NGAO Wavefront Error Budget
Keck Adaptive Optics Note XXX

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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
Tel	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 (m)	**Layer Strength ($m^{1/3}$)**	**Wind Speed (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 $m^{1/3}$, 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	$\geq$ .0004 sec
Optimized Parameter	H band Strehl Ratio	=73%

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

Keck Wavefront Error Budget Summary

Mode:	NGAO NGS
Instrument:	TBD
Observation:	Io

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

High-order Errors (NGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		41 nm	64 Subaps
Bandwidth Error		20 nm	220 Hz (-3db)
High-order Measurement Error		25 nm	5 mV
LGS Tomography Error		0 nm	1 natural guide star
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		20 nm	18 zenith angle, H band
Scintillation Error		15 nm	0.38 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	59 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		8 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		20 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		0 nm	30 m/s Na layer vel
DM Finite Stroke Errors		1 nm	4.0 um P-P stroke
DM Hysteresis		13 nm	from TMT
High-Order Aliasing Error		9 nm	64 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		30 nm	Alloc
Uncorrectable Instrument Aberrations		30 nm	TBD Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	75 nm		
Angular Anisoplanatism Error		14 nm	0.5 arcsec
Total High Order Wavefront Error	96 nm	**97 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.07	0.21	0.40	0.54	0.64	0.72	0.80	0.88	0.93

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.05 mas	1 nm	5.0 mag (mV)
Tilt Bandwidth Error (one-axis)		3.44 mas	56 nm	10.5 Hz
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS x reduction
Residual Atmospheric Dispersion	r'	0.83 mas	15 nm	20 x reduction
Science Instrument Mechanical Drift		0.04 mas	1 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.08 mas	1 nm	Alloc 0.5 mas / min
Residual Telescope Pointing Jitter (one-axis)		5.03 mas	77 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**6.2 mas**	97 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**135 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.19	0.29	0.42	0.51	0.60	0.67	0.75	0.84	0.90
Total Strehl (%)	0.01	0.06	0.17	0.28	0.38	0.48	0.60	0.73	0.84

Sky Coverage			
Galactic Lat.	30 deg		
Corresponding Sky Coverage	**0.0%**	This fraction of sky can be corrected to the Total Effective WFE shown	

Assumptions / Parameters

r0	0.175 m	at this zenith	Wind Speed	7.76 m/s	Zenith Angle	18 deg			
Theta0_eff	1.26 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	3299 Hz	SH	using	CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.21 arcmin	HO WFS Noise	3.3 e- rms			
Science Target:	SCAO				HOWFS anti-aliasing	YES			
LOWFS Target:	NGS	Num TT 0	Num 3x3	0	LO WFS rate	200 Hz	NGS	using	CCID56
LOWFS Star Type:	G	Num TTFA 0	Num HOWFS	1	LO WFS Noise	3.3 e- rms			

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 ≤ 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 m ($\leq$64 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

Mode: NGAO LGS
Instrument: TBD
Observation: KBO

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%) u'	g'	r'	i'	Z	Y	J	H	K
Atmospheric Fitting Error		41 nm	64 Subaps									
Bandwidth Error		26 nm	165 Hz (-3db)									
High-order Measurement Error		41 nm	150 W									
LGS Tomography Error		72 nm	6 beacon(s)									
Asterism Deformation Error		31 nm	0.50 m LLT									
Multispectral Error		20 nm	18 zenith angle, H band									
Scintillation Error		15 nm	0.38 Scint index, H-band									
WFS Scintillation Error		10 nm	Alloc									
	105 nm											
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts									
Uncorrectable Dynamic Telescope Aberrations		11 nm	Dekens Ph.D									
Static WFS Zero-point Calibration Error		25 nm	Alloc									
Dynamic WFS Zero-point Calibration Error		35 nm	Alloc									
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc									
Go-to Control Errors		43 nm	Alloc									
Residual Na Layer Focus Change		20 nm	30 m/s Na layer vel									
DM Finite Stroke Errors		1 nm	4.0 um P-P stroke									
DM Hysteresis		13 nm	from TMT									
High-Order Aliasing Error		14 nm	64 Subaps									
DM Drive Digitization		1 nm	16 bits									
Uncorrectable AO System Aberrations		30 nm	Alloc									
Uncorrectable Instrument Aberrations		32 nm	TBD Instrument									
DM-to-lenslet Misregistration		15 nm	Alloc									
DM-to-lenslet Pupil Scale Error		15 nm	Alloc									
	95 nm											
Angular Anisoplanatism Error		97 nm	5 arcsec									
Total High Order Wavefront Error	142 nm	**172 nm**	**High Order Strehl**	0.00	0.01	0.05	0.13	0.23	0.34	0.48	0.65	0.79

