Effect of Keck Segment Figure Errors on Keck AO Performance

KECK ADAPTIVE OPTICS NOTE 469

Christopher Neyman, Ralf Flicker, and Sergey Panteleev
March 7, 2007

ABSTRACT

The effect of Keck segment figure errors on adaptive optics correction with the current and future AO systems is calculated. Our modeling assumed a standard Shack Hartman wavefront sensor and a deformable mirror with influence functions typical of stacked piezoelectric actuators. The segment errors were taken from the Keck II telescope after the June 2005 segment exchange. The material in this KAON was originally presented in a poster at the CfAO fall meeting in November 2005.

1. Introduction

The wavefront error of individual segments may be a limiting factor in the achievable AO correction of future large telescopes such as the Thirty Meter Telescope and for next generation AO systems at Keck Observatory. Therefore, we wanted to know the effect of segment wavefront errors on our current and future AO systems at Keck Observatory.

The segment figures were measured with the Ultra Fine Screen (UFS) mode of the telescope facility wavefront sensor (PCS). The measurements were analyzed to make wavefront maps for each segment. A Fourier reconstruction method that fits the wavefront directly was used to produce the maps. Details can be found in the Keck adaptive optics note by Neyman [1].

Next, the maps were combined to make a wavefront phase sheet for the entrance pupil of the Keck telescope. The phase sheet is input to an adaptive optics simulation to determine the amount of residual error that would remain after correction by an AO system. The sample AO systems are representative of the current Keck AO system with 20 actuators across the pupil, general purpose next generation AO systems with 32 and 40 actuators across the pupil and extreme AO systems with 60 actuators across the pupil.

The wavefront maps for the AO simulation were done after all the Keck II primary segments were warped during June 2005 over the course of 3 nights. This “rewarping” was part of an ongoing observatory effort to improve the image quality of the Keck telescopes. This careful warping resulted in a reduction in the average segment rms wavefront error by ~20%.

2. Keck II Segment Focus Buildup

The segments of the Keck primary mirror are removed and recoated every two years. While installed in the telescope, each segment is set to the correct shape by a warping harness. The harness sets the correct segment figure by applying forces to the segment back at 36 points, see Figure 1. When a segment is installed after coating, these forces must be set to insure that the segment is in the correct shape. Segments are installed in an un-warped state and then measured with the PSC system at night to determine the correct forces that should be applied. Warping harness forces are applied during the next day and the segment figure is verified with PCS measurements the subsequent night. The segment figures are measured with a high-resolution mode of the PCS system. This mode is known as Ultra Fine Screen (UFS) which is essentially a high resolution Hartmann wavefront sensor. The normal mode of this system is to fit the 217 measured spot images to Zernike polynomials. Depending on the segment type, either 15 or 45 polynomials are used to fit the wavefront to the measurement. This wavefront measurement is used to determine the applied warping forces. An extra focus was gradually warped into the segments during the last 2-3 exchanges on K2, see Figure 2. We believe that the focus bias was implemented due to incorrect selection of the reference segment during the previous segment exchange two years earlier in 2003.

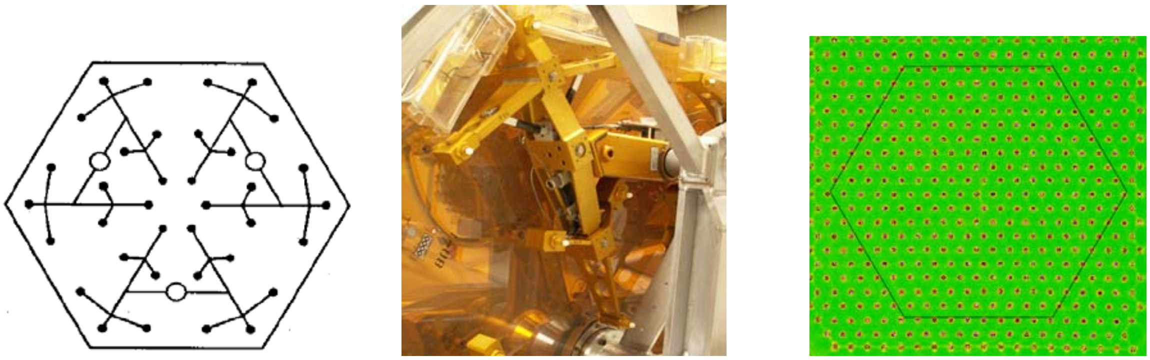

Figure 1: The locations of the warping harness actuators are shown in the diagram on the left, a photograph of one segment is shown center, and a PCS ultra fine screen point source reference image is shown at left. The boundary of a segment is shown for reference in the left hand image. The 217 images contained within the segment boundary are used to calculate the wavefront of the segment.

