NGAO Wavefront Error Performance Budgets

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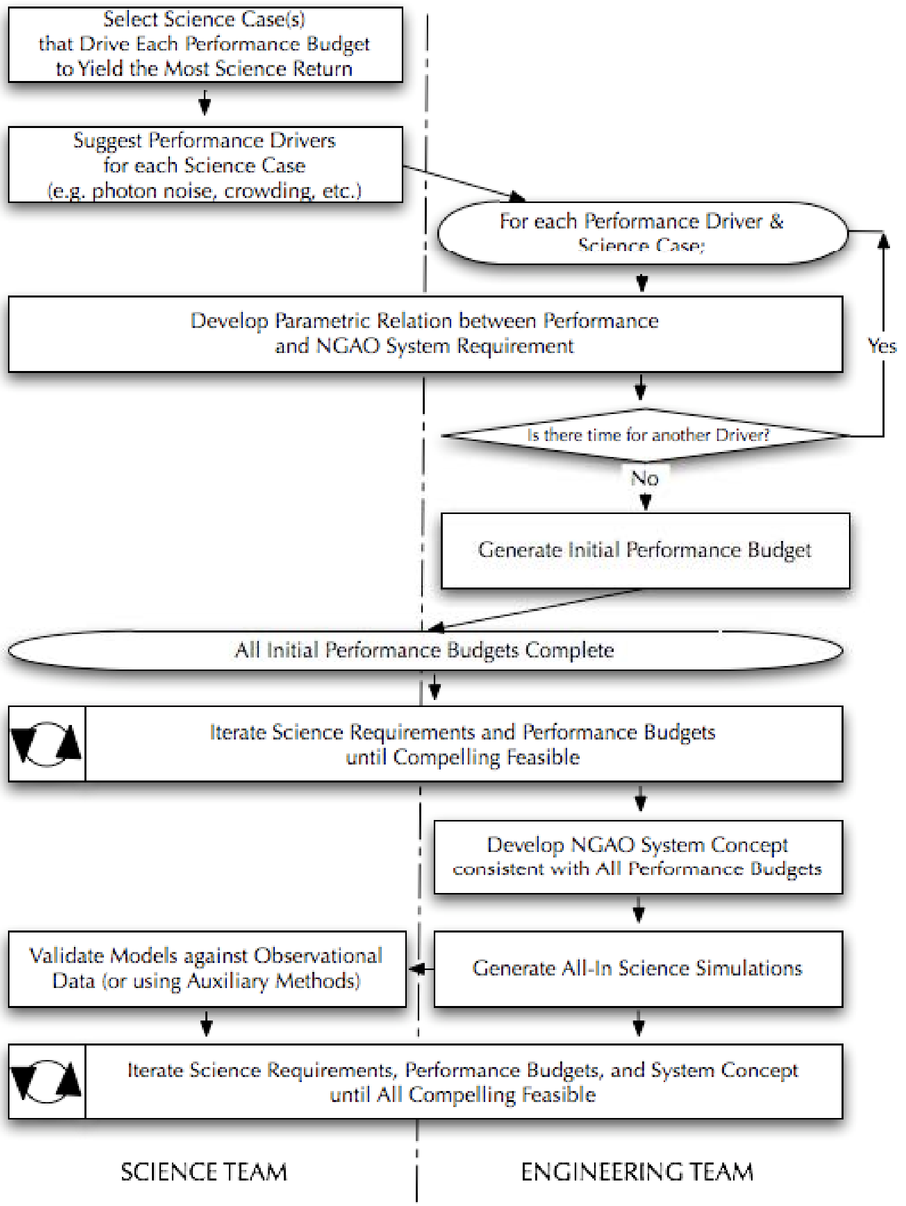
Performance Budgets

- High-level Estimates of NGAO Science Performance
- Initial Stage of Requirements Flowdown Process

NGAO Science Requirements / Performance Budget Process

Version 1.0 9/22/06



NGAO Requirements History

NGAO Key Science Case	2006 Keck 2 AO Performance in 75th Percentile Best Seeing (approx.)	Expected Keck 1 AO Performance in Median Seeing (approx.)	NGAO Requirements in Median Seeing			
			Proposal	SDR	B2C	PDR
Galaxy Assembly	557	529	197	257	204	185
Nearby AGN's	557[3]	529[4]	197[5]	N/A	182	181
Galactic Center	N/A	387	182	184	189	193
Exoplanets	378	311	N/A	155[9]	171	174
Minor Planets	557[3]	529[4]	131	175	177	181
Io	258	210	125	148[12]	N/A	117

[1] Slight revisions to the Key Science Cases have been made during PD phase. See McGrath and Max, "Science Case Parameters for Performance Budgets" for more details.
[2] June 20, 2006 NGAO Design and Development Proposal, Table 13.
[3] KAON 461, Table 1 for LGS mode with 18th magnitude TT star.
[4] KAON 461, Appendix 3 for LGS mode with 18th magnitude TT star.
[5] June 20, 2006 NGAO Design and Development Proposal, Figure 49, for 30% sky coverage, z = 30 deg, having 173 nm HO error and
[6] Performance increase driven by reduced FoR for this science case brought on by Build-to-Cost decision to eliminate a d-IFU instrument from the NGAO program.
[7] Jessica Lu, private communication, who reports NGWFC median performance of 401 nm RMS. Here, we assume Keck 1 LGS will provide the same improvement as shown in KAON 461, Table 2, for LGS with 10th magnitude TT star, namely the subtraction of 105 nm in quadrature, so sqrt(401^2 – 105^2) = 387 nm.
[8] KAON 461, Table 1 for LGS mode with 10th magnitude TT star.
[9] KAON 461, Appendix 2 for LGS mode with 10th magnitude TT star.
[10] Performance decrease driven primarily by simplification to laser asterism and reduction in laser power.
[11] KAON 461, Table 1 for NGS 'bright star' performance.
[12] KAON 461, Appendix 1 for NGS mode with 8th magnitude TT star. Note, NGWFC should have similar performance, as the Keck 1 LGS upgrade will not affect NGS science performance.

