

# 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
Ē	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
$\operatorname{Spagna}$	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)	$(m^{1/3})$	(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	$\geq$ .0004 sec
<b>Optimized Parameter</b>	H band Strehl Ratio	=73%

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

	Summary			Science Band
Node: NGAO NGS				u' g' r' l' Z Y J H K
istrument: TBD			λ (μm)	0.36 0.47 0.62 0.75 0.88 1.03 1.25 1.64 2.20
Uservation: Io			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
		Wavefront		Strobl Batic (%)
High-order Errors (NGS Mode)		Error (rms)	Parameter	Strehl Ratio (%)
Neurophysics Filling Course		41 mm	64 B-4	
Atmospheric Fitting Error Bendwidth Error		41 nm 20 nm	64 Subaps 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 mm	18 zenith angle, H band	
Scintillation Error		15 nm	0.38 Scint index, H-band	
WFS Scintillation Error	59: nm	10 nm	Alice	
Uncorrectable Static Telescope Aberrations	Dor Hill	43 nm	64 Acts	
Uncorrectable Dynamic Telescope Aberration	8	8 nm	Dekens Ph.D	
Static WFS Zero-point Calibration Error		25 nm	Alioc	
Dynamic WFS Zero-point Calibration Evor		20 nm	Alloc	
Leeky Integrator Zero-point Calibration Error		15 nm	Alice	
Go-to Control Errors		0 nm	Alloc	
Residual Na Layer Focus Change		0 nm	30 m/s No layer vel	
DM Finite Stroke Errors DM Hysteresis		1 nm 13 nm	4.0 um P-P stroke from TMT	
High-Order Aliesing Error		9 nm	64 Subapa	
DM Drive Digitization		1 nm	16 bits	
Uncorrectable AD System Aberrations		30 nm	Alloc	
Uncorrectable Instrument Abemations		30 nm	TBD Instrument	
DM-to-lenslet Misregistration		15 nm	Alloc	
DM-to-lensiet Pupil Scale Error		15 nm	Alloc	
Angular Anisoplanatism Error	75 nm	14 nm	0.5 arcsec	
Total High Order Wavefront E	<b>100</b> 100	97 nm	High Order Strehl	0.07 0.21 0.40 0.54 0.64 0.72 0.80 0.88 0.93
Tip/Tilt Errors	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)
	Boi Filter			
Till Measurement Error (one-axis)	0.05 mas	1 m	5.0 mag (mV)	
Till Bandwidth Error (one-axis)	3.44 mas	56 mm	10.5 Hz	
Till Anisoplanetism Error (one-axis)	0.00 mes	0 mm	0.0 arcsec	
Residual Centroid Anisoplanatism	0.00 mas	0 mm	NGS x reduction 20 x reduction	
	7 0.83 mas	15 mm		
		4		
Science Instrument Mechanical Drift Loop Exposure Field Rotation Ferrors	0.04 mas	1 m	Aloc 0.25 mas / min	
Long Exposure Field Rotation Errors	0.08 mas	1 m 1 m 77 m		
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis)	0.08 mas 5.03 mas	1 mi 77 mi	Alco 0.25 mas / min Alco 0.5 mas / min 29 Hz input disturbance	
Long Exposure Field Rotation Errors	0.08 mas	1 mm	Aloc 0.25 mas / min Aloc 0.5 mas / min	0.19 0.29 0.42 0.51 0.60 0.67 0.75 0.84 0.9
Long Exposure Field Rotation Errors Residual Telescope Pointing Jahr (one-axis) Total Tip/Tilt Error (one-axis)	0.08 mas 5.03 mas	1 ms 77 ns 97 nm	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tillt Strehl	
Long Exposure Field Rotation Errors Residual Telescope Pointing Jibr (one-axis) Total Tip/Tilt Error (one-axis)	0.08 mas 5.03 mas	1 mi 77 mi	Alco 0.25 mas / min Alco 0.5 mas / min 29 Hz input disturbance	
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis)	0.08 mas 5.03 mas 6.2 mas	1 ms 77 ns 97 nm	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tillt Strehl	
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis)	0.08 mas 5.03 mas 6.2 mas	1 ms 77 ns 97 nm	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tillt Strehl	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jiter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic La Corresponding Sky Coverage	0.08 mas 5.03 mas 6.2 mas	1 em 77 em 97 nm 135 nm	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%)	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Li Corresponding Sky Coverage Assumptions / Parameters	0.08 mss 5.03 mss 6.2 mas 11. 30 deg	1 es 77 nm 97 nm 135 nm 0.0%	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disubtance Tip/Tilt Strehl Total Strehl (%)	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Li Corresponding Sky Coverage Assumptions / Parameters	0.08 mas 5.03 mas 6.2 mas at. 30 dag m at this zenith	1 es 77 os 97 om 135 om 0.0%	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mits Zenith Angle	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Li Corresponding Sky Coverage Assumptions / Parameters	0.08 mss 5.03 mss 6.2 mas 11. 30 dag 11. 30 dag	1 es 77 ns 97 nm 135 nm 0.0%	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disarbance Tip/Tilt Strehl Total Strehl (%) Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle m HO WFS Rate	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Li Corresponding Sky Coverage Assumptions / Parameters r0 0.175 Thata0_eff 1.26 Sodem Aband. 4	0.08 mas 5.03 mas 6.2 mas at. 30 dag m at this zenith	1 es 77 os 97 om 135 om 0.0%	Aloc 0.25 mas / min Aloc 0.5 mas / min 20 Hz input disubtance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle m HO WFS Rate aromin HO WFS Rate	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84
Long Exposure Field Rotation Errors Residual Telescope Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Li Corresponding Sky Coverage Assumptions / Parameters r0 0.175 Thata0_eff 1.26 Sodium Abund. 4	0.08 mss 5.03 mss 6.2 mas 11. 30 dag 11. 30 dag	1 es 77 ns 97 nm 135 nm 0.0%	Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disarbance Tip/Tilt Strehl Total Strehl (%) Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle m HO WFS Rate	0.01 0.06 0.17 0.28 0.38 0.48 0.60 0.73 0.84

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

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

Keck Wavefront Error Budget Sum	mary						Scie	nce B	Band			
NGAO LGS	-			u'	g'	r'	- P	Z	Y	J	н	К
nstrument: TBD			λ (ωπ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	22
bservation: KBO			δλ. (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.3
			λ/D (mas)	7	10	13	15	18	21	26	34	46
		Wavefront		-			Ctrob	l Rati	a /0/ 1			
High-order Errors (LGS Mode)		Error (rms)	Parameter				ouren	i Rau	0 (%)			
Atmospheric Fiting Error Bandwidth Error		41 nm 26 nm	64 Subaps 165 Hz (-3db)									
High-order Measurement Error		20 nm 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-bend									
WFS Scintillation Error	105 om	10 nm	Alice									
Uncorrectable Static Telescope Aberrations	105 nm	43.000	Ed Arts									