3. June 2005 Segment Warping: Focus adjustment

During 3 nights in June 2005; all 36 segments were un-loaded and warped. Now the warping harness is able to correct some higher order aberrations. Previously warping forces were mostly correcting focus. Average warping forces were reduced by 30% and the number of warping forces that exceed the allowed limit has been dropped from 12 to 5 (there is a limit set for the forces in order not to over-strain the glass). The change in rms wavefront on a per segment basis is show in Figure 3.

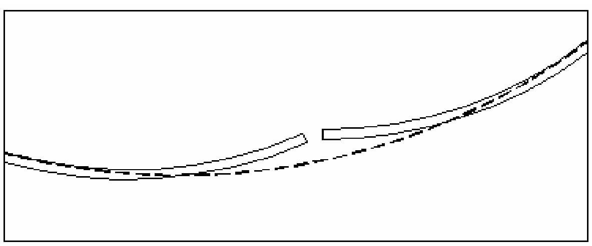

Figure 2: The figure above shows schematically a cross section of the segments before rewarping. Segments were bent incorrectly adding extra focus to the wavefront. After releasing and rewarping, the segments were closer to the correct reference surface, represented by the dotted line.

When averaged over all 36 segments between 2003 and June 2005, segment wavefront rms improved by 20% from 112 nm to 80 nm. The wavefront improvement, if not considering Type 1 segments (numbers 1-6 that are blocked by the secondary), was from 82 nm to 64 nm rms.

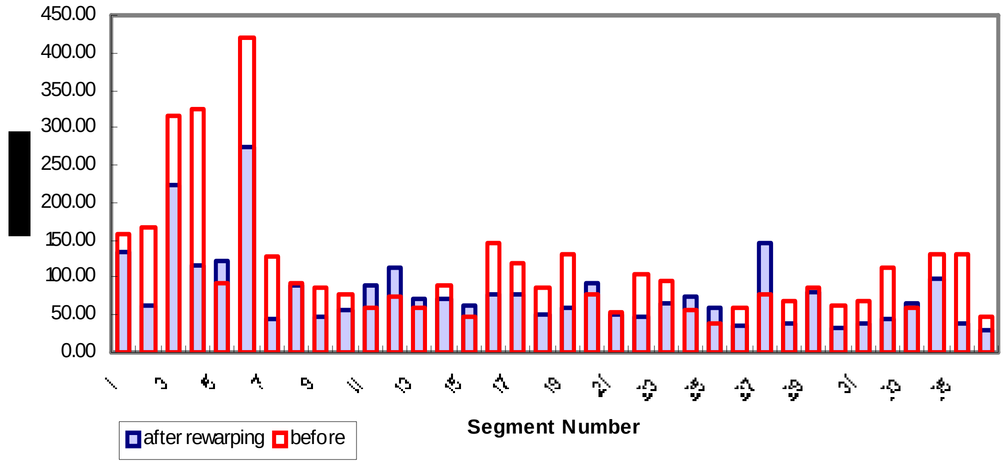

Figure 3: The rms wavefront error of each segment shown before and after the warping in June 2005.

