

# NGAO Wavefront Error Budget Keck Adaptive Optics Note XXX

Matthew Britton, COO Richard Dekany, COO

June 11, 2007

## 1 Wavefront Error Budget Spreadsheet

This study was conducted using a Microsoft Excel spreadsheet developed over several years as an engineering tool for evaluation of adaptive optics system performance. The primary purpose of the spreadsheet is to compute adaptive optics and instrumental wavefront error budgets for different architectures and science cases, along with Strehl ratios computed using the Marechal approximation. The spreadsheet also computes ensquared energy fractions using a core/halo model for the point spread function, and calculates sky coverage estimates for tip tilt guide stars employed in laser guide star architectures from common star density models. This study used version 1.18 of the spreadsheet.

The spreadsheet functionality is embedded in a series of 35 individual Excel sheets, listed in Table 1. Roughly speaking, each sheet effects calculations related to a particular error term, and these individual error terms are RSS'd together to provide an estimate of the adaptive optics error budget. The Excel solver may be used to perform a conjugate gradient search that finds the system parameters which optimize the value of another parameter. Examples of parameters that may be varied include the high order wavefront sensor frame rate, the laser asterism radius, and the brightness and angular offset of the tip tilt guide star. In this study, the Excel solver was used to maximize the H band Strehl ratio.

Sheet Name Description

Input Summary Selection of science case and system architecture
Optim Wavefront error budget table, used to run optimizer
EE Ensquared energy estimates from core/halo PSF model
Uncorrectable static and dynamic telescope aberrations

Atm Vertical turbulence and wind profiles

HO Flux NGS photodetections in high order wavefront sensor LGS Flux LGS photodetections in high order wavefront sensor

HO Cent Centroid error in high order wavefront sensor HO Meas Measurement error in high order wavefront sensor

FA Tomog Error arising from tomographic reconstruction from multiple guide stars

Ast Def Deformation of LGS asterism due to uplink beam wander Na H Error arising from altitude changes of the sodium layer

Fit High order fitting error Alias High order aliasing error

Stroke Tip tilt and deformable mirror stroke requirements Hyst Error arising from deformable mirror hysteresis

Go\_to Go-to control error for MEMS mirrors

Dig Actuator digitization error

TT Flux NGS photodetections in tip tilt sensor
TT Meas Measurement error in tip tilt sensor

Bandw High order and tilt servo errors, error arising from telescope pointing jitter

Scint Errors arising from scintillation in the high order wavefront sensor

Aniso Errors arising from anisoplanatism CA Centroid anisoplanatism error

Chromatic Errors arising from chromatic dispersion Atm Dispersion Atmospheric dispersion calculations

Cal Calibration errors

Notes Notes

Sky Coverage Calculation of sky coverage

Spagna Near infrared star density model from NGST study

Bachall Visible star density model

Parenti Near infrared star density model from the Infrared Handbook Allen Visible star density model from Allen's Astrophysical Quantities

Specific Fields Notes on specific science cases

Table 1: Individual pages in the Excel spreadsheet. The first page is used for selection of the science case and AO architecture, and the second is used for running the optimizer, and presents a summary of the wavefront error budget. The remaining pages effect calculations of the various error budget terms using models of the underlying error processes. In this spreadsheet, errors are assumed independent, and are added in quadrature to arrive at an overall error budget.

Science Case	AO Architecture
Io	NGSAO
Kuiper Belt Objects	LTAO
Exo Jupiter	LTAO
Extended Groth Strip	MOAO
Galactic Center	LTAO

Table 2: NGAO science cases and adaptive optics architectures. The three architectures under consideration are natural guide star AO (NGS), laser tomography AO (LTAO) and multiobject AO (MOAO).

Layer Height	Layer Strength	Wind Speed
(m)	$(\mathbf{m}^{1/3})$	(m/s)
0	5.85e-13	6.4
2100	1.12e-13	10.5
4100	1.41e-14	15.6
6500	3.13e-14	18.4
9000	5.18e-14	14.6
12000	5.09e-14	7.5
14800	3.20e-14	4.5

Table 3: Turbulence and wind profiles assumed in these error budgets. The integrated turbulence profile has a value of 2.61e-13 m<sup>1/3</sup>, with  $r_0 = 18$  cm, a  $\theta_0 = 1.37$ ,  $d_0=2.4$  m, and  $f_G=41$  Hz.