Uncorrectable Dynamic Telescope Abernations		43 mm 11 mm	Dekens Ph.D									
Static WFS Zero-point Calibration Error		25 nm	Alloc									
Dynamic WFS Zero-point Calibration Evor		35 nm	Alloc									
Leaky Integrator Zero-point Celibration Error		15 nm	Alice									
Go-to Control Errors		43 nm	Alioc									
Residual Na Layer Focus Change		20 nm	30 m/s Na layer vel									
DM Finite Stroke Errors		1 nm 13 nm	4.0 um P-P stroke from TMT									
DM Hysteresis High-Order Aliesing Error		13 nm 14 nm	64 Subace									
DM Drive Digitization		1.00	16 bits									
Uncorrectable AO System Abernations		30 nm	Alloc									
Uncorrectable Instrument Aberrations		32 nm	TBD Instrument									
OM-to-lensiet Misregistration		15 nm	Alice									
DM-to-lensiet Pupil Scale Error		15 nm	Alloc									
Angular Anisoplanatism Error	95 nm	97 nm	5 prosec									
Total High Order Wavefront Error	142 nm	172 nm	High Order Strehl	0.00	0.01	0.05	0.42	0.32	0.24	0.48	0.65	0.7
Total high order wavenont circl	142 1111	172 1111	high older streni	0.00	0.01	0.00	V.10	0.25	0.04	0.40	0.00	0.7
Tip/Tilt Errors	Angular	Equivalent	Parameter				Streh	l ratio	os (%)			
	Error (rms)	WFE (rms)		<u> </u>								
Bci Filter	2.00	44.000	40 E anno Ambili									
Tit Measurement Error (one-axis)	2.59 mas	44 mm 20 mm	19.5 mag (mV) 21.2 Mz									
Tit Measurement Error (one-axis) Tit Bandwidth Error (one-axis)	2.50 mas 1.71 mas 2.84 mas	44 mm 29 mm 48 mm	19.5 mag (mV) 21.2 Hz 34.9 arcsec									
Tit Measurement Error (one-axis)	1.71 mes	29 mm	21.2 Hz									
Tit Measurement Evor (one-axis) Tit Bandwidth Evor (one-axis) Tit Anisoglanatism Evor (one-axis) Residual Cantroid Anisoptenatism Residual Annospheric Dispersion H	1.71 mes 2.84 mes 0.95 mes 0.14 mes	29 mm 48 mm 16 mm 3 mm	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction									
Titi Maasuvament Error (one-axis) Titi Bandwidh Error (one-axis) Titi Anisopianatism Error (one-axis) Residual Cantrold Anisopianatism Residual Atmospheric Dispension Bisience Instrument Mechanical Drift	1.71 mas 2.84 mas 0.95 mas 0.14 mas 1.25 mas	29 nm 48 nm 16 nm 3 nm 36 nm	21.2 Hz 34.9 ansae 10 x reduction 20 x reduction Alloc 0.25 mas / min									
Tit I Maasurement Ervar (one-axis) Tit I Bardwidt Ervor (one-axis) Tit Antisoplanatism Ervor (one-axis) Residual Controld Antisoplanatism Residual Annospheric Dispersion H Bosience Instrument Mechanical Drift Long Exposure Field Rotakion Ervors	1.71 mas 2.84 mas 0.95 mas 0.14 mas 1.25 mas 2.50 mas	20 mm 48 mm 16 mm 3 mm 36 mm 70 mm	21.2 Hz 34.9 ansacc 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.5 mas / min									
Titi Maasuvament Error (one-axis) Titi Bandwidh Error (one-axis) Titi Anisopianatism Error (one-axis) Residual Controld Anisopianatism Residual Atmospheric Dispension Bisience Instrument Mechanical Drift	1.71 mas 2.84 mas 0.95 mas 0.14 mas 1.25 mas	29 nm 48 nm 16 nm 3 nm 36 nm	21.2 Hz 34.9 ansae 10 x reduction 20 x reduction Alloc 0.25 mas / min									
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Til Maasurement Error (one-axis) Til Mankudh Error (one-axis) Til Anisolah Error (one-axis) Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Telescope Pointing Jitter Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	1.71 mas 2.84 mas 0.96 mas 0.14 mas 1.25 mas 2.50 mas 2.50 mas	29 nm 48 nm 16 nm 3 nm 36 nm 70 nm 42 nm 103 nm	21.2 Hz 34.9 ancsec 10 x reduction 20 x reduction Aloc 0.55 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl									
Titi Maasurement Error (one-axis) Titi Asadwidh Error (one-axis) Titi Asigolandism Error (one-axis) Residual Cantrold Antooplanatism Residual Cantrold Antooplanatism Residual Cantrold Antooplanatism Residual Cantrold Machanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis)	1.71 mas 2.84 mas 0.96 mas 0.14 mas 1.25 mas 2.50 mas 2.50 mas	20 nm 48 nm 16 nm 3 nm 36 nm 70 nm 42 nm	21.2 Hz 34.9 ancsec 10 x reduction 20 x reduction Alloc 0.55 mas / min Alloc 0.5 mas / min 29 Hz input disturbance							0.77		
Tel Maasurement Ervir (one-axis) Til Anticoplanatism Ervir (one-axis) Til Anticoplanatism Ervir (one-axis) Resistual Controld Anticoplanatism Resistual Anticoplanatism H Solience Instrument Mechanical Drift Long Exposure Field Relation Ervirs Resistual Telescope Poleting Jibr (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error	1.71 mas 2.84 mas 0.96 mas 0.14 mas 1.25 mas 2.50 mas 2.50 mas	29 nm 48 nm 16 nm 3 nm 36 nm 70 nm 42 nm 103 nm	21.2 Hz 34.9 ancsec 10 x reduction 20 x reduction Aloc 0.55 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl									
Tri Maasuremeet Ervir (one-axis) Tri Anisoplanatism Ervir (one-axis) Tri Anisoplanatism Ervir (one-axis) Resistual Cantrold Anisoplanatism Resistual Anisophine Toppanion H Sosience Instrument Mechanical Drift Long Exposure Field Rotatism Ervirs Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Bky Coverage	1.71 mes 2.84 mes 0.05 mes 1.25 mes 2.50 mes 5.7 mes	29 nm 48 nm 16 nm 3 nm 36 nm 70 nm 42 nm 103 nm	21.2 Hz 34.9 ancese 10 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%)	0.00	0.00	0.02	0.07					
Tel Maasurement Error (one-axis) Tel Aniscopianation Error (one-axis) Tel Aniscopianation Error (one-axis) Resistual Control Anisopianation Resistual Anisopherio Espersion H Solence Instrument Machanical Drift Long Exposure Field Rolation Errors Resistual Telescopa Pointing Jibr (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage	1.71 mes 2.84 mes 0.05 mes 1.25 mes 2.50 mes 5.7 mes	29 em 48 mm 16 em 3 nm 36 em 70 em 42 nm 103 nm 199 nm	21.2 Hz 34.9 ancsec 10 x reduction 20 x reduction Aloc 0.55 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl	0.00	0.00	0.02	0.07					
Til Measurement Error (one-axis) Til Anisoplanatian Error (one-axis) Til Anisoplanatian Error (one-axis) Residual Cantrol Anisoplanatian Residual Cantrol Anisoplanatian Residual Anisopherio Espansion H Boismoe Instrument Machanical Drift Long Exposure Field Realison Errors Residual Telescope Pointing Jitter (one-axis) <b>Total Tip/Tilt Error (one-axis)</b> <b>Total Effective Wavefront Error</b> Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters	1.71 mea 2.64 mea 0.95 mea 0.14 mea 1.25 mea 2.50 mea 5.7 mea 30 deg	29 ms 48 ms 16 ms 3 nm 3 nm 42 nm 103 nm <b>199 nm</b>	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.25 mas / min 29 Hz input disturbance <b>Tip/Tilt Strehl</b> <b>Total Strehl (%)</b> This fraction of sky can be corrected to	0.00 the Total	0.00 Effectiv	0.02	0.07					