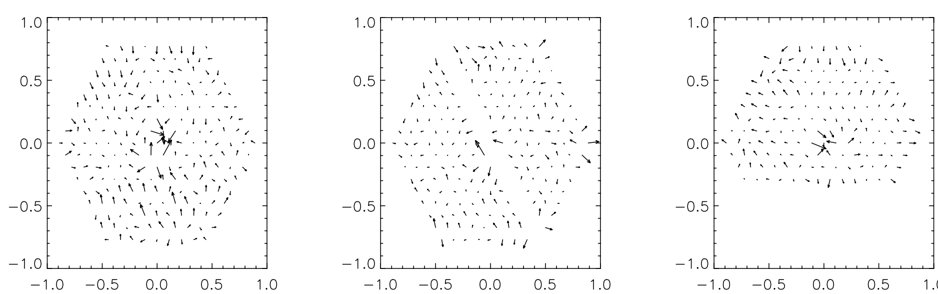

Figure 4: The UFS slope data are represented as 217 arrows in the above plot. Data for each of the three types of segment boundaries shown above can be handled by the algorithm. These are from left to right: full hexagonal segments, slope data obscured by the secondary support struts, and third segments that are obscured by the secondary mirror baffling.

4. Segment Figures from the June 2005 Warping

In order to determine the effect of segment aberrations on current and future Keck AO systems, we wanted to use measurements of the actual segment figures as input to our adaptive optics simulation. The standard UFS wavefront reconstruction is known to miss the “humps” or “dimples” around each segment’s central radial support. It may also miss features because of the limited number of Zernike polynomials that it uses to fit the wavefront. We adapted a zonal wavefront reconstruction method suggested by the Roddiers [2]. It is based on solving Poisson’s equation using Fourier transforms. In order to satisfy boundary conditions Fourier transform methods are generally restricted to square or rectangular domains. This method uses a Grechberg-Saxton algorithm to solve Poisson’s equation on an arbitrary domain. The algorithm is able to work on Hexagonal domains and on segments that are partially blocked by the secondary, see Figure 4. Modifications are added to work around missing data that is blocked by the spider. More details are given in a technical note by Neyman [1]. As an example of the reconstructed wavefronts, two typical segment wavefront maps after the Keck II segment exchange in June 2005 are shown in Figure 5 . Segment 4 has a wavefront error of at 113 nm rms and segment 35 has a wavefront error at 41nm rms.

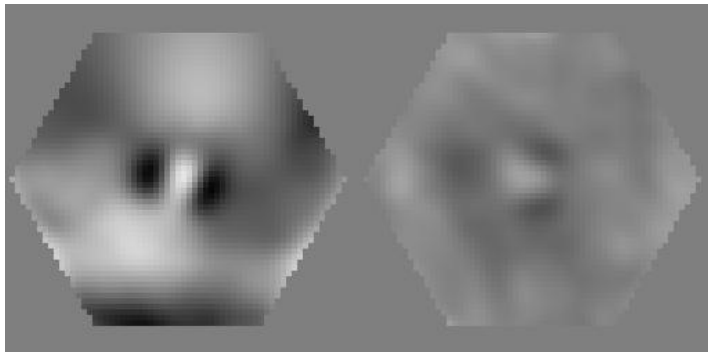

Figure 5: Example segments in Keck II after the June 2005 exchange. Segment 4 (left) compared to segment 35 (right). The same color map is used on both images.

5. AO Correction of Segment Errors

We compared two independent methods for estimating the ability of AO to correct for segment aberrations. The first method simulated a standard closed loop AO system in the absence of noise and atmospheric turbulence. This method includes fundamental limitations such as WFS aliasing errors, algorithm dependent wavefront reconstruction errors and DM fitting errors. The other method is a direct least-squares fit of the DM's influence functions to the distorted wavefront, assuming perfect information about the aberration. This method foregoes all WFS limitations and reconstruction errors, and is Strehl optimal (minimum variance) in a least-squares sense. This method reflects the theoretical ability of the DM to compensate for the segment errors if perfect information was available. Several levels of correction were simulated; these roughly correspond to the current Keck system (20x20), the future NGAO system (48x48), and an extreme AO system (60x60). Results are given in Table 1 below. For each level of AO correction the two methods differ by approximately 40nm rms in all cases. As expected, the residual error is lower when only the effects of actuator fitting are considered. For comparison, the table also includes the standard atmospheric fitting error; see Hardy [3], for the same order of AO correction with a Fried parameter of 18 cm.

Table 1: Summary of AO simulation results for correction of Keck segment errors, see text for details.