KAON 721

- The NGAO wavefront error budget spreadsheet tool
  - Informed by series of Keck technical reports…
    - KAON 417, Sodium Abundance Data from Maui Mesosphere
    - KAON 452, MOAO versus MCAO Trade Study Report
    - KAON 465, NGAO LGS Wavefront Sensor: Type and Number of Subapertures Trade Study
    - KAON 471, NGAO Wavefront Error and Ensquared Energy Budgets (SD Phase)
    - KAON 475, Tomography Codes Comparison and Validation for NGAO
    - KAON 492, NGAO Null-Mode and Quadratic Mode Tomography Error
    - KAON 504, NGAO Performance vs. Technical Field of View for LOWFS Guide Stars
    - KAON 621, Noise Propagator for Laser Tomography AO
    - KAON 635, Point & Shoot Study
    - KAON 644, Build-to-Cost Architecture Performance Analysis
    - KAON 710, Latency, Bandwidth, and Control Loop Residual Relationships
  - …and extensive validation
    - KAON 461, Wavefront Error Budget Predictions & Measured Performance for Current & Upgraded Keck AO
    - KAON 470, NGAO Sky Coverage Modeling
    - KAON 629, Error Budget Comparison with NFIRAOS
    - As-built performance analysis for Palomar AO
    - PALM-3000 and RoboAO Error Budget Development and Tracking

KAON 721

- Expanded during PD Phase to include
  - Explicit Holding of Performance Margins
  - Implemented New RTC-based Bandwidth and Compute Latency Model
  - Truth Wavefront Sensor Error Budget
  - CCID74 Performance Model
  - Optical Transmission Values
    - Consistent with KAON 723 (Performance Flowdown Spreadsheet)
- Improved Reliability and Usability
  - Automated Routine Optimizations with Macros / Buttons
  - Repaired Bugs
    - Sky Coverage Calculations, LO WFS Background Calculations
  - Formalized Revision Control and Tracking

Flowdown Products

- Version 1 (Sep 2009)
  - Transmission & Emissivity
    - AO system (all paths), Fixed and Patrolling BTO
  - LGS beacon Spot Size
  - Pupil Registration Framework
  - Go-to Errors
  - Non-sidereal and Long-exposure Tracking Errors
  - Initial Efficiency Budgets
    - Acquisition timeline for LGS
  - Relative Astrometry Flowdown
  - High-Contrast Flowdown
- Added in Version 2 (Feb 2010)
  - TWFS budget
  - Optical Surface Figure Quality
  - Pupil Registration Tolerances
  - Update to HO and TT bandwidth latency to reflect servo design
  - *Revisions to Rel Astrometry Flowdown*
  - Timeline Flowdowns for NGS Mode, HODM Dithers, LOWFS Offsets, and Instrument Switches
  - System Uptime MTBF Framework

Science Case Parameters (draft)

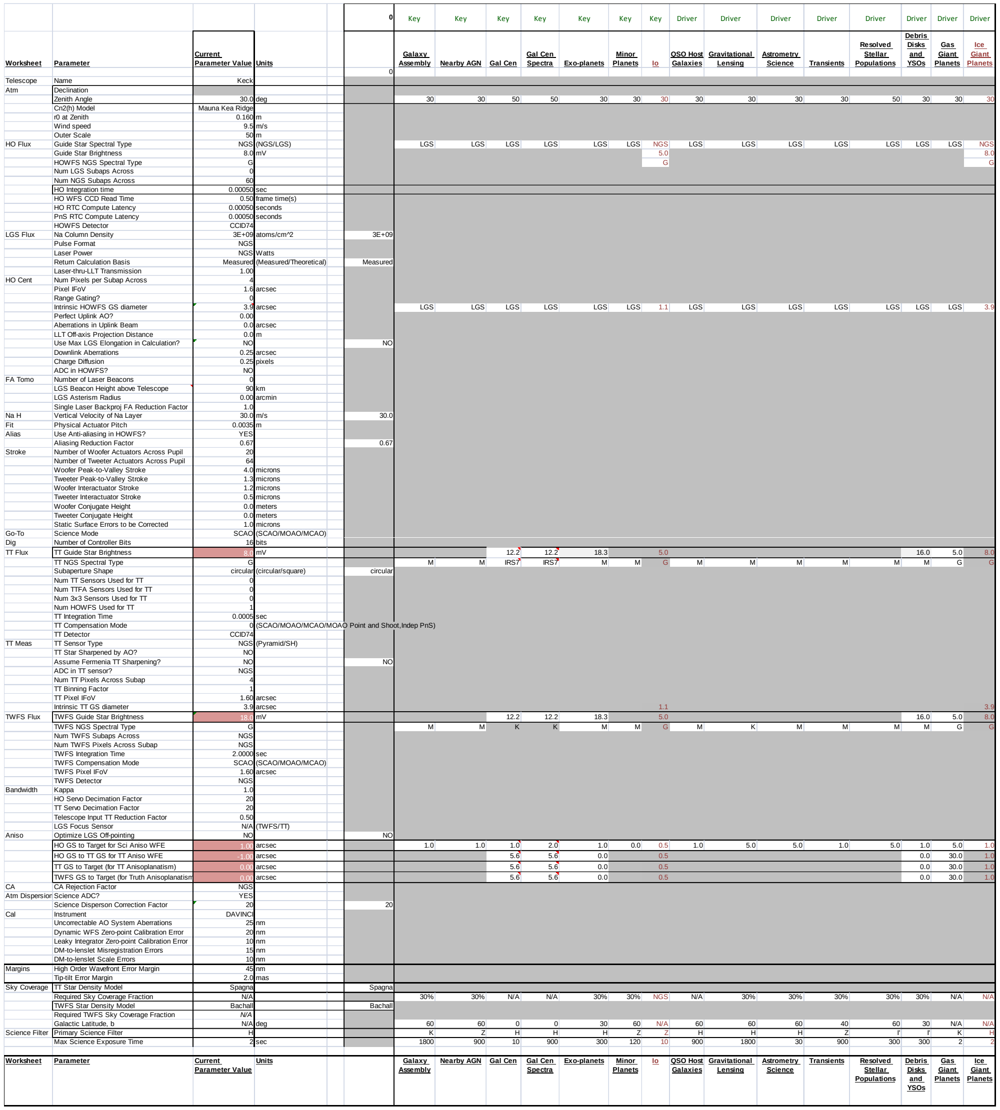
Science Case Name	Zenith Angle (Deg)	Guide stars	NGS color	Required sky coverage (%)	Galactic latitude, |b| (deg)	Science Filter	Evaluation Filter	Max Single Exposure Time (Sec)	LGS/NGS	NGAO Key Science Case	Error Budget Case Name (if different then Science Case Name)	Applicable to NGAO (Yes/No)
Key Science Drivers												
Galaxy Assembly, e.g. Extended Groth S	30	Field Stars	M	30	≥60	Z, J, H, K	J, K	1800	LGS	Y		Key Science Driver
Nearby AGNs	30	Field Stars	M	30	≤60	Z, J, K	Z	900	LGS	Y		Key Science Driver
Galactic Center	50	IRS 7, 9, 12N	N/A	N/A	N/A	H, K	K	<10 (image) 900 (spectra)	LGS	Y		Key Science Driver
Exo-planets	30	Field Stars	M	30	≤30	J, H	H	300	LGS	Y		Key Science Driver
Minor Planets	30	Field Stars	M	30	≤60	Z	Z	120	LGS	Y		Key Science Driver
Science Drivers												
QSO Host Galaxies	30	Field Stars, possibly the science object	M/ A?	30	≤60	Z, J, H, K	K	900	LGS			Science Driver
Gravitational Lensing	30	Field Stars	M	30	≥60	I, Z, J, H, K	J, K	1800?	LGS			Science Driver
Astrometry Science	30	Field Stars	M	30	≤60	H, K	H	30 ?	LGS			Science Driver
Transients	30	Field Stars	M	30	40	Z, J, H, K	Z	900	LGS	N		Science Driver
Resolved Stellar Populations	50?	Field Stars	M?	30	?	I, K	I	300?	LGS			Science Driver
Debris Disks and Young Stellar Objects	30	Field Stars	M	30	≤30	I, Z, J, H	I	300	LGS			Science Driver
Size, Shape, and Composition of Minor P	30	Field Stars	M	30	≤60	I, Z, J	I	120	LGS			Science Driver
Gas Giant Planets		Satellites (non-sidereal)	G	N/A	N/A	J, H, K	K	2?	NGS?			Science Driver
Ice Giant Planets		Satellites (non-sidereal)	G	N/A	N/A	J, H, K	H	2?	LGS			Science Driver

