

# Adaptive optics for meter-class telescopes

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## ABSTRACT

Adaptive optics (AO) is a powerful tool to enhance the performance of ground-based telescopes as assessed by measures of resolution, contrast, and sensitivity. We report results from several AO systems developed by HartSCI for telescopes in the 0.7–1 m size range that target objectives in both space domain awareness and astronomy. The data, comprising on-sky images as well as controlled bench-top tests of improvements in image quality and coupling efficiency into a single-mode fiber, quantify performance over a range of atmospheric seeing conditions and object brightness. Cost-effective AO systems are now available that substantially augment the capabilities of telescopes of this size.

## 1. BACKGROUND

Adaptive optics (AO) as a tool to enhance imaging performance is now ubiquitous on large telescopes, both for astronomy and space domain awareness (SDA). By reducing the blur induced by atmospheric turbulence, images are substantially sharpened. Image contrast and sensitivity to faint sources are also improved by the concentration of energy into a smaller solid angle in the focal plane. These performance enhancements are of direct benefit in supporting SDA objectives such as the detection and tracking of closely-spaced objects, improved fidelity in images of resolved objects, and detection of faint objects against a bright background. Furthermore, the tighter point-spread function (PSF) is of great value in improving the throughput of systems that couple the light into an optical fiber, for example for fiber-fed spectroscopy or free space optical communications (FSOC).

Historically, AO systems have been expensive. For that reason they are generally confined to large telescopes, and each one is a unique design. But substantial cost reductions have recently been realized in critical components such as deformable mirrors, fast cameras with low read noise for wavefront sensing, and high-speed computing. These advances have allowed the development of standardized AO system designs at a cost that makes them attractive for operators of smaller telescopes in the one meter class where the performance enhancement, while not as dramatic as on larger telescopes, is still of great value. The key quantity here is  $D/r_0$ , where  $D$  is the aperture diameter and  $r_0$  is the Fried length or atmospheric coherence scale. The larger this ratio, the more AO has to offer. The particular value, then, for meter-class telescopes is at shorter wavelengths in the visible and near infrared, where  $r_0$  is smaller than the bands typically addressed by AO.

AO is a core corporate capability of HartSCI. In this paper, we report on the performance of AO systems designed and deployed by the company for telescopes in the 0.7–1 m size range. We show data recorded with the ClearStar AO™ system deployed to one of the 70 cm PlaneWave Instruments CDK700 telescopes of the Miniature Exoplanet Radial Velocity Array (MINERVA) on Mt. Hopkins, Arizona. We also show test data from an AO system under construction for a 1 m telescope at the Starfire Optical Range (SOR) of the Air Force Research Laboratory (AFRL). We put these results in the context of the expanded SDA objectives that can be addressed by telescopes of comparable size, equipped with cost-effective AO systems, that may be deployed to sites around the world

## 2. AO SYSTEM DESIGN

The basic layout of an AO system, illustrated in Fig. 1, incorporates wavefront corrector elements, a wavefront sensor (WFS), and a computer. The computer's primary task is first to read the sensor, then compute and apply appropriate control signals to the correctors. In addition, a beam splitter in the optical path separates a portion of

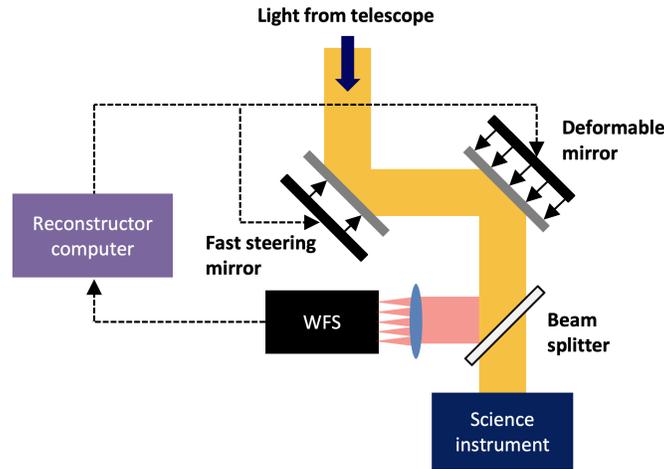


Fig. 1: The basic layout of an AO system that includes corrector elements, a wavefront sensor, a control computer to link the sensor with the corrector, and a beam splitter to separate light into the sensor and science channels.

