Wavefront Error Budget Comparison between Keck NGAO and TMT NFIRAOS

KECK ADAPTIVE OPTICS NOTE 629

Christopher Neyman and Richard Dekany
December 5, 2008

ABSTRACT

This note outlines a detailed comparison made between the Thirty Meter Telescope Observatory NFIRAOS wavefront error budget and the Keck Observatory NGAO wavefront error budget, and the extent to which they have been anchored with simulations or data. Our goal has been to understand where additional simulations or improved parametric tools would benefit the NGAO preliminary design. This work was part of the preliminary design phase of NGAO, a standard phase of new instrument development at W. M. Keck Observatory.

1. Introduction

Keck Next Generation Adaptive Optics (NGAO) passed its System Design Review in April 2008. This study is a response to the Review Committee asking the NGAO team to develop a more comprehensive simulation tool [1-2]. The Narrow Field Infra-Red Adaptive Optics System (NFIRAOS) passed its Preliminary Design Review in October 2008. Since NFIRAOS is "one step ahead" of NGAO in the design process it was an opportune time to make a comparison of their respective wavefront error budgets. The aim of the comparison was not to achieve equal term-by-term results for both systems but rather to understand areas were NGAO analysis would benefit from additional modeling. Since NGAO and NFIRAOS are on telescopes of much different sizes, some effects insignificant for NGAO are key error budget drivers for NFIRAOS. The order (i.e. number of correcting elements across the telescope pupil) is similar for the two AO systems; though the physical size of the corresponding subapertures is much different, see Table 1. Also the atmospheric parameters (see Table 2) and other starting assumptions differ between the two teams. On November 13, 2008, the authors met face-to face with Brent Ellerbroek, Luc Giles, and Lianqi Wang of the NFIRAOS team. A term-by-term comparison was made of the respective adaptive optics (AO) wavefront error budgets for approximately corresponding science cases (NGAO QSO Survey and NFIRAOS zenith). The results of the comparisons from this meeting are captured in Tables 4-6 and the Appendix. In the following section, we will give an overview of the differences in approach between the error budgets. Following that we give a summary of individual error budget terms with significant or unresolved discrepancies. The appendix contains a more detailed discussion of the definition of each term and commentary on the results for each system.

2. Error budget comparison

The AO error budgets for both Keck and TMT are dynamic documents that have evolved as the design of each system has progressed. At the time of this comparison, the reference for the NFIRAOS error budget was the Preliminary Design Report book [3] and the actual error term values were taken directly from the supporting spreadsheet [4]. The NGAO baseline system has changed since the April system design review in response to a new programmatic cost cap imposed in Fall 2008. Because the current system is significantly different, we used the most current version of the NGAO error budget [5] tool Version 1.39, provided by one of the authors. Both design teams employ approximately the same organization of error budget terms:

- LGS related fundamental error terms
- LGS related component, implementation errors, and second order effects
- NGS related tip tilt and other low spatial order corrections

This organization was chosen as it allows decoupling of fundamental and engineering-related limitations in the correction of atmospheric aberrations using laser guide stars (LGS's). The natural guide star (NGS) related terms are mostly concerned with the correction of tip-tilt errors and various quadratic modes that cannot be sensed or are poorly measured with conventional LGS's.

	NFIRAOS	**NGAO**
Order of LGS WFS's	60 × 60	64x64
LGS WFS subaperture size	50 cm	17 cm
LGS Asterism	35 arc sec radius pentagon + 1 on-axis	30 arc sec radius triangle + variable radius triangle (Point & Shoot LGS)
Order of main DM (ground conjugate)	63 x63 (includes guard band)	64x64
Order of secondary DM	76 x 76 (includes guard band)	N/A
Conjugation range of secondary DM	12 km	N/A
AO frame rate	800 Hz	1100 Hz

Table 1. Key parameters for NFIRAOS and NGAO designs. The new NGAO baseline architecture has MOAO correction only for tip-tilt stars in order to improve sky coverage; for this comparison we assume that the science instrument correction is provided by a single DM located in main optical relay (e.g. there are no MOAO-related error terms in the science instrument error budget.)

