W. M. KECK OBSERVATORY

Keck Telescope Wavefront Errors: Implications for NGAO

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ABSTRACT

This note details the effect of telescope static and dynamic wavefront errors on the performance of future AO systems at Keck observatory. Measurements at Keck are used to bound probable values of the input errors. Current understanding of all errors appears sufficient to design the NGAO system. A notable exception is the full aperture tip tilt vibrations at 29 Hz. These errors appear to have significant impact on sky coverage.

1. Introduction

A segmented primary mirror has many advantages when designing a large optical telescope. The 10m Keck telescopes were the first constructed with a segmented primary. The soon to be completed 10.4 m Gran Telescopio Canarias is another. Many future large telescope designs feature segmented primary mirrors such as the Thirty Meter Telescope and the European Extremely Large Telescope. However, the segmented nature of the primary and its support system provide some additional challenges to adaptive optics system designers. The authors have reexamined some issues for AO design on segmented mirror telescopes using computer simulations. We detail in this report the effect of both static and dynamic optical errors that can affect AO performance. We also examine the feasibility of some proposed techniques for mitigating these effects.

1.1. NGAO WBS Elements

The direction and scope of this trades study was formulated as part of the NGAO system design management plan [1]. Several work breakdown structure elements are included in its scope. As part of the planning for this study, the original language of the trade study was modified [2]. For reference, the relevant changes are repeated below, revisions to the original working are included in italic font.

NGAO system design WBS elements:

- 3.1.1.1.2 Telescope Dynamic Performance Data
  Improve/document our understanding of the actual primary mirror (*telescope*) wavefront errors. (*set specifications from simulation*)
- 3.1.1.1.3 Telescope Static Wavefront Errors
  Improve/document our understanding of the actual primary mirror (*telescope*) wavefront errors. (*set specifications from simulation*)
- 3.1.2.1.9 Telescope Wavefront Errors
  Review new data on the telescope static and dynamic wavefront errors. Determine how and whether NGAO can correct for these errors. Determine the performance benefit of a large LOWFS patrol field to enable use of the brightest possible NGS (*Pending Results of LOWFS study*). Consider whether a separate sensor outside the NGAO FOV would be useful for measuring/correcting the telescope errors. Complete when impact on current Keck LGS AO system understood and impact on NGAO reviewed

1.2. Methodology

Our goal will be to determine the effect of static telescope errors such as: segment figure, phasing (segment piston), and stacking (segment tip and tilt) errors on the performance of higher order AO systems. The second part of this trade study is directed towards the effect of dynamic errors including segment motion (individual segment tip and tilt), telescope line of sight jitter (tip and tilt), and telescope focus. We will not perform an exhaustive study of the exact magnitude of these effects in the current system. Instead, we will use the current understanding of these errors as inputs to a Monte Carlo simulation of the NGAO system. We will also make worst case and best case estimates of these errors so as to bound the performance of future NGAO systems. By the rationale commonly adopted for NGAO trade studies, the effects of wavefront errors resulting from dynamic telescope aberrations can be estimated in a simulation that is focused on this effect alone, without needing to run a full-fledged simulation of the entire LGS-based tomography AO system. The trade study team believes the following methodology supports the goals of the NGAO system design and is consistent with the available resources.

1.3. AO Simulation Methods

The LAOS code (used for other NGAO simulations) is currently not developed so as to allow us to easily simulate dynamic telescope/segment errors with arbitrary temporal power spectral densities (PSDs). However, this capability was implemented in another code, the Yorick Adaptive Optics simulation (the YAO package), during the KPAO phase of the NGAO project. The YAO code [3] (version 3.8) will be used for this trade study, simulating a 48x48 Shack Hartmann natural guide star AO system, in order to avoid including any effects from tomography errors. The noise can be set to zero; the fitting error is measured separately and can be subtracted off in quadrature. The residual contains only wavefront errors resulting from wavefront sensor aliasing, imperfect wavefront estimation and control (reconstruction and servo-lag) in the simulation. Active segment control is not simulated, but the input PSDs are estimated to include what we believe are the residuals from the active control system. It is important to note in the dynamic wavefront error study that we are not attempting to produce a comprehensive study on the vibration environment of the telescope, but rather what level the vibration must be to not impact NGAO performance. We are setting a vibration spec.