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%) u'	g'	r'	i'	Z	Y	J	H	K
Tilt Measurement Error (one-axis)		2.59 mas	44 nm	19.5 mag (mV)									
Tilt Bandwidth Error (one-axis)		1.71 mas	29 nm	21.2 Hz									
Tilt Anisoplanatism Error (one-axis)		2.84 mas	48 nm	34.9 arcsec									
Residual Centroid Anisoplanatism		0.95 mas	16 nm	10 x reduction									
Residual Atmospheric Dispersion	H	0.14 mas	3 nm	20 x reduction									
Science Instrument Mechanical Drift		1.25 mas	36 nm	Alloc 0.25 mas / min									
Long Exposure Field Rotation Errors		2.50 mas	70 nm	Alloc 0.5 mas / min									
Residual Telescope Pointing Jitter (one-axis)		2.50 mas	42 nm	29 Hz input disturbance									
Total Tip/Tilt Error (one-axis)		**5.7 mas**	103 nm	**Tip/Tilt Strehl**	0.22	0.32	0.45	0.55	0.63	0.70	0.77	0.85	0.91

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	Galactic Lat.	30 deg
Corresponding Sky Coverage	**10.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.175 m	at this zenith	Wind Speed	7.76 m/s	Zenith Angle	18 deg			
Theta0_eff	1.26 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	2469 Hz	SH	using	CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.52 arcmin	HO WFS Noise	2.7 e- rms			
Science Target:	MOAO				HOWFS anti-aliasing	NO			
LOWFS Target:	MOAO	Num TT 3	Num 3x3	0	LO WFS rate	550 Hz	SH	using	SNAP
LOWFS Star Type:	M	Num TTFA 0	Num HOWFS	0	LO WFS Noise	4.5 e- rms			

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 m ($\leq$64 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.

Keck Wavefront Error Budget Summary

Mode:	NGAO LGS
Instrument:	TBD
Observation:	Exo Jup LGS

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		41 nm	64 Subaps
Bandwidth Error		29 nm	138 Hz (-3db)
High-order Measurement Error		35 nm	150 W
LGS Tomography Error		43 nm	6 beacon(s)
Asterism Deformation Error		29 nm	0.50 m LLT
Multispectral Error		19 nm	10 zenith angle, H band
Scintillation Error		14 nm	0.36 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	84 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		13 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		35 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		43 nm	Alloc
Residual Na Layer Focus Change		19 nm	30 m/s Na layer vel
DM Finite Stroke Errors		1 nm	4.0 um P-P stroke
DM Hysteresis		13 nm	from TMT
High-Order Aliasing Error		14 nm	64 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		30 nm	Alloc
Uncorrectable Instrument Aberrations		30 nm	TBD Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	94 nm		
Angular Anisoplanatism Error		24 nm	1 arcsec
Total High Order Wavefront Error	127 nm	**129 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.01	0.06	0.19	0.32	0.44	0.55	0.67	0.79	0.88

