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PERFORMANCE PREDICTIONS FOR THE KECK TELESCOPE ADAPTIVE OPTICS SYSTEM

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ABSTRACT

The second Keck ten meter telescope (Keck-II) is slated to have an infrared-optimized adaptive optics system in the 1997-1998 time frame. This system will provide diffraction-limited images in the 1-3 micron region and the ability to use a diffraction-limited spectroscopy slit. The AO system is currently in the preliminary design phase and considerable analysis has been performed in order to predict its performance under various seeing conditions. In particular we have investigated the point-spread function, energy through a spectroscopy slit, crowded field contrast, object limiting magnitude, field of view, and sky coverage with natural and laser guide stars.

1. INTRODUCTION

A few adaptive optics systems are now in use at astronomical telescopes and several more are planned at major observing sites for the near future. The Keck 10 meter telescopes, located at Mauna Kea with its superb seeing conditions, promises to yield very high resolution images when adaptive optics systems are installed.

The first Keck AO system will be optimized for the near infrared ($1-3\mu$) and be installed on the second Keck (Keck II) which is due to be commissioned this fall. The system will reside on one of the Nasmyth platforms and will feed infrared imaging and spectroscopy instruments (NIRC-II and NIRSPEC). The system will have a Sodium laser guidestar, which will allow atmospheric correction to the diffraction limit for a large fraction of the sky at observing wavelengths as short as 1 micron.

An extensive effort in site characterization, performance prediction modeling, and system design trade off studies, has led to a baseline system that is now in detailed design phase. LLNL is drawing on its experience with the Lick laser guidestar adaptive optics system in constructing the wavefront controller and the Sodium guidestar laser for Keck. The inevitable trade between desired performance and available funds has led to the following baseline system: a 349 degree-of-freedom (241 active on the aperture, $d=56$ cm interactuator spacing) continuous face-sheet deformable mirror, a 90 Hz capable closed loop wavefront reconstructor, and a 10 Watt output power (roughly 9th magnitude guidestar) sodium beacon laser. This system will perform very well in J, H, and K bands under ordinary seeing conditions on Mauna Kea. This paper presents the predicted performance of this system, and also discusses some possible future directions.

2. PREDICTED SYSTEM PERFORMANCE - STREHL RATIO

Adaptive optics system performance is ultimately tied to the conditions of the atmosphere. On Mauna Kea, this is a good starting point, since seeing is *typically* around 1/4 arcsecond, a factor of 4 better than many other large telescope sites. In an ongoing seeing characterization effort at the Keck I telescope led by G. Channan of UC Irvine, a large amount of data including long exposure images, speckle images, and high speed Hartmann wavefront data has been collected. As a result of the knowledge obtained from this study and earlier work at the summit, our system design studies have assumed a set of three nominal seeing conditions, generically labeled case A (good), case B (ordinary), and case C (bad). These are summarized in Table 1. The intention is to try to estimate the minimum AO system performance expected during 20%, 50%, and 80% of the observing hours.

Table 1. Baseline seeing conditions

Case A: $r_0 = 40$ cm, $f_g = 13.5$ Hz, $\theta_0 = 10$ arcsec, $d_0 = 10$ meters

Case B: $r_0 = 20$ cm, $f_g = 45$ Hz, $\theta_0 = 4$ arcsec, $d_0 = 5$ meters

Case C: $r_0 = 10$ cm, $f_g = 90$ Hz, $\theta_0 = 2$ arcsec, $d_0 = 2.5$ meters

Figure 1 is a summary graph showing predicted AO corrected Strehl versus wavelength. Curves for both natural guide stars and the 10 Watt sodium beacon are shown. The analysis assumes negligible tip/tilt error, that is, that a suitably bright natural tip/tilt reference star is available on or very near the center of the field of view to reduce pointing error to much less than the diffraction limit. Figure 2 shows the relative degradation of Strehl versus field angle at various wavelengths.

Strehl performance for Keck AO with a bright natural guidestar is limited by wavefront fitting error with the 56 cm actuator spacing on the deformable mirror. When the laser guide star is used, focal anisoplanatism (due to the guidestar being at a finite distance from the atmosphere) is an almost equally significant contributor to Strehl reduction as deformable mirror fitting error. For the laser guide star and natural sources brighter than 10th magnitude, the Strehl reduction due to servo bandwidth error and sensor signal-to-noise error are relatively small.

Strehl calculations are based on a quadrature-sum of independent wavefront errors assuming a Kolmogorov atmosphere and the Marechal approximation:

$$S = \exp \{ \sigma_{wfs}^2 + \sigma_{bw}^2 + \sigma_{dm}^2 + \sigma_{iso}^2 + \sigma_{cone}^2 \} \quad (1)$$

where

$$\sigma_{wfs}^2 = \eta(1/SNR)^2(\lambda_{gs}/\lambda_{obs})^2 \quad (2)$$

$$\sigma_{bw}^2 = (f_0/f_g)^{5/3} \quad (3)$$

$$\sigma_{dm}^2 = \mu(d/r_0)^{5/3} \quad (4)$$

$$\sigma_{iso}^2 = (\theta/\theta_0)^{5/3} \quad (5)$$

$$\sigma_{cone}^2 = (D/d_0)^{5/3} \quad (6)$$

This model has been described in detail previously [1].