In making this comparison, we have endeavored to compare terms that are equivalent between the two budgets. Often these terms are given different names by the two teams. In Table 3 and subsequent tables below both, the NFIRAOS and NGAO names are given in their respective columns. The grouping of terms was chosen to be consistent with NGAO conventions; this results in some NFIRAOS terms moving into a different category. For example, the NFIRAOS errors "Differential atmospheric refractive index" and "Chromatic anisoplanatism" have been moved from implementation errors to fundamental errors to be grouped with the NGAO fundamental error they are most closely related to which is titled "Multispectral Error" in the NGAO error budget. The one exception to using the NGAO ordering was to move the NGAO "High-Order Aliasing Error" to the fundamental error section where the NFIRAOS team classifies their "LGS WFS aliasing" error.

	NFIRAOS TMT ORD profile	NGAO MK ridge
Zenith angle (degrees)	0°	20°
Fried parameter r_0 (cm)	15	15
Isoplanatic angle θ_0 (arc seconds)	2.5	2.4
Greenwood frequency f_G (Hz)	29	29

Table 2. Atmospheric parameters used in this comparison. Parameters are base on integrating C_n^2 profiles based on measured data. The TMT ORD profile is based on the Gemini-South Cerro Pachon site survey campaign. The NGAO profile is based on TMT site survey data (13 N) see KAON 503.

The NGAO error budgets are organized around specific scientific observation scenarios, for example QSO survey, black hole at the galactic center, etc. As such, the error budgets are computed for the expected observation zenith angle, using NGS available for specific targets (i.e. galactic center) or randomly selected NGS assuming average star densities for the expected observations. In contrast, the NFIRAOS error budgets are computed for observations at different zenith angles with a NGS star density that is typical of the galactic pole. The low density of NGS background stars in the NFIRAOS error budgets is most like the NGAO QSO survey science case. We have used the QSO survey case to compare to the NFIRAOS zenith case. The QSO survey case corresponds to a zenith angle of 20 degrees. The difference in zenith angles actually results in the other atmospheric parameters for the two error budgets being almost identical (Table 2).

A key difference between the NFIRAOS and NGAO system engineering philosophy is the definition of sky coverage and how it is evaluated. For NGAO the sky coverage is the probability, averaged over galactic azimuth, that a collection of three usable NGS will be found sufficiently near the target object for the system to deliver a corresponding Strehl ratio, at the galactic latitude associated with each respective science case. For the case of the QSO survey science case, galactic latitude b=30 is assumed, resulting in a star density that is approximately equal to the mean star density over the celestial sphere. NFIRAOS uses the star density at the galactic pole to estimate the distribution of tip-tilt errors over randomly drawn star fields. The median tip-tilt error is then used in the error budget for system performance estimation. Since the system achieves its median performance half of the time, this error is labeled 50% sky coverage, although performance averaged over the entire sky would certainly be better. The NFIRAOS also models the other higher order wavefront spatial modes, above tip and tilt, that must be estimated from NGS's. This is done from a modal decomposition of the tomography error. (See Appendix sections 3.5, 3.11 and 3.12). All of these effects result in the NGS related error budget terms being significantly different between the two systems even for the cases that we chose to compare.

Overall the NFIRAOS team has used simulations of several effects simultaneously to estimate the overall performance of their system. These are the terms 'fitting' through 'simulation undersampling' in Table 4. The error budget terms were ordered as:

- Fitting
- Projection
- Servo lag @ 800Hz
- LGS WFS aliasing
- Tomography
- LGS WFS noise
- LGS WFS nonlin.
- TMT pupil function
- Simulation undersampling

Simulations were run that cumulatively included each error in succession; the error budget terms were computed from the quadrature difference between successive simulations. In the case of implementation and component errors, the NFIRAOS approach was sometimes allocations and sometimes the result of simulating that effect alone in a simplified single NGS or LGS simulation. The RMS wavefront error quadrature difference with the effect 'on' and 'off' is quoted as the error budget term.

