ADVANCEMENT OF AO TECHNOLOGY FOR THE NEXT GENERATION OF EXTREMELY LARGE TELESCOPES

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Abstract. Micro-electro mechanical devices (MEMS) deformable mirrors offer a compact and affordable path to complex next generation AO instruments on large telescopes. In this presentation we discuss the motivators and challenges of next generation AO and describe our plans and experimental progress on two MEMS-based AO systems: the high-contrast Gemini Planet Imager, the ShaneAO laser guidestar system, and the proposed Keck Next Generation AO system.

1. INTRODUCTION

The first generation of laser guidestar adaptive optics systems reaped a huge advantage in both image resolution and sensitivity using a single guidestar and with wavefront correction optimized for near-infrared science bands. Although newer technology can now promise systems that achieve higher Strehl and AO correct into shorter science bands, the payoff of increased object sensitivity per unit system complexity is not so obvious. Yet, science observers definitely want the new generation high-Strehl systems. The traditional design metric, sensitivity, or exposure time to a given signal-to-noise (“speed”), is not the whole picture for AO therefore. There is also a premium given to the resolving power, e.g. increased star counts in crowded fields, finer details in galaxies, and other “resolved object” information, that form part of the story.

First, let’s cover the key design choices, the technologies available, and show how they impact the system performance as we move forward to 1) larger aperture telescopes (ELTs > 10m diameter at the primary) and 2) shorter wavelength AO-corrected science bands.

1.1 Large Aperture Telescopes

The larger telescope aperture area of course demands deformable mirrors with high actuator count, a count that scales with area. Furthermore, more deformable mirrors are required in order to extend the field of view of the AO correction. An important consideration also is that,

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as the aperture diameter is increased, the stroke (dynamic range) required of the DM actuators increases, in proportion to $D^{5/6}$.

With larger apertures the cone beam of a single laser guidestar is insufficient and becomes the dominant contributor to wavefront measurement error unless supplemented by an array of guidestars. These need to be positioned at roughly 2x isoplanatic angle (θ_0) spacing over the field of sky traversed by the cylinder of natural star rays intercepted by the telescope, and even wider if the objective is to have a field of view greater than θ_0.

1.2 AO for the Visible Bands

Visible band (or, let's say, shorter than J band) science observing places a similar demand of DM actuator count, this time with the actuator spacing scaling according to $r_0 \sim \lambda^{-6/5}$. The guide star count, going as $(1/\theta_0)^2$ will similarly scale up, since $\theta_0 \sim \lambda^{-6/5}$.

As well, there is increased demand for precision throughout the optical system and many error budget terms that were previously negligible become important to manage carefully: calibration error, non-common path error, flexure, and drifts with temperature.

2. PERFORMANCE METRICS

2.1 Speed

One metric we think is most often used, implicitly or explicitly, in assessing a general-purpose AO system's performance is speed, which is 1/ the amount of time needed to achieve a given signal-to-noise (SNR) on a given brightness unresolved science object (star). This quantity depends on a number of factors including the object brightness and color, sky background, science detector (read noise and dark current), AO system Strehl, seeing, science wavelength band, optical throughput, thermal emission, etc. A calculation spreadsheet is available from the author. Signal-to-noise is calculated only in the region of sky where there is signal, i.e. in the diffraction-limited Airy core when AO corrected and in the seeing disk without AO. The metric highlights the advantage of AO which sharpens stars making them detectable above the diffuse background.

Figure 1 plots speed (time to reach SNR=5 on an m_V=30 A star) in seconds, versus telescope diameter, assuming we increase the number of DM actuators (degrees of freedom) in proportion to telescope area (constant sampling). Curves for H band and V band science are shown with cases AO is used (Strehl subject to best-fit by DM) and AO is not used (Strehl is set by uncorrected seeing). The speed obviously increases dramatically with increasing telescope diameter. However the surprising thing to notice however is the impact of adding AO. While there is a dramatic AO improvement for H band science, there is almost no gain in speed for V band science. It's not as though the system weren't designed to work in V band. In this example the actuator spacing is 10 cm, roughly r_0 in V, and the V band Strehl is 78%. Instead, the dominating issue is that the background noise from thermal emission is much higher in H than in V, so reducing the solid angle to the diffraction-limit produces a huge reduction in noise while there is hardly any thermal noise improvement in reducing the V band solid angle.

