Computer Simulations of Adaptive Optics Point Spread Functions for NGAO

KECK ADAPTIVE OPTICS NOTE 466

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March 2, 2007

ABSTRACT

AO computer simulations were undertaken during the spring of 2006 to support generation of the science use cases for the Next Generation Adaptive Optics (NGAO) proposal to the Keck Science Steering Committee. The following document was originally published as Section 16 of the NGAO Proposal for Design and Development [1].

1. Introduction

Several sets of point spread functions (PSF) for the NGAO system were generated using computer simulations. The simulations were intended to represent the image morphology of various high Strehl AO systems for determining the feasibility of example science cases. The simulations were not intended to be high fidelity representations of any “point” or system design. Many effects that must be evaluated in the final system error budget are not currently included in the computer models and were left out of the PSF simulations. However, it is hoped that the simulations are still useful for determining the level of correction that is needed for a particular science case to be feasible.

2. Linear Adaptive Optics Simulator Code (LAOS)

The PSF were generated using a computer simulation developed at the Thirty Meter Telescope project office by Brent Ellerbroek and Luc Gilles [2]. The computer code: Linear Adaptive Optics Simulator (LAOS) is a Monte Carlo simulation of a basic multiple laser guide adaptive optics system. Like all Monte Carlo simulations, LAOS determines the performance of an AO system by using random number generators to simulate random processes in the physical system then averaging over these random events to determine the likely behavior of the system. LAOS uses random number generators to simulate atmospheric turbulence and noise in the photo detection process. Each randomly generated wavefront is measured and corrected using the computer in a way that is analogous to how it is corrected by the actual AO system.

The LAOS simulation is coded in the MATLAB computer language, a high level language optimized for numerical computation. The LAOS simulation’s distinguishing feature from other AO Monte Carlo simulations is its minimum variance wavefront estimators using sparse matrix techniques [3]. The user can select between two sparse matrix solvers, a computationally efficient multigrid preconditioned conjugate gradient (MG-PCG) algorithm [4] or (ii) a sparse Cholesky solver [3]. Further details of the LAOS code are discussed in its user manual published by TMT [2]. The LAOS code has been checked by Ellerbroek and Gilles, against analytical models of AO performance on 8-m telescopes.

2.1. Tomography

The correction of the atmospheric turbulence is performed in two steps. The first is an estimation of the three dimensional turbulence above the telescope (tomography), followed by a fitting of the estimate to user selectable number of tip/tilt and deformable mirrors. In the tomography step, the volume turbulence is estimated from a set of NGS and LGS measured with Shack-Hartmann sensors. This measurement is then used to generate the commands to a set of tip/tilt and deformable mirrors so that the residual wavefront error is minimized over a set of user selectable scientific observation points in the field of regard of the telescope. LAOS fitting step can be performed for both multiconjugate scenarios (MCAO) using a set of mirrors effectively located at different attitudes above the telescope pupil or multi object scenarios (MOAO) where independent deformable mirrors are used to correct each science direction.

2.2. Atmospheric model and propagation

The atmospheric turbulence is modeled as a series, typically 7, of the infinitely thin phase perturbations or phase screens located at altitudes above the telescope pupil corresponding to strong layers of atmospheric turbulence. Each screen is a statically independent random realization of the turbulence. The statistics of each screen are matched to Kolmogorov turbulence with or without a finite outer scale. The time evolution of the atmosphere is simulated by shifting the screen between updates of the AO control loop that are consistent with the wind velocity measured at altitude. The wavefronts for both NGS and LGS are calculated by summing the phase perturbations along ray paths from the source through the phase screens to the entrance aperture of the telescope. The LGS wavefronts are rescaled to simulate the conical ray paths that finite range LGS take through the atmosphere. The ray optics model of atmospheric propagation is generally considered appropriate when observing at astronomical sites where the wavefront amplitude variations (scintillation) are small.