the light from the main beam to illuminate the WFS. Other elements that may be included to address functional requirements include cameras for target acquisition, tracking, and scoring, as well as atmospheric dispersion correction (ADC) and components to accommodate laser guide stars.

HartSCI produces a range of image compensation systems that are unified by common software. The ClearStar AO system is a standard off-the-shelf product designed to deliver correction to the diffraction limit at wavelengths longward of 700 nm from telescopes of about 1 m aperture. To correct the wavefront it includes a Thorlabs DMP40 deformable mirror (DM) and a separate fast steering mirror (FSM). The WFS is a Shack-Hartmann type fed by a dichroic beam splitter with a cut at 700 nm. A built-in white light source and software functionality make the system fully self contained for calibration. Specifications are listed in Table 1. The system is shown in Fig. 2 mounted to the Nasmyth port of Telescope 4 of the MINERVA array, a PlaneWave Instruments CDK700 on Mt. Hopkins, Arizona. ClearStar AO is designed to support both imaging and fiber-fed applications; results and performance assessment from both modes of operation are presented below.

Table 1: ClearStar AO System Specifications

CHARACTERISTIC	SPECIFICATION
Correction speed	Up to 1000 updates per second
Wavefront sensor	$8 \times 8$ Shack-Hartmann
Actuator count	45
Full-stroke tip-tit control	$\pm 2$ arcmin on sky
Output focal ratio	$f/12$
External connectivity	Ethernet
Power draw	80 W
Weight	40 kg

## 2.1 Static and Non-Common Path Aberration

A key aspect of AO system calibration is the measurement and correction of static and non-common path aberrations. The former are aberrations in the optical train from imperfections of fabrication and alignment. The latter are aberrations that arise in optics downstream from the beam splitter in either the WFS arm or the science arm. Aberration in the WFS arm is measured by the WFS and duly applied to the DM even though it is not seen by the science instrument, and there is therefore no need to correct it. By contrast, aberration in the science arm is not seen by the WFS and therefore is not corrected even though it would be helpful to do so.

The solution is to measure these errors explicitly in the focal plane of the science arm and apply the results as offsets to the measured wavefronts. Our strategy for the measurement is an algorithm called the Eye Doctor [1] which iteratively

