UCRL-JC-128256
PREPRINT

The Effect of the Keck Telescope's Segmented Primary on the Performance of the Keck Adaptive Optics System

D. Gavel

This paper was prepared for submittal to the
SPIE 1997 International Symposium on Optical Science, Engineering, and Instrumentation
San Diego, CA
July 27-August 1, 1997

June 1, 1997

Lawrence Livermore National Laboratory

including segmented correcting mirrors and/or hexagonal arrangements of actuators, with the possibility that there may be some advantage in aligning the adaptive optic system geometry to map neatly onto the primary. For example, segment aberrations might be corrected better. These other options were ruled out early for two reasons, which will be explained below: 1) a continuous face sheet gives the of best fit to atmospheric wavefronts for a given number of actuators, and 2) an expensive pupil de-rotation mechanism would be required to keep the AO system along segment edges.

2.1 Fit to atmospheric wavefront

In this analysis, we show that, for a given number of actuators, the fitting error to atmospheric phase is lower for a continuous face sheet deformable mirror with a rectangular grid of actuators than for either a segmented correcting mirror or hexagonal grid deformable mirror.

We consider first a segmented correcting mirror. The number of measured wavefront slopes is twice the number of segments (tip and tilt on each segment). There are three degrees of freedom (piston, tip, and tilt) per segment. The need for 50 % more actuators than measured degrees of freedom is offset somewhat by the fact that flat segments give a better fit to the wavefront *on a per-measurement* basis than does a continuous sheet. However, the offset is not enough to recover the performance *on a per actuator* basis, which is given by[1]

$$\sigma_{dm} = \mu_N^{1/2}\left(D/\sqrt{N_{act}}r_0\right)^{5/6} \tag{1}$$

where σ_{dm} is the root mean square corrected wavefront error, in radians, D is the diameter of the primary, N_{act} is the number of actuators, r_0 is Fried's seeing parameter and μ_N is a parameter that depends on the kind of correction mirror. μ_N is approximately 0.35 for flat segments (slightly variable by about 10% depending on the exact shape of the tessellating element, square, triangular, rhomboid, hexagonal, etc.), while $\mu_N = 0.26$ (see below) for continuous facesheet rectangular grid mirrors. Thus, per actuator, the continuous facesheet fits better. Since the cost of the AO system is almost linear with the number of controlled actuators, this favors the continuous facesheet.

To determine the fitting error coefficient μ_N, for continuous face sheets, we performed a number of Monte Carlo simulations using models for the deformable mirror and Hartmann wavefront sensor. Random phase screens were generated to simulate an atmosphere with Kolmogorov statistics (-11/3 power law in the spatial frequency spectrum) and $r_0 = 20$ cm at $\lambda = 0.5$ μm (1/2 arcsecond seeing). Actuator settings were adjusted to minimize the mean square Hartmann slope readings, indicating flattest corrected wavefront, and the resulting fitting error, σ_{dm} read off. The simulations were performed using an aperture mask shaped like the Keck mirror and done for a number of cases varying the number of actuators. Using (1), we are able to solve for the average μ_N. The results indicate an average $\mu_N = 0.26$ ($\pm$ 0.01) for rectangular grids and $\mu_N = 0.32$ ($\pm$ 0.01) for a hexagonal grid. The difference is significant enough to favor the rectangular grid.

2.2 Alignment to rotating pupil

The Keck telescope has an altitude-azimuth mounting, which means that both the pupil and the image rotate (at different rates) with respect to a coordinate system fixed to the Nasmyth platform, where the AO bench and science instruments to be fed by adaptive optics are located. Pupil de-rotation on the optical bench is an expensive proposition, comparable in cost to the deformable mirror itself.

Given that segment phasing and tilting is already accomplished with the Keck primary active control system, and that warping harnesses remove higher order aberrations from segments to a degree better than the anticipated AO atmospheric fitting error, it is difficult to justify additional expense, or reduced atmospheric correction performance, in order for the AO system to specifically correct primary mirror errors. The better atmospheric fit and cost savings from not having to de-rotate the pupil on the AO system optical bench outweigh any possible benefit in using the AO system to further correct the primary mirror. A continuous face sheet deformable mirror is therefore preferred.