The YAO simulation code has implemented static phase maps on the primary mirror segments, as measured with the UFS and reconstructed as reported in [4]. A previous study (using YAO) investigated the ability of a high-order AO system to correct for these aberrations, and was used in the NGAO proposal (June 2006). This study summarizes those results plus adds cases for phasing (segment piston).

The relevant YAO simulation parameters and methodology are:

- Simulate each effect individually, as opposed to “all in” numbers
- Useful for later parameterization in wavefront error budget
- NGS AO simulation
- 48x48 SH (4x4 pix per sub-ap, 0.5" pixel size)
- 49x49 actuators (Fried geometry)
- PZT modeled influence functions
- No turbulence
- No noise
- WFS integration time = 1ms integration + 1 frame delay (readout), pure integrator
- A standard SVD-based wavefront reconstructor was used

2. Telescope Static Errors

2.1. Segment Figures

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. 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 Phasing Camera System (PCS) 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.

The wavefront maps for the AO simulation were taken from UFS measurements of all the Keck II segments when they 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. When averaged over all 36 segments from 2003 to 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. The numbers represent the best segment figure to date and we adopt them as our baseline.

The raw UFS centroid measurements were analyzed to make wavefront maps for each segment to be used as input to our AO simulations. 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. A Fourier reconstruction method that fits the wavefront directly was used to produce the maps. More details on the segment wavefront maps and its effects on AO systems can be found in the Keck Adaptive Optics Note by Neyman, Flicker and Panteleev [4]. These wavefront maps had zero piston and when combined, they represent the Keck telescope with perfect phasing.

2.2. AO Correction of Segment Figure 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 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 were stitched together with an amplitude map for the Keck pupil determined from the gray pixel approximation [5]. 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. The original segment maps individually have zero piston and when they are combined, they model the primary with zero phasing error. 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 1 and Figure 2. The same colormap is used in both images.

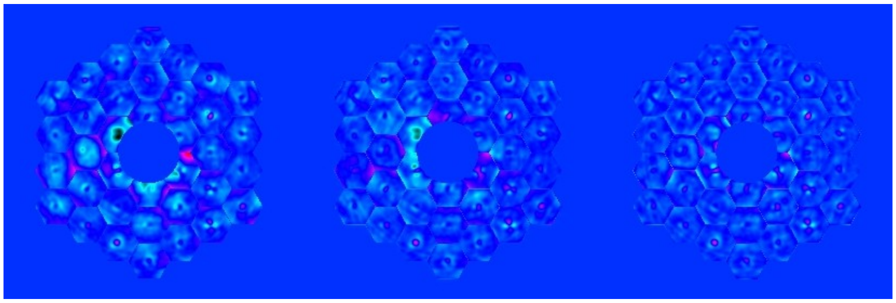

Figure 1: An example of AO correction with the 20xx20 AO system of Table 1. The images are from left to right: the uncorrected segment aberrations, after AO correction, and after optimal fitting of the AO actuators to the input wavefront.

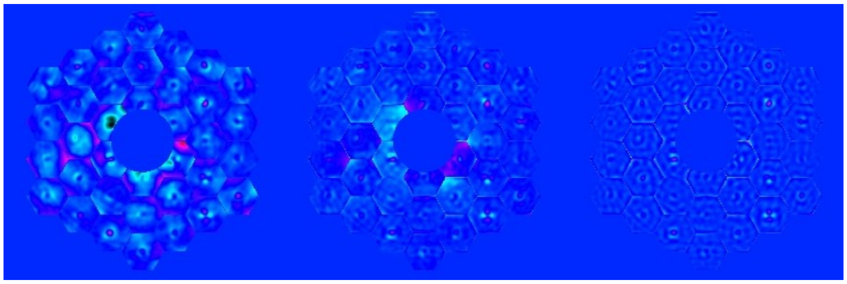

Figure 2: An example of AO correction with the 48 x 48 AO system of Table 1. The images are from left to right: the uncorrected segment aberrations, after AO correction, and after optimal fitting of the AO actuators to the input wavefront.