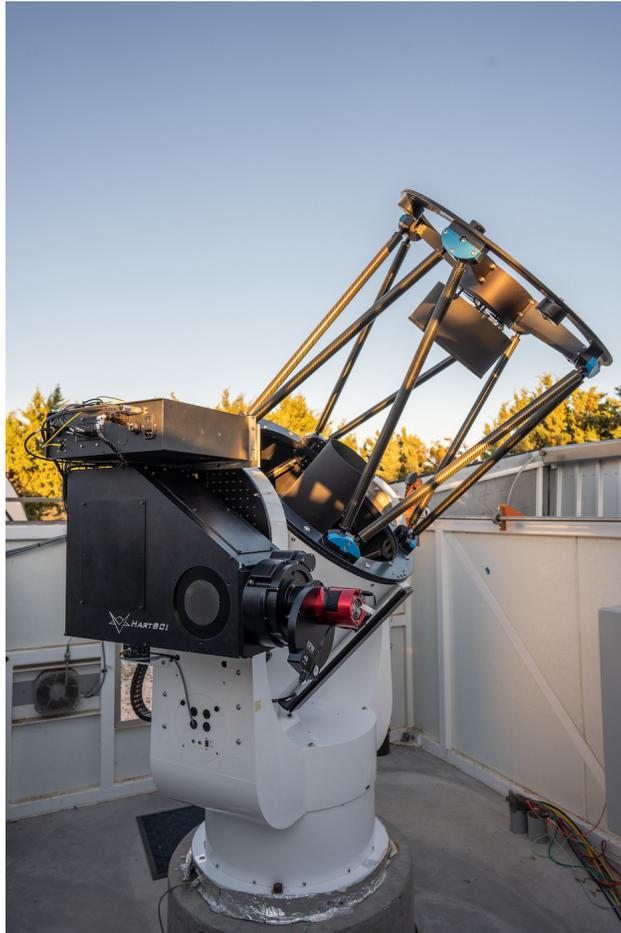


Fig. 2: The ClearStar AO system mounted on one of the Nasmyth ports of a PlaneWave Instruments CDK700 telescope. (Photograph courtesy M. Dieterich.)

applies modal commands to the DM and assesses the PSF on the system's scoring camera. This method can be used both with the built-in calibration source and with a star on sky. The success of this approach, which takes about 2 minutes to complete, is illustrated by the PSFs of Fig. 3. In this instance, the system was deliberately configured with substantial initial error on the DM as an explicit test of the algorithm's efficacy. Here, the Strehl ratio indicates a residual uncorrectable wavefront error in the entire system of about 80 nm rms.

## 2.2 Software

A critical aspect of the AO systems developed by HartSCI is that they are united by a common software base that is mature and robust. The system software is written primarily in C++, architected as a core base of functionality with modular interfaces to support a broad and extensible range of opto-mechanical hardware components such as cameras, DMs, optical flip mounts, and stages. Full-speed telemetry can be recorded at multiple points along the real-time processing chain from the WFS camera pixels through the commands issued to the DM and FSM. All the telemetry streams are written to a single time-stamped HDF5 file. DM control is effected with a set of modes orthonormal in the space of the WFS measurements that are tailored to the hardware of each specific AO system. During the calibration process, the modal influence functions on the WFS are measured and saved so that reconstructor matrices incorporating a specified number of modes can be built in real time. In this way, the number of controlled modes becomes a parameter that can be optimized to a particular observation in the same way as the loop gains, and can be changed on the fly in closed loop.

A web browser-based graphical user interface (GUI) can be run on any remote machine, Fig. 4, and all system functions can be accessed through a simple HTTP-based application programmers' interface (API). The API enables full

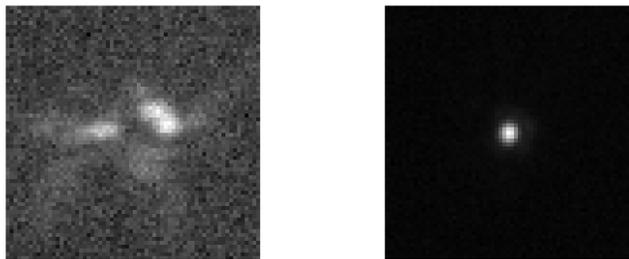


Fig. 3: PSFs measured with an internal calibration source before (left) and after (right) running the Eye Doctor algorithm to correct fixed and non-common path aberration.