The Effect of the Keck Telescope's Segmented Primary on the Performance of the Keck Adaptive Optics System

Don Gavel
Lawrence Livermore National Laboratory
P. O. Box 808, Livermore, CA, 94550

ABSTRACT

The 349 degree of freedom Keck adaptive optics system will be mapped on to the 36 segment Keck primary mirror. Each telescope segment is independently controlled in piston and tilt by an active control system and each segment also has its own set of aberrations. This presents a unique set of problems for the Keck adaptive optics system, not encountered with continuous primaries. To a certain extent the low order segment aberrations, beginning with focus, can be corrected statically by the adaptive optic system. However, the discontinuous surface at the segment edges present special problems in sensing and correcting wavefront with laser guide stars or natural guide stars.

1. INTRODUCTION

The Keck telescope adaptive optic (AO) system is designed to optimize performance in the 1 to 3 micron region of observation wavelengths (J, H, and K astronomical bands). Currently, this system is under construction at CARA in Hawaii and LLNL in Livermore, California. The AO correction element is a 349 degree of freedom continuous face sheet deformable mirror, with actuators spaced on a rectangular grid. Given average Mauna Kea seeing conditions, the predicted wavefront fitting error with this mirror configuration is 118 nm rms. This correction leads to a Strehl of 0.74 at 1.5 microns observing wavelength, an improvement of two orders of magnitude over the uncorrected Strehl of 0.006.

Keck's primary mirror consists of 36 hexagonal mirror segments nested against each other to form a scalloped hexagon primary, covering an area equivalent to that of a 10 meter diameter circular aperture. Segment alignment and pupil shape are issues that affect the adaptive optic system performance. The segments must be very accurately aligned with each other, either physically or through correction by the AO system, in order to produce diffraction-limited images. Also, since the Keck telescope is mounted in the altitude-azimuth configuration, the pupil image rotates with respect to instruments mounted on convenient platforms such as the Nasmyth, where the AO system and science instruments are located. It is important for the AO system to know where the pupil edges are so that it senses and corrects only in areas illuminated by starlight.

In this paper we consider three important issues relating Keck primary geometry and AO system performance: 1) what is the best type of deformable mirror to use, 2) will the AO system correct, or be fooled by, segment misalignments, and 3) how will the rotating pupil affect the wavefront correction accuracy.

2. CHOICE OF DEFORMABLE MIRROR

Figure 1 shows the layout of actuators and Hartmann lenslets over the Keck aperture in the current baseline design. Note that the lenslet/actuator locations are not particularly aligned with the segment boundaries and that all segments do not have the same number of lenslets and or actuators. This has both good and bad implications for AO system performance. The fact that some lenslets bridge pairs of segments is potentially a good feature, since information about mismatches at the edges will show up on the Hartmann sensor. On the other hand, if the objective is to sense and correct high order aberrations on the segments themselves, this arrangement of Hartmann lenslets will have some difficulty, since lenslets are not assigned exclusively to segments. There are several segments that have only two lenslets that collect light from that segment exclusively and not from adjoining ones as well.

The decision to use a continuous face sheet deformable mirror with a rectangular grid of actuators was made early in the design phase of the Keck AO project. We considered other possible configurations, The issue remains, however, of whether segment tilt errors might be *amplified* by the AO system, possibly because they fool the wavefront sensor by introducing discontinuities in the wavefront. This problem is addressed with simulation studies described in section 3.

3. SEGMENT MISALIGNMENTS

Phase errors introduced by misaligned mirror segments are quite different from phase error induced by the atmosphere. Segment pistons, tilts, and any other single segment aberration will introduce discontinuities in wavefront phase at segment boundaries. The continuous deformable mirror correction can only approximate the discontinuities.

It is possible that strange configurations of mirror segments might fool the AO system, which implicitly assuming a continuous wavefront, and cause an amplification of the error. To study this issue, we performed simulations of AO system response to segment misalignments. This was done assuming the baseline AO system design with a 341 actuator deformable mirror and corresponding Hartmann sensor in a rectangular grid arrangement (Figure 1).