Even though a laser guide star allows coverage of areas of the sky where a suitably bright wavefront reference source may not be available, a (somewhat dimmer) natural star must be used for tip and tilt measurement and correction. The tip/tilt information is not available from the laser guide star because its position on the sky is randomized by the propagation of laser light up through the atmosphere. The availability of natural tip/tilt guidestars is the performance limiter for high sky coverage.

In any given portion of the sky to be imaged, there is a choice between using a bright tip/tilt guide star that is far away in angular distance from the area of interest, which would introduce isoplanatic error, or a dim star nearby, which would introduce pointing error due to low signal-to-noise ratio. For any given star field, a Strehl-optimizing choice of guide star can be made. Figure 3 shows average laser guide star corrected Strehl versus sky coverage, assuming that the optimal tip/tilt guide star choice is always made. Curves for natural guidestar corrected Strehl are also shown. A brighter source is needed for wavefront correction than for tip/tilt correction, thus laser guided AO has higher sky coverage for a given performance than natural guide star AO. However, even laser guided AO sky coverage is limited by the availability of natural guide stars.

2. PREDICTED SYSTEM PERFORMANCE - POINT SPREAD FUNCTION

Knowledge of the AO corrected Strehl gives an indication of system performance, and is a good parameter to optimize in the system design. However, knowledge of the point spread function allows for proper photometric reduction of astronomical images, and for correct selection of spectrograph slit width.

The corrected point spread is *not* a narrowed up version of the seeing point spread, nor is it a diffraction-limited Airy pattern, but is instead a hybrid object consisting of a diffraction-limited core on top of a halo of scattered light, the halo being of width comparable to the uncorrected seeing disk. The point spread function can be calculated if it is understood how the AO correction effects the structure function of wavefront phase. With a bright natural guide star on axis, (so we can neglect servo bandwidth, measurement, and anisoplanatism errors), the structure function is determined by the spacing of actuators on the deformable mirror. The structure function is [2]

$$\mathcal{D}_{\phi}(r) = 4\pi \int_0^{\infty} K(\kappa) 0.023 r_0^{5/3} \kappa^{-11/3} [1 - \cos(2\pi\kappa r)] \kappa d\kappa \quad (7)$$

where $K(\kappa)$ is the low spatial frequency rejection filter, characteristic of the deformable mirror best fit to the aberrated wavefront. We use $K(\kappa) = [1 - e^{0.588\pi\kappa^2 d^2}]^2$ where d is the inter-actuator spacing, which simulates a Gaussian shaped mirror deformation in response to the motion of an actuator. The point spread

function is then given by

$$p(\theta) = 8 \int_0^1 J_0(2\pi u \theta D / \lambda) \tau_0(u/D) \exp \left[-\frac{1}{2} \mathcal{D}_\theta(u/D) \right] u du \quad (8)$$

where $\tau_0(u/D)$ is the modulation transfer function (MTF) of the unaberrated aperture. In these calculations we use the hard circular aperture

$$\tau_0(u/D) = (2/\pi) \left[\cos^{-1}(u/D) - (u/D)(1 - (u/D)^2)^{1/2} \right]. \quad (9)$$

The true unaberrated MTF for Keck is of course slightly different because of the hexagonal shape and secondary and spider obscurations. The difference has an effect on the diffraction-limited PSF, yielding a 6-fold symmetric shape instead of a circularly symmetric Airy pattern. The effect on PSF's with atmosphere (AO corrected or uncorrected) however is minor.

Figure 4 shows the point spread function for the Keck adaptive optics system ($d=56$ cm) at various wavelengths, compared to the uncorrected seeing PSF. Note that the AO system acts to pull light out of the seeing halo and put it into the diffraction-limited core. Generally, the PSF is supported from below by the diffraction pattern until about 0.5 arcseconds from the central peak. Beyond that, the corrected PSF is above the diffraction pattern and below the uncorrected PSF, and asymptotes to the uncorrected PSF at large angles. Behavior of the PSF at large angles is studied in section 5 below.

Figure 5 shows the corresponding energy through a spectrograph slit.

3. LASER GUIDE STAR EFFECTS

The laser guide star is a suitable reference when bright natural guide stars are not within one isoplanatic patch distance of the astronomical object of interest. The artificial guide star is by necessity located a finite distance from the aperture (90 km is the distance to the sodium layer in the mesosphere). The light rays from the artificial star travel in a cone to the telescope aperture whereas the rays from the astronomical object are nearly collimated. As a result, some portions of the atmosphere seen by the science light are not sampled by the reference guide star light, and the error known as focal anisoplanatism results. The effect is severe on larger diameter telescopes and in fact drives the choice of Sodium guide stars over lower altitude Rayleigh beacons for the Keck telescope.