In the case of NGAO, we have tended to estimate individual terms of the error budget for a number of input values and then use this data to estimate a parametric relationship between wavefront error and the input parameter values. These relationships are coded into the error budget spreadsheet. This technique is inherently conservative as it estimated the error in correcting wavefront error that is already counted as uncorrected by other error terms. For example, the high spatial frequencies that cannot be corrected by the AO DM, i.e. fitting error may also be "double counted" as part of the finite bandwidth error, etc. It was the opinion of Brent Ellerbroek of TMT that there are likely significant uncertainties that arise from not having an integrated Monte Carlo simulation approach to modeling for NGAO (e.g. these double-counting errors). In his opinion, some of the minor issues discussed in the following section and the Appendix are probably small compared to this effect. In contrast, the TMT approach of successive inclusion of physical effects into a wave-optics simulation has a different uncertainty. The quadrature differencing of simulation results is dependent on the order in which effects are added to the simulations, so there may be a tendency to underestimate the error contribution from the final term considered relative to the initial terms. In other words, the Monte Carlo approach tends not to double count wavefront errors, but there is some uncertainty (or you might say choice) in engineering decisions that flow requirements down to subsystems.

NGAO Terms	(nm)	NFIRAOS Terms	(nm)
Total Fundamental Errors	114	**Total Fundamental Errors**	138
Total Implementation Errors	94	**Total Implementation Errors**	105
Total High Order Wavefront Error	149	**Total LGS Modes**	174
Total Tip/Tilt Error (one-axis)	121	**Total NGS Modes**	48
Total Effective Wavefront Error	192	**Grand Total (LGS and NGS modes)**	180

Table 3. Summary terms for the NGAO and NFIRAOS error budgets

NGAO Terms	(nm)	NFIRAOS Terms	(nm)
Atmospheric Fitting error	46	Fitting	81
Bandwidth Error	47	Servo Lag @ 800Hz	21
High-order Measurement Error	52	LGS WFS Noise	43
LGS Tomography Error	73	Tomography	65
High-Order Aliasing Error	15	LGS WFS Aliasing	34
Asterism Deformation Error	19		
Scintillation Error	17		
WFS Scintillation Error	10		
		Projection	50
		LGS WFS Nonlin.	25
		TMT Pupil Function	28
		Simulation Undersampling	26
		2nd order: Differential Atmospheric Refractive Index	20
Multispectral Error	5	2nd order: Chromatic Anisoplanatism	0
Total Fundamental Errors	114	**Total Fundamental Errors**	138

Table 4. Fundamental errors from LGS sources for NGAO and NFIRAOS

NGAO Terms	(nm)	NFIRAOS Terms	(nm)
Uncorrectable Static Telescope Aberrations	43	Telescope: Static	32
Uncorrectable Dynamic Telescope Aberrations	31	Telescope Dynamic	14
		Telescope: Dome Seeing	16
		Telescope: Mirror Seeing	14
		Telescope: TMT Pupil Misreg.	12
Static WFS Zero-point Calibration Error	25	AO: NCPA Calibration Errors	35
Leaky Integrator Zero-point Calibration Error	15		
Go-to Control Errors	0		
Residual Na Layer Focus Change	31	LGS Na Variability: Na Layer Overall Altitude Tracking	10
DM Finite Stroke Errors	0	DM: Saturation	6
DM Hysteresis	13	DM: Hysteresis	24
DM Drive Digitization	1		
Uncorrectable AO System Aberrations	30	AO: Uncorrectable Errors	35
Uncorrectable Instrument Aberrations	30	Science Instrument Errors	30
DM-to-lenslet Misregistration	15	AO :DM/WFS Pupil Misregistration	16
DM-to-lenslet Pupil Scale Error	15	AO: DM/WFS Pupil Distortion	12
		DM: Influence Function	0
		DM: Flattening	45
		Control Algorithm: Algorithm Precision	15
		Control Algorithm: Numerical Precision	20
		Control Algorithm: Turbulence profile mismatch	20
Dynamic WFS Zero-point Calibration Error	40	LGS Na Variability: Offset Calibration	10
		LGS Na Variability: Gain Calibration	10
		LGS Na Variability: Na Layer Differential Altitude Variability	5
		LGS Na Variability: Pt. Src Tomographic Approximation	0
		LGS Na Variability: Rayleigh	40
Angular Anisoplanatism Error	15		
Total Implementation Errors	94	**Total Implementation Errors**	105