Performance Summary

NGAO Key Science Case	High-order RMS Wavefront Error (nm)	RMS TT Error (mas)	Effective Total RMS Wavefront Error (nm)	Science Pass-band	Strehl Ratio	Ensquared Energy within a 70 mas spaxel	Single-Integration Time (sec)
Galaxy Assembly	163	4.9	185	K	76%	74	1800
Nearby AGN's	163	4.7	181	Z	19%	26 w/in 34 mas	900
Galactic Center	190	2.2	193	H	58%	59	10
Exoplanets	162	3.8	174	H	64%	68	300
Minor Planets	164	4.7	181	K	77%	25	120
Io	115	2.1	117	K	89%	83	10

KAON 721 Input Summary Captures

both Science Case Parameters and Highest-Level Architecture Choices



					0	Key	Key	Key	Key	Key	Key	Key	Driver	Driver	Driver	Driver	Driver	Driver	Driver	Driver
Worksheet	**Parameter**	**Current Parameter Value**	**Units**			**Galaxy Assembly**	**Nearby AGN**	**Gal Cen**	**Gal Cen Spectra**	**Exo-planets**	**Minor Planets**	**Io**	**QSO Host Galaxies**	**Gravitational Lensing**	**Astrometry Science**	**Transients**	**Resolved Stellar Populations**	**Debris Disks and YSOs**	**Gas Giant Planets**	**Ice Giant Planets**
					0															
Telescope	Name	Keck																		
Atm	Declination																			
	Zenith Angle	30.0	deg			30	30	50	50	30	30	30	30	30	30	30	50	30	30	30
	Cn2(h) Model	Mauna Kea Ridge																		
	r0 at Zenith	0.160	m																	
	Wind speed	9.5	m/s																	
	Outer Scale	50	m																	
HO Flux	Guide Star Spectral Type	NGS	(NGS/LGS)			LGS	LGS	LGS	LGS	LGS	LGS	NGS	LGS	LGS	LGS	LGS	LGS	LGS	LGS	NGS
	Guide Star Brightness	8.0	mV									5.0								8.0
	HOWFS NGS Spectral Type	G										G								G
	Num LGS Subaps Across	0																		
	Num NGS Subaps Across	60																		
	HO Integration time	0.00050	sec																	
	HO WFS CCD Read Time	0.50	frame time(s)																	
	HO RTC Compute Latency	0.00050	seconds																	
	PnS RTC Compute Latency	0.00050	seconds																	
	HOWFS Detector	CCID74																		
LGS Flux	Na Column Density	3E+09	atoms/cm^2		3E+09															
	Pulse Format	NGS																		
	Laser Power	NGS	Watts																	
	Return Calculation Basis	Measured	(Measured/Theoretical)		Measured															
	Laser-thru-LLT Transmission	1.00																		
HO Cent	Num Pixels per Subap Across	4																		
	Pixel IFoV	1.6	arcsec																	
	Range Gating?	0																		
	Intrinsic HOWFS GS diameter	3.9	arcsec			LGS	LGS	LGS	LGS	LGS	LGS	1.1	LGS	LGS	LGS	LGS	LGS	LGS	LGS	3.9
	Perfect Uplink AO?	0.00																		
	Aberrations in Uplink Beam	0.0	arcsec																	
	LLT Off-axis Projection Distance	0.0	m																	
	Use Max LGS Elongation in Calculation?	NO			NO															
	Downlink Aberrations	0.25	arcsec																	
	Charge Diffusion	0.25	pixels																	
	ADC in HOWFS?	NO																		
FA Tomo	Number of Laser Beacons	0																		
	LGS Beacon Height above Telescope	90	km																	
	LGS Asterism Radius	0.00	arcmin																	
	Single Laser Backproj FA Reduction Factor	1.0																		
Na H	Vertical Velocity of Na Layer	30.0	m/s		30.0															
Fit	Physical Actuator Pitch	0.0035	m																	
Alias	Use Anti-aliasing in HOWFS?	YES																		
	Aliasing Reduction Factor	0.67			0.67															
Stroke	Number of Woofer Actuators Across Pupil	20																		
	Number of Tweeter Actuators Across Pupil	64																		
	Woofer Peak-to-Valley Stroke	4.0	microns																	
	Tweeter Peak-to-Valley Stroke	1.3	microns																	
	Woofer Interactuator Stroke	1.2	microns																	
	Tweeter Interactuator Stroke	0.5	microns																	
	Woofer Conjugate Height	0.0	meters																	
	Tweeter Conjugate Height	0.0	meters																	
	Static Surface Errors to be Corrected	1.0	microns																	
Go-To	Science Mode	SCAO	(SCAO/MOAO/MCAO)																	