Size of AO Simulation	Sub-ap. Size (cm)	Residual Wavefront Errors (nm)			Atmospheric Fitting Error (nm) (r_0 =18cm)
		Input	After AO Correction	After Optimal Actuator Fitting	
20x20	56.2	79	66	50	100.7
32x32	35.2	79	59	41	68.2
48x48	23.4	79	51	32	48.5
60x60	18.8	79	43	26	40.4

The segment phase maps determined from the latest Keck warping data were used to model the primary mirror. Individual segment phase maps were stitched together with an amplitude map for the Keck pupil determined from the gray pixel approximation [4]. This approximation allows the simulation to correctly account for gaps between segments. The final phase map was 1024x1024 pixels on side with each pixel representing 2.3 cm at the Keck pupil. We used a physical optics model of a standard Shack-Hartmann wavefront sensor (no spatial filter) coupled to a deformable mirror model that consists of an influence functions typical of stacked piezoelectric actuators. Examples of AO correction of the Keck II segment errors are shown in Figure 6 and Figure 7. The same color map is used in both images.

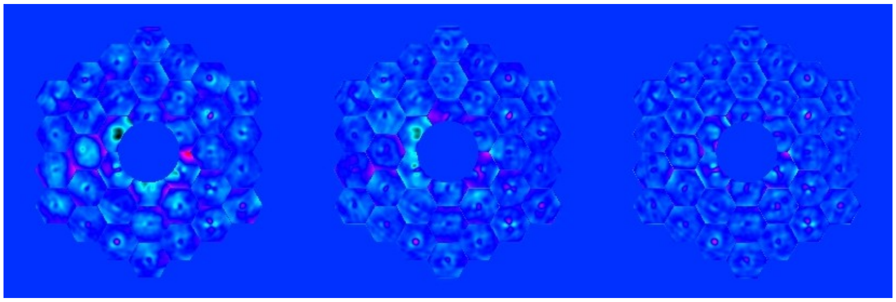

Figure 6: An example of AO correction with the 20xx20 AO system of Table 1. The images are from left to right: the uncorrected segment aberrations, after AO correction, and after optimal fitting of the AO actuators to the input wavefront.

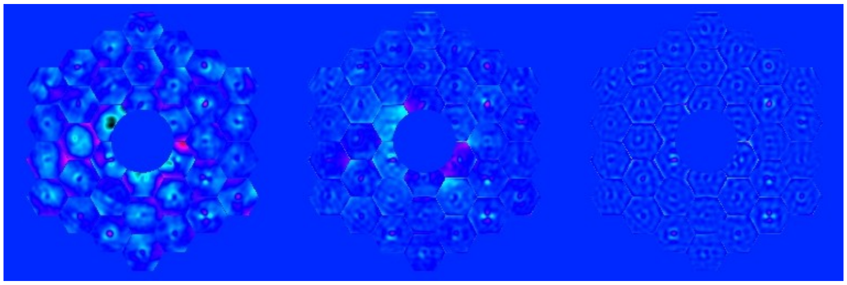

Figure 7: An example of AO correction with the 48 x 48 AO system of Table 1. The images are from left to right: the uncorrected segment aberrations, after AO correction, and after optimal fitting of the AO actuators to the input wavefront.

6. Conclusion

The results of Table 1 can be used to infer the performance of the current and future AO systems when correcting the static error from typical Keck segments. We have not considered the effects of segment tip tilt errors (also know as stacking) and the piston errors between segments (also known as phasing errors) in this report. The report has also not considered the dynamic effects of segment vibrations. We hope to address these effects in future design studies.

References

1. C. Neyman, "An Algorithm for Reconstruction of Keck Telescope Segment Figures", Keck Adaptive Optics Note, KAON 468, March 7, (2007).
2. F. Roddier and C. Roddier, "Wavefront reconstruction using iterative Fourier transforms", Applied Optics, 30, 1325-1327, (1991).
3. J. Hardy, "Adaptive optics for astronomical telescopes", Oxford University Press, (1998).
4. M. Troy and G. Chanan, "Diffraction effects from giant segmented-mirror telescopes", Applied Optics, 42, 3745-3753, (2003).