Table 5. Error budget terms from LGS related components, implementation errors, and second order effects for NGAO and NFIRAOS

NGAO Terms	(nm)	NFIRAOS Terms	(nm)
Tilt Measurement Error (one-axis)	30	Tip/Tilt: Median NGS WFS Noise	13
Tilt Bandwidth Error (one-axis)	27	Tip/Tilt: Median Atmospheric Servo Lag	14
Tilt Anisoplanatism Error (one-axis)	48	Tip/Tilt: Median Anisoplanatism	8
Residual Atmospheric Dispersion	3		
Induced Plate Scale Deformations	0		
Science Instrument Mechanical Drift	42		
Long Exposure Field Rotation Errors	83		
Residual Telescope Pointing Jitter (one-axis)	10	Tip/Tilt: Telescope Windshake	17
		Tip/Tilt: Telescope Mechanical Vibration	10
Residual Centroid Anisoplanatism	18	Tip/Tilt: Physical Optics Effects	35
		Plate scale: Atmospheric Errors & NGS WFS Noise	15
		Plate scale: Telescope Windshake	5
Total Tip/Tilt Error (one-axis)	121	**Total NGS modes**	48

Table 6. Errors from NGS, both fundamental and implementation errors are included together for both NGAO and NFIRAOS

3. Key discrepancies and recommendations for future work

The following are key discrepancies between the two error budgets and our recommendations. The relevant section of the Appendix is referenced after each item in parentheses.

1. Error budget double counting: Lack of integrated modeling results in over specification of NGAO system. As mentioned at the end of section 2, the use of scaling laws and single parameter simulations by NGAO results in some "double counting" of wavefront errors. NGAO will pursue a more integrated approach to modeling during PD phase. (1.1-1.15) Specifically, we will plan to perform 'all-in' Monte Carlo simulations of the NGAO system performance to verify the system performance based on error flowdown based on our systems engineering spreadsheet tool.
2. WFS alias errors: The NGAO scaling law has a minor error that will be fixed in future releases of the error budget spread sheet. (1.5)
3. LGS WFS noise: NGAO will address this error with integrated modeling in PD phase. In addition, we will continue to monitor Na laser return experimental results and update error budget accordingly. (1.3)
4. LGS WFS nonlinear: Physical optics effects not included in NGAO modeling to date, will add these in PD phase. (1.12)
5. Differential atmospheric refractive index error: This term is 20 nm at TMT, will add an allocation for it to NGAO error budget (1.7)
6. Reconstructor compensation for pupil rotation/nutation update: NGAO does not account for update delays in calculating a new reconstructor for the changing Keck geometry pupil geometry. We will model this effect with simulations in the PD phase and update our error budget accordingly. (2.5)
7. Residual Na layer focus change: NGAO appears to estimate a much larger error for this term than TMT. We will update our input assumptions and scaling factors. (2.9)
8. Turbulence profile mismatch: The C_n^2 profile in the tomography estimate may be incorrect or stale. NGAO will include this effect as part of our PD phase modeling and update our error budget accordingly. (2.21)
9. Na layer differential altitude variability: It appears that these effects should be small based on TMT modeling. NGAO team will confirm this during the PD phase. (2.24)