Dig	Number of Controller Bits	16	bits																	
TT Flux	TT Guide Star Brightness	8.0	mV					12.2	12.2	18.3		5.0						16.0	5.0	8.0
	TT NGS Spectral Type	G				M	M	IRS7	IRS7	M	M	G	M	M	M	M	M	M	G	G
	Subaperture Shape	circular	(circular/square)		circular															
	Num TT Sensors Used for TT	0																		
	Num TTFA Sensors Used for TT	0																		
	Num 3x3 Sensors Used for TT	0																		
	Num HOWFS Used for TT	1																		
	TT Integration Time	0.0005	sec																	
	TT Compensation Mode	0	(SCAO/MOAO/MCAO/MOAO Point and Shoot,Indep PnS)																	
	TT Detector	CCID74																		
TT Meas	TT Sensor Type	NGS	(Pyramid/SH)																	
	TT Star Sharpened by AO?	NO																		
	Assume Fermenia TT Sharpening?	NO			NO															
	ADC in TT sensor?	NGS																		
	Num TT Pixels Across Subap	4																		
	TT Binning Factor	1																		
	TT Pixel IFoV	1.60	arcsec																	
	Intrinsic TT GS diameter	3.9	arcsec									1.1								3.9
TWFS Flux	TWFS Guide Star Brightness	18.0	mV					12.2	12.2	18.3		5.0						16.0	5.0	8.0
	TWFS NGS Spectral Type	G				M	M	K	K	M	M	G	M	K	M	M	M	M	G	G
	Num TWFS Subaps Across	NGS																		
	Num TWFS Pixels Across Subap	NGS																		
	TWFS Integration Time	2.0000	sec																	
	TWFS Compensation Mode	SCAO	(SCAO/MOAO/MCAO)																	
	TWFS Pixel IFoV	1.60	arcsec																	
	TWFS Detector	NGS																		
Bandwidth	Kappa	1.0																		
	HO Servo Decimation Factor	20																		
	TT Servo Decimation Factor	20																		
	Telescope Input TT Reduction Factor	0.50																		
	LGS Focus Sensor	N/A	(TWFS/TT)																	
Aniso	Optimize LGS Off-pointing	NO			NO															
	HO GS to Target for Sci Aniso WFE	1.00	arcsec			1.0	1.0	1.0	2.0	1.0	0.0	0.5	1.0	5.0	5.0	1.0	5.0	1.0	5.0	1.0
	HO GS to TT GS for TT Aniso WFE	-1.00	arcsec					5.6	5.6	0.0		0.5						0.0	30.0	1.0
	TT GS to Target (for TT Anisoplanatism)	0.00	arcsec					5.6	5.6	0.0		0.5						0.0	30.0	1.0
	TWFS GS to Target (for Truth Anisoplanatism	0.00	arcsec					5.6	5.6	0.0		0.5						0.0	30.0	1.0
CA	CA Rejection Factor	NGS																		
Atm Dispersion	Science ADC?	YES																		
	Science Disperson Correction Factor	20			20															
Cal	Instrument	DAVINCI																		
	Uncorrectable AO System Aberrations	25	nm																	
	Dynamic WFS Zero-point Calibration Error	20	nm																	
	Leaky Integrator Zero-point Calibration Error	10	nm																	
	DM-to-lenslet Misregistration Errors	15	nm																	
	DM-to-lenslet Scale Errors	10	nm																	
Margins	High Order Wavefront Error Margin	45	nm																	
	Tip-tilt Error Margin	2.0	mas																	
Sky Coverage	TT Star Density Model	Spagna			Spagna															
	Required Sky Coverage Fraction	N/A				30%	30%	N/A	N/A	30%	30%	NGS	N/A	30%	30%	30%	30%	30%	N/A	N/A
	TWFS Star Density Model	Bachall			Bachall															
	Required TWFS Sky Coverage Fraction	*N/A*																		
	Galactic Latitude, b	N/A	deg			60	60	0	0	30	60	N/A	60	60	60	40	60	30	N/A	N/A
Science Filter	Primary Science Filter	H				K	Z	H	H	H	Z	Z	H	H	H	Z	I'	I'	K	H
	Max Science Exposure Time	2	sec			1800	900	10	900	300	120	10	900	1800	30	900	300	300	2	2
Worksheet	**Parameter**	**Current Parameter Value**	**Units**			**Galaxy Assembly**	**Nearby AGN**	**Gal Cen**	**Gal Cen Spectra**	**Exo-planets**	**Minor Planets**	**Io**	**QSO Host Galaxies**	**Gravitational Lensing**	**Astrometry Science**	**Transients**	**Resolved Stellar Populations**	**Debris Disks and YSOs**	**Gas Giant Planets**	**Ice Giant Planets**

KAON 721 Error Budget

High-level allocation of wavefront error meeting performance requirements

Based upon detailed engineering models of system performance and high-level performance allocations (further developed in KAON 723)