Tel Measurement Error (one-axis) Tel Bardwidt Error (one-axis) Tel Anisoplanatism Error (one-axis) Resistual Control Anisoplanatism Resistual Annaspheric Dispension H Boismo Instrument Mechanical Drift Long Exposure Field Rotanical Drift Long Exposure Drift Rotanical Drift Long Long Exposure Drift	1.71 mea 2.84 mea 0.16 maa 0.14 mea 2.50 mea 2.50 mea 2.50 mea 30 deg	29 es 48 es 46 es 3 es 3 es 3 es 42 es 103 nm 103 nm 109 nm 10.0% Wind Speed 7.76	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction 20 x reduction Alloc 0.5 mas / min Alloc 0.5 mas / min 29 Hz input diskutbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle	0.00 the Total	0.00 Effectiv	0.02	0.07	0.15	0.24			
Til Measurement Error (one-axis) Til Anisoplanatian Error (one-axis) Til Anisoplanatian Error (one-axis) Residual Cantrol Anisoplanatian Residual Anisopherio Espersion H Boismoe Instrument Machanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) <b>Total Tip/Tilt Error (one-axis)</b> <b>Total Effective Wavefront Error</b> <b>Sky Coverage</b> Galactic Lat. <b>Corresponding Sky Coverage</b> Assumptions / Parameters Total 1.28 prosec	1.71 mea 2.64 mea 0.15 mea 0.14 mea 1.25 mea 2.50 mea <b>5.7 mas</b> 30 deg al this zenith al this zenith	29 ms 48 ms 46 ms 3 nm 3 nm 70 ms 42 nm 103 nm 103 nm 199 nm 10.0% 10.0%	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.25 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to m/s Zenith Angle m HO WFS Rate	0.00 the Total 18 2469	0.00 Effectiv deg Hz	0.02	0.07	0.15	0.24			
Til Measurement Error (one-axis) Til Anisopianation Error (one-axis) Til Anisopianation Error (one-axis) Residual Centroid Anisopianation Residual Anisopherio Espersion H Solience Instrument Machaenical Drift Long Espocare Field Realison Errors Residual Telescope Pointing Jiber (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Gelactic Lat. Corresponding Sky Coverage Assumptions / Parameters Total_geff 1.28 proces Sodum Abund. 4 x 10 <sup>2</sup>	1.71 mea 2.84 mea 0.16 maa 0.14 mea 2.50 mea 2.50 mea 2.50 mea 30 deg	29 es 48 es 46 es 3 es 3 es 3 es 42 es 103 nm 103 nm 109 nm 10.0% Wind Speed 7.76	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction 20 x reduction Aloce 0.5 mas / min Aloce 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to más Zenith Angle m HO WFS Rate arcmin HO WFS Rate	0.00 the Total 2469 2.7	0.00 Effectiv	0.02	0.07	0.15	0.24			
Til Maasurement Error (one-axis) Til Maasurement Error (one-axis) Til Arisoplanatian Error (one-axis) Resistual Cantroid Antaoplanatian Resistual Antaopherio Espansion H Boismoe Instrument Machanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters Total	1.71 mea 2.64 mea 0.15 mea 0.14 mea 1.25 mea 2.50 mea <b>5.7 mas</b> 30 deg al this zenith al this zenith	29 ms 48 ms 46 ms 3 nm 3 nm 70 ms 42 nm 103 nm 103 nm 199 nm 10.0% 10.0%	21.2 Hz 34.9 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.25 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to m/s Zenith Angle m HO WFS Rate	0.00 the Total 18 2469	0.00 Effectiv dag H2 e- ms	0.02 wwFE	0.07 shown using	0.15	0.24			

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)
	High order integration time	No limit
	Tip tilt integration time	$\geq .0004$
	LGS asterism radius	No limit
<b>Optimized Parameter</b>	H band Strehl Ratio	74%

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

Keck Wavefront Error Budget Sum	mary						Scie	nce E	Sand			
Apde: NGAO LGS	-			u'	g'	r	- P	Z	Y	J	н	K
istrument: TBD			λ (um)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	22
bservation: Exo Jup LGS			δλ. (μm)			0.14	0.15		0.12	0.16		0.3
			λ/D (mas)	7	10	13	15	18	21	26	34	46
									18.13			· ·
High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter				Streh	I Rati	o (%)			
		Error (rms)										
Atmospheric Fitting Error		41 nm	64 Subaps									
Bandwidth Error		29 nm	138 Hz (-3db)									
High-order Measurament Error LGS Tomography Error		35 nm 43 nm	150 W 6 beacon(s)									
Asterism Deformation Error		43 mm 29 mm	0.50 m LLT									
Multispectral Error		19 nm	10 zenith angle, H band									
Scintillation Error		14 nm	0.36 Scint index, H-bend									
WFS Scintillation Error		10 nm	Alice									
	-84 nm											
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts									
Uncorrectable Dynamic Telescope Abernations		13 nm	Dekens Ph.D									
Static WFS Zero-point Calibration Error		25 nm	Alice									
Dynamic WFS Zero-point Calibration Error Leeky Integrator Zero-point Calibration Error		35 nm 15 nm	Alloc									
Go-to Control Errors		15 nm 43 nm	Aloc									
Residual Na Layer Focus Change		19 nm	30 m/s Na layer vel									
OM Finite Stroke Errors		1 nm	4.0 µm P-P stroke									
DM Hysteresis		13 nm	from TMT									
High-Order Aliesing Error		14 nm	64 Subaps									
DM Drive Digitization		1 nm	16 bits									
Uncorrectable AO System Abernations		30 nm	Alloc									
Uncorrectable Instrument Aberrations		30 nm 15 nm	TBD Instrument Alloc									
DM-to-lenslet Miaregistration DM-to-lenslet Pupil Scale Error		15 nm 15 nm	Alloc									
Die-io-enant Pope Scene Entor	94 nm	12 110	Pass									
Angular Anisoplanatism Error		24 mm	1 arcsec									
Total High Order Wavefront Error	127 nm	129 nm	High Order Strehl	0.01	0.06	0.19	0.32	0.44	0.55	0.67	0.79	0.8
	Angular	Equivalent					Etroh	l ratio	n /9/1			
Tip/Tilt Errors	Error (rms)	WFE (rms)	Parameter				Suen	rauc	18 ( 70)			
Sci Filter												
Tit Measurement Error (one-axis)	0.18 mas	3 mm	13.0 mag (mV)									
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis)	0.96 mas	16 mm	38.5 Hz									
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisoplanatism Error (one-axis)	0.96 mas 0.00 mas	16 mm 0 mm	38.5 Hz 0.0 arcsec									
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisoptanatism Error (one-axis) Residual Controid Anisoptanatism	0.96 mas	16 mm	38.5 Hz									
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisoplanatism Error (one-axis)	0.96 mas 0.00 mas 0.93 mas	16 mm 0 mm 16 mm	38.5 Hz 0.0 arcsec 10 x reduction									
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisoglanatism Error (one-axis) Residual Cantoid Anisoptanatism Residual Annospheric Dispersion H	0.96 mas 0.00 mas 0.93 mas 0.08 mas	16 mm 0 mm 16 mm 1 mm	38.5 Hz 0.0 arcsec 10 x reduction 20 x reduction									