10. NGS star model: NGAO will consider updating to TMT standard Besacon star density model from our current Spagna model. (3)
11. Centroid anisoplanatism and other NGS physical optics effects: NGAO will participate in the CfAO sponsored study with TMT that addresses these effects as part of large sky coverage simulation. (3.10)
12. Plate scale and quadratic modes in NGS sensing: NGAO error budget does not address these terms explicitly in the current version. NGAO will add these errors as part of truth wavefront sensor budget. (3.5, 3.11, 3.12)

References

1. New Generation Adaptive Optics (NGAO): System Design Review, Review Panel Report to Director, Keck Observatory, section 6, page 9, April 21st & 22nd, 2008.
2. Next Generation Adaptive Optics: Response to NGAO SDR Panel Recommendations, Adaptive Optics Note 593, P. Wizinowich, R. Dekany, C. Max, D. Gavel, item 4, page 3, May 5, 2008.
3. Preliminary Design Report NFIRAOS, Thirty Meter Telescope Project (Pasadena California), TMT.AOS.PDD.08.020.REL01, November 6, 2008.
4. NFIRAOS Wavefront Error Budget, Thirty Meter Telescope Project (Pasadena California), TMT.AOS.TEC.05.044.DRF10, October 8, 2008.
5. Richard Dekany, NGAO error budget version 1.39, QSO survey science case, private communication, November 10, 2008.

Appendix: Term by term comparision of NFIRAOS and NGAO AO error budgets

1. High Order Fundamental Errors

1.1. Atmospheric fitting error (Fitting)

Definition: This error results from the finite number of actuators and their influence functions. The deformable mirror (DM) fitting term of the error budget is the residual wavefront error remaining after the wavefront error has been corrected by the deformable mirrors in the AO system.
Values: 46 nm / 81 nm
Commentary: The Fried parameters (r_0) for both systems are close to 15 cm. The subaperture size for NGAO (d_{sub} = 0.17 m) is considerably smaller than NFIRAOS (0.5 m). Classical analysis of NFIRAOS would predict almost ~100 nm of wavefront error. However, the 12 km conjugate mirror in NFIRAOS has its actuators staggered relative to the ground conjugate mirror. This results in an effective fitting error predicted for d_{sub} = 0.32 m. This gain is only applicable on axis see projection error term below.

1.2. Bandwidth error (Servo lag at 800 Hz)

Definition: This term accounts for the time delay for integrating on the WFS and reading it out followed by real time computer (RTC) computations to command the DMs.
Values: 47 nm / 21 nm
Commentary: The Greenwood frequency for both systems are roughly comparable (fG~29 Hz). NGAO assumes classical result and a closed loop bandwidth that is 20 times smaller than the sampling frequency. The NFIRAOS reports a relatively small error because the servo lag is added late in the development of the simulation-based approach. Some larger error terms that result in imperfect correction are therefore not double-counted when the servo error is added to the simulation.

1.3. High-order measurement error (LGS WFS noise)

Definition: This error is driven by the guide star signal level (photon noise), the spot size on the WFS subapertures, WFS CCD parameters (dark current, read noise) and the spot position estimation algorithm and reconstruction method (noise propagation).
Values: 52 nm / 43 nm
Commentary: When photon-noise limited, because of matched filter, NFIRAOS 900 PDE should be about sqrt (1.5) worse. Which is approximately the difference between the two systems.

1.4. LGS tomography error (Tomography)

Definition: Given the finite number of laser beacons “Tomographic reconstruction error” is the additional error resulting when wavefront measurements from one or several guidestars are used to estimate the atmospheric wavefront errors in a separate evaluation direction (MOAO) or across an extended field of view (MCAO).
Values: 73 nm / 65 nm
Commentary: The NFIRAOS errors are smaller with the same number of lasers used in both systems: NFIRAOS (6: Pentagon + Center) compared to NGAO (3 Science+ 3 point and shoot) because of the more complete metapupil overlap intrinsic to using a larger aperture. In the case of NFIRAOS this term interacts with the error from fitting many turbulent layers (~7-8) to a finite number of DMs (2), see Projection error term below.