Equations (7)-(9) can also be used to determine the point spread due to focal anisoplanatism. According to Sasiela [3], the filter function is

$$K(\kappa) = 2 \left[1 - 2 \frac{J_1(kDz/2H)}{kDz/2H} \right] \quad (10)$$

where z is a characteristic height of turbulence above the telescope aperture, and H is the altitude of the guide star. For the following calculations, z was chosen so as to match the PSF at 0 to the expected Strehl for focal anisoplanatism = $\exp\{-(D/d_0)^{5/3}\}$.

Figure 6 shows cone-effect point-spreads for Keck. These point spreads must be convolved with the deformable mirror fitting error PSF calculated earlier to give an estimate of the Keck laser guided AO system PSF, which is dominated by these two components.

4. THE FUTURE: EXTENSION TO VISIBLE WAVELENGTHS

As the observing wavelength gets shorter, the demands on AO wavefront correction accuracy increase. To extend adaptive optics correction to the 0.3 to 0.7 micron region requires upgrading the system by adding more deformable mirror degrees of freedom to reduce fitting error, using more laser guide star beacons to reduce the focal anisoplanatism, and using more total laser power to produce the additional beacons and to keep up with the higher bandwidth requirements. A system study [1] shows that for a given amount of laser power, there is a Strehl-optimizing number of guide stars and degrees of freedom. For Keck, the solution lies on the curve in 3-space as shown in Figure 7. Strehl of 0.5 at 0.8 microns requires 300 Watts of laser power into 6 guide stars and a 1700 degree-of-freedom deformable mirror.

5. A SPECIAL APPLICATION: DETECTING PLANETS AROUND NEARBY STARS

An important side benefit of adaptive optics at a large telescope like the Keck 10 meter has come to light recently. The search for Jupiter size planets around the nearest 50 or so stars may be feasible. Since the large telescope aperture collects the light from the dim ($m_v=22$ or so) planet efficiently and the adaptive optics system increases the planet's Strehl by nearly three orders of magnitude, there is a chance that the dim planet may, after image processing, be extracted from the scattered light background of the parent star.

For a planet located 5 astronomical units from the parent star (as Jupiter is) and a parent star 3.3 parsecs (11 light years) away from earth, the planet's image will appear 1.5 arcseconds from the parent star's. With uncorrected seeing the peak planet flux is 6 orders of magnitude lower than the scattered light from the star. With AO correction the planet's light is peaked up and concentrated in a diffraction-limited area and scattered light from the star (mostly atmospheric halo at this distance angle) only will be about three orders of magnitude above the planet. This is in a regime where background subtraction techniques, such as those used in infrared astronomy, may be able to detect the planet after about 7 hours integration in J band. Figure 8 shows the levels of the AO corrected planet image and the scattered light.

Note from the figure that there is no help from the present adaptive optics system in reducing the scattered light from the parent star, that is, the halo at 1.5 arcseconds is almost unaffected by AO. Roughly 5000 degrees of freedom ($d=17$ cm) would be needed before any effect on the star's PSF at 1.5 arcseconds would be noticable. However, such a complex AO system may not be necessary. The average halo background could be subtracted during post processing. Then the planet will be detectable if the variance of the remaining speckle noise is smaller than the planet signal. The integration time needed to get a 1000:1 signal-to-noise is less than one hour on the Keck. 7 hours assures that the planet is at least 5 times above the noise. Integration time scales as

$$t \propto \sigma^2/D^4 \quad (11)$$

where σ is rms wavefront error and D is telescope aperture diameter. The scaling law is explained as follows:

1) smaller wavefront error gives a brighter planet (Strehl degradation is proportional to σ^2 in the high Strehl limit) 2) larger telescope aperture reduces integration time by a factor of $1/D^2$ by making the planet image

area smaller against the constant background, increasing the signal-to-noise proportionally, and 3) larger telescope aperture reduces integration time by another factor of $1/D^2$ since collection rate is proportional to area.

The 1.5 arcsecond separation puts a severe limit on the number of nearby stars that can be surveyed for planets. There are only about 10 stars closer than 3.3 parsecs.

When the two Keck telescopes are connected in an interferometer, the baseline of 80 meters is another factor that reduces integration time, or equivalently increases distance to the star of interest. The scaling law is

$$t \propto \sigma^2 / D^3 B \quad (12)$$

where B is the baseline. For $B = 80$ meters, the integration time is shortened by a factor of 8, or the distance is increased by a factor of $8^{1/2} = 2.8$, or 8.4 parsecs. (This is assuming that both Kecks are corrected by a 241 degree-of-freedom AO system.) There are at least 100 stars within that distance, which provides for a better statistical survey.

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Figure 1. Adaptive optics corrected Strehl.

Figure2. Strehl degradation due to field angle separation from the guide star.

Comparison of Laser and Natural Guide Stars

Figure 3. Sky coverage with natural star and laser guide star adaptive optics.

Figure 4. Adaptive optics correct point spread functions

Figure 5. Enclosed energy in a spectrograph slit

Figure 6. Point spread function due to cone effect

Figure 7. Optimum parameters for an upgraded Keck adaptive optics system (Strehls at 0.8 microns)

Figure 8. Keck adaptive optics system used for detecting planets around nearby stars