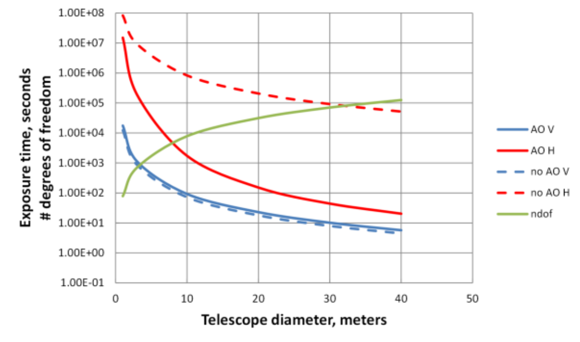

Figure 1. Exposure time to a given SNR as a function of telescope diameter and science band, with and without AO. "Signal" is counted in the diffraction-limited core (AO case) or seeing disk (no AO case). Noise is a combination of background, thermal emission, dark current and read noise, with backgrounds and emission counted only in the pixel region of the signal photons. Assumptions are r_0 = actuator spacing = 10 cm, warm fore-optics, throughput = 50%.

2.2 Speed Resolution Product

So does AO correction in the V band produce any science advantage? Certainly a major advantage is the fact that multiple closely-spaced objects, or the structure of galaxies, can be resolved at scales that the seeing disk would otherwise blur out. This advantage increases at shorter wavelengths and larger apertures because the diffraction-limit gets smaller. To capture this advantage in a metric, we propose a factor that rewards resolution. The metric relative to no AO becomes

$$I = \left(\frac{\tau_{noAO}}{\tau_{withAO}}\right)\left(\frac{\theta_{seeing}}{\theta_{DL}}\right)^2 \tag{1}$$

where τ is the exposure time to a given SNR and θ is the size of the science object. The new factor is monotonic in the number of separate patches of field on sky resolvable by AO that are otherwise blurred into one by the uncorrected seeing. It has a minimum value of 1, when the AO correction is no better than seeing (telescope diameter = r0).

With the new metric, V band science with AO becomes more appealing (Figure 2).

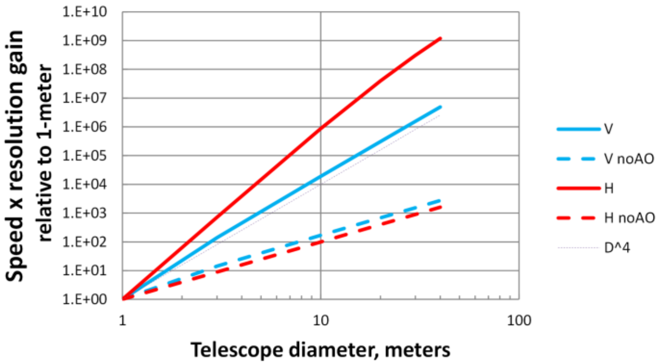

Figure 2. Speed-Resolution product to a given SNR as a function of telescope diameter and science band, under the same conditions as Figure 1. The fine dashed line is D^4 which is often stated as the science improvement scaling law for AO.

3. SCALES OF COMPLEXITY

These wonderful science gains come at the expense of tougher, or at least expensive engineering that scales up with telescope diameter (down with wavelength), sometimes quite unfavorably. We can look at our high-ticket items mentioned earlier: degrees of freedom and lasers.

3.1 Degrees of Freedom

Increased degrees of freedom map into 1) more actuators on the deformable mirror, 2) more pixels in the wavefront sensor, and 3) more real-time computations needed. #1 and #2 scale with telescope area and inversely with wavelength. Computations, naively scaling matrix-multiply algorithms, scale roughly with the square of these and cleverer algorithms such as Fourier domain techniques scale more favorably, but never less than proportionally.