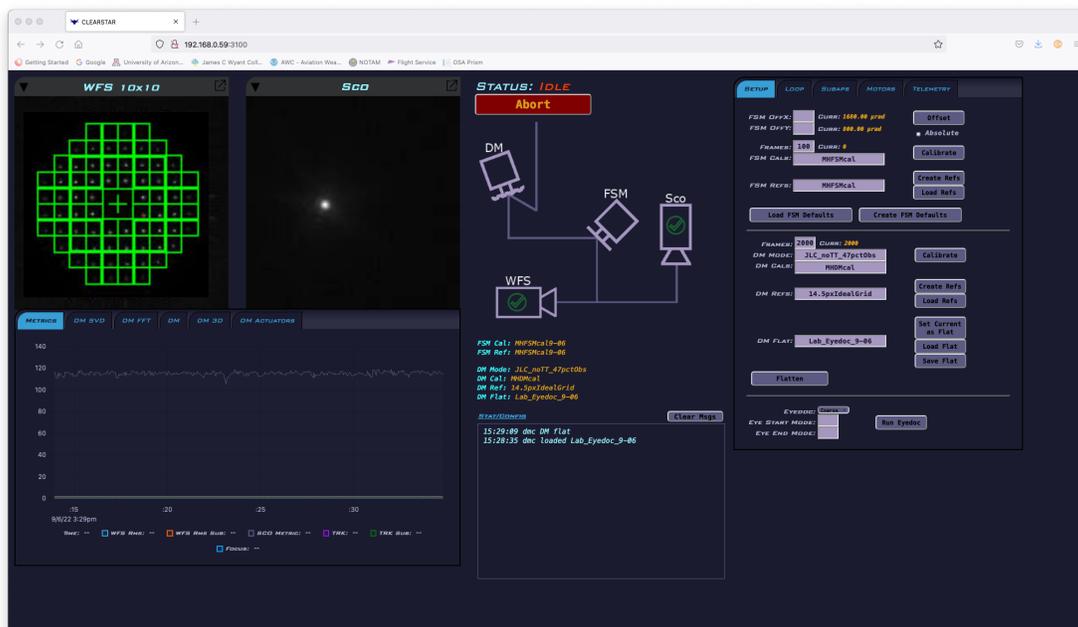


Fig. 4: AO system GUI screen. Live updates are displayed from the WFS and scoring cameras, along with multiple selectable diagnostic metrics, status information, and tabs that access all system functions.

automation and seamless integration into observatory control systems. One of the swappable software modules allows bidirectional communication with the telescope control system. This is necessary to support offload of accumulated tilt and focus error to the telescope, positioning of the AO system’s ADC prisms as a function of elevation angle, and if required, clock synchronization.

### 3. ON-SKY PERFORMANCE

The ClearStar AO system has been tested during night-time telescope runs at the MINERVA site during the first half of 2022. In a typical data collection, the system’s scoring camera was used to capture fast-framing images of stars with and without AO correction. A filter was placed in front of the camera with a center wavelength of 850 nm and a bandwidth of 25 nm. The reason for the relatively narrow band is that it allows a specific wavelength to be associated with the data which is useful both for photometric calibration and to quantify statistical characteristics of the wavefront aberration, in particular the spatial and temporal coherence scales  $r_0$  and  $\tau_0$ .

An example of the system’s performance is shown in Fig. 5. Images of the binary star  $\gamma$  Leonis were recorded in

natural seeing conditions of 1.3 arcsec. For this test, the primary component ( $m_V = 2.4$ ) was used for wavefront sensing at a rate of 1 kHz. The stars are separated by about 4 arcsec with a difference in brightness of  $\Delta m \approx 1.4$ . With correction, the image widths of both stars are reduced to 0.28 arcsec, almost at the diffraction limit of the 70 cm aperture. Furthermore, between the two 40 s integrations, the signal-to-noise ratio (SNR) for the secondary component is improved by a factor of 7. Since SNR increases only as the square root of integration time, this implies that the AO system reduces the time required to reach a chosen SNR value by a factor of 50.

