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Performance of Keck Adaptive Optics with Sodium Laser Guide Stars

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The Keck telescope adaptive optics system is designed to optimize performance in the 1 to 3 micron region of observation wavelengths (J, H, and K astronomical bands). The system uses a 349 degree of freedom deformable mirror, so that the interactuator spacing is 56 cm as mapped onto the 10 meter aperture. 56 cm is roughly equal to r0 at 1.4 microns, which implies the wavefront fitting error is 0.52 $(\lambda/2\pi)(d/r_0)^{5/6} =$ 118 nm rms. This is sufficient to produce a system Strehl of 0.74 at 1.4 microns if all other sources of error are negligible, which would be the case with a bright natural guidestar and very high control bandwidth. Other errors associated with the adaptive optics system will however contribute to Strehl degradation, namely, servo bandwidth error due to inability to reject all temporal frequencies of the aberrated wavefront, wavefront measurement error due to finite signal-to-noise ratio in the wavefront sensor, and, in the case of a laser guidestar, the so-called cone effect where rays from the guidestar beacon fail to sample some of the upper atmosphere turbulence. Cone effect is mitigated considerably by the use of the very high altitude sodium layer guidestar (90 km altitude), as opposed to Rayleigh beacons at 20 km. However, considering the Keck telescope's large aperture, this is still the dominating wavefront error contributor in the current adaptive optics system design.

The laser guidestar brightness and the servo bandwidth are specifically chosen so as to make them not the dominant sources of error. For example, with the 20 watt sodium laser beacon, the return signal is predicted to be greater than 0.3 photons/second/ms/cm^2 at the telescope aperture, which gives a signal-to-noise of 10 per subaperture per frame at 1000 Hz readout rate. Measurement error is less than 100 nm (Strehl ¿ 0.78 at 1.2 microns) at this signal level, and less than 50 nm if a 500 Hz readout rate is used. Similarly, the computer system is sufficiently powerful to run the 349 channel control loop with disturbance rejection bandwidth up to 100 Hz. The servo error is 30 nm (Strehl = 0.97 at 1.2 microns) at 100 Hz bandwidth and 50 nm at 50 Hz bandwidth, assuming a typical Greenwood frequency of 20 Hz at $\lambda = 1.2\ \mu m$.

Table 1 summarizes the current Keck error budget. Analysis is based on the formulas presented in reference [1], and follows the the work of Fried, Greenwood, Tyler, and others, [2-5]. The table assumes that the seeing is typical for Mauna Kea, $r_0 = 20$ cm, $f_g = 50$ Hz at $\lambda = 0.55\ \mu m$, and that the servo bandwidth has been adjusted to minimize the total rms wavefront error. The optimum bandwidth, in this case 57 Hz, is the result of a trade between servo bandwidth and the signal-to-noise ratio. Incidentally, bandwidth optimization can occur on-line as the seeing conditions vary simply by changing parameters in the controller software. Also shown in Table 1 is the budget for a hypothetical 900 degree-of-freedom system with three 20 Watt laser guide stars, which is the next logical upgrade in the direction of visible wavelength correction. The graph in Figure 1 shows the Strehl performance versus wavelength in the current and upgrade designs.

Table 1. Performance error budget for Keck adaptive optics system

Error Source	1 LGS, 349 DOF	3 LGS, 900 DOF
DM Fitting	115 nm	69 nm
Cone Effect	127 nm	80 nm
WF Measurement SNR	50 nm	50 nm
Servo Bandwidth	46 nm	49 nm
Total rms	184 nm	126 nm

The servo system has been designed to be an insubstantial source of wavefront error relative to fitting error and cone effect. This is accomplished by providing enough compute power for the 349 channel controller to operate at high bandwidth, and by carefully designing the compensation algorithms so as to best mimic

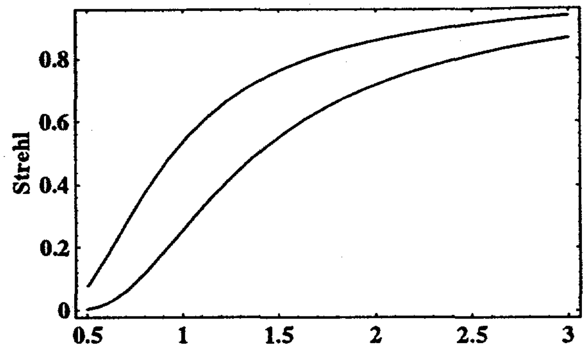

Figure 1. Strehl versus wavelength for the Keck laser guidestar adaptive optics system. Bottom: current design with one laser guidestar. Top: upgraded system with 3 laser guidestars.