Till Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisopiantism Error (one-axis) Residual Controld Anisopianatism Residual Atmospheric Dispension H Science Instrument Mechanical Drift	0.96 mas 0.00 mas 0.99 mas 0.08 mas 1.25 mas	16 nm 0 nm 16 nm 1 nm 36 nm	38.5 Hz 0.0 ansaec 10 x reduction 20 x reduction Alice 0.25 mas / min									
Tit Measurement Error (one-axis) Tit Bankwidh Error (one-axis) Tit Anisopianatism Error (one-axis) Residual Controld Anisopianatism Residual Controld Anisopianatism Basinos Instrument Mechanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis)	0.96 mas 0.00 mas 0.93 mas 0.08 mas 1.25 mas 2.50 mas	16 mm 0 mm 16 mm 1 mm 36 mm 70 mm	38.5 Hz 0.0 ancsec 10 x reduction 20 x reduction Aloc 0.5 mas / min Aloc 0.5 mas / min 29 Hz input disturbance	0.44	0.58	0.70	0.78	0.83	0.87	0.91	0.94	0.9
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisogianatism Error (one-axis) Residual Cantroid Anisogianatism Residual Atmospharic Dispersion H Science Instrument Mechanical Dvitt Long Exposure Field Rotation Errors	0.96 mas 0.00 mas 0.93 mas 1.25 mas 2.50 mas 1.38 mas	16 mm 0 mm 16 mm 16 mm 36 mm 70 mm 23 mm	38.5 Hz 0.0 ancsec 10 x reduction 20 x reduction Altoc 0.25 mas / min Altoc 0.5 mas / min	0.44	0.58	0.70	0.78	0.83	0.87	0.91	0.94	0.9
Til Maasurement Error (one-axis) Til Bandwidth Error (one-axis) Til Ansgenatism Error (one-axis) Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Centroid Anisoplanatism Residual Telescope Pointing Jitter (one-axis) <b>Total Tip/Tilt Error (one-axis)</b>	0.96 mas 0.00 mas 0.93 mas 1.25 mas 2.50 mas 1.38 mas	16 mm 0 mm 16 mm 16 mm 36 mm 70 mm 23 mm	38.5 Hz 0.0 arcsac 10 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 Hz input disturbance Tip/Tilt Strehl								0.94	
Tel Maasurement Ervir (one-axis) Tel Bandwidh Ervor (one-axis) Tel Anisciplanatism Ervor (one-axis) Resistual Controld Anisoptanatism Resistual Anisopherio Espersion H Solience Instrument Mechanical Drift Long Esposure Field Routaison Ervors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error	0.66 mas 0.00 mas 0.69 mas 1.25 mas 1.25 mas 1.38 mas <b>3.4 mas</b>	16 nm 0 nm 16 nm 1 nm 36 nm 23 nm 23 nm	38.5 Hz 0.0 ancsec 10 x reduction 20 x reduction Aloc 0.5 mas / min Aloc 0.5 mas / min 29 Hz input disturbance									
Tel Maasurement Ervir (one-axis) Tel Bandwidh Ervor (one-axis) Tel Anisciplanatism Ervor (one-axis) Resistual Controld Anisoptanatism Resistual Anisopherio Espersion H Solience Instrument Mechanical Drift Long Esposure Field Routaison Ervors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error	0.96 mas 0.00 mas 0.93 mas 1.25 mas 2.50 mas 1.38 mas	16 nm 0 nm 16 nm 1 nm 36 nm 23 nm 23 nm	38.5 Hz 0.0 arcsac 10 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 Hz input disturbance Tip/Tilt Strehl									
Tel Maasurement Ervir (one-axis) Tel Bandwidh Ervor (one-axis) Tel Anisciplanatism Ervor (one-axis) Resistual Controld Anisoptanatism Resistual Anisopherio Espersion H Solience Instrument Mechanical Drift Long Esposure Field Routaison Ervors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error	0.66 mas 0.00 mas 0.69 mas 1.25 mas 1.25 mas 1.38 mas <b>3.4 mas</b>	16 nm 0 nm 16 nm 1 nm 36 nm 23 nm 23 nm	38.5 Hz 0.0 arcsac 10 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 Hz input disturbance Tip/Tilt Strehl	0.00	0.03	0.13	0.25					
Tel Maasuremeet Ervor (one-axis) Tel Bandwidh Ervor (one-axis) Tel Aniscoplanatism Ervor (one-axis) Resistual Control Anisopanatism Resistual Anisopherio Espersion H Solence Instrument Mechanical Drift Long Exposure Field Rotation Ervors Resistual Telescope Pointing Jibr (one-axis) Total Tip/Tilt Ervor (one-axis) Total Effective Wavefront Ervor Sky Coverage Galactic Lat. Corresponding Sky Coverage	0.66 mas 0.00 mas 0.69 mas 1.25 mas 1.25 mas 1.38 mas <b>3.4 mas</b>	16 nm 0 nm 16 nm 36 nm 70 nm 23 nm 63 nm 141 nm	38.5 Hz 0.0 arcsac 10 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 x reduction 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%)	0.00	0.03	0.13	0.25					
Tri I Maasurement Ervir (nne-axis) Tri I Maisurement Ervir (nne-axis) Tri Anisopianatian Ervir (nne-axis) Resistual Cantroid Anisopianatian Resistual Cantroid Anisopianatian Resistual Cantroid Anisopianatian Resistual Cantroid Anisopianatian Resistual Cantroid Anisopianatian Resistual Cantroid Anisopianatian Resistual Telescope Pointing Jitler (ane-axis) Total Tip/Tilt Error (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters	0.66 mea 0.00 mas 0.03 mas 0.08 mea 1.25 mea 1.38 mea <b>3.4 mas</b>	16 nm 0 nm 16 nm 36 nm 70 nm 23 nm 63 nm 141 nm	38.5 Hz 0.0 arcsac 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to:	0.00	0.03 Effectiv	0.13	0.25					
Tel Maasurement Ervor (one-axis) Tel Bandvidh Ervor (one-axis) Tel Anisciplanatism Ervor (one-axis) Resistual Controid Anisoptanatism Resistual Anisoptane Eriopansian H Solence Instrument Mechanical Drift Long Exposure Field Rotation Ervors Resistual Telescope Poeting Jibr (one-axis) Total Tip/Tilt Ervor (one-axis) Total Effective Wavefront Ervor Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters	0.66 mes 0.00 mes 0.03 mas 0.06 mes 1.25 mes 1.25 mes 1.38 mes 3.4 mes 30 deg	16 nm 0 nm 16 nm 1 nm 36 nm 70 nm 23 nm 63 nm 141 nm 0.0%	38.5 Hz 0.0 arcsae 10 x reduction 20 x reduction 20 x reduction 20 x reduction Aloc 0.5 mas / min Aloc 0.5 mas / min 29 Hz input diskutbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle	0.00 the Total	0.03 Effectiv	0.13	0.25	0.37	0.48			
Til Maasurement Ervor (one-axis) Til Bandwidh Ervor (one-oxis) Til Anisoplanatism Ervor (one-oxis) Residual Cantroid Anisoplanatism Residual Cantroid Anisoplanatism Residual Anisopherio Expansion H Solence Instrument Mechanical Drift Long Exposure Field Rotation Ervors Residual Telescope Pointing Jitar (one-axis) <b>Total Tip/Tilt Error (one-axis)</b> <b>Total Effective Wavefront Error</b> <b>Sky Coverage</b> Galactic Lat. <b>Corresponding Sky Coverage</b> Assumptions / Parameters 10 0.178 m Thata0_eff 1.33 arcsec	0.66 mea 0.00 mea 0.08 mea 1.25 mea 2.50 mea 1.38 mea <b>3.4 mas</b> 30 deg al Ihia zanith al Ihia zanith	16 nm 0 nm 16 nm 36 nm 70 nm 23 nm 63 nm 63 nm 141 nm 0.0% Wind Speed 7.93 Outer Scale 50	38.5 Hz 0.0 arcsac 10 x reduction 20 x redu	0.00	0.03 Effectiv deg Hz	0.13	0.25		0.48			