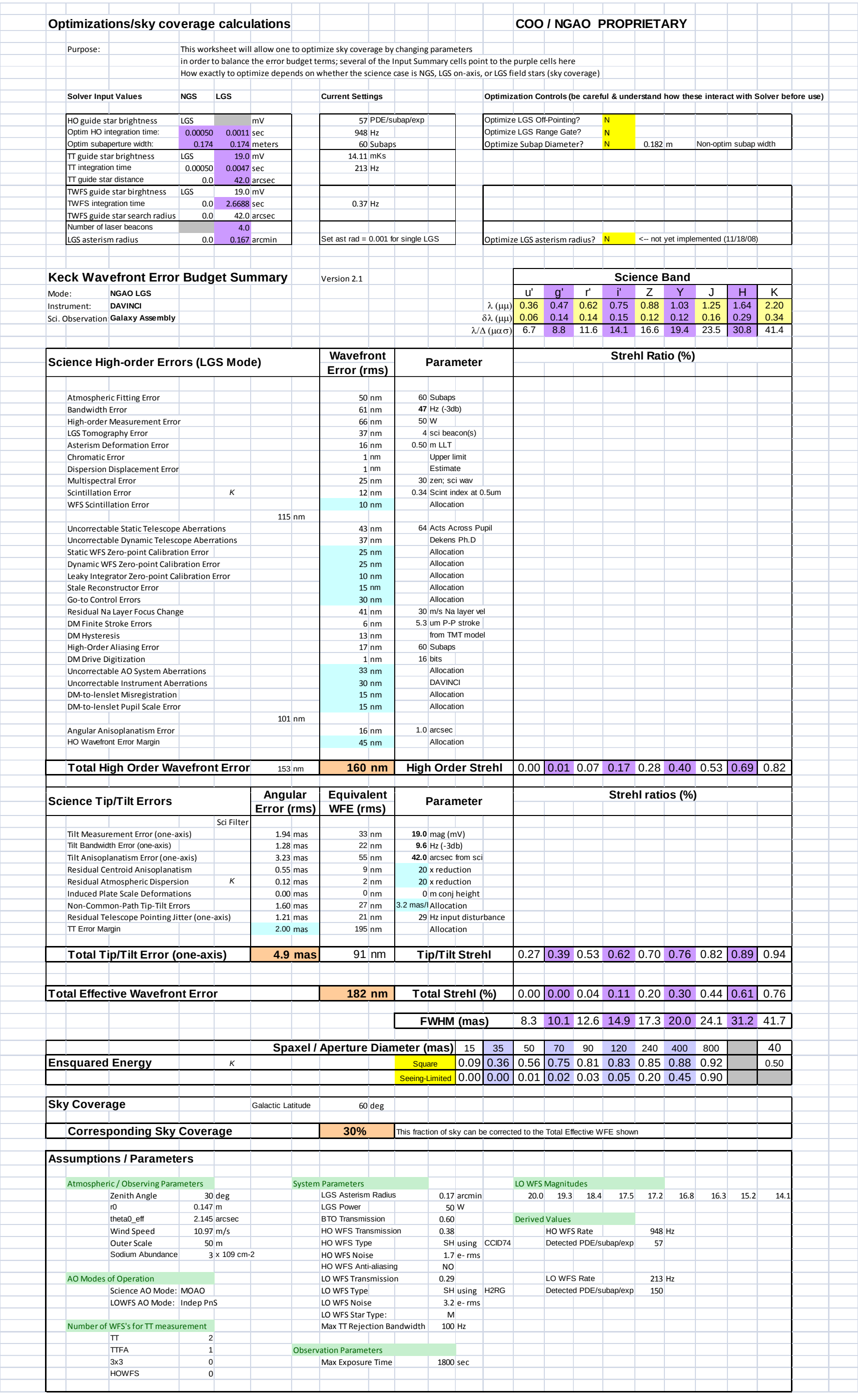
Anchored to Keck 2 LGS performance and vetted against NFIRAOS error budget during PD phase

In addition to on-sky validation at Palomar

Provides estimates of:

- High-order Wavefront Errors
- Tip-tilt Errors
- Strehl Ratios
- Ensquared Energy Estimates

Output table summarizes key input assumptions and parameters (seeing, sodium density, wavefront sensor frame rates, etc.)



Optimizations/sky coverage calculations COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	57	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	948	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	19.0	mV	14.11	mKs
TT integration time	0.00050	0.0047	sec	213	Hz
TT guide star distance	0.0	42.0	arcsec		
TWFS guide star birghtness	LGS	19.0	mV		
TWFS integration time	0.0	2.6688	sec	0.37	Hz
TWFS guide star search radius	0.0	42.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimization Controls (be careful & understand how these interact with Solver before use)				
Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary Version 2.1

Mode: NGAO LGS
Instrument: DAVINCI
Sci. Observation Galaxy Assembly

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	Strehl Ratio (%)								
Atmospheric Fitting Error			50 nm	60 Subaps									
Bandwidth Error			61 nm	**47** Hz (-3db)									
High-order Measurement Error			66 nm	50 W									
LGS Tomography Error			37 nm	4 sci beacon(s)									
Asterism Deformation Error			16 nm	0.50 m LLT									
Chromatic Error			1 nm	Upper limit									
Dispersion Displacement Error			1 nm	Estimate									
Multispectral Error			25 nm	30 zen; sci wav									
Scintillation Error	K		12 nm	0.34 Scint index at 0.5um									
WFS Scintillation Error			10 nm	Allocation									
		115 nm											
Uncorrectable Static Telescope Aberrations			43 nm	64 Acts Across Pupil									
Uncorrectable Dynamic Telescope Aberrations			37 nm	Dekens Ph.D									
Static WFS Zero-point Calibration Error			25 nm	Allocation									
Dynamic WFS Zero-point Calibration Error			25 nm	Allocation									
Leaky Integrator Zero-point Calibration Error			10 nm	Allocation									
Stale Reconstructor Error			15 nm	Allocation									
Go-to Control Errors			30 nm	Allocation									
Residual Na Layer Focus Change			41 nm	30 m/s Na layer vel									
DM Finite Stroke Errors			6 nm	5.3 um P-P stroke									
DM Hysteresis			13 nm	from TMT model									
High-Order Aliasing Error			17 nm	60 Subaps									
DM Drive Digitization			1 nm	16 bits									
Uncorrectable AO System Aberrations			33 nm	Allocation									
Uncorrectable Instrument Aberrations			30 nm	DAVINCI									
DM-to-lenslet Misregistration			15 nm	Allocation									
DM-to-lenslet Pupil Scale Error			15 nm	Allocation									
		101 nm											
Angular Anisoplanatism Error			16 nm	1.0 arcsec									
HO Wavefront Error Margin			45 nm	Allocation									
Total High Order Wavefront Error		153 nm	**160 nm**	**High Order Strehl**	0.00	0.01	0.07	0.17	0.28	0.40	0.53	0.69	0.82

Science Tip/Tilt Errors		Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)								
	Sci Filter												
Tilt Measurement Error (one-axis)		1.94 mas	33 nm	**19.0** mag (mV)									
Tilt Bandwidth Error (one-axis)		1.28 mas	22 nm	**9.6** Hz (-3db)									
Tilt Anisoplanatism Error (one-axis)		3.23 mas	55 nm	**42.0** arcsec from sci									
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction									
Residual Atmospheric Dispersion	K	0.12 mas	2 nm	20 x reduction									
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height									
Non-Common-Path Tip-Tilt Errors		1.60 mas	27 nm	3.2 mas/l Allocation									
Residual Telescope Pointing Jitter (one-axis)		1.21 mas	21 nm	29 Hz input disturbance									
TT Error Margin		2.00 mas	195 nm	Allocation									
Total Tip/Tilt Error (one-axis)		**4.9 mas**	91 nm	**Tip/Tilt Strehl**	0.27	0.39	0.53	0.62	0.70	0.76	0.82	0.89	0.94