the ideal servo assumed in the scaling law formula for rms servo error:

$$\sigma_{servo} = \frac{\lambda}{2\pi}\left(\frac{f_g}{f_c}\right)^{5/6} \tag{1}$$

Here f_c is the controller bandwidth and f_g is the Greenwood frequency. Greenwood frequency is specified at a given wavelength and this wavelength is substituted for λ in the formula above. Strehl contribution is given by S = $\exp[(f_g/f_c)^{5/3}]$. The rms servo error is more fundamentally given by the integral over frequency of the controller's disturbance rejection function, $H(f)$, times the wavefront disturbance spectrum, $\Phi(f)$:

$$\sigma_{servo} = \int_0^\infty H(f)\Phi(f)df \tag{2}$$

Standard control law theory gives the disturbance rejection function as

$$H(f) = ||1 + L(f)||^{-2} \tag{3}$$

where $L(f)$ is the cascade of all of the dynamics around the loop, including wavefront sensor stare time, sample and hold, compute delay, and hysteresis in the deformable mirror actuators. Disturbance rejection curves for the Keck system are shown in Figure 2. We have found that the unity gain crossover of $H(f)$ can be substituted for f_c in equation (1) to provide a reasonable approximation to the integral.

Figure 3 shows how the unity gain crossover of the disturbance rejection function (i. e. control bandwidth) varies as a function of compute delay and sample time. To obtain a bandwidth of greater than 100 Hz it is necessary to sample at 1000 Hz and have a compute delay of less than 800 μs. This same compute delay and a sample rate of 500 Hz will give a control bandwidth of about 60 Hz.

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References

1 D. T. Gavel, J. R. Morris, and R. G. Vernon, *Systematic Design and Analysis of Laser Guide Star Adaptive Optics Systems for Large Telescopes*, **JOSA-A**, 11, 2, February, 1994, 914–924.

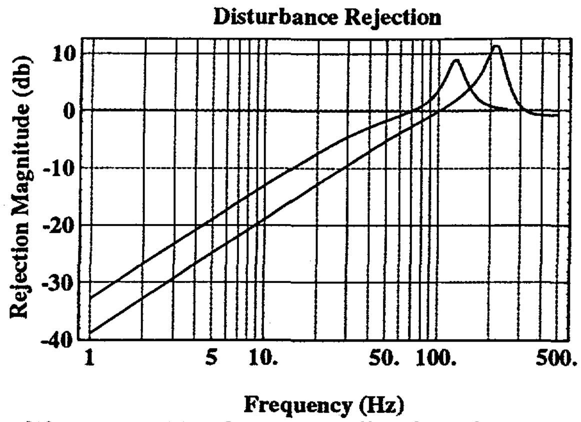

Figure 2. Wavefront controller disturbance rejection curves assuming compute delay is $\tau = 800\ \mu s$ and sample periods of T = 2 ms (top) and T = 1ms (bottom).

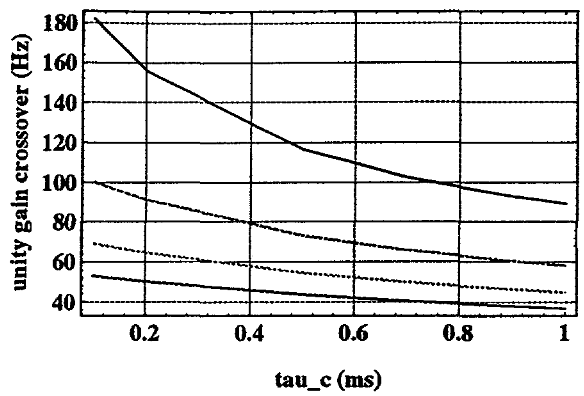

Figure 3. Crossover frequency vs compute delay for sample times (top to bottom) T = 1, 2, 3, and 4 ms.

2 D. Fried, *Statistics of a Geometric Representation of Wavefront Distortion*, **JOSA**, 55, 11, November 1965, 1427–1435.

3 D. Greenwood, *Bandwidth Specification for Adaptive Optics Systems*, JOSA, 67, 3, March, 1977, 390–393.

4 G. Tyler, *Turbulence-induced Adaptive-optics Performance Degradation: Evaluation in the Time Domain*, **JOSA-A**, 1, 3, March, 1984, 251–262.

5 G. Tyler, *Rapid Evaluation of d_0: the Effective Diameter of a Laser-Guide-Star Adaptive-Optics System*, **JOSA-A**, 11, 1, January, 1994, 325–338.