2.3. Segment Phasing Errors

The segments of the Keck telescope must be aligned to the theoretical "parent" primary mirror surface to a fraction of the wavelength of light. The PCS broadband and narrowband phasing algorithms accomplish this alignment. The broadband algorithm has a larger capture range but lower accuracy than the narrow band algorithm. A specialized Shack-Hartmann masks and optical filters enable the measurement of the phase difference between segments. The details of the hardware, the algorithms, and typical phasing results are given in reference [6] and reference [7]. The accuracy of the narrowband algorithm is 12 nm rms. The broadband algorithm accuracy is 60nm rms. It is important to note that references 6 and 7 report phasing errors as surface deformations. As such their reported errors are one half the errors in this report which uses wavefront errors throughout. As noted by Chanan et al. [7], an interaction between the segment figures and the ability to phase the telescope exists. This comes about because the PCS system is in fact minimizing the difference between segment edges, not the overall wavefront error of the telescope. We did not model this interaction as part of this study. Phasing algorithms that minimize the overall wavefront error are a subject of ongoing work by Mitch Troy and Gary Chanan.

Using the same methodology that was used to simulate the effects of segment figures in the previous section, we produced wavefront maps of an otherwise perfect primary with various amounts of rms phasing error between segments, see Table 2 . An order 49x49 AO system was used to correct these errors 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 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. The errors typical after phasing and AO correction are 3 nm rms (narrowband) and 19 nm rms (broadband).

Table 2: Simulation results for correction of primary segment phasing (piston) errors with an order 49x49 AO system.

Uncorrected Piston (rms nm)	Uncorrected wavefront (rms nm full aperture)	Corrected Wavefront (rms nm)	Optimal Act. Fitting (rms nm)
10	8.5	3	2
20	17.5	6	4
40	34	13	8
60	52.5	19	12
80	70	22.5	16
100	88	33.5	20

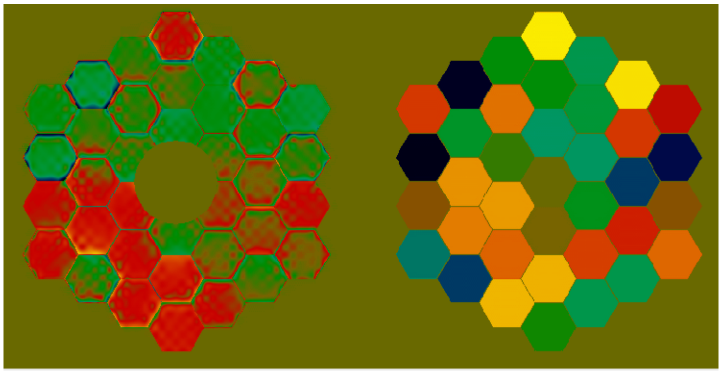

Figure 3: Input segment phasing error, right hand image, of 100 nm rms and after correction by an order 49x49 AO system, left hand image.

3. Telescope Dynamic Errors

The presence of vibration in the Keck telescope segments was noted as early as 1994 [8,9]. The effect was extensively studied by Dekens [10] in his PhD thesis using optical measurement with a high speed CCD camera. Dekens reported both tip tilt motion of individual segments and full aperture tip tilt motion with the dominate frequency being located around 29 Hz. This frequency is typical of electrical motors that run at 1750 revolutions per minute used throughout the observatory.

During the installation of the Keck interferometer a large amount of effort was put forth by both the Keck staff and JPL team [11,12] to understand the vibration problem and reduce its effects. These efforts were successful and the interferometer is able to meet its fringe tracking specifications. The interferometer success was due to three efforts:

1) A reduction in vibrations by isolation of vibration sources such as pumps and air conditioners
2) The use of accelerometers to measure vibrations and correct for them in real time
3) The use of metrology and other control loops to remove the effects of vibration

The use of accelerometers by the interferometer to reduce tip tilt vibrations did not prove successful although it has indicated that the worst offender is likely the secondary mirrors, with the tertiary also providing some jitter. The interferometer has been able to suppress the residual angular beam wander that is not corrected by the AO systems with its own tracking systems. The jitter is removed by the Keck Angel Tracker (KAT) which is composed of a tracking mirror and position sensitive detector for each telescope located in the Keck basement. Although the sampling frequency of this servo is as low as 100Hz, the controller is able to reject a significant amount of 29 Hz by the use of a specialized control technique. This method makes use of the fact that the vibration is located at a precise frequency of 29 Hz. Mark Colavita [13] has named this technique the “parametric oscillator” and it is similar to the standard method of “higher harmonic control” used in other dynamic systems.