1.5. High-order aliasing error (LGS WFS aliasing)

Definition: This error results from high spatial frequency wavefront errors being incorrectly measured as low spatial frequency errors by the wavefront sensor. The error is most pronounced at spatial frequencies close to the WFS/DM cut-off frequency. This is a fundamental higher order error in the NFIRAOS budget it is located here to be consistent with the NGAO budget.
Values: 15 nm / 34 nm
Commentary: NGAO error budget claims to use a scaling law from Rigaut, Veran and Lai 1996, However the leading coefficient is incorrect in the NGAO error budget (it should use square root (0.333) and not its current value of 0.33). The correct RMS wavefront error for NGAO should be closer to 27 nm. The NFIRAOS result is also much better than the scaling law predicts, based on the scaling law the NFIRAOS alias error would be expected to be between 45-65 nm. The use by NFIRAOS of regularized, minimum variance reconstructor (the canonical scaling law assumes least-squares reconstructors) reduces this error significantly in comparison with standard noise-weighted "least squares" pseudo-inverse reconstructor.

1.6. Asterism deformation error (NFIRAOS does not calculate)

Definition: Tomographic reconstruction of multiple LGS wavefront measurements typically requires an assumption on the actual geometry of the laser asterism on the sodium layer. However, due to tip tilt indeterminacy of the individual beacons, the true sampling of the volume of atmosphere above the telescope is instantaneously variable. For example, the nominal square geometry of an asterism is at any given time in reality a general quadrilateral.
Values: 19 nm / NA
Commentary: Due to LGS uplink tip tilt correction, this appears to be a relatively small error for both NGAO and NFIRAOS.

1.7. NGAO does not calculate (Higher order effects: Differential atmospheric refractive index)

Definition: The differential atmospheric refractive index dispersion error arises from the fact that the AO system will slightly over-correct atmospheric turbulence, since the atmospheric refractive index, and hence the OPD, in J band is about 1.3% smaller than at the LGS wavefront sensing wavelength of 589 nm.
Values: NA / 20 nm
Commentary: NFIRAOS: includes slight changes in atmospheric refractive index that cause path length errors, even at zenith. The resulting tip/tilt/piston-removed error is about 20 nm RMS for a turbulence outer scale of 30 m, and about 30 nm RMS for an infinite outer scale.

1.8. Multispectral error (Higher order effects: chromatic anisoplanatism)

Definition: Chromatic anisoplanatism arises from atmospheric differential refraction, which causes the LGS and science beams to follow slightly different (curved) paths through the atmosphere when projected at a non-zero zenith angle.
Values: 5 nm / 0 nm (~10nm 30 zenith angle)
Commentary: The chromatic anisoplanatism effect goes to zero at zenith. TMT error budget we compared to was calculated at zenith. NGAO quasar survey science case error budget is at a zenith angle of 20 degrees. The resulting error for NFIRAOS is zero at zenith and 10 nm RMS at a zenith angle of 30 degrees.

1.9. Scintillation error (NFIRAOS does not calculate)

Definition: Phase errors imparted on the wavefront at high altitudes in the Earth's atmosphere couple into amplitude errors generating the phenomenon of scintillation as a result of the physics of wave propagation.
Values: 17 nm / NA
Commentary: We assume only phase compensation for the NGAO point design, resulting in a residual Strehl ratio degradation even for a system performing perfect phase conjugation

1.10. WFS scintillation error (NFIRAOS does not calculate)

Definition: Just as scintillation directly degrades the delivered science image quality, it also indirectly introduces wavefront compensation errors via coupling of phase and amplitude terms in a high-order wavefront sensor. Across the dimension of one WFS subaperture, scintillation of the wavefront would have no impact on a pure local tilt error alone. However, in the presence of local focus and other aberrations within a subaperture, amplitude fluctuations can be misinterpreted by the sensor as false tip/tilt signal, resulting in reconstruction errors.
Values: 10 nm / NA
Commentary: For NGAO: pedigree of this term is from point source (NGS) calculations (would be better when considering an extended LGS source).