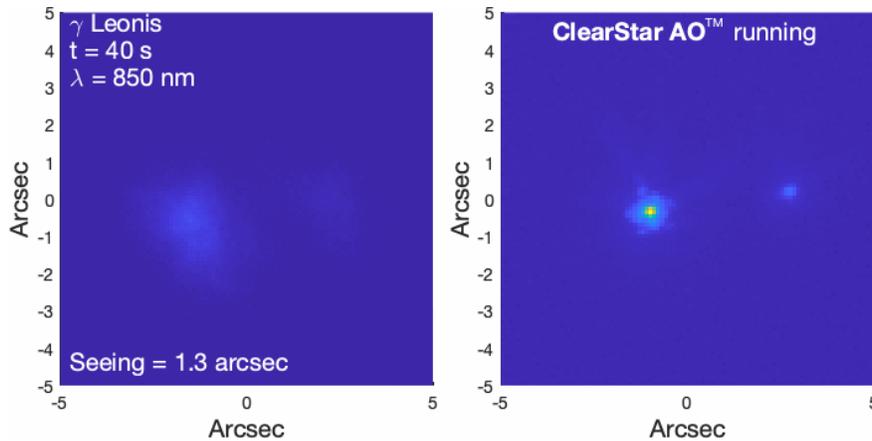


Fig. 5: Images of the 4 arcsec binary star  $\gamma$  Leonis recorded with and without AO correction at a wavelength of 850 nm. Natural seeing at the time was approximately 1.3 arcsec at the imaging wavelength. The AO system corrects this almost to the diffraction limit with a Strehl ratio of approximately 50%. The uncorrected image is shown on a  $2\times$  boosted color scale.

A useful way to quantify AO system performance is through the modulation transfer function (MTF). Observations of Vega under relatively poor seeing conditions for the Mt. Hopkins site are illustrated in Fig. 6. Image quality of 1.7 arcsec was improved by ClearStar AO to a resolution close to the diffraction limit with Strehl ratio of approximately 30%, and indeed the MTF computed from the image with AO running shows power out to the cut-off. By contrast, with AO off, the MTF disappears below the noise floor at a spatial frequency below  $0.3D/\lambda$ . For comparison, the MTF for a synthetic model of the CDK700 pupil is also shown, the characteristic plateau between  $0.3$  and  $0.7D/\lambda$  reflecting the 47% central obscuration of the telescope.

#### 4. BENCHTOP TESTING

Several AO systems for 1-m telescopes are in production now at HartSCI's facility, including a site at the SOR and the PlaneWave Instruments PW1000 telescopes at the Navy Precision Optical Interferometer (NPOI) outside Flagstaff, Arizona. Although those systems have yet to be deployed on sky, we report here the results of performance tests made in the laboratory with simulated atmospheric turbulence.

##### 4.1 Imaging

Critical to AO system assessment is the performance as a function of guide star brightness and the prevailing spatial and temporal coherence scales of the atmospheric aberration. Typically, performance is quantified either as residual wavefront error or as the Strehl ratio at a given wavelength. We have carried out tests of the SOR system to establish performance as a function of brightness,  $r_0$  and  $\tau_0$ . An example is shown in Fig. 7, where the plots trace the Strehl ratio for imaging at 850 nm for three different values of the Fried length, specified at the standard wavelength of 500 nm. At the same wavelength the coherence time in this instance was set to 3 ms. The solid lines show the results of modeling carried out in support of the program, and the correspondingly colored crosses show the results of measurements made in the simulator with the AO system's scoring camera. It is worth noting that under the more benign conditions modeled, with  $r_0 = 10$  cm, in the bright limit the total residual wavefront error is reduced to 100 nm rms.

This particular system includes a remotely-selectable choice of two lenslet arrays for the WFS, with  $10 \times 10$  and  $7 \times 7$  lenslets respectively across the pupil. Hence, the spatial sampling of the wavefront may be selected for optimal