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.18 mas	3 nm	13.0 mag (mV)
Tilt Bandwidth Error (one-axis)		0.96 mas	16 nm	38.5 Hz
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		0.93 mas	16 nm	10 x reduction
Residual Atmospheric Dispersion	H	0.08 mas	1 nm	20 x reduction
Science Instrument Mechanical Drift		1.25 mas	36 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		2.50 mas	70 nm	Alloc 0.5 mas / min
Residual Telescope Pointing Jitter (one-axis)		1.38 mas	23 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**3.4 mas**	63 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**141 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.44	0.58	0.70	0.78	0.83	0.87	0.91	0.94	0.97
Total Strehl (%)	0.00	0.03	0.13	0.25	0.37	0.48	0.61	0.74	0.85

Sky Coverage	Galactic Lat.	30 deg	
Corresponding Sky Coverage		**0.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.178 m	at this zenith	Wind Speed	7.93 m/s	Zenith Angle	10 deg					
Theta0_eff	1.33 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	2071 Hz	SH	using	CCID56		
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.14 arcmin	HO WFS Noise	2.5 e- rms					
Science Target:	MOAO				HOWFS anti-aliasing	NO					
LOWFS Target:	MOAO	Num TT 3	Num 3x3	0	LO WFS rate	2500 Hz	SH	using	SNAP		
LOWFS Star Type:	M	Num TTFA 0	Num HOWFS	0	LO WFS Noise	4.5 e- rms					

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 m ($\leq$64 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.

Keck Wavefront Error Budget Summary

Mode: NGAO LGS
Instrument: TBD
Observation: Extended Groth Strip

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		44 nm	64 Subaps
Bandwidth Error		30 nm	151 Hz (-3db)
High-order Measurement Error		45 nm	150 W
LGS Tomography Error		89 nm	6 beacon(s)
Asterism Deformation Error		38 nm	0.50 m LLT
Multispectral Error		23 nm	34 zenith angle, H band
Scintillation Error		20 nm	0.49 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	124 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		12 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		35 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		43 nm	Alloc
Residual Na Layer Focus Change		23 nm	30 m/s Na layer vel
DM Finite Stroke Errors		1 nm	4.0 um P-P stroke
DM Hysteresis		13 nm	from TMT
High-Order Aliasing Error		15 nm	64 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		30 nm	Alloc
Uncorrectable Instrument Aberrations		30 nm	TBD Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	95 nm		
Angular Anisoplanatism Error		43 nm	1.5 arcsec
Total High Order Wavefront Error	156 nm	**162 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.07	0.16	0.27	0.39	0.52	0.69	0.81

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		4.58 mas	77 nm	20.4 mag (mV)
Tilt Bandwidth Error (one-axis)		1.92 mas	33 nm	17.6 Hz
Tilt Anisoplanatism Error (one-axis)		4.37 mas	74 nm	50.2 arcsec
Residual Centroid Anisoplanatism		1.02 mas	17 nm	10 x reduction
Residual Atmospheric Dispersion	K	0.14 mas	3 nm	20 x reduction
Science Instrument Mechanical Drift		7.50 mas	250 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		15.00 mas	399 nm	Alloc 0.5 mas / min
Residual Telescope Pointing Jitter (one-axis)		3.01 mas	51 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**18.3 mas**	288 nm	**Tip/Tilt Strehl**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.03	0.04	0.08	0.11	0.14	0.19	0.25	0.36	0.51
Total Strehl (%)	0.00	0.00	0.01	0.02	0.04	0.07	0.13	0.25	0.41

Total Effective Wavefront Error — **329 nm** — **Total Strehl (%)**

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage **30.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.161 m	at this zenith	Wind Speed	7.15 m/s	Zenith Angle	34 deg			
Theta0_eff	1.01 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	2265 Hz	SH	using	CCID56
Sodium Abund.	4×10^{9}	atoms/cm^2	LGS Ast. Rad.	0.80 arcmin	HO WFS Noise	2.8 e- rms			
Science Target:	MOAO				HOWFS anti-aliasing	NO			
LOWFS Target:	MOAO	Num TT 3	Num 3x3	0	LO WFS rate	407 Hz	SH	using	SNAP
LOWFS Star Type:	M	Num TTFA 0	Num HOWFS	0	LO WFS Noise	4.5 e- rms			