## 2 Science Cases

This study presents optimal error budget solutions for five science cases selected as representative of the NGAO system. These five science cases, together with the adaptive optics architecture required to carry out the observation, are listed in Table 2. An error budget was developed for each science case that maximized the H band Strehl ratio when appropriate system parameters were allowed to vary. For each case the variable parameters are tabulated, along with any constraints placed on these parameters. (e.g. positivity constraints or physical limits on device characteristics.) The resulting optimal error budget is tabulated for each science case. These error budgets were computed assuming that the observations were to be carried out at zenith, with the baseline turbulence and wind profile listed in Table 3 (the CN N2 profiles).

Versions of the Excel spreadsheet are available for each science case at URL http://www.oir.caltech.edu/twiki\_oir/bin/view.cgi/Keck/NGAO/SystemArchitecture For each science case, the spreadsheet contains the tabulated set of optimization parameters. This is intended to permit users to download and inspect the spreadsheet for each science case without the need to modify and optimize any parameters.

### 2.1 Io

An NGAO wavefront error budget for observations of the planet Io is shown in Figure 1. Io is used as the tip tilt and high order natural guide star for this science case. The AO frame rate was capped at 2.5 kHz and the number of high order subapertures was fixed at 64 across the pupil. In this scenario there were no optimization constraints, as shown in Table 4. The optimizer provided the solution in Figure 1 with a high order wavefront error whose largest term is uncorrectable telescope aberrations and a tip tilt error dominated by residual telescope pointing jitter. This scenario delivers an H band Strehl ratio of 73%.

Variable Parameters High order integration time ≥ .0004 sec Optimized Parameter H band Strehl Ratio =73%

Table 4: Optimized parameter and constraints for the Io observing scenario.

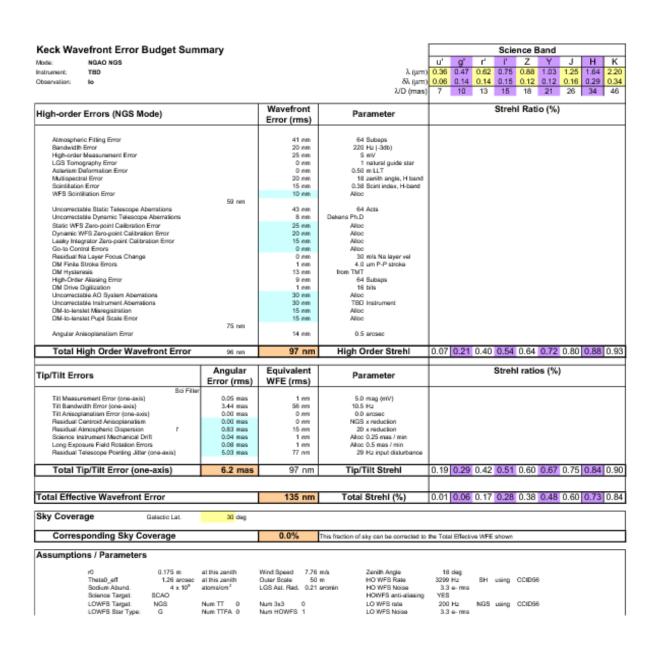


Figure 1: Wavefront error budget for the Io observing scenario.

### 2.2 Kuiper Belt Objects

An NGAO wavefront error budget for observations of a Kuiper Belt Object is shown in Figure 2. This observational scenario uses 6 laser beacons in an LTAO configuration, with a natural guide star used for tip tilt guiding. H band Strehl ratio was optimized by allowing the parameters in Table 8 to vary under the constraints indicated in this table. The optimizer chose a solution with a high order control loop rate of nearly 2.5 kHz and with the maximum number of subapertures. The optimal LGS asterism radius was about 30 asecs.

The tip tilt guiding parameters were optimized subject to the constraint of 10% sky coverage. With this sky coverage constraint, the optimizer chose a tip tilt guide star with mV=19.5 from a field of 70 asecs, and ran the tip tilt control loop at 550 Hz. These tip tilt guide star parameters are to be interpreted in a statistical sense, in that a guide star of visual magnitude  $\leq 19.5$  will be available in a field of size 70 asec over 10% of the sky.