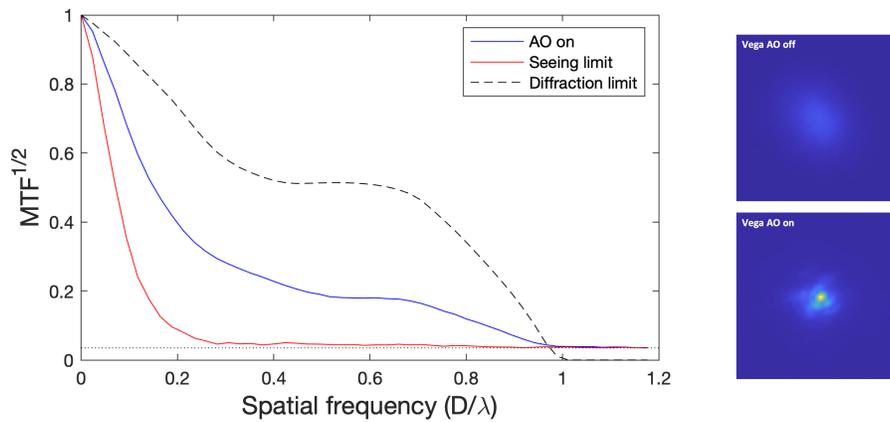


Fig. 6: Azimuthally-averaged MTFs computed from 2-minute integrations of Vega in seeing of 1.7 arcsec. The corresponding PSFs are also shown. A synthetic MTF, computed from a model of the CDK700 pupil, is shown as the upper dashed line. The dotted line shows the noise floor for the measurements. For clarity, the square root of the MTF is shown in all cases.

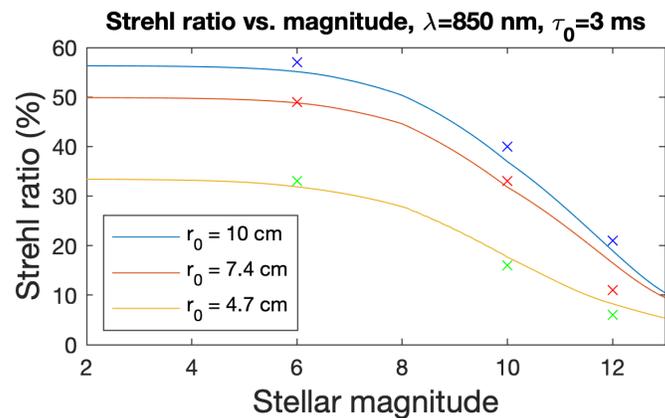


Fig. 7: Strehl ratio as a function of stellar brightness and Fried length. The curves show the results of modeling; the crosses show measured results from the 1 m system. (Imaging wavelength is 850 nm. Values of  $r_0$  and  $\tau_0$  are given for 500 nm.)

correction as well as the WFS integration time, loop gains, and the number of controlled modes in the reconstructor. While these parameters are currently set by hand, work is underway on software upgrades to automate all of them in real time on the basis of metrics computed from the AO system telemetry data.

#### 4.2 Single-Mode Fiber Coupling

As noted earlier, ClearStar AO is designed to feed an optical fiber as well as deliver an image. Fiber-fed instrumentation is generally used either for single-object spectroscopy or for FSOC. Both multi-mode and single-mode fibers may be used, depending on the application. Where possible, though, a single-mode fiber (SMF) is preferable to avoid mode noise which corrupts spectroscopic signals and makes coherent communication protocols extremely challenging.

The image of a point source, uncorrected by AO, is broken into a random and changing pattern of speckles. When projected onto the end of a SMF with the plate scale designed to match the telescope's diffraction limit to the mode field diameter, the coupling will vary dramatically as the speckle structure sweeps over the fiber tip. This is illustrated in Fig. 8 using synthetic PSFs computed from Kolmogorov phase screens. Not only will signal dropout occur any time a speckle does not happen to land on the fiber tip, but even when one does, it will still only couple in at most the fraction of total power in that single speckle. On the other hand, when the PSF is corrected to the diffraction limit by AO and the core is well aligned with the fiber tip, coupling efficiency is very substantially improved.

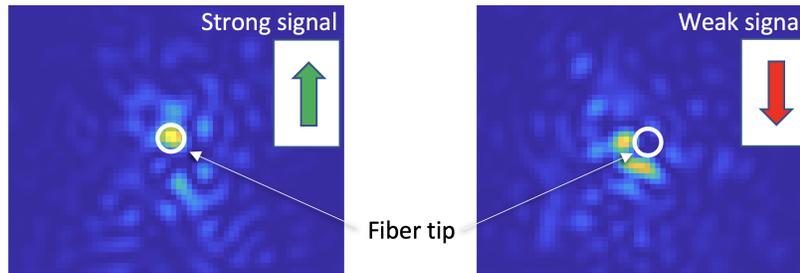


Fig. 8: Illustration of variable SMF coupling illuminated by a speckled PSF uncorrected by AO. The fiber tip, scaled to match the mode field to the speckle size, is shown as the white circle. When a random speckle happens to land on the fiber (left) coupling is high. Otherwise (right) little signal makes it into the fiber.

