This technique requires an ensemble of about 100 single, short exposed images of the same object that each freeze a statistically independent realization of the aberrations introduced by the instantaneous PSF. The majority of the algorithms use bispectrum analysis to compute a reconstructed image that is free of those aberrations that have zero mean in the ensemble, implying that static aberrations are not removed. As long as diffraction-limited information distributed over the FOV is captured in the majority of the short-exposed images, the technique is capable of achieving diffraction-limited spatial resolution over the full FOV in each reconstruction. The enhanced signal-to-noise ratio in each short exposed image due to a) the use of AO in combination with b) the large photon flux makes this particular technique very attractive for solar observations.

The ATST Visible Broadband Imager is a first-light imaging instrument for ATST that will make use of ATST’s infrastructure to compute reconstructed images in near real-time [35, 15, 34] (see Fig. 5 for the pipeline layout). It will use speckle imaging techniques to compute
reconstructed images in near real-time that have diffraction-limited spatial resolution over a large FOV using Graphics Processing Units. Photometric accuracy is maintained through the simultaneous analysis of the ATST AO data stream to compute the field-dependent speckle transfer function [36]. This has the benefits that a telescope operator will immediately have high spatial resolution images at his dispense for decision making, while the data volume that has to be transported to a permanent storage facility is significantly reduced. An example of the performance of the ATST VBI speckle imaging algorithms can be seen in Fig. 1.

3.3 AO Supported Observations of Solar Limb Structures

Ground-based observation of structures close to the solar limb has historically been of great scientific importance: they provide access to mapping the internal structure of features in the higher layers of the solar atmosphere such as the chromosphere and corona. Structures in these atmospheric regions can otherwise often only be studied with high spatial resolution using satellite data because in the visible and infrared wavelength regime they are often so dim that long exposure times are required to achieve an adequate signal-to-noise ratio, in particular for spectropolarimetric measurements (see e.g. [10]). This implies that in order to resolve the fine structure from ground, AO is needed to compensate atmospheric turbulence induced aberrations.

The main reason why this is difficult in general is the fact that these faint structures are hardly visible over the bright limb in continuum wavelengths, and filters with narrow bandpasses operating in absorption lines are required to image them accurately. While still an improvement over current systems that use the limb itself at continuum wavelengths and thus only correct in the direction perpendicular to the limb, employing these narrow filters reduces the photon flux per subaperture to a degree where only a low order correction is possible. In order to generate the necessary signal-to-noise per subaperture image for a well-defined cross-correlation function peak, the subaperture size projected into the pupil has to be increased while keeping the
pixel sampling constant. At the same time, the sensor read-out rate has to be decreased to a few hundred Hertz to allow for longer exposure times. Thus, a solar limb structure AO has problems that are very similar to – if not worse than – the issues when sensing using a star; for example, in this scenario low read-out noise wavefront sensor cameras become a requirement.

Recently, experiments were carried out at NSO’s Dunn Solar Telescope (DST) that demonstrate the ability to use chromospheric structures as seen in the Hα line core (at 656.3 nm) with a 0.05 nm bandpass for wavefront sensing [26]. Figure 6 shows a sample image of the structure in the wavefront sensor subaperture images, when using chromospheric features. In this example, the number of used subapertures has been reduced from the 76 commonly used at the DST, to 21 to increase the photon flux per subaperture. The images still show relatively low signal-to-noise ratio, and elongated structure, similar to those seen when sensing with laser guide stars. However, the structure does vary with different subapertures, still allowing the use of regular two-dimensional cross-correlation functions for unbiased wavefront gradient measurements. While these similarities are coincidence in this particular data set, chromospheric structures visible at the limb often show similar behavior.

Further advances in this area are highly desirable, and will provide a path forward for systems that can be implemented at large aperture solar telescopes.

4 Conclusions

In this contribution, we have presented the current state-of-the-art in solar AO, and pointed out what its perceived biggest challenges are when trying to support achieving the scientific goals of current and future extremely large aperture solar telescopes; ATST must be considered such a telescope. Many issues of solar AO have been addressed and benefited ATST in the sense that
the majority of the ATST HOAO could be based on current conventional solar AO systems that are in day-to-day use today.

Nevertheless, the science demands of future large aperture solar telescopes are pushing solar AO in several research directions, the most prominent one being to extend the corrected FOV to help increase the scientific output. Using an extended source for wavefront sensing with a Shack-Hartmann wavefront sensor is viable for solar MCAO, but also creates some challenges that make it attractive to continue to research alternate approaches to measure aberrations introduced by Earth’s turbulent atmosphere. On the other hand, post-processing technology combined with conventional AO corrected data produces good results today and should be pursued in parallel, to achieve the highest possible spatial resolution within the complete FOV represented in the data.

Large aperture solar telescopes are going to push the discovery space in particular related to chromospheric and coronal spectro-polarimetric measurements. To achieve the highest possible spatial resolution, solar AO needs to be capable of using structures near the solar limb for wavefront sensing. The necessary modifications result in photon starvation that cause challenges very similar to those incurred for night-time AO systems.

With ATST now progressing with its construction, further research on enhancing solar AO performance is progressing in the direction to support the most demanding science cases. At the same time, the conventional ATST HOAO system based on well known design and technology will ensure robust operation from the beginning so that many of the most significant science use cases can be addressed immediately.

References

12. J. Marino, Optical Engineering, 51(10), (2012), 101709
32. G. P. Weigelt, Optics Communications, 21, (1977), 55–59