3.1 Random segment tilts

Figure 2a shows a cross-section through a wavefront phase front caused by random segment tilt errors. The cross-section is from one end of the aperture to the other (10.9 meters), across six segments and the secondary obscuration in the middle. The solid line shows the linear discontinuous wavefront before correction. Units on the graph's y axis are radians of wavefront phase. Assuming 1 micron observing wavelength, $\pm$ 1 radian at the edge of a segment is the equivalent of $\pm$ 75 nm edge discontinuity, or $\pm$ 0.05 μradians of segment tilt (accounting for doubling of surface error due to reflection). This is on the order of what is currently attained by phasing and stacking of the Keck primary using the active control system.

The dashed line shows the deformable mirror fit to the wavefront after 20 iterations of the control loop. The fit appears rather bad at the sharp discontinuities, however the corrected image of a point source shows reasonable Strehl improvement (figure 2b). The Keck AO control loop is designed to operate at 400 iterations per second in laser guide star mode and as fast as 1000 iterations per second in natural guide star mode, so the simulation results suggest that the AO system will partially correct (spatially) random segment tilts if they are constant or slowly varying on time scales longer than 50 ms.

3.2 Segment tilts that might appear as overall tilt

A more insidious configuration of segment misalignments might be the "Venetian blind" mode, shown in Figure 3a. This arrangement has all the segments erroneously tilted the same direction. Such a situation might confuse a Hartmann (local tilt) sensor so that the adaptive optic reconstructor would produce a flat wavefront correction, albeit having an overall tilt. Indeed, after the first iteration of the controller the deformable mirror shape (shown with the dashed line in Figure 3a) looks basically like full aperture tilt. However, after 20 iterations the reconstructed wavefront begins to approximate the true sawtooth wavefront shape (Figure 3b). The point spread function is not improved, but it is not significantly worsened (Figure 3c).

Convergence to a reasonable final corrected state is at least partially explained by the fact that some Hartmann subapertures overlap segment boundaries in the baseline configuration. The centroid of a Hartmann spot is proportional to the area weighted average slope over the subaperture. Thus centroids from subapertures that overlap segment boundaries give information about segment discontinuities, although is it seems to be "weak" information in the sense that it takes a number of iterations to respond to it.

3.3 Segment tilts that might appear as overall focus

Another specific arrangement of segments that might cause trouble with the Hartmann sensor is a pseudo-focus configuration where segment tilts are proportional to distance from the center of the primary.

Again, the first iteration (Figure 4a) looks like overall wavefront focus, but after 20 iterations (Figure 4b), the corrected wavefront roughly fits the perturbation. The point spread is considerably improved (Figure 4c).

The conclusion is that wavefront error due to segment tilts are generally not amplified by the AO system, and in some cases, the AO system can partially correct for them.

4. ROTATING PUPIL

As mentioned above, it was determined early on to allow the Keck pupil to remain rotating with respect to coordinates attached to the AO system optical bench. As a consequence, the boundary of the Keck pupil, which is a scalloped hexagon shape, will rotate slowly with respect to the fixed actuator/lenslet geometry, and portions of the deformable mirror and wavefront sensor will come in and out of illumination (see Figure 5). The reconstruction algorithm must be smart enough to realize when certain Hartmann lenslets and deformable mirror regions are not in the pupil, and adjust its optimal reconstruction accordingly.

The wavefront reconstructor maps Hartmann centroid measurements to actuator commands through a system control matrix. The system control matrix is the pseudo-inverse of an influence matrix, which maps actuator motions to Hartmann centroid values. The influence matrix is generated by the following calibration procedure: A point source of light is inserted at the telescope focus and directed through the AO system. It is optional whether or not to mask off the deformable mirror with the pupil image of the Keck primary. We then move one actuator at a time and measure the motion of each Hartmann spot, then record the ratio of spot motion to actuator motion in appropriate locations in the matrix. For optimal operation, the calibration procedure must be repeated with the pupil mask for every possible orientation of pupil and actuator/lenslet grid. Since this is an infinity of positions, we must compromise and choose a discrete number of positions where calibrations are to be performed. Each matrix thus determined must then be pseudo-inverted and made available to the reconstructor at appropriate times during AO operation on the sky.