Fiber coupling tests have been carried out with the ClearStar AO system. The test setup modeled a 70 cm telescope. White light from a point source passed through the atmospheric simulator, the AO system with an 850 nm filter and the fiber feed unit to a SMF with 5  $\mu\text{m}$  mode field diameter. The photometric measurements used a fast-framing CMOS camera close coupled to the output of the fiber. The modeled seeing was about 2.5 arcsec; the long-exposure PSFs with and without correction in a focal plane conjugate to the fiber tip are shown in Fig. 9. The coupling enhancement is very encouraging, as shown in Fig. 10 which plots the ratio of the measured power to the power with the atmosphere simulator removed. The ratio therefore reflects only the effect of the atmospheric aberration, with and without AO correction. The values, recorded over two continuous but separate 60 s periods, are slightly conservative in that they do not account for losses in the simulator itself which is not perfectly transmissive. The mean gain with AO is a factor of 6.0 or 7.8 dB. Furthermore, AO greatly reduces the dropout rate when the signal drops below the noise floor.

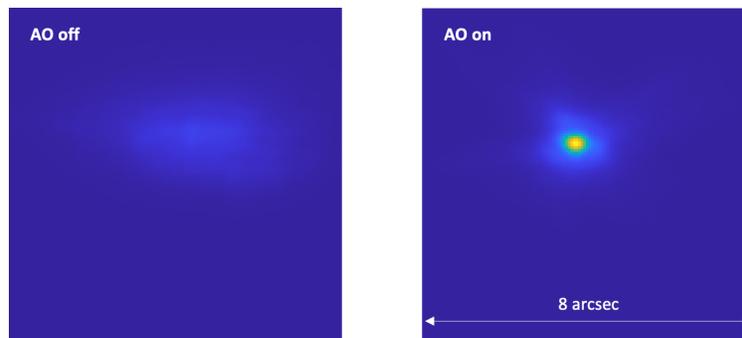


Fig. 9: Long-exposure PSFs measured by the ClearStar AO system's scoring camera under the same conditions as the SMF coupling in Fig. 10.

## 5. DISCUSSION AND VALUE TO SDA OBJECTIVES

The development of AO over the past 60 years has benefitted enormously from a symbiosis between two communities. Invented by an astronomer [2], the technique was first fully put into practice by AFRL, who then released their innovations back to the astronomers [3]. Further advances aimed at studying the most distant sources in the Universe with the world's biggest telescopes are now available to support the mission of the Air Force and Space Force. Meanwhile, progress continues in both communities, with opportunity to bring the advances to bear on priorities in SDA.

The prevailing paradigm amongst both DoD and astronomical communities is that each AO system be uniquely tailored to the target telescope and mission. This approach may be necessary for the ultimate in performance; however, our increasing reliance on space-based assets at the same time that space is becoming more congested and polluted demands a greater investment in SDA. This is leading to the deployment of world-wide networks of small to mid-size telescopes (see, for example, Ref. [4]). The demand for data products from these networks demonstrates their intelligence value, which as we note below could nonetheless be substantially improved with the addition of AO. A