In this error budget, the dominant term in the high order budget was tomography error. The dominant term in the tilt error budget is tilt anisoplanatism.

Variable Parameters	High order integration time	No Limit
	Subaperture width	$\geq .171 \text{ m } (\leq 64 \text{ subaps})$
	Tip tilt guide star brightness	No Limit
	Tip tilt integration time	No Limit
	Tip tilt guide star search radius	No Limit
	LGS asterism radius	No Limit
	Sky Coverage	=10%
Optimized Parameter	H band Strehl Ratio	56%

Table 5: Optimized parameter and constraints for the Kuiper Belt Object observing scenario.

#### Keck Wavefront Error Budget Summary Science Band NGAO LGS Mode: 0.88 1.03 1.25 1.64 2.20 0.36 0.47 0.62 0.75 Instrument: δλ.(μm) 0.06 0.14 0.14 0.15 0.12 0.12 0.16 0.29 0.34 (D (mas) 7 10 13 15 18 21 26 34 46 Observation: KBO ルD (mas) Strehl Ratio (%) Wavefront High-order Errors (LGS Mode) Parameter Error (rms) 64 Subaps 165 Hz (-3db) 150 W 6 beacon(s) 0.50 m LLT 18 zenith angle, H band 0.38 Scint index, H-band Atmospheric Fitting Error Bandwidth Error High-order Measurement Error 26 nm 41 nm LGS Tomography Error Asterism Deformation Error Multispectral Error Scintillation Error 72 nm 31 nm 20 nm 15 nm WFS Scintillation Error 10 nm Alloc 105 nm Uncorrectable Static Telescope Aberrations Uncorrectable Dynamic Telescope Aberrations Static WFS Zero-point Calibration Error 43 nm 11 nm 64 Acts Dekens Ph.D 25 nm 35 nm Alloc State WHS Zelo-point Calebration Error Dynamic WFS Zero-point Calibration Error Leaky Integrator Zero-point Calibration Error Go-to Control Errors Residual Na Layer Focus Change DM Finite Stroke Errors Alloc 15 nm 43 nm 20 nm 1 nm 4.0 um P-P stroke OM Hysteresis 13 nm from TMT High-Order Aliesing Error 64 Subapa 16 bits 14 nm High-Crose Assaing Error DM Drive Digitization Uncorrectable AO System Abernations Uncorrectable Instrument Abernations Alloc TBO instrument OM-to-lenslet Misregistration OM-to-lenslet Pupil Scale Error 15 nm Alloc 15 nm Alloc 95 nm 97 nm Total High Order Wavefront Error 172 nm High Order Strehl 0.00 0.01 0.05 0.13 0.23 0.34 0.48 0.65 0.79 142 nm Angular Equivalent Strehl ratios (%) Tip/Tilt Errors Parameter WFE (rms) Error (rms) Tit Measurement Error (one-axis) 19.5 mag (mV) 21.2 Hz Titl Bandwidth Error (one-axis) 1.71 mas 29 mm Till Bandwidth Error (one-axis) Till Anisoplanatism Error (one-axis) Residual Centroid Anisoplanatism Residual Atmospheric Dispersion Science Instrument Mechanical Drift Long Exposure Field Rotation Errors 2.84 mas 0.95 mas 0.14 mas 1.25 mas 48 nm 16 nm 3 nm 36 nm 34.9 arcsec 10 x reduction 20 x reduction Alloc 0.25 mas / min 70 mm Alloc 0.5 mas / min Residual Telescope Pointing Jitter (one-axis) 2.50 mas 42 nm 29 Hz input disturbance Tip/Tilt Strehl Total Tip/Tilt Error (one-axis) 0.22 0.32 0.45 0.55 0.63 0.70 0.77 0.85 0.91 5.7 mas 103 nm Total Effective Wavefront Error 199 nm Total Strehl (%) 0.00 0.00 0.02 0.07 0.15 0.24 0.37 0.56 0.72 Sky Coverage 30 deg Corresponding Sky Coverage 10.0% This fraction of sky can be corrected to the Total Effective WFE shown Assumptions / Parameters 0.175 m Wind Speed 7.76 m/s at this zenith Zenith Angle HO WFS Rate Theta0\_eff 1.26 arcsec at this zenith Outer Scale 50 m 2469 Hz 8H using CCID66 Sodium Abund. Science Target HOWFS Noise HOWFS anti-aliasing 2.7 e- ms NO $4 \times 10^{9}$ atoms/on<sup>2</sup> LGS Ast. Red. 0.52 arcmin MOAO LOWES Target: LOWES Star Type: 550 Hz SH using SNAP MOAO Num 3x3 LO WFS rate Num TTFA 0 Num HOWES 0 LO WFS Noise 4.5 e- ms

Figure 2: + Wavefront error budget for Kuiper Belt Objects.