The objective is to determine the number of calibrations needed (rotation angle sample positions) so that an acceptable level of wavefront fitting error will be maintained between positions. To calculate and compare system performance, we simulated the AO system response to Kolmogorov atmosphere phase screens at various pupil rotations.

For the first set of simulations, the calibration was performed with the Keck pupil mask in place. The initial orientation is 0 degrees relative rotation, as in Figure 1. In this case 252 lenslets are at least 50% illuminated, and the influence matrix is 349 $\times$ 504. Two other orientations, 5 and 10 degrees respectively, are shown in Figure 5, which each also illuminate 252 lenslets by at least 50%.

It is possible to create the influence matrix that is independent of rotation by not using a pupil mask during calibration. Then only one matrix is needed for all orientations, although it is not optimal for any orientation. Without the pupil mask, 351 lenslets are illuminated during calibration. During operation with starlight, many subapertures will not be illuminated, so those positions (detected when the photo count is zero) will arbitrarily return a zero slope error to the reconstructor.

The calculations were done at an infrared wavelength of $\lambda = 1.6\ \mu$m where the seeing coherence cell is $r_0 = 60$cm. The screens first had full aperture tilt removed, to simulate the action of a separate tip/tilt control loop. The standard model for fitting error predicts[1]

$$\sigma_{wf} = \sqrt{0.3}(d/r0)^{5/6} = 0.55 \text{ radians rms} \qquad (2)$$

which corresponds to a Strehl ratio of 0.74. Results for the case of using a reconstruction matrix derived from calibrating with the Keck pupil stop in place are summarized in Table 1. Results for the case of using a circumscribing circle pupil stop during calibration are summarized in Table 2.

Table 1. Wavefront fitting error, case 1: Keck pupil stop used during calibration.

Rotation	rms fitting error	% error increase
0	0.66	-
5	0.71	6%
10	0.79	12%

Table 2. Wavefront fitting error, case 2: circular pupil stop used during calibration.

Rotation	rms fitting error
0	2.95
5	2.80
10	2.93

As expected, the fitting error using the circular pupil calibration does not vary much with Keck pupil rotation. However, fitting error is much worse with this reconstruction matrix than with one tuned to a particular Keck pupil.

The fitting error with the Keck pupil used during calibration is very close to the theoretically predicted error (about 20% high, but this could be attributed to statistics of this single Monte Carlo screen simulation). There is a 6% increase in error when the pupil rotates by 5 degrees and a 12% increase at 10 degree pupil rotation. The increase is significant, since it is clear from the maps of errors on the pupil that large errors are creeping in areas where lenslets that were ignored during calibration are becoming illuminated as the pupil rotates.

It seems reasonable to let the pupil rotate by 5 degrees or so before worrying about updating the control matrix. Because of 6 fold symmetry, only 60 degrees total need to be covered, so that leads to a requirement of at least 12 different control matrices ready to load during operation.

5. CONCLUSION

The segmented primary of the Keck telescope introduces special difficulties that have not been dealt with before in AO systems. Even so, it is anticipated that the AO system will perform close to what would be expected if the primary were monolithic.

The choice of AO mirror is driven by the marginal (per actuator) benefit of correcting the atmosphere, not by the possibility of the AO system fixing imperfections in the primary mirror. Keck's primary can be sufficiently corrected by the active control system so that its phase and tilt errors will not upset operation of the AO system.

Rotation of the Keck pupil with respect to the AO deformable mirror and wavefront sensor requires that the control matrix be updated on a regular basis. The baseline design will provide for 24 matrices for updating after every 2.5 degrees of pupil rotation. The update will happen automatically and is is not expected to be a significant burden on system operation.

REFERENCES

[1] **Adaptive Optics for Keck Observatory**, Keck Observatory Report No. 208, September, 1994.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

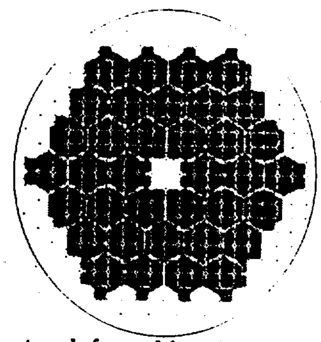


Figure 1. Mapping of 241 actuator deformable mirror and Hartmann lenslet array onto the Keck segmented primary. Dots represent actuators, small circles are lenslets, larger hexagons are the primary mirror segments.

