NGAO Wavefront Error Budget
Keck Adaptive Optics Note 471

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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 ($\mathbf{m^{1/3}}$)**	**Wind Speed (m/s)**
0	1.18e-13	5.2
500	4.93e-14	8.5
1000	2.59e-14	12.6
2000	2.52e-14	14.9
4000	4.35e-14	11.9
8000	3.37e-14	6.1
16000	2.22e-14	3.7

Table 3: Turbulence and wind profiles assumed in these error budgets. At zenith, the integrated turbulence profile has a value of 3.17e-13 $m^{1/3}$, with r_0 = 16 cm, a θ_0 = 2.3 asec, d_0=4.14 m, and f_G=23 Hz.

2 Observing Scenarios

This study presents optimal error budget solutions for five observing scenarios selected as representative of the NGAO system. These five observing scenarios, together with the adaptive optics architecture required to carry out the observation, are listed in Table 2. An error budget was developed for each observing scenario 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 observing scenario. 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.

Variable Parameters	High order integration time	$\geq$ .0004 sec
Optimized Parameter	H band Strehl Ratio	=87%

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

The baseline adaptive optics architecture assumed in this study was a 64x64 actuator deformable mirror and an asterism of six laser guide stars, with one additional NGS used for tip tilt guiding. The only exception to this was for the Io observing scenario, in which an NGS AO architecture was assumed. In this scenario, Io was employed for both the high order and tip tilt wavefront sensing.

Versions of the Excel spreadsheet are available for each observing scenario at URL `http://www.oir.caltech.edu/twiki_oir/bin/view.cgi/Keck/NGAO/SystemArchitecture` For each observing scenario, the spreadsheet contains the tabulated set of optimization parameters. This is intended to permit users to download and inspect the spreadsheet for each observing scenario 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 observing scenario. The AO frame rate was constrained to be less than 2.5 kHz.

The optimizer provided the solution in Figure 1. The dominant error terms in the high order budget are atmospheric fitting error and uncorrectable static telescope aberrations. The tilt error budget is dominated by pointing jitter. This scenario delivers an H band Strehl ratio of 87%.

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		46 nm	64 Subaps
Bandwidth Error		15 nm	167 Hz (-3db)
High-order Measurement Error		21 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		13 nm	0.33 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	59 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		10 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		4 nm	4.0 um P-P stroke
DM Hysteresis		13 nm	from TMT
High-Order Aliasing Error		10 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
	76 nm		
Angular Anisoplanatism Error		9 nm	0.5 arcsec
Total High Order Wavefront Error	96 nm	**96 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.07	0.21	0.41	0.54	0.65	0.73	0.80	0.88	0.93

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.22 mas	4 nm	5.0 mag (mV)
Tilt Bandwidth Error (one-axis)		0.57 mas	10 nm	38.5 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	I'	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)		1.38 mas	23 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**1.7 mas**	32 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**98 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.75	0.84	0.90	0.93	0.95	0.96	0.97	0.98	0.99
Total Strehl (%)	0.05	0.18	0.37	0.51	0.61	0.70	0.78	0.87	0.92

	Spaxial Size (mas)	50	70	80	120	240	480	1000		480
Ensquared Energy	I'	0.55	0.55	0.55	0.56	0.60	0.70	###		0.80

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	0.155 m	at this zenith	Wind Speed	7.76 m/s	Zenith Angle	18 deg	
Theta0_eff	2.13 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	2502 Hz	SH using CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.75 arcmin	HO WFS Noise	2.8 e- rms	
Science Target:	SCAO				HOWFS anti-aliasing	YES	
LOWFS Target:	NGS	Num TT 0	Num 3x3	0	LO WFS rate	2502 Hz	NGS using CCID56
LOWFS Star Type:	G	Num TTFA 0	Num HOWFS	1	LO WFS Noise	2.8 e- rms	
Max Exposure Time	10 sec				Max mechanical tip/tilt rejection bandwidth	50 Hz	

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

Variable Parameters	High order integration time	No Limit
	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	61%

Table 5: Optimized parameter and constraints for the Kuiper Belt Object 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 9 to vary under the constraints indicated in this table. The optimizer chose a solution with a high order control loop rate of nearly 2.25 kHz. The optimal LGS asterism radius was about 20 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 514 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 40 asec over 10% of the sky.