Figure 3 shows the scaling of number of actuators with telescope size and wavelength band. We assume that the sampling is good for imaging at the given band, i.e. actuator spacing equals r0. Infrared science systems on 30-emeter+ ELTs will need on the order of 10,000 actuators. Visible science systems need an order of magnitude more.

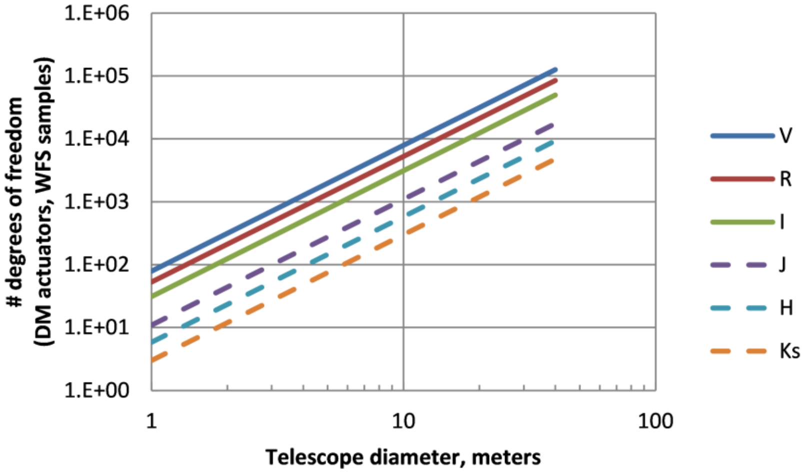

Figure 3. Degrees of freedom needed for AO systems with constant sampling versus telescope diameter and science wave band. The assumption is sampling is done at r_0.

3.2 Lasers

As mentioned earlier, approximately one guidestar is need per isoplanatic patch, leading to a quidestar spacing of $2\theta_0$. Figure 4 shows the number of guidestars versus telescope diameter and wavelength band. ELT systems will need on the order of 10 guidestars to capture a 4 arcminute field, while visible systems are heading for nearly 100. Clearly a breakthrough is needed to properly probe the sky with lasers in the visible as scaling the number of high power lasers, associated wavefront sensor and overall system complexity seems daunting. A suggestion might be to create a grid of guidestars with an interference pattern from one powerful laser. A clever means of combining and sensing the guidestars with a minimum amount of optomechanical hardware would also need to be developed.

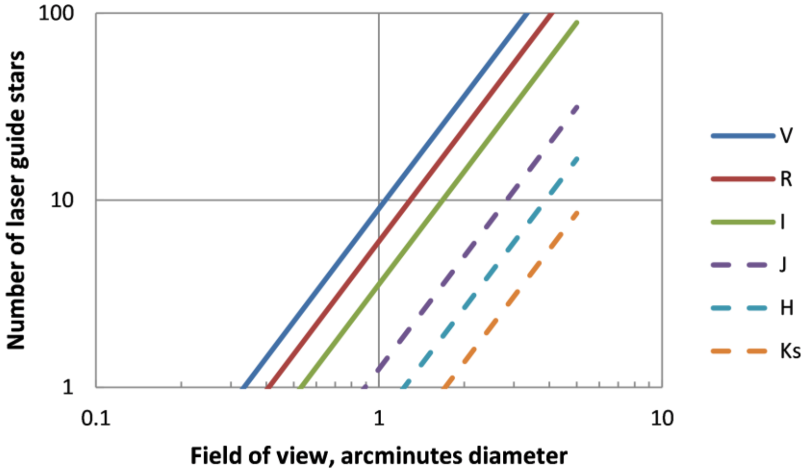

Figure 4. Number of guidestars needed for AO systems versus telescope diameter and science wave band. The assumption is sampling is done at θ_0.

4. AO SYSTEMS

The following is a brief description of two next generation systems, one for the 3-meter telescope at Lick Observatory and one for the 10-meter telescope at Keck Observatory. These are both examples of the press toward shorter wavelengths. Each of these systems will employ MEMs technology for high degree of freedom wavefront correction and new lasers that are designed for maximum return efficiency from the sodium layer.