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 m ($\leq$64 subaps)
	Tip tilt integration time	$\geq$ .0004 sec
	LGS asterism radius	$\leq$ 2 amin
Optimized Parameter	H band Strehl Ratio	36%

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

Keck Wavefront Error Budget Summary

Mode:	NGAO LGS
Instrument:	NIRC2
Observation:	Gal Cen

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%)								
Atmospheric Fitting Error		48 nm	64 Subaps									
Bandwidth Error		41 nm	113 Hz (-3db)									
High-order Measurement Error		48 nm	150 W									
LGS Tomography Error		41 nm	6 beacon(s)									
Asterism Deformation Error		51 nm	0.50 m LLT									
Multispectral Error		27 nm	46 zenith angle, H band									
Scintillation Error		27 nm	0.68 Scint index, H-band									
WFS Scintillation Error		10 nm	Alloc									
	110 nm											
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts									
Uncorrectable Dynamic Telescope Aberrations		15 nm	Dekens Ph.D									
Static WFS Zero-point Calibration Error		25 nm	Alloc									
Dynamic WFS Zero-point Calibration Error		35 nm	Alloc									
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc									
Go-to Control Errors		43 nm	Alloc									
Residual Na Layer Focus Change		28 nm	30 m/s Na layer vel									
DM Finite Stroke Errors		1 nm	4.0 um P-P stroke									
DM Hysteresis		13 nm	from TMT									
High-Order Aliasing Error		16 nm	64 Subaps									
DM Drive Digitization		1 nm	16 bits									
Uncorrectable AO System Aberrations		30 nm	Alloc									
Uncorrectable Instrument Aberrations		110 nm	NIRC2 Instrument									
DM-to-lenslet Misregistration		15 nm	Alloc									
DM-to-lenslet Pupil Scale Error		15 nm	Alloc									
	144 nm											
Angular Anisoplanatism Error		198 nm	7.1 arcsec									
Total High Order Wavefront Error	181 nm	**268 nm**	**High Order Strehl**	0.00	0.00	0.00	0.01	0.03	0.07	0.16	0.35	0.56

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)								
Tilt Measurement Error (one-axis)		0.11 mas	2 nm	12.2 mag (mV)									
Tilt Bandwidth Error (one-axis)		0.81 mas	14 nm	38.5 Hz									
Tilt Anisoplanatism Error (one-axis)		0.52 mas	9 nm	5.5 arcsec									
Residual Centroid Anisoplanatism		1.11 mas	19 nm	10 x reduction									
Residual Atmospheric Dispersion	K	0.22 mas	4 nm	20 x reduction									
Science Instrument Mechanical Drift		0.13 mas	5 nm	Alloc 0.25 mas / min									
Long Exposure Field Rotation Errors		0.25 mas	10 nm	Alloc 0.5 mas / min									
Residual Telescope Pointing Jitter (one-axis)		1.38 mas	23 nm	29 Hz input disturbance									
Total Tip/Tilt Error (one-axis)		**2.0 mas**	38 nm	**Tip/Tilt Strehl**	0.68	0.79	0.87	0.91	0.93	0.95	0.96	0.98	0.99
Total Effective Wavefront Error			**271 nm**	**Total Strehl (%)**	0.00	0.00	0.00	0.01	0.02	0.07	0.16	0.34	0.55

Sky Coverage	Galactic Lat.		
		30 deg	
Corresponding Sky Coverage		**0.2%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.145 m	at this zenith	Wind Speed	6.43 m/s	Zenith Angle	46 deg			
Theta0_eff	0.78 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	1702 Hz	SH	using	CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.13 arcmin	HO WFS Noise	2.2 e- rms			
Science Target:	MOAO				HOWFS anti-aliasing	NO			
LOWFS Target:	MOAO	Num TT 3	Num 3x3	0	LO WFS rate	2500 Hz	SH	using	SNAP
LOWFS Star Type:	IRS7	Num TTFA 0	Num HOWFS	0	LO WFS Noise	4.5 e- rms			

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.