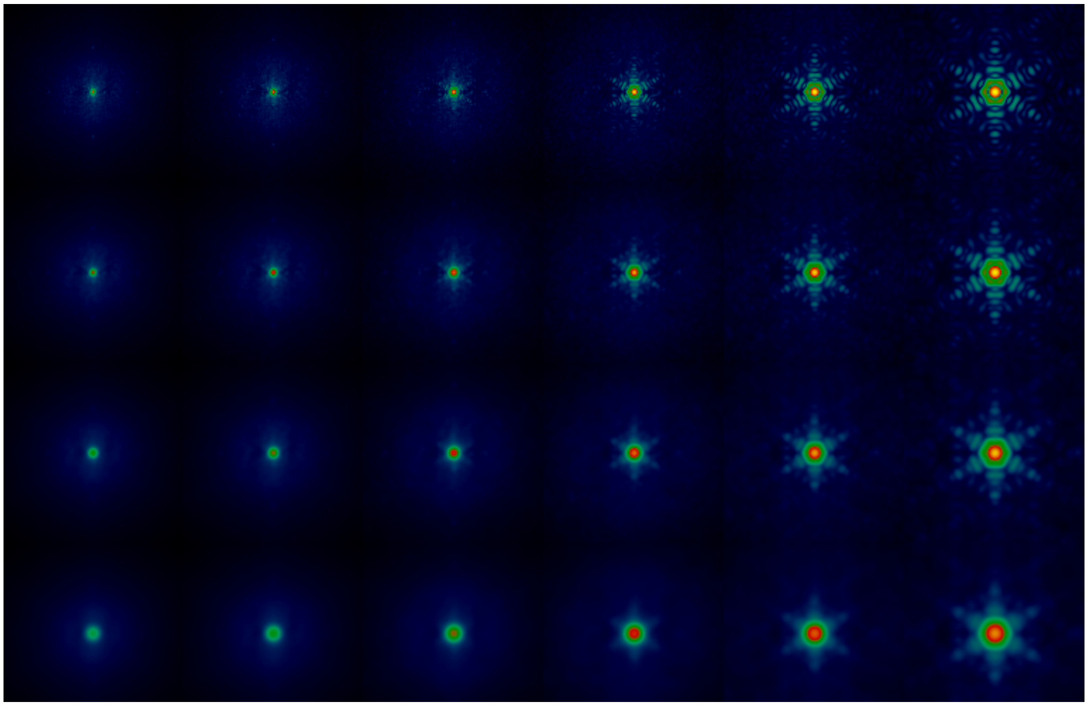

Figure 1: Grid of 120 nm PSF from LAOS simulations, each column represents a different wavelength band. Columns starting from the left are wavelengths of 0.55 μm, 0.65 μm, 0.85 μm, 1.2 μm, 1.65 μm, and 2.2 μm, corresponding to the centers of the V, R_c, I_c, J, H, and K photometric bands. Each row corresponds to different tip/tilt errors starting at the top, single axis tip tilt errors are: 0 mas, 8 mas, 15 mas, and 25 mas. Each individual PSF is approximately 0.8 arc seconds on a side. The total rms wavefront error for the second row down from the top is 120 nm.

2.3. DM and WFS models

Any simulation on an AO system must simulate the performance by a series of approximations. The LAOS code simulates the actuators on deformable mirrors by linear splines between actuator locations. This results in some increase in the AO system actuator fitting error over actuator models that use Gaussian functions or higher order polynomials.

The wavefront sensor is simulated by the calculation of the average gradient of the wavefront phase over the subaperture area (technically it is the line integral of the phase around the boundary, but these are equivalent by Green's theorem). This gradient[1] is used as the noise free measurement. Other AO simulations actually calculate the image from each lenslet subaperture by a series of parallel diffraction calculations, one for each lenslet. In LAOS, using the wavefront gradient directly, results in a sensor model that is perfectly linear for all wavefront slopes. Further the response is not a function of the seeing or the size of the LGS spot and as such is immune to calibration errors that occur when the spot size is different than the spot size used to calibrate the system. Noise in the measurement process is simulated by a Gaussian noise added to the gradient measurement. The user can set this value to simulate the magnitude of the guide star. For laser guide stars, the effects of spot elongation are modeled by a directionally dependent noise for the gradient measurements.

The AO control loop delay can be set to zero in LAOS to simulate perfect temporal correction (infinite bandwidth control system). Delays can also be added to the control loop to simulate the delay between sensing and correction that occur in any realistic control system. LAOS is unique in that it uses wavefront estimators (reconstructors) that require knowledge of the open loop wavefront error. The LAOS simulation estimates the open loop wavefront error from the closed loop measurements and the shape of the deformable mirrors. It has been shown that this type of control results in closed loop stability and robustness against system errors, see Gilles 2005 [5] for more detail on pseudo open-loop control.

Error Term	Point Design	PSF simulation	Comments
Atmospheric Fitting Error	Yes	Yes	
Bandwidth Error	Yes	Yes	
High-order Measurement Error	Yes	Yes	
LGS Tomography Error	Yes	Yes	
Multispectral Error	Yes	No	
Scintillation Error	Yes	No	
WFS Scintillation Error	Yes	No	
Uncorrectable Telescope Aberrations	Yes	Partial	Only lower order Zernikes
Static WFS Zero-point Calibration Error	Yes	No	
Dynamic WFS Zero-point Calibration Error	Yes	No	
Residual Na Layer Focus Change	Yes	No	
DM Finite Stroke Error	Yes	No	
DM Hysteresis	Yes	No	
High-order Aliasing Error	Yes	Yes	
Uncorrectable AO System Aberrations	Yes	No	
Uncorrectable Instrument Aberrations	Yes	No	
DM-to-lenslet Misregistration	Yes	No	