Tri Maasurement Ervor (one-axis) Tri Mansudh Ervor (one-axis) Tri Aniscopianatism Ervor (one-axis) Resistual Centroid Anisopanatism Resistual Anisopheric Diofit Long Esposure Field Rolation Ervors Resistual Telescopa Poeting Jitar (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters rd 0.178 m Thata_stf 1.33 arcsec Sodium Abund. 4 s 10°	0.96 mes 0.00 mes 0.08 mes 0.08 mes 1.25 mes 1.25 mes 1.38 mes 3.4 mes 30 deg	16 nm 0 nm 16 nm 1 nm 36 nm 70 nm 23 nm 63 nm 141 nm 0.0%	38.5 Hz 0.0 arcsac 10 x reduction 20 x reduction 20 x reduction 20 x reduction Aloc 0.5 mas / min 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to må Zenith Angle m HO WFS Rate arcmin HO WFS Rate	0.00 the Total 2071 I 2.5 4	0.03 Effectiv	0.13	0.25	0.37	0.48			
Til Maasurement Ervir (one-axis) Til Mansverth Ervir (one-axis) Til Arisoplanatism Ervir (one-axis) Resistual Cantroid Anacoplanatism Resistual Anospheric Disparsion H Sosience Instrument Mechanical Drift Long Exposure Field Rotation Ervirs Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Ervir (one-axis) Total Effective Wavefront Ervir Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters Total Disparation (0.178 m Thata0_eff 1.33 arcsec	0.66 mea 0.00 mea 0.08 mea 1.25 mea 2.50 mea 1.38 mea <b>3.4 mas</b> 30 deg al Ihia zanith al Ihia zanith	16 nm 0 nm 16 nm 36 nm 70 nm 23 nm 63 nm 63 nm 141 nm 0.0% Wind Speed 7.93 Outer Scale 50	38.5 Hz 0.0 arcsac 10 x reduction 20 x redu	0.00	0.03 Effectiv deg Hz e- ms	0.13 wwFE	0.25 shown using	0.37	0.48			

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 Subaperture width Tip tilt integration time	No Limit $\geq .171 \text{ m} (\leq 64 \text{ subaps})$ No Limit
	Tip tilt guide star search radius LGS asterism radius Sky Coverage	No Limit No Limit =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 Sum	marv					Scien	ce Band	d		
Mode: NGAO LGS	,			u' g'	Ľ	ľ	Z Y		Н	К
Instrument: TBD			λ. (μm)		0.62	0.75 (	.88 1.0	3 1.28		
Observation: Extended Groth Strip			δλ. (µm)		0.14	0.15 0	.12 0.1	2 0.16	0.29	0.34
			λ/D (mas)	7 10	13	15	18 21	26	- 34	46
		Wavefront				Strahl	Ratio (%	41		
High-order Errors (LGS Mode)		Error (rms)	Parameter		,	Suem	Kauo ()	no j		
Atmospheric Fitting Error Bandwidth Error		44 nm 30 nm	64 Subaps 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 WFS Scintillation Error		20 nm 10 nm	0.49 Scint index, H-bend Alloc							
WPS Schalabon Emar	124 nm	10 mm	ABC							
Uncorrectable Static Telescope Aberrations	12-4 1001	43 nm	64 Acta							
Uncorrectable Dynamic Telescope Aberrations		12 nm	Dekens Ph.D							
Static WFS Zero-point Calibration Error		25 nm	Alice							
Dynamic WFS Zero-point Calibration Error		35 nm	Alice							
Leaky Integrator Zero-point Calibration Error		15 nm	Alice							
Go-to Control Errors Residual Na Layer Focus Change		43 nm 23 nm	Alloc 30 m/s Na layer vel							
DM Finite Stroke Errors		23 nm 1 nm	4.0 um P-P stroke							
DM Hysteresis		13 nm	from TMT							
High-Order Aliesing Error		15 nm	64 Subapa							
DM Drive Digitization		1 nm	16 bits							
Uncorrectable AO System Aberrations		30 nm	Alloc							
Uncorrectable Instrument Aberrations DM-to-lenslet Misregistration		30 nm 15 nm	TBD Instrument Alloc							
DM-to-lensiet Pupil Scale Error		15 mm	Aloc							
Diricherant op Cone City	95 nm	12 111	Pess							
Angular Anisoplanatism Error		43 nm	1.5 arcsec							
Total High Order Wavefront Error	156 nm	162 nm	High Order Strehl	0.00 0.01	0.07	0.16 0	.27 0.3	9 0.54	2 0.69	0.81
Total High Order Wavefront Error			High Order Strehl	0.00 0.01					2 0.69	0.81
Total High Order Wavefront Error	Angular	Equivalent	High Order Strehi Parameter	0.00 0.01			.27 0.3		2 0.69	0.81
Tip/Tilt Errors				0.00 0.01					2 0.69	0.81
Tip/Tilt Errors	Angular Error (rms)	Equivalent	Parameter	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors	Angular	Equivalent WFE (rms)		0.00 0.01					2 0.69	0.81
Tip/Tilt Errors Bil Filer Til Measurement Error (one-axis) Til Bandwidth Error (one-axis) Til Ansignatism Error (one-axis)	Angular Error (rms) 4.58 mas 1.52 mas 4.37 mas	Equivalent WFE (rms) 77 en 33 en 74 en	Parameter 20.4 mag (mV) 17.6 Hz 50.2 ansae	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors Boi Filer Til Measurement Error (one-axis) Til Bandwidth Error (one-axis) Til Anisoplanatism Error (one-axis) Residual Controid Anisoplanatism	Angular Error (rms) 4.58 mas 1.02 mas 4.37 mas 1.02 mas	Equivalent WFE (rms) 77 em 33 em 74 em 17 em	Parameter 20.4 mag (mV) 17.6 Hz 50.2 ansae 10 a reduction	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors Boi Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Anisoplanatism Error (one-axis) Residual Cantrold Antioplanatism Residual Amospherio Expension K	Angular Error (rms) 4.58 mas 1.02 mas 4.57 mas 1.02 mas 0.14 mas	Equivalent WFE (rms) 77 ms 33 ms 74 ms 17 ms 3 ms	Parameter 20.4 mog (mV) 17.6 H2 50.2 arcsec 10 a reduction 20 a reduction	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors Til Measurement Error (one-axis) Til Measurement Error (one-axis) Til Andwidth Error (one-axis) Residual Centroid Anisoptenatism Residual Antrospheric Dispension Science Instrument Mechanical Drift	Angular Error (rms) 4.58 mas 1.52 mas 4.37 mas 1.02 mas 0.14 mas 7.50 mas	Equivalent WFE (rms) 77 en 35 en 74 en 17 en 3 en 250 en	Parameter 20.4 mag (mV) 17.5 Hz 50.2 ansae 10 x reduction 20 x reduction Aloc 0.25 mas /min	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors Boi Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Anisoplantism Error (one-axis) Residual Centroid Anisoplantism Residual Atmospheric Dispersion Solence Instrument Mechanical Drift Long Engosure Field Rotatison Errors	Angular Error (rms) 4.58 mes 1.82 mes 4.37 mes 0.14 mes 7.50 mes 15.00 mes	Equivalent WFE (rms) 77 ms 33 ms 74 ms 17 ms 3 ms	Parameter 20.4 mog (mV) 17.6 H2 50.2 arcsec 10 a reduction 20 a reduction	0.00 0.01					2 0.69	0.8
Tip/Tilt Errors Boi Filter Til Measurement Error (one-axis) Til Bandwidt Error (one-axis) Til Arisogianatism Error (one-axis) Residual Centriod Ansopharatism Residual Centriod Ansopharatism Residual Centrod Ansopharatism Residual Telescope Poeting Jitter (one-axis)	Angular Error (rms) 4.58 mas 1.52 mas 4.57 mas 1.02 mas 0.14 mas 1.50 mas 15.00 mas 3.01 mas	Equivalent WFE (rms) 77 nm 33 nm 74 nm 74 nm 3 nm 250 nm 51 nm	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcsac 10 a reduction 20 fizi input disluttence		1	Strehl	atios (9	%)		