More recently, an independent survey of vibrations at Keck was made by Tomas Erm [14,15] of the Thirty meter Telescope project. The measurements by Erm confirmed that the dominate vibration is centered around 29Hz, an attempt to determine if this is a resonant frequency of the telescope azimuth and elevation drive was inconclusive.

The current Keck adaptive optics systems [16] also observe 29 Hz vibrations in both full aperture tip tilt and higher order phase aberrations. The AO error budget for tracking bright stars is much higher [16] than would be expected from the simple scaling laws of Greenwood. All the above sources have reported that the 29 Hz vibration amplitude is highly variable with time although the frequency is very stable.

3.1. Telescope Full Aperture Tip and Tilt

Our methodology for this study has been to determine the probable effect of telescope errors on NGAO performance and from that develop NGAO vibration specifications. After comparing all the available data sources from the previous section, we adopted an overall power for 29 Hz of 0.015 arc seconds rms. This level is consistent with measurements from Dekens, Erm, the interferometer accelerometers, and the KAT mirror tracking commands. We adopted the spectrum given by Erm as it appears to be the highest resolution measuremen to date made of vibration spectrum around 29Hz. Erm has found that the 29 Hz line consist of three 3 peaks: 28.3, 29.06, and 29.68 Hz. The vibration peaks were modeled as Lorentzian functions. Simulations were run for the baseline vibration level and 2 times and one half the baseline values. The results from the NGS AO simulation correcting for only tip tilt motions vibrations (no atmosphere) showed no significant rejection when the sampling rate was less than 300 Hz. This is not surprising given that we used only a simple integral control law in the simulation, which typically have error rejection bandwidths of only 1/10 to 1/20 of the sampling frequency. The low level of error rejection has profound implications for sky coverage where one wants to use the faintest possible natural guide stars. We have not simulated specialized control techniques such as the Keck interferometer’s parametric oscillator [13] or a Kalman filter [17]. Both of these techniques have been shown to be a useful way of suppressing vibrations.

3.2. Telescope Focus from Secondary Mirror Vibrations

Given that the telescope secondary has been shown to be a major cause of full aperture tip tilt error, it is not surprising that it also moves in piston. Based on measurements from the interferometer accelerometer and by Erm, we adopted an rms piston motion for the secondary of 1 micron of rms piston which results in 20 nm rms wavefront error at the Nasmyth focus. It is not clear at present how much of the focus errors can be corrected by high bandwidth sensing of the LGS and how much will come from NGS sensing at lower bandwidths. We have not pursued this issue further.

3.3. Segment motions

As mentioned in the introduction of this section, the individual segments have been observed to tip and tilt individually. Dekens [10] noted some partial correlation between segment motions. Erm [15] noted a large correlation between segment motions when analyzing data from the actuator control systems (ACS) fast data capture mode. This result has been disputed by Troy [18] based on his experience with a comparison study [19] of AO data and fast data capture of the ACS system. For the present study, we have assumed that the segment motion is completely uncorrelated between segments. Further study in this area is recommended for the future.

Both studies estimate that the rms segment motion may be 0.015 arc seconds for a typical segment. For our computer simulation, we adopted a power spectrum for segment motion composed of three peaks at 28.3, 29.06, and 29.68 Hz. The spectra were normalized such that the rms motion would be 0.015 arc seconds. We also ran tests with powers of 0.5, 2, and 4 times this baseline value. The input spectrum is shown in Figure 4. The segment motions were assumed to be completely uncorrelated.