In this error budget, the dominant term in the high order budget was anisoplanatism and tomography error. The dominant term in the tilt error budget arises from field rotation errors.

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
Atmospheric Fitting Error		46 nm	64 Subaps
Bandwidth Error		17 nm	149 Hz (-3db)
High-order Measurement Error		39 nm	150 W
LGS Tomography Error		65 nm	6 beacon(s)
Asterism Deformation Error		22 nm	0.50 m LLT
Multispectral Error		20 nm	18 zenith angle, H band
Scintillation Error		13 nm	0.33 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	96 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		20 nm	30 m/s Na layer vel
DM Finite Stroke Errors		4 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		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		63 nm	5 arcsec
Total High Order Wavefront Error	136 nm	**150 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.02	0.10	0.21	0.33	0.45	0.58	0.72	0.84

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		3.04 mas	51 nm	19.5 mag (mV)
Tilt Bandwidth Error (one-axis)		1.09 mas	19 nm	20.3 Hz
Tilt Anisoplanatism Error (one-axis)		3.42 mas	58 nm	35.0 arcsec
Residual Centroid Anisoplanatism		1.05 mas	18 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	71 nm	Alloc 0.5 mas / min
Residual Telescope Pointing Jitter (one-axis)		2.61 mas	44 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**6.2 mas**	110 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**184 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 (%)	0.00	0.01	0.04	0.11	0.20	0.30	0.43	0.61	0.75

Spaxial Size (mas)	50	70	80	120	240	480	1000		260
Ensquared Energy (H)	0.61	0.71	0.73	0.75	0.79	0.86	0.91		0.80

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	0.155 m	at this zenith	Wind Speed	7.76 m/s	Zenith Angle	18 deg			
Theta0_eff	2.13 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	2241 Hz	SH	using	CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.34 arcmin	HO WFS Noise	2.6 e- rms			
Science Target:	MOAO				HOWFS anti-aliasing	NO			
LOWFS Target:	MOAO	Num TT 3	Num 3x3	0	LO WFS rate	514 Hz	SH	using	SNAP
LOWFS Star Type:	M	Num TTFA 0	Num HOWFS	0	LO WFS Noise	4.5 e- rms			
Max Exposure Time	300 sec				Max mechanical tip/tilt rejection bandwidth	50 Hz			

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

Variable Parameters	High order integration time	No limit
	Tip tilt integration time	$\geq .0004$
	LGS asterism radius	No limit
Optimized Parameter	H band Strehl Ratio	76%

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

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. 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 1.675 kHz and a laser asterism radius of .1 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 field rotation errors.

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		45 nm	64 Subaps
Bandwidth Error		21 nm	112 Hz (-3db)
High-order Measurement Error		31 nm	150 W
LGS Tomography Error		41 nm	6 beacon(s)
Asterism Deformation Error		21 nm	0.50 m LLT
Multispectral Error		19 nm	10 zenith angle, H band
Scintillation Error		12 nm	0.31 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	78 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		16 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		4 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		16 nm	1 arcsec
Total High Order Wavefront Error	123 nm	**124 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.01	0.07	0.21	0.35	0.47	0.58	0.69	0.80	0.89

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)		0.58 mas	10 nm	38.5 Hz
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		1.03 mas	18 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	71 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)		**3.3 mas**	62 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**137 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.45	0.58	0.71	0.78	0.83	0.87	0.91	0.95	0.97
Total Strehl (%)	0.00	0.04	0.15	0.27	0.39	0.50	0.63	0.76	0.86

		Spaxial Size (mas)	50	70	80	120	240	480	1000		70
Ensquared Energy	H		0.71	0.79	0.80	0.82	0.84	0.89	0.92		0.80

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	0.159 m	at this zenith		Wind Speed	7.93 m/s	Zenith Angle	10 deg			
Theta0_eff	2.25 arcsec	at this zenith		Outer Scale	50 m	HO WFS Rate	1675 Hz	SH	using	CCID56
Sodium Abund.	4 x 10^9	atoms/cm^2		LGS Ast. Rad.	0.10 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:	M	Num TTFA	0	Num HOWFS	0	LO WFS Noise	4.5 e- rms			
Max Exposure Time	300 sec					Max mechanical tip/tilt rejection bandwidth	50 Hz			

Figure 3: Wavefront error budget for Exo Jupiter LGS.