Tip/Tilt Errors Boi Filer Til Massurament Error (one-axis) Til Bandwidt Error (one-axis) Til Anisoglianatism Error (one-axis) Residual Centroid Anisoglianatism Residual Amospheric Dispersion Sosience Instrument Mechanical Drift Long Ergosure Field Rotatison Errors	Angular Error (rms) 4.58 mes 1.82 mes 4.37 mes 0.14 mes 7.50 mes 15.00 mes	Equivalent WFE (rms) 77 em 33 em 74 em 17 em 3 em 30 em	Parameter 20.4 migg (mV) 17.6 Hz 50.2 arcsec 10 x reduction 20 x reduction Aloce 0.25 miss / min Aloce 0.5 miss / min		1	Strehl		%)		
Tip/Tilt Errors Bil Filer Til Massurement Error (one-axis) Til Bandwidth Error (one-axis) Til Arisoglanatism Error (one-axis) Residual Cantoid Arisoglanatism Residual Cantoid Arisoglanatism Residual Cantoid Arisoglanatism Residual Taliacopa Pointing Jitar (one-axis) Total Tip/Tilt Error (one-axis)	Angular Error (rms) 4.58 mas 1.52 mas 4.57 mas 1.02 mas 0.14 mas 1.50 mas 15.00 mas 3.01 mas	Equivalent WFE (rms) 33 nm 74 nm 3 nm 250 nm 300 nm 51 nm 288 nm	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcase 10 x reduction 20 x reduction Aloce 0.25 mas / min Aloce 0.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl	0.03 0.04	0.08	Strehl (	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bil Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Arisogianatiam Error (one-axis) Residual Cantroid Arisogianatiam Residual Cantroid Arisogianatiam Residual Atmospheric Dispersion K Science Instrument Mechanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	Angular Error (rms) 4.58 mas 1.52 mas 4.57 mas 1.02 mas 0.14 mas 1.50 mas 15.00 mas 3.01 mas	Equivalent WFE (rms) 77 nm 33 nm 74 nm 74 nm 3 nm 250 nm 51 nm	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcsac 10 a reduction 20 fizi input disluttence		0.08	Strehl (	atios (9	%) 9 0.25	5 0.36	0.51
Tip/Tilt Errors Boi Filter Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Arisoglanatism Error (one-axis) Residual Cantroid Arisoglanatism Residual Cantroid Arisoglanatism Residual Cantroid Arisotechanical Drit Science Instrument Mechanical Drit Long Exposure Field Rotation Errors Residual Telescope Poeting Jitter (one-axis)	Angular Error (rms) 4.58 mas 1.52 mas 4.57 mas 1.02 mas 0.14 mas 1.50 mas 15.00 mas 3.01 mas	Equivalent WFE (rms) 33 nm 74 nm 3 nm 250 nm 300 nm 51 nm 288 nm	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcase 10 x reduction 20 x reduction Aloce 0.25 mas / min Aloce 0.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl	0.03 0.04	0.08	Strehl (	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bi Filer Til Massurement Error (one-axis) Til Bandwidth Error (one-axis) Til Arisoglanatism Error (one-axis) Residual Cantrod Arisoglanatism Residual Cantrod Arisoglanatism Residual Cantrod Arisoglanatism Residual Cantrod Arisoglanatism Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat.	Angular Error (rms) 4.58 mes 1.50 mes 0.14 mes 7.50 mes 3.01 mes 15.00 mes 3.01 mes	Equivalent WFE (rms) 33 nm 74 nm 3 nm 250 nm 300 nm 51 nm 288 nm	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcase 10 x reduction 20 x reduction Aloce 0.25 mas / min Aloce 0.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl	0.03 0.04	0.08	0.11 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors  Sci Filer  Til Measurement Error (one-axis)  Til Anisoplanatism Error (one-axis)  Til Anisoplanatism Error (one-axis)  Residual Centroid Antsoplanatism Residual Antsophero Erioparsion K Science Instrument Mechanical Drift Long Ergosume Fild Rotation Errors Residual Telescope Pointing Jitter (one-axis)  Total Tip/Tilt Error (one-axis)  Total Effective Wavefront Error  Sky Coverage Galactic Lat.  Corresponding Sky Coverage	Angular Error (rms) 4.58 mes 1.50 mes 0.14 mes 7.50 mes 3.01 mes 15.00 mes 3.01 mes	Equivalent WFE (rms) 77 nm 33 nm 74 nm 74 nm 300 nm 51 nm 288 nm 288 nm	Parameter 20.4 mag (mV) 17.8 Hz 50.2 arcsac 10 a reduction 20 a reduction Alece 0.5 mas / min Alece 0.5 mas / min 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%)	0.03 0.04	0.08	0.11 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bit Filer Titi Measurement Error (one-axis) Titi Bandwidth Error (one-axis) Titi Bandwidth Error (one-axis) Residual Centroid Aeizoplanalism Residual Centroid Aeizoplanalism Residual Amospheric Diopersion K Sosience Instrument Mechanical Drift Long Ergosure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters	Angular Error (rms) 4.58 mes 1.02 mes 4.37 mes 0.14 mes 7.50 mes 3.01 mes 15.00 mes 3.01 mes 18.3 mas	Equivalent WFE (rms) 77 em 37 em 74 em 74 em 3 em 250 em 51 em 288 nm 288 nm 329 nm 329 nm	Parameter 20.4 misg (mV) 17.6 Hz 50.2 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.55 mas / min 29 Hz input diskutbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to	0.03 0.04 0.00 0.00	0.08	0.11 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bid Filer Til Measurement Error (one-axis) Til Bandwidth Error (one-axis) Til Anisopianatism Error (one-axis) Til Anisopianatism Error (one-axis) Residual Centroid Anisophanism Residual Centroid Anisophanism Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters r0 0.161 m	Angular Error (ms) 4.58 mas 1.52 mas 4.37 mas 1.52 mas 7.50 mas 15.00 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas	Equivalent WFE (rms) 77 em 74 em 74 em 3 em 250 em 300 em 51 em 288 nm 288 nm 329 nm 329 nm 329 nm 30.0%	Parameter 20.4 mag (mV) 17.8 Hz 50.2 arcase 10 x reduction 20 x re	0.03 0.04 0.00 0.00	0.08 0.001	0.11 0 0.02 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bit Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Bandwidt Error (one-axis) Residual Centrod Arbanical Drift Long Engosure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters Thata0_eff 1.01 arcsec	Angular Error (ms) 4.58 mas 1.02 mas 0.14 mas 7.50 mas 3.01 mas 3.01 mas 15.00 mas 3.01 mas 18.3 mas 18.3 mas	Equivalent WFE (rms) 77 em 73 em 74 em 74 em 74 em 3250 em 51 em 2280 em 51 em 288 nm 288 nm 329 nm 329 nm 30.0%	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.55 mas / min 20 Hz input diskutbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle m HO WFS Rate	0.03 0.04 0.00 0.00 the Total Effect 34 deg 2265 Hz	0.08 0.01	0.11 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Boi Filer Til Massurement Error (one-axis) Til Bandwidth Error (one-axis) Til Anisogianatism Error (one-axis) Tilt Anisogianatism Error (one-axis) Residual Canteid Anisophanism Residual Canteid Anisophanism Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters Thial_seff 1.01 arcsec Sodem Abund. 4 x 10 <sup>6</sup>	Angular Error (ms) 4.58 mas 1.52 mas 4.37 mas 1.52 mas 7.50 mas 15.00 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas 3.01 mas	Equivalent WFE (rms) 77 em 74 em 74 em 3 em 250 em 300 em 51 em 288 nm 288 nm 329 nm 329 nm 329 nm 30.0%	Parameter 20.4 mag (mV) 17.5 Hz 50.2 arcsae 10 a reduction 20 arcs / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mb Zenith Angle m HO WFS Rate arcmin HO WFS Rate arcmin HO WFS Rate	0.03 0.04 0.00 0.00 Ne Total Effect 24 deg 226 te - ma	0.08 0.01	0.11 0 0.02 0	atios (9	%) 9 0.25	5 0.36	0.5