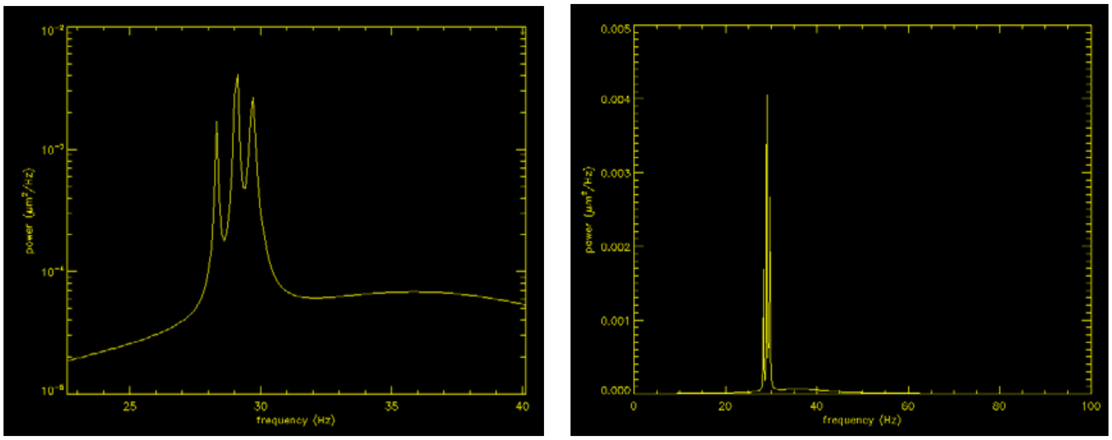

Figure 4 The baseline power spectrum used for simulations of segment motion, the left hand image is expanded to show the 3 peaks.

The segment motions simulations were undertaken using standard Monte Carlo simulation techniques for AO system studies. The typical atmospheric phase screen was replaced with a phase mask representing the 36 Keck segments, each with a different tilt time series taken from a random draw of the input power spectrum. A single time step ‘snap shot’ from a simulation is shown in Figure 5. The images across the top row represent the input motion of the segments and the bottom row represents noise free correction with an AO system having 49 actuators across the Keck primary. The power input increases in the columns of the figure going from left to right.

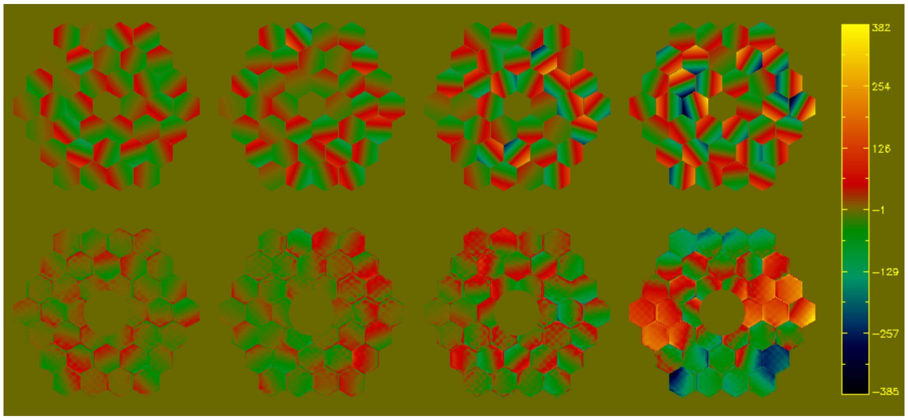

Figure 5. A single frame 'snap shot' of the segment motions simulation. The top row represents the input phase aberration and the image directly below is after correction by the AO system..

The residual (bottom row in Figure 5) after AO correction shows low order aberrations that are not present in the input phase. The AO system appears to amplify correlations between segments resulting in a residual wavefront that has aberrations resembling lower order spatial modes. This is most noticeable in the far right hand column when the input disturbance is large. The possibility of this phenomenon was first mentioned by Dekens [10]. The wavefront sensor and reconstructor normally used in AO systems assumes that the slope measurement represents a continuous wavefront. Unfortunately, with segment motion, this is not the case. When segments are perfectly synchronized in their motion, the AO system reconstructs full aperture tilt. After correction, the residual wavefront shows a "stair step" appearance, see Figure 6 right hand image. If the segment motions are partially correlated, then low order wavefront aberrations result, see Figure 6 left hand image.

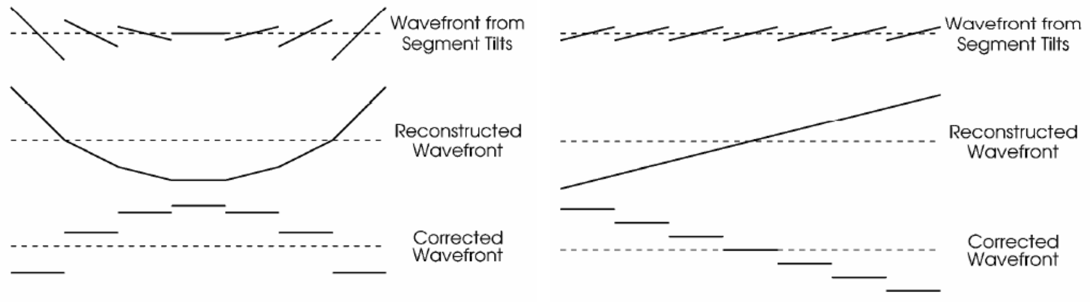

Figure 6. When segment vibration is perfectly synchronous, the AO correction shows a "stair step" appearance, right hand image. When the motion is partially correlated, the resulting wavefront shows low order aberrations, left hand image.