Variable Parameters	High order integration time	No Limit
	Tip tilt integration time	No Limit
	Tip tilt guide star search radius	No Limit
	LGS asterism radius	No Limit
	Sky Coverage	=30%
Optimized Parameter	H band Strehl Ratio	25%

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

Spaxial Size (asec)	**Ensq. Energy Fraction**
.05	37%
.07	57%
.08	65%
.12	81%
.24	88%
.48	93%
1.00	95%

Table 8: Fractional 2.2 μm ensquared energy as a function of spaxial size for the Extended Groth observing scenario.

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 1.88 kHz and a laser asterism radius of .75 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 45 asec and a tip tilt update rate of 300 Hz.

For this observing scenario, 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 field rotation errors.

In this particular science, case, ensquared energy is the metric of interest rather than

Strehl ratio. The values of ensquared energy fraction at 2.2 μm as a function of spaxial size are listed in Table 8.

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		49 nm	64 Subaps
Bandwidth Error		21 nm	125 Hz (-3db)
High-order Measurement Error		40 nm	150 W
LGS Tomography Error		96 nm	6 beacon(s)
Asterism Deformation Error		27 nm	0.50 m LLT
Multispectral Error		23 nm	34 zenith angle, H band
Scintillation Error		17 nm	0.42 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	123 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		14 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		4 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		30 nm	TBD Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	96 nm		
Angular Anisoplanatism Error		28 nm	1.5 arcsec
Total High Order Wavefront Error	156 nm	**159 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.18	0.29	0.40	0.54	0.70	0.82

Tip/Tilt Errors		Angular Error (rms)	Equivalent WFE (rms)	Parameter
	Sci Filter			
Tilt Measurement Error (one-axis)		3.91 mas	66 nm	20.4 mag (mV)
Tilt Bandwidth Error (one-axis)		1.45 mas	25 nm	14.2 Hz
Tilt Anisoplanatism Error (one-axis)		5.20 mas	87 nm	49.7 arcsec
Residual Centroid Anisoplanatism		1.12 mas	19 nm	10 x reduction
Residual Atmospheric Dispersion	K	0.14 mas	3 nm	20 x reduction
Science Instrument Mechanical Drift		7.50 mas	251 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		15.00 mas	400 nm	Alloc 0.5 mas / min
Residual Telescope Pointing Jitter (one-axis)		3.73 mas	63 nm	29 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**18.5 mas**	289 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**329 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.03	0.04	0.07	0.11	0.14	0.18	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

Spaxial Size (mas)		50	70	80	120	240	480	1000		110
Ensquared Energy	K	0.37	0.57	0.65	0.81	0.88	0.93	0.95		0.80

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	0.143 m	at this zenith	Wind Speed 7.15 m/s	Zenith Angle	34 deg
Theta0_eff	1.71 arcsec	at this zenith	Outer Scale 50 m	HO WFS Rate	1879 Hz SH using CCID56
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad. 0.75 arcmin	HO WFS Noise	2.3 e- rms
Science Target:	MOAO			HOWFS anti-aliasing	NO
LOWFS Target:	MOAO	Num TT 3	Num 3x3 0	LO WFS rate	298 Hz SH using SNAP
LOWFS Star Type:	M	Num TTFA 0	Num HOWFS 0	LO WFS Noise	4.5 e- rms
Max Exposure Time	1800 sec			Max mechanical tip/tilt rejection bandwidth	50 Hz

Figure 4: Ensquared energy fraction for the Extended Groth Strip observing scenario.

Variable Parameters	High order integration time	No Limit
	Tip tilt integration time	$\geq$ .0004 sec
	LGS asterism radius	No Limit
Optimized Parameter	H band Strehl Ratio	64%

Table 9: Optimized parameter and constraints for the Galactic Center 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 1.34 kHz and an asterism radius of .09 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 5 asec field. Tip tilt errors are negligably small in this scenario. The 64% H band Strehl ratio corresponds to system performance at the edge of the 5 asec field.