### 2.3 Exo Jupiter with LGS

An NGAO wavefront error budget for observations of exojupiters is shown in Figure 3. This observing scenario utilizes six laser beacons in an LTAO configuration. The science target is used as the tip tilt guide star, and is assumed to have mV=13. The H band Strehl ratio was optimized by allowing the parameters in Table 6 to float under the constraints indicated in this table. The optimizer chose a solution with the maximum allowed number of subapertures. For this mV=13 science target, the limiting 2.5 kHz tip tilt control loop rate was chosen by the solver. Optimizing the H band Strehl ratio generated a high order control loop rate of about 2 kHz and a laser asterism radius of .14 amin.

The dominant terms in the high order budget were errors from fitting, tomography, uncorrectable static telescope aberrations, and go-to control errors. The tip tilt error budget was dominated by tilt bandwidth error.

Variable Parameters Subaperture width  $\geq .171 \text{ m } (\leq 64 \text{ subaps})$ 

Tip tilt integration time No limits
Tip tilt integration time  $\geq .0004$  sec
LGS asterism radius  $\leq 2$  amin  $\geq .08$  amin

Optimized Parameter H band Strehl Ratio 74%

Table 6: Optimized parameter and constraints for the Exo Jupiter LGS observing scenario.

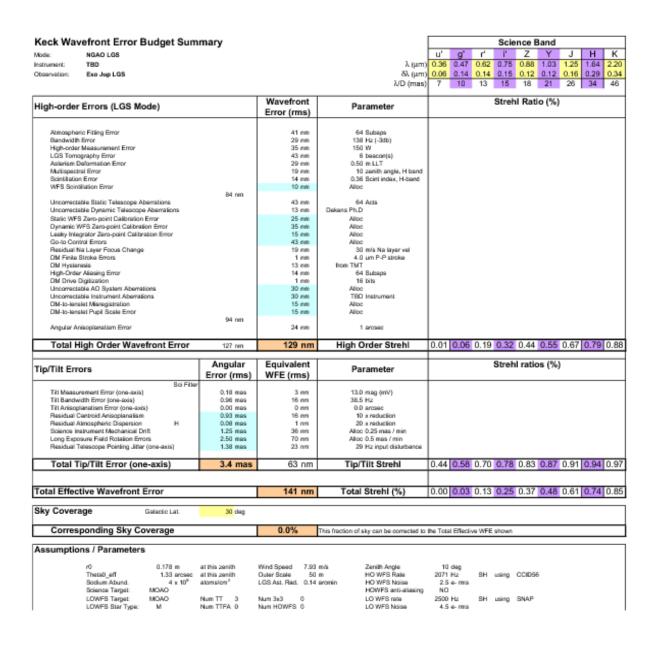


Figure 3: Wavefront error budget for Exo Jupiter LGS.

### 2.4 Extended Groth Strip

An NGAO wavefront error budget for galactic observations in the extended Groth strip is shown in Figure 4. This observing scenario uses six laser beacons in an MOAO or LTAO configuration. Optimization of the H band Strehl ratio yields a high order update rate of 2.25 kHz, the maximum allowed number of subapertures, and a laser asterism radius of .8 amin.

The requirement of 30% sky coverage yields a limiting tip tilt guide star magnitude of  $m_V=20.4$ , with a tip tilt guide star search radius of 50 asec and a tip tilt update rate of 400 Hz.

For this science case, the high order budget is dominated by tomography error. Due to the long integration times required in this observing scenario, the tilt error budget is dominated by mechanical drift and field rotation errors.

Variable Parameters High order integration time No Limit

Subaperture width  $\geq .171 \text{ m } (\leq 64 \text{ subaps})$ 

Tip tilt integration time  $\geq .0004$  sec Tip tilt guide star search radius  $\leq 120$  asec LGS asterism radius  $\leq 2$  amin Sky Coverage = 30%

Optimized Parameter H band Strehl Ratio 36%

Table 7: Optimized parameter and constraints for the Extended Groth Strip observing scenario.