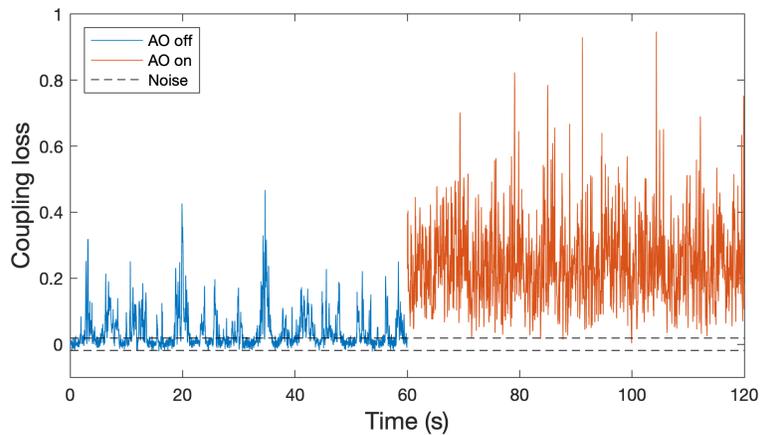


Fig. 10: Measured coupling efficiency into a SMF at 850 nm with and without AO correction, shown as a fraction of the power transmitted with no atmospheric aberration. The dashed black lines are drawn at  $\pm 1$  standard deviation of the noise in the power measurement.

low-cost standardized off-the-shelf solution is essential for such applications. They cannot each be a ‘science project’. These considerations have motivated HartSCI to develop the ClearStar AO system, and others currently in production.

The primary utility of the AO technology in supporting SDA rests on three ways in which AO, by compressing the PSF, improves image quality:

1. Higher angular resolution;
2. Higher point-source sensitivity;
3. Improved contrast in the vicinity of bright objects.

Each of these can be exploited in support of SDA objectives. For satellites in low earth orbit (LEO) and medium earth orbit (MEO), high resolution imaging enables change detection on smaller scales, improved capability assessment through more precise identification of external features and subsystems, and better health monitoring with more detailed information on system configuration. Even at GEO and higher orbits, where better resolution is of much less value because of the diffraction limit, the improved contrast enabled by AO allows the detection of potentially threatening CSOs by reducing the photon noise from scattered light in the vicinity of the primary spacecraft. The reduction in PSF width improves the telescope’s sensitivity to the CSO because the noise background against which the CSO must be detected is substantially reduced. Hence, for any given telescope, smaller CSOs may be detected at closer range with the aid of the AO system than in the natural seeing limit imposed by the atmosphere.

AO also delivers higher sensitivity to unresolved objects because the object light is seen against less background. This is of particular value during daylight data collection when very high shot noise overwhelms faint signals. Hence, daytime AO observations can extend custody and orbit determination to fainter, smaller space objects.

## 6. CONCLUSIONS

The increasing crowding of the space environment, particularly but certainly not exclusively in LEO, and the exploitation of orbits well beyond GEO call for a substantial enhancement of precision SDA capabilities, both in quantity and quality. In this context, ‘precision’ means a fine knowledge of how much light came from an object, from where, and when. To be of value, photometry, astrometry, spectrometry, and polarimetric analysis all depend on that knowledge.

For reasons of cost, much of the new SDA capacity in the EO/IR bands will likely continue to rely on ground-based assets, and atmospheric turbulence will continue to blur information that might otherwise have been extracted. AO as a technology can mitigate that loss and deliver more precise knowledge through sharper PSFs, with higher contrast and SNR, and down to fainter magnitude limits.

AO is not a panacea. Its corrected field of view is limited and it requires a beacon of light on the far side of the turbulence to be sensed. Yet despite its clear value to SDA, the primary reason impeding the broad acceptance of AO on telescopes smaller than the flagship sites operated by AFRL at the SOR and Maui is that the cost has historically been out of reach. Both the initial expense and the longer term cost of ownership have been high, the latter driven by the need for expert human supervision to run and maintain the systems. That paradigm has now shifted, thanks to advances in AO component technology, process automation, and control software. For the first time, high-order AO systems can be made as high-end consumer products. In this sense, AO is catching up with the telescopes whose capabilities they enhance; apertures up to 1.5 m are now available as standardized off-the-shelf items, and it is likely that even larger telescopes will shortly be commercially available. In combination, these telescopes equipped with AO offer a new cost-effective source for expanded and precise space domain awareness.

## 7. ACKNOWLEDGEMENTS

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