Keck Wavefront Error Budget Summary

			Science Band								
			u'	g'	r'	i'	Z	Y	J	H	K
Mode:	NGAO LGS	λ (µm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
Instrument:	TBD	δλ (µm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
Observation:	Gal Cen	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		53 nm	64 Subaps	
Bandwidth Error		30 nm	89 Hz (-3db)	
High-order Measurement Error		42 nm	150 W	
LGS Tomography Error		39 nm	6 beacon(s)	
Asterism Deformation Error		36 nm	0.50 m LLT	
Multispectral Error		27 nm	46 zenith angle, H band	
Scintillation Error		23 nm	0.58 Scint index, H-band	
WFS Scintillation Error		10 nm	Alloc	
	99 nm			
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts	
Uncorrectable Dynamic Telescope Aberrations		19 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		4 nm	4.0 um P-P stroke	
DM Hysteresis		13 nm	from TMT	
High-Order Aliasing Error		18 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	
	99 nm			
Angular Anisoplanatism Error		96 nm	5 arcsec	

				u'	g'	r'	i'	Z	Y	J	H	K
Total High Order Wavefront Error	140 nm	**170 nm**	**High Order Strehl**	0.00	0.01	0.06	0.14	0.24	0.34	0.48	0.65	0.79

Tip/Tilt Errors		Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)
	Sci Filter				
Tilt Measurement Error (one-axis)		0.10 mas	2 nm	12.2 mag (mV)	
Tilt Bandwidth Error (one-axis)		0.49 mas	8 nm	38.5 Hz	
Tilt Anisoplanatism Error (one-axis)		0.63 mas	11 nm	5.5 arcsec	
Residual Centroid Anisoplanatism		1.23 mas	21 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	

				u'	g'	r'	i'	Z	Y	J	H	K
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		**174 nm**	**Total Strehl (%)**	0.00	0.00	0.05	0.12	0.22	0.33	0.47	0.64	0.78

	Spaxial Size (mas)	50	70	80	120	240	480	1000		110
Ensquared Energy K		0.56	0.72	0.76	0.80	0.83	0.89	0.94		0.80

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	0.129 m	at this zenith	Wind Speed	6.43 m/s	Zenith Angle	46 deg			
Theta0_eff	1.29 arcsec	at this zenith	Outer Scale	50 m	HO WFS Rate	1340 Hz	SH	using	CCID56
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad.	0.09 arcmin	HO WFS Noise	2.0 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			
Max Exposure Time	30 sec				Max mechanical tip/tilt rejection bandwidth	50 Hz			

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

Scenario	Exp. Time	TT GS	HO GS	LGS Ast. (asec)	TT Error	Sky Cvge	HO Error	1.65 μm Strehl
Io	10 sec	Sci. Target	Sci. Target	-	1.7 mas	n/a	96 nm	87%
Kuiper Belt	300 sec	Field Star	6xLGS	41	6.2 mas	10%	150 nm	61%
Exo Jupiter	300 sec	Sci. Target	6xLGS	12	3.3 mas	n/a	124 nm	76%
Ext. Groth	1800 sec	Field Star	6xLGS	90	18.5 mas	30%	159 nm	25%
Gal. Ctr.	30 sec	IRS 7	6xLGS	11	2.0 mas	n/a	170 nm	64%

Table 10: Summary of the error budgets for the five observing scenarios considered in this study. The second column shows the integration time assumed for the scenario. The third and fourth columns indicate the tilt and high order guide stars assumed for the scenario, respectively. For the Io and Exo Jupiter scenarios, the tilt guide star is the science object. For the Galactic Center, the tilt guide star is specified to be IRS 7. For the remaining two scenarios, a field star is used for tilt guiding. The fifth column indicates the optimal diameter of the LGS asterism for cases where lasers are employed for high order sensing. The sixth column indicates the tilt error budget. In scenarios where tilt guiding is performed using a field star, the tilt error budget depends on the proximity of the tilt star to the science target. For these cases, the seventh column indicates the fraction of sky over which the tilt error is less than or equal to the value in column five. The high order error budget is listed in the eighth column. The final column indicates the H band Strehl ratio attained in the observing scenario.

2.6 Summary

Table 10 summarizes the system performance predicted by the wavefront error budget spreadsheet for the five observing scenarios considered in the NGAO study.