Total Effective Wavefront Error	**182 nm**	**Total Strehl (%)**	0.00	0.00	0.04	0.11	0.20	0.30	0.44	0.61	0.76
		FWHM (mas)	8.3	10.1	12.6	14.9	17.3	20.0	24.1	31.2	41.7

		Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		40
Ensquared Energy	K	Square	0.09	0.36	0.56	0.75	0.81	0.83	0.85	0.88	0.92		0.50
		Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.20	0.45	0.90		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		**30%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	MOAO
LOWFS AO Mode:	Indep PnS

Number of WFS's for TT measurement	
TT	2
TTFA	1
3x3	0
HOWFS	0

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	1800	sec

LO WFS Magnitudes								
20.0	19.3	18.4	17.5	17.2	16.8	16.3	15.2	14.1

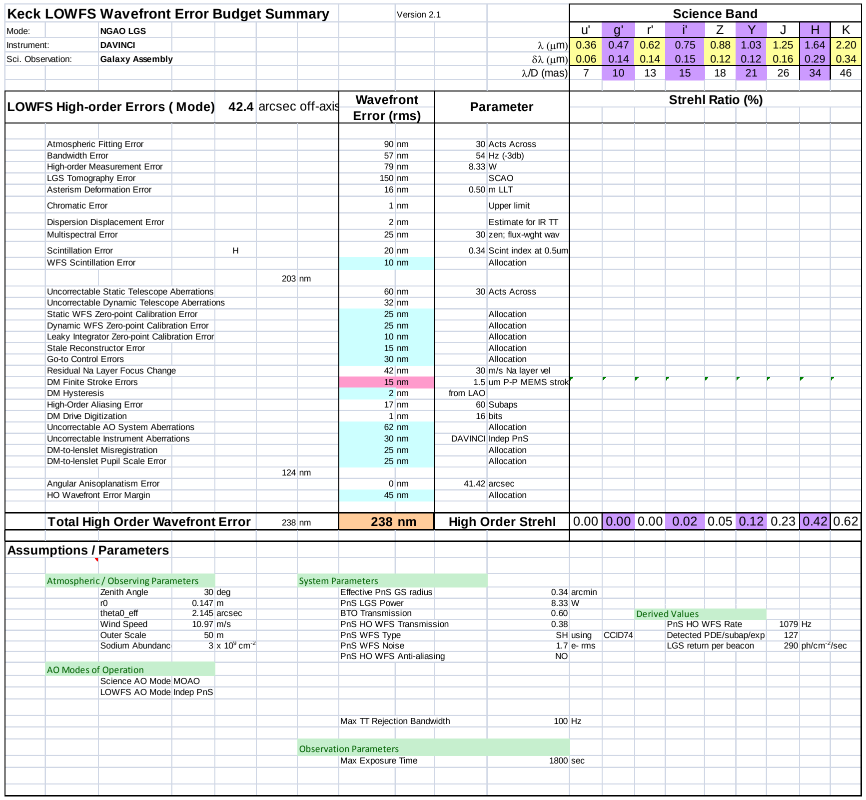
Derived Values		
HO WFS Rate	948	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	213	Hz
Detected PDE/subap/exp	150	

KAON 721 TT Sharpening Budget

Separate WFE budget for short-exposure correction of NGS stars used for TT sensing

Reuses many of the performance calculations for the science path

Separately optimized for frame rate, patrolling laser power, off-axis distance, etc.



Keck LOWFS Wavefront Error Budget Summary Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation: **Galaxy Assembly**

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

LOWFS High-order Errors (Mode)	42.4 arcsec off-axis	Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		90 nm	30 Acts Across
Bandwidth Error		57 nm	54 Hz (-3db)
High-order Measurement Error		79 nm	8.33 W
LGS Tomography Error		150 nm	SCAO
Asterism Deformation Error		16 nm	0.50 m LLT
Chromatic Error		1 nm	Upper limit
Dispersion Displacement Error		2 nm	Estimate for IR TT
Multispectral Error		25 nm	30 zen; flux-wght wav
Scintillation Error	H	20 nm	0.34 Scint index at 0.5um
WFS Scintillation Error		10 nm	Allocation
	203 nm		
Uncorrectable Static Telescope Aberrations		60 nm	30 Acts Across
Uncorrectable Dynamic Telescope Aberrations		32 nm	
Static WFS Zero-point Calibration Error		25 nm	Allocation
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation
Stale Reconstructor Error		15 nm	Allocation
Go-to Control Errors		30 nm	Allocation
Residual Na Layer Focus Change		42 nm	30 m/s Na layer vel
DM Finite Stroke Errors		15 nm	1.5 um P-P MEMS strok
DM Hysteresis		2 nm	from LAO
High-Order Aliasing Error		17 nm	60 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		62 nm	Allocation
Uncorrectable Instrument Aberrations		30 nm	DAVINCI Indep PnS
DM-to-lenslet Misregistration		25 nm	Allocation
DM-to-lenslet Pupil Scale Error		25 nm	Allocation
	124 nm		
Angular Anisoplanatism Error		0 nm	41.42 arcsec
HO Wavefront Error Margin		45 nm	Allocation
Total High Order Wavefront Error	238 nm	**238 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.02	0.05	0.12	0.23	0.42	0.62

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundanc	3	x 10^9 cm^{-2}

AO Modes of Operation	
Science AO Mode	MOAO
LOWFS AO Mode	Indep PnS

System Parameters			
Effective PnS GS radius	0.34	arcmin	
PnS LGS Power	8.33	W	
BTO Transmission	0.60		
PnS HO WFS Transmission	0.38		
PnS WFS Type	SH	using	CCID74
PnS WFS Noise	1.7	e- rms	
PnS HO WFS Anti-aliasing	NO		
Max TT Rejection Bandwidth	100	Hz	

Derived Values		
PnS HO WFS Rate	1079	Hz
Detected PDE/subap/exp	127	
LGS return per beacon	290	ph/cm^{-2}/sec

Observation Parameters		
Max Exposure Time	1800	sec

Performance Summary for All NGAO Science Case

Notes:

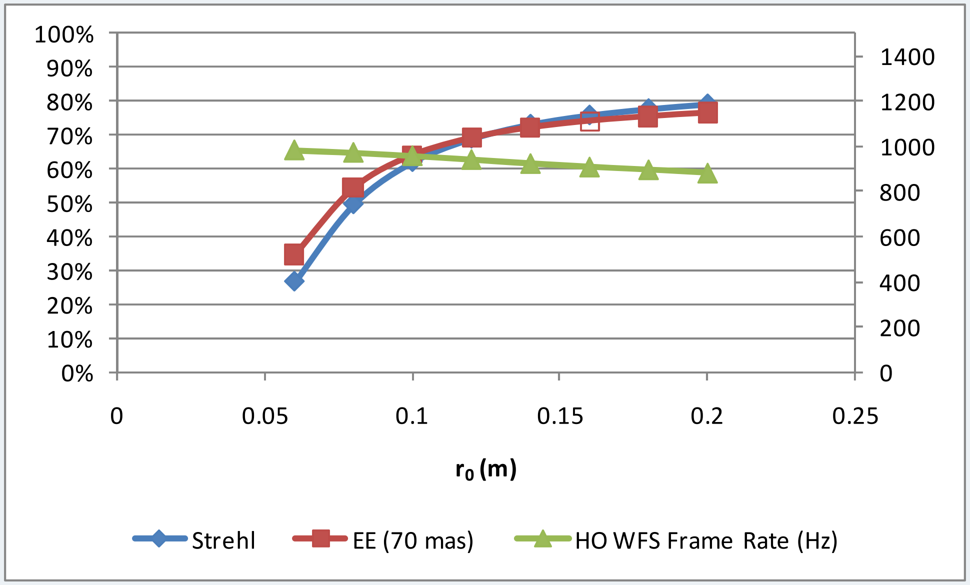
Resolved Stellar Pops driven by choice of science target FoV, due to NGAO anisoplanatism

KAON 721 Case	Science Case	High-order RMS Wavefront Error (nm)	RMS TT Error (mas)	Effective Total RMS Wavefront Error (nm)	Ensquared Energy within a 70 mas spaxel	Observing Passband
1	Galaxy Assembly	160	4.9	182	75%	K
2	Nearby AGN	161	4.8	179	29%	Z
3	Galactic Center	186	2.2	190	60%	H
4	Galactic Center Spectra	189	2.4	194	59%	H
5	Exo-planets	158	7.8	207	69%	H
6	Minor Planets	159	5.0	179	30%	Z
7	Io	116	2.1	119	54%	Z
8	QSO Host Galaxies	154	2.3	157	71%	H
9	Gravitational Lensing	171	5.0	192	65%	H
10	Astrometry Science	171	4.7	189	65%	H
11	Transients	156	2.6	162	31%	Z
12	Resolved Stellar Populations	215	6.4	236	6%	I'
13	Debris Disks and YSOs	157	3.1	165	19%	I'
14	Gas Giant Planets	169	3.5	180	73%	K
15	Ice Giant Planets	190	4.4	204	59%	H

WFE Trade Studies

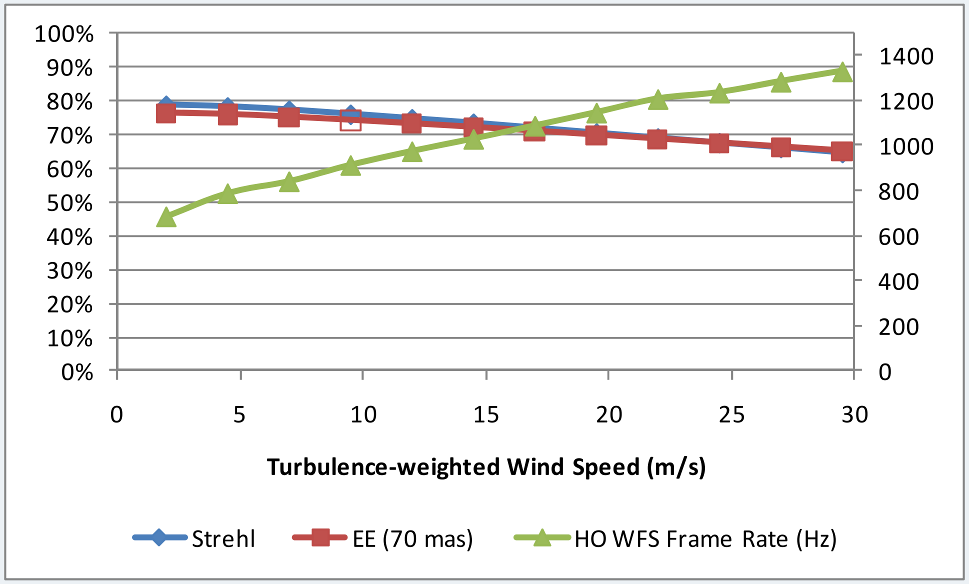
- Performance vs. Seeing
- Performance vs. Wind Speed
- Performance vs. Laser Return
- Seeing, Wind Speed, and Sodium Abundance Monte Carlo Results
- Performance vs. Sky Fraction
- Performance vs. LO WFS Passband
- Performance vs. DAVINCI Spaxel Sampling