The computer simulations were run for various AO systems parameters including number of actuators and system update rate. Results typical of AO systems planned for NGAO at Keck are given in Table 3. The number of actuators was set at 48 across the pupil and the update rates of 1 kHz and 500 Hz were simulated. An infinite bandwidth simulation was also run. For the infinite bandwidth simulation, the correction is only limited by the number of actuators on the deformable mirror. We label the result as fitting error in analogy to a similar error when correcting a wavefront distorted by the atmosphere. For future AO systems that attempt to correct the wavefront to 150 nm rms or lower, segment vibration errors must be considered but will not be the dominant error term. The NGAO error budget is already carrying an error term for uncorrectable segment dynamic errors of 23 nm rms.

Table 3. Summary of simulation results when correcting segment vibrations. All results are for an AO system with 49 actuators across the Keck pupil. The fitting error is the infinite bandwidth (no delay) result.

Uncorrected Tilt (rms milli arc sec)	Uncorrected Wavefront (rms nm)	Corrected Wavefront 1000 Hz (rms nm)	Corrected Wavefront 500 Hz (rms nm)	Fitting Error (rms nm)
11.8	31	17	25	10
15.7	44	25	36	14
22.2	62	42	55	20
31.4	87	92	93	28

Segment vibrations of the primary mirrors of the Keck Telescopes can be partially corrected by an AO system. The AO correction results in a "stair stepped" residual wavefront. Typical errors after AO correction are significant but comparable to other terms in the error budget for future AO systems.

4. Mitigation Strategies and Future Work

The main results of this trade study can be summarized as:

- Full aperture tip tilt errors could dominate tip/tilt error budget
  - Resulting in poor sky coverage
  - "Encircled Energy Science" might be impacted less
- Segment motion
  - Acceptable error, comparable to NGAO June 2006 proposal, and current error budget
- Segment figures
  - Acceptable error, comparable to NGAO June 2006 proposal, and current error budget
- Segment phasing
  - Small, needs to be added to NGAO budget, interaction with figure errors not tested

The trade study WBS asked if a large field of view sensor could be used to provide "image stabilization" for NGAO. For a baseline we assume that the stars are outside the corrected field of view of NGAO and therefore have a seeing limited image size. For simplicity we assume conventional low noise detectors such as optical CCD and a standard proportional integral controller, the sampling frequency must be between 300 to 600 Hz in order to have significant error rejection at 29 Hz. Further, the spots are seeing limited, therefore the signal to noise ratio for good tracking requires bright guide stars of the order visual magnitude 14. At the galactic north pole, the standard star models predicts that the acquisition (patrol) field must be of the order 20 arc minutes diameter for high sky coverage. If the advanced control methods allowed the system to run at sample rates of 100 Hz then stars of visual magnitude 16 would be useable. High sky coverage would only require a 5 arc minute patrol field. This appears more consistent with the low order wavefront sensor field of view. An image stabilization system could provide jitter reduction for NGAO, it would be best located before the AO relay so that it could access a large part of the telescopes field of view.

Our recommendations would be

1. Perform additional analysis of the gains in tracking beyond the simple PI controller considered in this study. Examples would be parametric oscillators and Kalman filters.
2. Understand what might be done to reduce 29 Hz vibration in telescope segments, secondary, and tertiary.
3. Continue to investigate ways to improve the segment figures. Leverage information from the TMT study of warping harness at Keck.

Based on this study, it appears that full aperture tilt needs to be given higher priority in the NGAO design and in mitigation efforts with the current Keck AO system. Other telescope wavefront errors appear to be accounted for correctly in the NGAO error budget. It would be advantageous to reduce 29 Hz vibration drivers such as pumps and motors even further.

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