High-contrast observation potential of the Palomar Adaptive Optics System (PALAO)

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Introduction

Developed by Jet Propulsion Laboratory for Caltech, the Palomar Adaptive Optics System (PALAO) system[1-6] is a 241 active actuator, facility-class, user instrument designed to conduct both forefront science and development of advanced adaptive optics techniques at the 5m diameter Hale Telescope .

The scientific potential of the PALAO system is realized through observations taken with a dedicated near infrared science camera. The Palomar High Angular Resolution Observer[7], or PHARO, is based upon a 1024x1024 HgCdTe array and possesses plate scales of 0.025 arcsec and 0.040 arcsec per pixel. PHARO also possesses a slit spectroscopic mode with two grisms providing two resolution modes, R>1000 in J, H, or K band, and R = 100-200 across J, H, and K simultaneously.

High-contrast AO observations

PALAO, in its initial configuration, is ideally suited for high contrast imaging and spectroscopy of bright astronomical objects. The detection and investigation of faint companions to bright stars requires that the atmospheric wavefront be corrected to the highest possible degree. This is because all AO systems can, due to various error sources, perform at best only partial correction of the incident wavefront. The corrected portion of the wavefront forms a tight core of diffraction-limited width, but this core is unavoidably surrounded by a halo of light extending out to a radius commensurate with that occurring in an uncorrected long-exposure image. The ratio of the corrected core irradiance to the irradiance expected with a perfect image is know as the Strehl ratio and is given by,

$$Strehl\ ratio = SR = e^{-\sigma^2}$$

where σ is the rms residual wavefront error after correction, in units of radians of optical path error. The Strehl ratio is a measure of the quality of wavefront correction, with a SR=1 corresponding to perfect correction.

The importance of both high Strehl ratio and large telescope diameter to high contrast imaging is demonstrated in the following Figure. Represented is a typical scenario of imaging a faint astronomical object near a bright one. The situation on the left corresponds to a modest Strehl ratio, while that on the right corresponds to high Strehl.

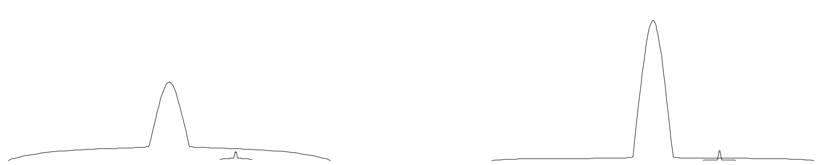

Figure 1. Adaptive optics corrected images of a faint companion in the presence of a bright astronomical source for left) moderate Strehl ratio, and right) high Strehl ratio.

Thus, within the regime bounded by the image core (typically 0.025-0.100 arcsec) and the extent of the halo (0.25-1.5 arcsec), the goal of high-contrast AO is to suppress the irradiance of the halo, while increasing the irradiance of the core. The contrast ratio between the faint object and the halo of the bright object, improves with both increasing Strehl and decreasing core diameter. Assuming pixel sampling matched to the FWHM of the image core, it can be shown that the contrast ratio between a faint companion and the halo of a bright primary is given by,

$$Contrast \quad ratio = \frac{SR}{(1 - SR)} * \left(\frac{D}{r_0} \right)^2$$

In order to achieve high Strehl, an AO system must correct the wavefront well. The primary limitations to how well an AO system can correct the wavefront can be tabulated into a performance error budget. The leading terms of the error budget for the case of observations of bright guide objects are shown for the Keck and Palomar AO systems in the Table below. Fitting error is an AO system's inability to correct atmospheric phase errors with spatial scales smaller than the deformable mirror actuator spacing. Bandwidth error is the error due to the finite lag of AO servo in the presence of an ever-changing atmosphere. These first two errors depend upon the assumptions one makes regarding the seeing conditions at the telescope site. For this comparison, we have selected three various conditions, corresponding to good conditions, median conditions, and poor conditions at Mauna Kea and Palomar Mountain. To describe these various conditions we use Fried's parameter, r0, for 0.55 um wavelength, and scale this value of r0 to the appropriate wavelength band of interest. For Keck, r0 values of 0.4m, 0.18m, and 0.066m correspond to seeing disk diameters of 0.28 arcsec, 0.63 arcsec, and 1.7 arcsec respectively, while at Palomar, we use r0 values of 0.30m, 0.10m, and 0.03m, corresponding to 0.33 arcsec, 1.0 arcsec, and 3 arcsec respectively. At Palomar 0.33 arcsec seeing (static telescope errors assumed corrected) occurs less than 5% of the time, but is regularly observed.

Error term (nm rms)	Keck 10m AO (r0 = 0.4,0.18,0.066m) good/median/poor seeing	Palomar 5m AO (r0 = 0.34,0.09,0.038m) good/median/poor seeing
Fitting error	63/123/285	40/125/255
Bandwidth	11/36/90	12/65/143
Calibration	30	30
Internal	20	20
Telescope	105	20
Science Instr.	35	35
Total RMS (nm)	133/173/321	68/151/297
Strehl @ 0.5um	0.06/0.01/0.00	0.48/0.03/0.00
Strehl @ 1.0um	0.50/0.30/0.02	0.83/0.41/0.03
Strehl @ 2.2um	0.87/0.78/0.43	0.96/0.83/0.49
Contrast increase (1.0um, good seeing)	625	1055
Contrast benefit @ 0.5um		5.0/3.1/NA
Contrast benefit @ 1.0um		1.7/1.6/1.1
Contrast benefit @ 2.2um		1.2/1.4/1.0

Table 1. Comparison of error budget terms for the Keck and Palomar AO systems. Because PALAO enjoys lower fitting error (due to higher actuator density) and lower telescope errors (due to its monolithic

primary), higher Strehl ratios are possible despite poorer seeing conditions. For most observations in good seeing, Palomar enjoys comparably high contrast to Keck AO. In the best seeing conditions at visible wavelengths, Palomar AO enjoys a substantial advantage in contrast ratio between a faint object and the residual halo surrounding a nearby bright object.

Calibration error is the error due to one's inability to provide a truly flat reference wavefront during calibration. Internal errors are various errors within the system such as alignment errors that are not corrected by the AO loop. Telescope errors arise from two sources. First, similar, to fitting error, the telescope always contains small errors on scales too small to correct with finite actuator spacing. In the case of a segmented primary, there are additional error sources due to segment vibrations, stacking errors, and several other sources.

Conclusion

Because it enjoys a higher actuator density than the Keck AO system, PALAO will correct an incident wavefront on finer spatial scales, thus reducing fitting error. Furthermore, compared to the wavefront errors induced by the segmented Keck primary mirror, PALAO enjoys substantially reduced telescope error. This combination more than compensates for the generally poorer seeing conditions at Palomar Mountain, relative to Mauna Kea. The result is potentially higher Strehl ratios and operation to shorter wavelengths. The higher Strehl is particularly advantageous in observing objects that would normally be obscured by the bright objects halo. As summarized in the preceding Table, under the best seeing conditions at both Palomar and Keck in the visible, PALAO exhibits an advantage in contrast compared to Keck AO.

Thus, although the 10m diameter Keck telescope enjoys a factor of two sharper diffraction-limited resolution than the 5m Palomar telescope, for the same wavelength, PALAO's superior control over the wavefront allows Palomar to operate to the same Strehl ratio at shorter wavelengths, resulting in comparable limits in resolution (approx. 0.020 arcsec).

References

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