Tip/Tilt Errors Bit Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Arisoglanatism Error (one-axis) Residual Cantrold Arisoglanatism Residual Amospheric Dispersion K Science Instrument Mechanization Errors Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters rd 0.561 m Thata0.eff 1.01 secsec Sodem Abund. 4 x 10 <sup>6</sup> Science Target MOVO	Angular Error (ms) 4.58 mas 1.02 mas 0.14 mas 7.50 mas 3.01 mas 3.01 mas 15.00 mas 3.01 mas 18.3 mas 18.3 mas	Equivalent WFE (rms) 77 em 73 em 74 em 74 em 74 em 3250 em 51 em 2280 em 51 em 288 nm 288 nm 329 nm 329 nm 30.0%	Parameter 20.4 mag (mV) 17.6 Hz 50.2 arcsec 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.55 mas / min 20 Hz input diskutbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle m HO WFS Rate	0.03 0.04 0.00 0.00 the Total Effect 34 deg 2265 Hz	0.08 0.01	0.11 0 0.02 0	.14 0.1 .04 0.0	%) 9 0.25	5 0.36	0.51
Tip/Tilt Errors Boi Filer Til Massurement Error (one-axis) Til Bandwidth Error (one-axis) Til Anisogianatism Error (one-axis) Tilt Anisogianatism Error (one-axis) Residual Canteid Anisophanism Residual Canteid Anisophanism Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters Thial_seff 1.01 arcsec Sodem Abund. 4 x 10 <sup>6</sup>	Angular Error (ms) 4.58 mes 1.52 mes 4.37 mes 0.14 mes 7.50 mes 3.01 mes 3.01 mes 15.00 mes 3.01 mes 18.3 mas 18.3 mas 30 deg	Equivalent WFE (rms) 77 nm 74 nm 74 nm 250 nm 51 nm 51 nm 288 nm 288 nm 329 nm 329 nm 329 nm 30.0%	Parameter 20.4 mag (mV) 17.6 Hz 50.2 ansac 10 a reduction 20 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to min Zenith Acgle m HO WFS hala anomin HO WFS hala anomin HO WFS hala	0.03 0.04 0.00 0.00 1% Total Effect 24 dag 2265 Hz 2.8 e mms	1 0.08 0.01 0.01 8H	0.11 0 0.02 0	.14 0.1 .04 0.0	%) 9 0.25	5 0.36	0.51

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. The 36% H band Strehl ratio corresponds to system performance at the corner of the 10 asec field.

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	No Limit
<b>Optimized Parameter</b>	H band Strehl Ratio	36%

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

Keck Wavefront Error Budget Sum	mary			Science Band
Mode: NGAO LGS				u'g'r'l'ZYJHK
Instrument: NIRC2			λ (um)	
Observation: Gal Con			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
				01-11 D-1-1013
High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%)
		Endr (maj		
Atmospheric Fitting Error		48 nm	64 Subaps	
Bandwidth Error		41 nm	113 Hz (-3db)	
High-order Measurement Error LGS Tomography Error		48 nm 41 nm	150 W 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-bend	
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 Celibration Evor		35 nm	Alloc	
Leaky Integrator Zero-point Calibration Error Go-to Control Errors		15 nm 43 nm	Alice	
Residual Na Layer Focus Change		43 nm 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 Aliesing Error		16 nm	64 Subaps	
DM Drive Digitization		1 nm	16 bits	
Uncorrectable AO System Aberrations		30 nm	Alice	
Uncorrectable Instrument Aberrations		110 mm	NIRC2 Instrument	
DM-to-lenslet Misregistration DM-to-lenslet Pupil Scale Error		15 nm 15 nm	Alice	
DM-ID-MISNE Pupe Scale Error	144 nm	15 nm	Albo	
Angular Anisoplanatism Error	14-4 1811	198 mm	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	Angular	Equivalent	Parameter	Strehl ratios (%)
		And a second sec	Farameter	
•	Error (rms)	WFE (rms)	Farameter	
Sci Filter				
- Boi Filter Tilt Measurement Error (one-axis)	0.11 mas	2 m	12.2 mag (mV)	
- Bol Filter Till Measurement Error (one-axis) Till Bandwidth Error (one-axis)	0.11 mas 0.81 mas		12.2 mag (mV) 38.5 Hz	
- Boi Filter Tilt Measurement Error (one-axis)	0.11 mas	2 m 14 m	12.2 mag (mV)	
TRI Moasurement Error (one-axis) TRI Bandwidh Error (one-axis) TRI Anisoplanatism Terror (one-axis) Residual Cantrold Anisoplanatism Residual Amospherio Tosparaism K	0.11 mes 0.81 mes 0.52 mes 1.11 mes 0.22 mes	2 mm 14 mm 9 mm 19 mm 4 mm	12.2 mag (mV) 38.5 Hz 5.5 srosec 10 x rotaction 20 x rotaction	
Till Measurement Error (one-axis) Till Bandwidth Error (one-axis) Till Affoglanatism Error (one-axis) Residual Centroid Anisoplanatism Residual Atmospheric Dispersion Science Instrument Mechanical Drift	0.11 mes 0.81 mes 0.52 mes 1.11 mes 0.22 mes 0.13 mes	2 mi 14 mi 9 mi 19 mi 4 mi 5 mi	12.2 mag (mV) 38.5 Hiz 5.5 anciae 10 x reduction 20 x reduction Aloc 0.25 mas / min	
Till Measurement Ervor (one-axis) Till Bandwidth Ervor (one-axis) Till Anisoplanatism Ervor (one-axis) Residual Cantoid Anisoplanatism Residual Cantoid Anisoplanatism Residual Annospharic Dispersion Brief Cantoid Anisoplanatism Residual Annospharic Dispersion Evrop Exposure Field Rotation Ervors	0.11 mas 0.81 mas 0.52 mas 0.22 mas 0.22 mas 0.13 mas 0.25 mas	2 mi 14 mi 9 mi 19 mi 4 mi 5 mi 10 mi	12.2 mag (mV) 38.5 Hz 5.5 ancsec 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min	
Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Anisoplantism Error (one-axis) Residual Centrold Anisoplanatism Residual Atmospheric Dispension Science Instrument Mechanical Drift	0.11 mes 0.81 mes 0.52 mes 1.11 mes 0.22 mes 0.13 mes	2 mi 14 mi 9 mi 19 mi 4 mi 5 mi	12.2 mag (mV) 38.5 Hiz 5.5 anciae 10 x reduction 20 x reduction Aloc 0.25 mas / min	
Till Measurement Ervor (one-axis) Till Bandwidth Ervor (one-axis) Till Anisoplanatism Ervor (one-axis) Residual Cantoid Anisoplanatism Residual Cantoid Anisoplanatism Residual Annospharic Dispersion Brief Cantoid Anisoplanatism Residual Annospharic Dispersion Evrop Exposure Field Rotation Ervors	0.11 mas 0.81 mas 0.52 mas 0.22 mas 0.22 mas 0.13 mas 0.25 mas	2 mi 14 mi 9 mi 19 mi 4 mi 5 mi 10 mi	12.2 mag (mV) 38.5 Hz 5.5 ancsec 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min	0.68 0.79 0.87 0.91 0.93 0.95 0.96 0.98 0.99