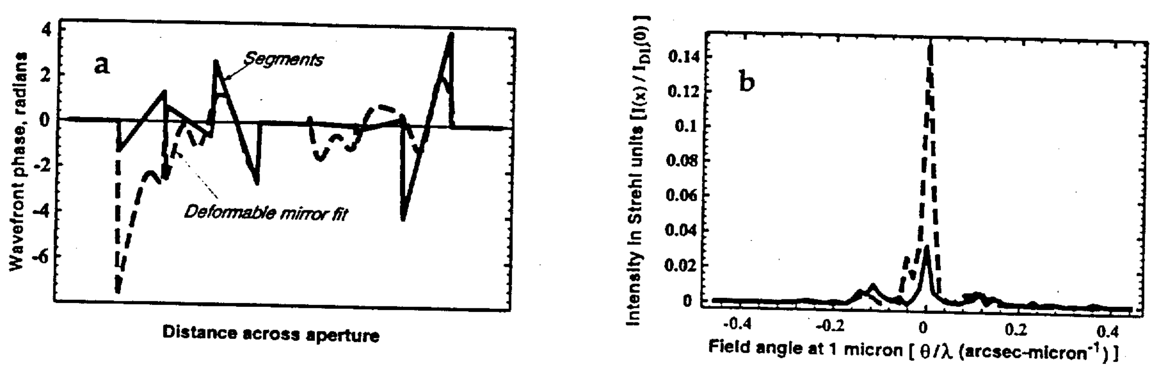
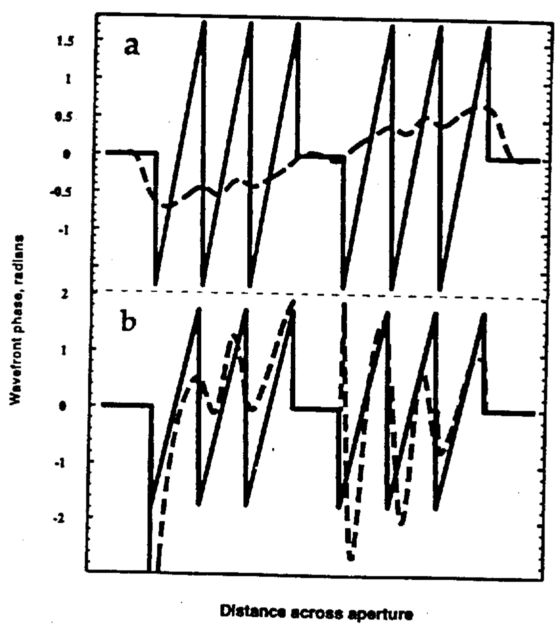


Figure 2. Correction of random tilts of Keck primary segments by the adaptive optics system. The deformable mirror is the 241 actuator continuous face sheet (Figure 1). a) Cross section of initial phase error (solid line) and fit by the deformable mirror (dashed line). b) Point spread functions, solid: before correction, dashed: after correction. The scale of the point spread function is with respect to the peak of a diffraction-limited point spread function.



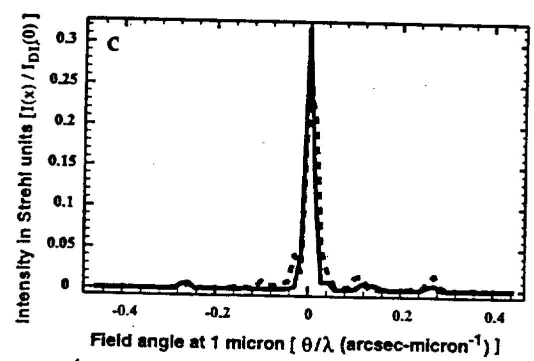


Figure 3. Correction of segment tilts where all segments are tilted the same direction. a) After one iteration of the controller the correction looks like full aperture tilt. b) After 20 iterations the correction more closely approximates the sawtooth pattern of the segments. c) Point spread functions, solid: before correction, dashed: after correction.