Table 1: The various terms used in the point design error budget for NGAO from KAON 400 [1]

2.4. Segmented telescope primary

The LAOS simulation has the ability to simulate the effects of static aberrations located at the telescope primary mirror. The aberrations are defined on segments that tile the entrance pupil of the telescope. The aberrations can be the result of positioning the segments relative to one another and higher order aberrations of the individual segment shapes or "optical figures" up to fifth order Zernike polynomials. The rms values of these segment errors are used to generate a random set of errors for the segments on the telescope. The same error set was used for all simulations. The rms errors used are typical of measurements from the PCS system on the two Keck telescopes. It is important to note that these errors do not correspond to the exact values on either Keck I or Keck II but should give a reasonable estimate to the performance expected from using AO systems behind one of these telescopes.

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[1] The latest release of LAOS in spring 2006 includes both a gradient model and a physical optics model of the wavefront sensor; we will be using these new features in future trades studies for the NGAO system design.

3. Simulations for NGAO science case

All simulations for the NGAO science case were done using the November 2005 release of the LAOS code. It was modified to accommodate a Keck pupil in the PSF computations but the AO simulation was conducted on a round 11 m pupil. The resulting AO corrected wavefront was masked to a Keck segmented pupil and Fourier transformed to produce the final PSF. The segment gaps were accounted for using the gray pixel approximation of Troy and Chanan [6]. A circular secondary obscuration was added to the final pupil mask; secondary supports (spiders) were not modeled.

3.1. Simulation of narrow field of view AO, on axis PSF

The original baseline for NGAO (then KPAO) performance was 120 nm rms wavefront error delivered to the user. This level of performance is a significant enhancement over the current Keck NGS performance, 250 nm, and the LGS performance, 350 nm. As mentioned in the introduction, these simulations were undertaken to simulate the performance gains when using an AO system with sub 200 nm rms wavefront error. Some terms (see Table 1) were not included in the modeling of the PSF but they are included in error budgets for the current proposed NGAO point design.

The terms left out of the PSF modeling account for about ~80 nm in the higher order error budget of the point design. The terms included in the point design error budget and in the simulations would total about ~70 nm in the point design. In order to achieve the mandated 120 nm for the simulations of the PSF, the AO systems that were simulated have fewer actuators, more noise, lower bandwidth, and fewer lasers than in the NGAO point design. The resulting higher order error was 90 nm rms; when this is combined with an 8 mas tracking blur the resulting total wavefront error is 120 nm.

In addition to the baseline wavefront error of 120 nm, similar simulations were run with 140 nm rms wavefront error and 170 nm wavefront error (these are sums of higher order wavefront error and tracking errors of 5 mas). A single LGS simulation was also run that produced 250 nm wavefront error as a simulation of the “best possible” performance with the upgraded Keck I LGS AO system. The sets of simulations all represented one second of integration. A set of 10 second integrations was produced for the 120 nm wavefront case. These PSF were similar so that it was felt that the one second integration time was an adequate representation. A grid of simulation PSF for the 120 nm case is shown in Figure 1.

3.2. High contrast simulations

At the request of the science teams, some additional simulations were produced to assess the contrast obtainable when observing dim targets. A typical science observation of this type would be the detection of a dimmer companion in a binary brown dwarf. The simulations included running the narrow field case for a five second integration. Applying a Blackman window to the pupil of the telescope simulated the effects of an idealized coronagraph. This apodization effectively suppresses diffraction at angular scales greater than ~5 times the diffractions limit (λ/D) at the expense of degrading angular resolution. While such an apodization is not easily constructed, it is similar in performance to a Lyot coronagraph and is simpler to simulate. In addition, the apodization still allows the central star to be visible in the simulation PSF, but with suppressed wings of the diffraction pattern. This should make it possible to combine the PSF with a model of the science object.

3.3. Seeing variability simulations

In addition to the KAON 237 based simulations for 120 nm wavefront error with good seeing, a set of ten one second simulations with different values of r_0 were produced to estimate the effects of observations made in changing atmospheric conditions. The values of r_0 range from 9 cm to 24 cm at 0.5 μm wavelength.

4. Future simulations

The current set of PSFs is in approximate agreement with the point design error budget. This is not surprising since the PSFs were simulations to match the wavefront error baseline and not to model an exact AO system. At present, almost 90 nm of wavefront error (only increase high order wavefront error from 100 to 135 nm rms) is not included in the simulations. We will be working with the TMT project office to include these effects in the LAOS simulations. The present May 2006 LAOS release includes a physical optics model for the wavefront sensor and now includes errors for three of the eleven terms not currently included in the simulation. The other five error terms will be added over the summer and fall of this year. It is not planned to include either scintillation or multispectral error in the LAOS simulation but these are relatively small terms in the final error budget.

References

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