Sci Filter Titl Measurement Error (one-axis) Titl Bandwidth Error (one-axis) Titl Aniogianatism Error (one-axis) Residual Centroid Aniopianatism Residual Atmospheric Dispersion K Science Instrument Mechanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jitter (one-axis)	0.11 mas 0.81 mas 0.52 mas 0.52 mas 0.13 mas 0.25 mas 1.38 mas	2 mm 14 mm 9 mm 19 mm 4 mm 5 mm 10 mm 23 mm	12.2 mag (mV) 38.5 Hz 5.5 ancase 10 x reduction 20 x reduction Aloc 0.5 mas / min Aloc 0.5 mas / min 29 H2 input disturbance	0.68 0.79 0.87 0.91 0.93 0.95 0.96 0.98 0.96
Bei Filter Titt Measurement Error (one-axis) Titt Bandwidth Error (one-axis) Titt Ansignantism Error (one-axis) Residual Controld Anisoptenatism Residual Controld Anisoptenatism Residual Controld Anisoptenatism Residual Telescope Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	0.11 mas 0.81 mas 0.52 mas 0.52 mas 0.13 mas 0.25 mas 1.38 mas	2 mm 14 mm 9 mm 19 mm 4 mm 5 mm 10 mm 23 mm	12.2 mag (mV) 38.5 Hz 5.5 ancase 10 x reduction 20 x reduction Aloc 0.5 mas / min Aloc 0.5 mas / min 29 H2 input disturbance	
Sci Filer Tri Maasuromeett Error (one-axis) Tri Aniscolanatism Error (one-axis) Resistual Control Anisoptanatism Resistual Anisoptano Espansion K Science Instrument Mechanical Drift Long Esposure Field Roulation Errors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	0.11 mas 0.51 mas 0.52 mas 0.12 mas 0.13 mas 0.25 mas 1.38 mas 2.0 mas	2 nm 14 nm 9 nm 19 nm 4 nm 5 nm 10 nm 23 nm 38 nm	12.2 mag (mV) 38.5 Hz 5.5 arcaac 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl	
Sci Filer Tri Maasuromeett Error (one-axis) Tri Aniscolanatism Error (one-axis) Resistual Control Anisoptanatism Resistual Anisoptano Espansion K Science Instrument Mechanical Drift Long Esposure Field Roulation Errors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	0.11 mas 0.81 mas 0.52 mas 0.52 mas 0.13 mas 0.25 mas 1.38 mas	2 nm 14 nm 9 nm 19 nm 4 nm 5 nm 10 nm 23 nm 38 nm	12.2 mag (mV) 38.5 Hz 5.5 arcaac 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl	
Sci Filer Tri Maasuromeett Error (one-axis) Tri Aniscolanatism Error (one-axis) Resistual Control Anisoptanatism Resistual Anisoptano Espansion K Science Instrument Mechanical Drift Long Esposure Field Roulation Errors Resistual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis)	0.11 mas 0.51 mas 0.52 mas 0.12 mas 0.13 mas 0.25 mas 1.38 mas 2.0 mas	2 nm 14 nm 9 nm 4 nm 5 nm 10 nm 23 nm 38 nm 271 nm	12.2 mag (mV) 38.5 Hz 5.5 arcaac 10 a reduction 20 a reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.55
Sci Filer Tri Maasuroment Error (one-axis) Tri I Anisoplanatism Error (one-axis) Residual Control Anisoplanatism Residual Control Anisoplanatism Residual Anisopheric Dispersion K Science Instrument Mechanical Drift Long Exposure Field Rolation Errors Residual Telescope Pointering Jibr (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage	0.11 mas 0.51 mas 0.52 mas 0.12 mas 0.13 mas 0.25 mas 1.38 mas 2.0 mas	2 nm 14 nm 9 nm 4 nm 5 nm 10 nm 23 nm 38 nm 271 nm	12.2 mag (mV) 38.5 Hz 5.5 arcaac 10 x reduction 20 x reduction Aloc 0.25 mas / min Aloc 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%)	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.58
Sci Filer Tri Massurement Error (one-axis) Tri Anisoplanatism Error (one-axis) Tri Anisoplanatism Error (one-axis) Residual Cantroid Anisoplanatism Residual Anisopherio Espansion K Solence Instrument Mechanical Drift Long Exposure Field Rotation Errors Residual Telescopa Pointing Jitter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters	0.11 mas 0.51 mas 0.52 mas 0.22 mas 0.22 mas 0.25 mas 1.38 mas <b>2.0 mas</b> <b>30</b> deg	2 nm 14 nm 9 nm 19 nm 4 nm 5 nm 10 nm 23 nm 23 nm 38 nm 271 nm	12.2 mag (mV) 38.5 Hz 5.5 arcsac 10 a reduction 20 a reduction Aloce 0.25 mas / min Aloce 0.5 mas / min 29 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.55
Sci Filer Til Maasuroment Error (one-axis) Til Answidth Error (one-axis) Til Ansolution (one-axis) Residual Control Anisopharatism Residual Control Anisopharatism Residual Anisophara Disparsion K Solence Instrument Machanical Drift Long Exposure Field Rotation Errors Residual Telescope Peinfing Jibr (one-axis) Total Tip/Tilt Error (one-axis) Fotal Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters r0 0.145 m	0.11 mas 0.51 mas 0.52 mas 0.13 mas 0.22 mas 0.23 mas 0.25 mas 1.38 mas 2.0 mas 30 deg	2 nm 14 nm 9 nm 4 nm 5 nm 10 nm 23 nm 38 nm 271 nm 0.2% Wind Speed 643	12.2 mag (mV) 38.5 Hz 5.5 arcsac 10 a reduction 20 a reduction Aloce 0.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to mis Zenith Angle	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.55
Sci Filer Til Massurement Error (one-axis) Til Bandwidt Error (one-axis) Til Anisoplanatism Error (one-axis) Residual Cantrold Antoppansion K Solence Instrument Mechanical Drift Long Exposure Field Rotation Errors Residual Telescope Pointing Jiter (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters rd 0.145 m Theia0_eff 0.76 mcsec	0.11 mas 0.51 mas 0.52 mas 0.52 mas 0.22 mas 0.25 mas 0.25 mas 1.38 mas <b>2.0 mas</b> <b>30</b> deg al Ihis zenith al Ihis zenith	2 nm 14 nm 9 nm 19 nm 4 nm 5 nm 10 nm 23 nm 38 nm <b>271 nm</b> <b>0.2%</b> Wind Speed 6.43 Outer Scele 50	12.2 mag (mV) 38.5 Hz 5.5 arcsac 10 a reduction 20 a reduction 20 a reduction 20 c.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to m/s Zenith Angle m HO WFS Rate	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.55
Sci Filer Til Measurement Error (one-axis) Til Measurement Error (one-axis) Til Ansolution Error (one-axis) Residual Centroid Antophanatism Residual Amespheric Dispersion K Science Indumment Mechanical Drift Long Exposure Field Rotation Errors Residual Telescope Peeting Jibr (one-axis) Total Tip/Tilt Error (one-axis) Total Effective Wavefront Error Sky Coverage Galactic Lat. Corresponding Sky Coverage Assumptions / Parameters r0 0.145 m	0.11 mas 0.51 mas 0.52 mas 0.13 mas 0.22 mas 0.23 mas 0.25 mas 1.38 mas 2.0 mas 30 deg	2 nm 14 nm 9 nm 4 nm 5 nm 10 nm 23 nm 38 nm 271 nm 0.2% Wind Speed 643	12.2 mag (mV) 38.5 Hz 5.5 arcsac 10 a reduction 20 a reduction 20 a reduction 20 c.25 mas / min 20 Hz input disturbance Tip/Tilt Strehl Total Strehl (%) This fraction of sky can be corrected to m/s Zenith Angle m HO WFS Rate	0.00 0.00 0.00 0.01 0.02 0.07 0.16 0.34 0.55
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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.