4.1 Lick Observatory ShaneAO

At Lick Observatory, we are constructing a second generation AO system that incorporates some of the new technology vectoring towards visible laser guidestar AO. While not on a large telescope, it will use a MEMs deformable mirror that samples the aperture for V band science (d=10cm actuator spacing). The wavefront sampling (sensing and control) are adjustable for optimization of the science gain for a given wavelength band and to cover a range of laser or natural guidestar return signal.

A new guidestar laser system is included in the design. This laser, developed at Lawrence Livermore National Laboratory, is based on a highly promising fiber amplifier technology and has a pulse and spectral format that is designed to optimize guidestar return efficiency.

The effort is an outgrowth of efforts with the Villages system which was a pathfinder for MEMs astronomy application on a 1-meter telescope [1].

The opto-mechanical design (Figure 5) has a dual pupil relay, the first containing a woofer deformable mirror with 52 actuators and the second containing a 1024 actuator MEMs mirror. The first relay passes a 2 arcminute field that allows for the selection of a tip/tilt star. This star will be partially corrected by the woofer. The second relay passes a 40 arcsecond diameter field into an infrared science detector.

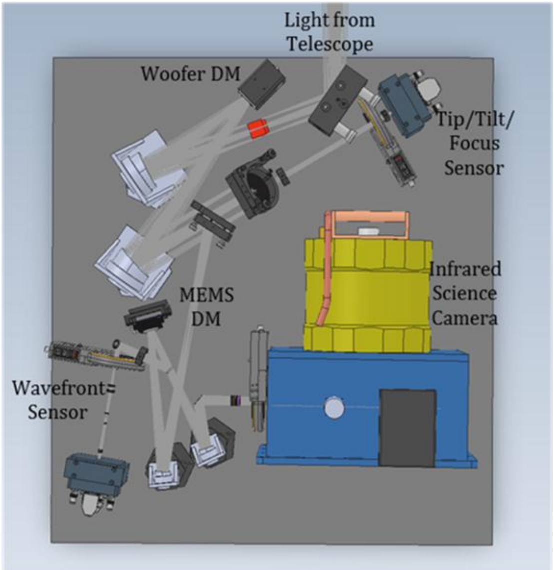

Figure 5. CAD layout of the key elements of the new ShaneAO system for Lick Observatory.

4.2 Keck Observatory NGAO

The Keck Observatory has been exploring a concept for a multiple guidestar AO system which would significantly increase the Strehl performance and expand science into the longer visible bands [2]. The multiple guidestars (4 in the design) provide the sensing needed to improve on the most significant error contributor in the current single-guidestar system: cone effect. The wavefront correction system is also a woofer-tweeter design, with the woofer being roughly 350 actuators (d~ 60 cm) and the tweeter having roughly 3200 actuators in the illuminated pupil. The woofer corrects low-order modes at high stroke and does the bulk of the correction over a 120 arcsecond wide field that can capture several tip/tilt stars. The tip/tilt stars are then further corrected with 1000-actuator MEMs mirrors (about 800 in the pupil) to produce sharp images of them. The tip/tilt star sharpening enables dimmer stars to be used which two advantages: 1) more stars are available and 2) they consequently can be located closer to the science object to reduce tilt anisoplanatism. The net result is a system that has high performance with acceptable high sky coverage.

The Keck Next Generation AO (NGAO) is on hold for the moment pending a funding source for full scale implementation. The project has completed the preliminary design phase. In the meantime, the NSF has funded an effort to add an infrared tip/tilt sensor to the present AO system. This sensor should increase the sky coverage since it can take advantage of tip/tilt star sharpening as well as use stars in dust obscured regions.

5. SUMMARY

In this paper we have considered the advancement of AO in the direction of large aperture telescopes and shorter wavelength science bands. The technology and complexity are indeed daunting at ELT sizes for V band AO science. We presented a simple metric, the speed-resolution product, that attempts to capture the motivators for short wavelength astronomical AO, but we are clearly past the sweet spot where reduction of the thermal emission background noise under a smaller PSF has a high payoff in IR bands. We then briefly summarized the efforts on second generation systems at Lick and Keck Observatory, which will utilize the latest advancements in deformable mirror and laser technology.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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