NGAO is extraordinarily robust to seeing variations



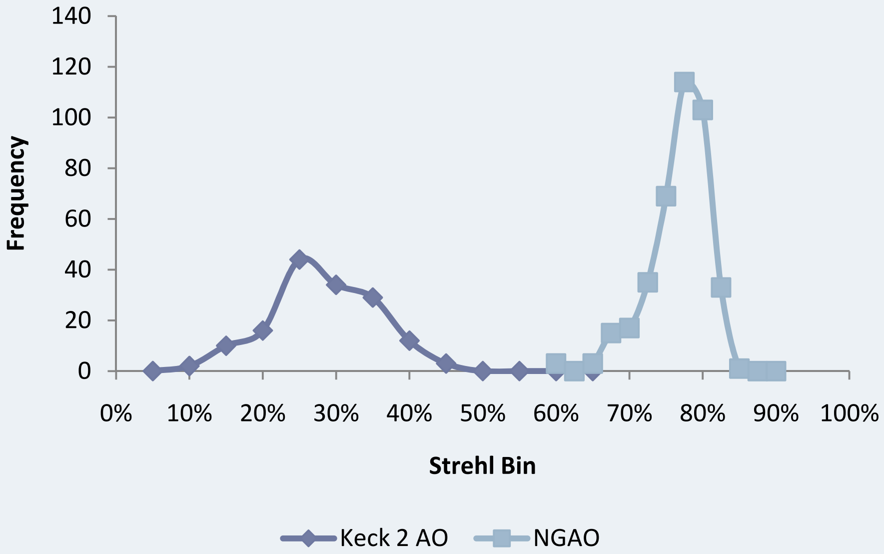
- Galaxy Assembly Science Case, K-band

NGAO is extraordinarily robust to wind speeds



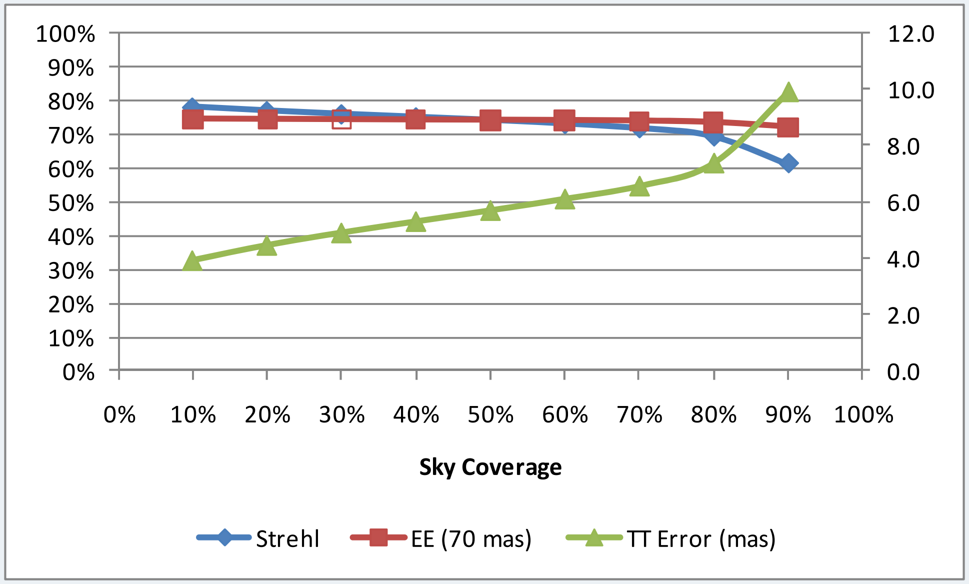
- Galaxy Assembly Science Case, K-band

NGAO improves the user experience



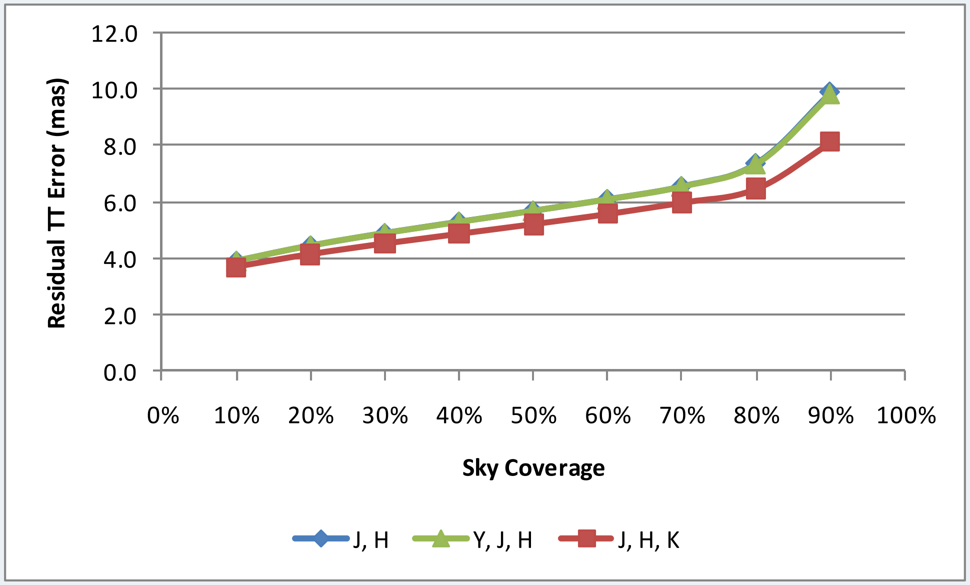
- Results of Monte Carlo draws for r0, wind speed, and Na abundance
  - Galaxy Assembly Science Case, K-band

NGAO covers a large sky fraction



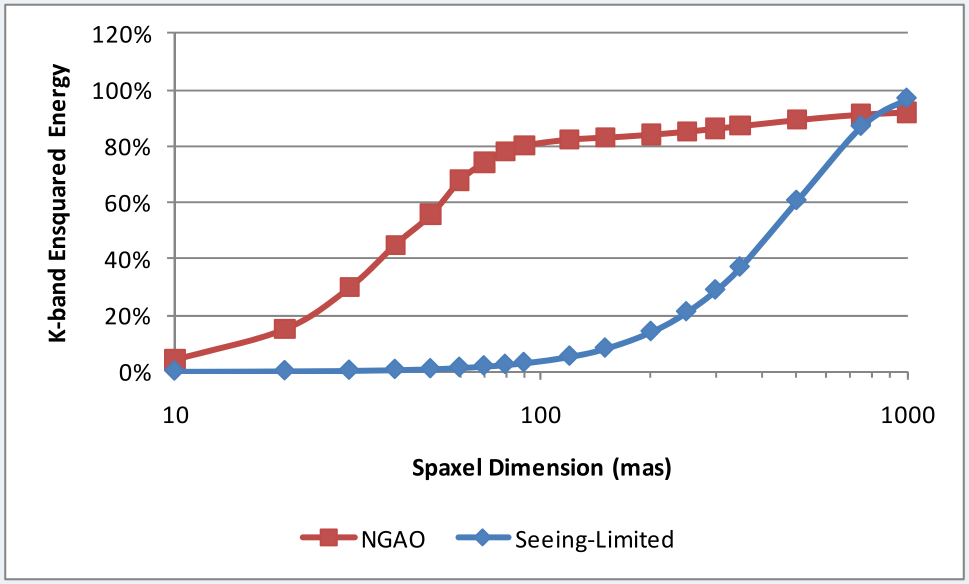
- Galaxy Assembly Science Case, K-band

LO WFS passband comparison



- The NGAO team currently favor J + H over J + H + K for simplification of the LO WFS cryostats
  - Will revisit this choice with science team early in the DD phase

DAVINCI spaxel sampling comparison



- Galaxy Assembly Science Case, K-band

Conclusions

- NGAO science and performance objectives have maintained close alignment
- NGAO architecture and design choices have been successfully modeled to PDR to ensure deliverable quality
  - Engineering models supported by experience and wave-optics simulations
  - Anchored internally and external to NGAO
- Trade studies demonstrate that our architecture is robust against variations in input assumptions
- We are confident of our model-based design choices and are ready to proceed to Detailed Design and Full-Scale Development.