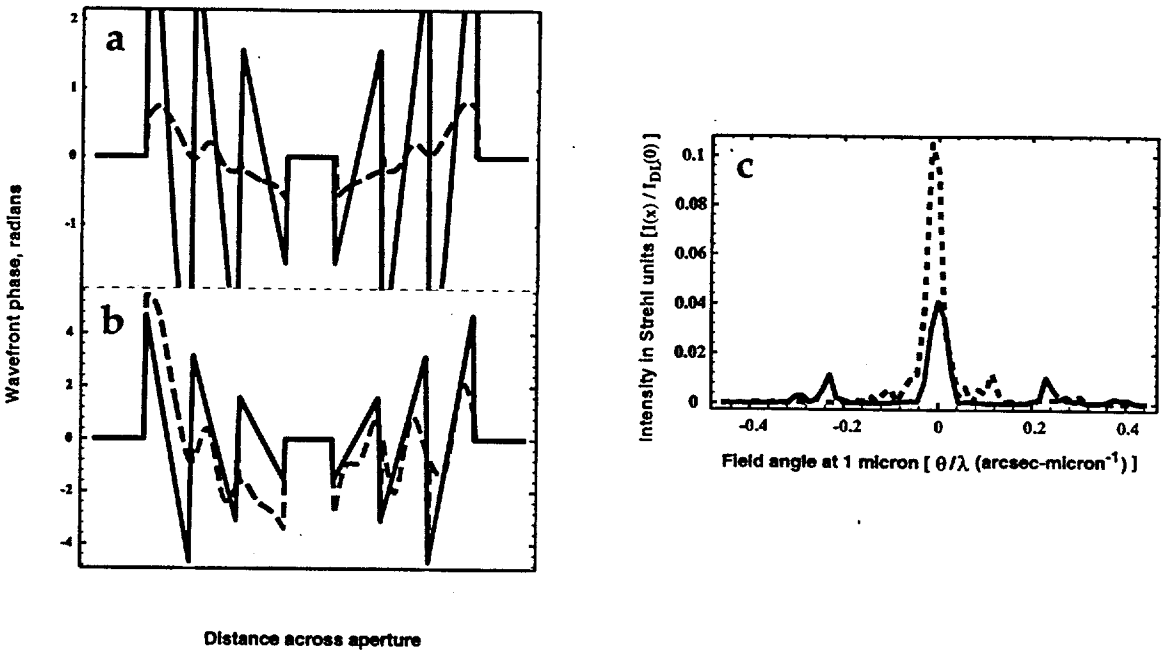


Figure 4. Correction of segment tilts where segments are tilted in a focus direction. a) After one iteration of the controller the correction is similar to full aperture focus. b) After 20 iterations a better fit to the segments is made. c) Point spread functions, solid: before correction, dashed: after correction.

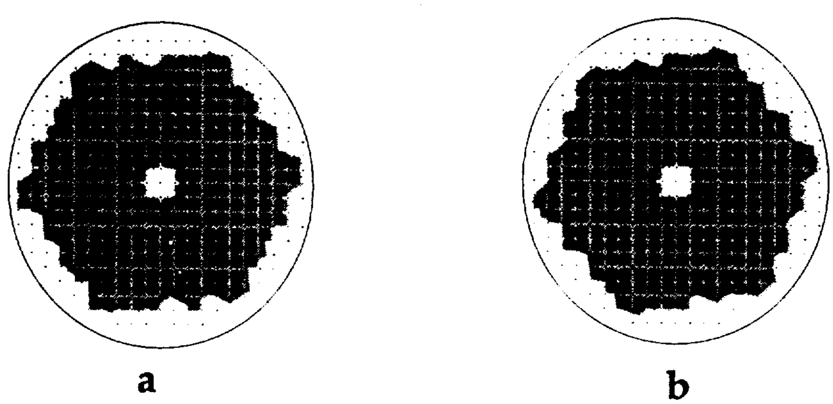


Figure 5. Rotation of the Keck primary pupil with respect to the actuator and lenslet grid in the AO system. a) 5 degree rotation. b) 10 degree rotation. Rotation occurs as the alt-az telescope tracks an astronomical object. A new reconstruction matrix must be loaded into the AO controller every so often since edge subapertures vary in illumination.

Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551