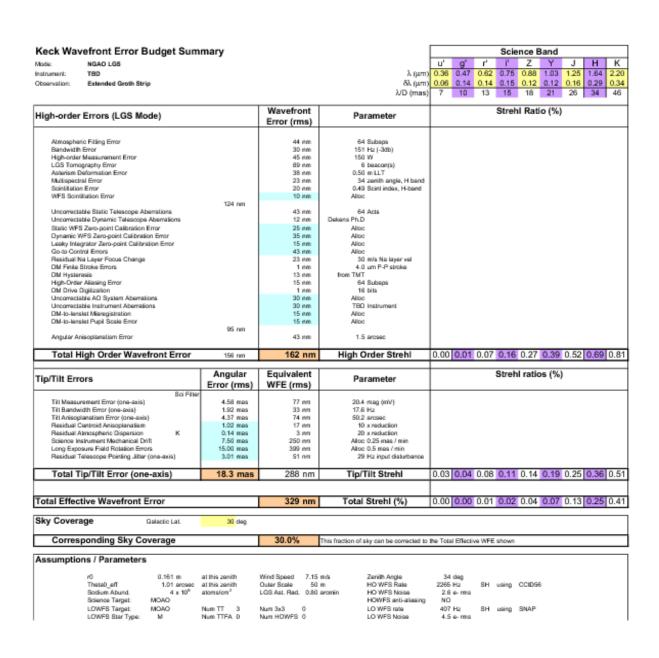


Figure 4: Wavefront error budget for Extended Groth Strip observing scenario.

### 2.5 Galactic Center

An NGAO wavefront error budget for observations of the galactic center is shown in Figure 5. This observing scenario uses an 6 beacons in an LTAO architecture, and employs the known tip tilt guide star IRS7. Maximizing the H band Strehl ratio yields a high order update rate of 1.7 kHz, 64 subapertures, and an asterism radius of .13 amin. The budget employs the maximum allowed tip tilt update rate of 2.5 kHz.

For this scenario, the high order budget is dominated by angular anisoplanatism across the 10 asec field. Tip tilt errors are negligably small in this case.

Variable Parameters High order integration time No Limit

Subaperture width  $\geq .171 \text{ m } (\leq 64 \text{ subaps})$ 

Tip tilt integration time  $\geq .0004 \text{ sec}$ LGS asterism radius  $\leq 2 \text{ amin}$ 

Optimized Parameter H band Strehl Ratio 36%

Table 8: Optimized parameter and constraints for the Galactic Center observing scenario.

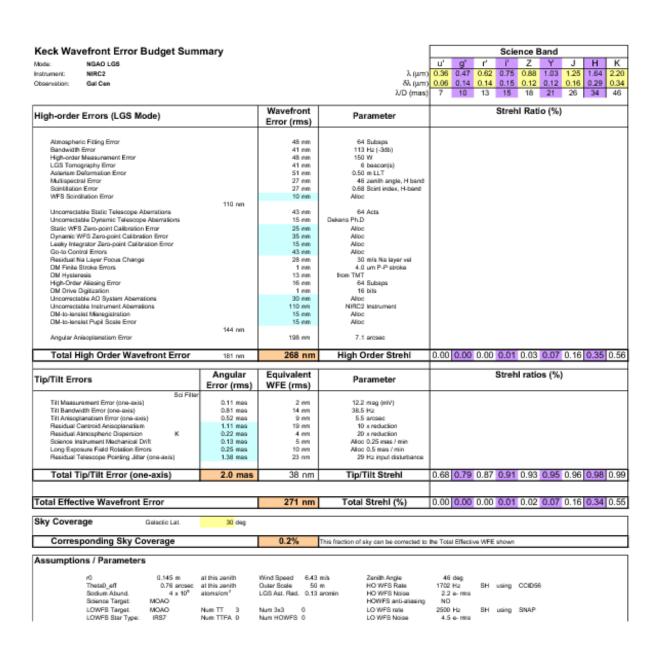


Figure 5: Wavefront error budget for the Galactic Center observing scenario.

# 3 Summary

This report summarizes the system performance predicted by the wavefront error budget spreadsheet for the five science cases considered in the NGAO study.