1.11. NGAO does not calculate (Projection)

Definition: Starting with a tomographic model of the atmosphere, we collapse it onto a few ideal DM planes, to maximize the performance over the science field of interest. Projection error is zero when performance is optimized for a 0" FoV. It grows as the field size increases because it is impossible to correct perfectly in every direction with a modest quantity (2) of DMs.
Values: NA / 50 nm
Commentary: MCAO generalized Anisoplanatism this error is not applicable for the NGAO MOAO architecture.

1.12. NGAO does not calculate (LGS WFS nonlinearity)

Definition: The LGS WFS nonlinearity error is defined as the incremental WFE for a physical optics WFS with finite linear dynamic range. The error is driven by the spot position estimation algorithm.
Values: NA / 25 nm
Commentary: For NGAO, this effect was included as a LGS WFS noise source and is included in the High-order measurement error term given above. For NFIRAOS, the error has been assessed by running wave optics LGS WFS simulations using a constrained matched filter and differencing in quadrature the results obtained from simulations using an ideal, geometric average gradient LGS WFS with infinite linear dynamic range. NFIRAOS simulation uses a typical. realization of a sodium layer profile, 0.5" pixels, and polar coordinate geometry CCD. Estimation algorithm is calibrated for 1 pixel shift by forcing the least squares solver to yield a computed answer of 0.5 arc second, the designed plates scale of the wavefront sensor.

1.13. NGAO does not calculate (TMT pupil function)

Definition: The TMT pupil function error is defined as the incremental WFE due to the primary mirror edge, secondary support struts, and the secondary mirror obscuration as simulated using the TMT pupil map.
Values: NA / 28 nm
Commentary: NFIRAOS: noise regularization works to minimum the potential degradation due to discontinuous pie segments of the pupil and the secondary struts which are 30 cm thick. These effects are relatively less important for NGAO at Keck which has only 2.5 cm thick struts. For NFIRAOS in order to be included in the reconstruction, a subaperture has to be >= 60% illuminated (determined to be optimal via simulations).

1.14. NGAO does not calculate (Simulation undersampling)

Definition: The simulation undersampling error is defined as the incremental wavefront error, which is unsampled in simulations using discrete turbulence phase screens.
Values: NA / 26 nm
Commentary: NGAO is missing this term as our methodology to date has been to include each effect into the error budget separately. NFIRAOS typically uses a phase screen resolution of 1/64 m in its PDR simulations that is 32 points per subaperture. The error was found to scale as $(\Delta x)^{\alpha}$, where Δx denotes the mesh size of the atmospheric screens (matching that of the telescope pupil amplitude map) and $\alpha \approx 0.4496$ based on least-squares fitted simulation results corresponding to Δx =1/16,1/32,1/64,1/128 and 1/256 m.

1.15. Anisoplanatism MOAO (NFIRAOS does not calculate)

Definition: As originally envisioned to work NGAO would feature MOAO correction. This error accounts for the residual uncorrected wavefront error across the typically small science fields or objects when using MOAO correction. The NFIRAOS system being MCAO does not include this error.
Values: 15 nm / NA
Commentary: These values are the residual wavefront error at 1 arc second radius from traditional anisoplanatism analytical formula. For the QSO survey, the object of interest is only about 1-2 arc seconds across (i.e. single QSO)

2. Higher Order Telescope, Component, and Implementation Errors

2.1. Uncorrectable static telescope aberrations (Telescope: static M1/M2/M3 errors)

Definition: Simulation results with and without phase screens included for representative telescope mirror fabrication, mounting, and alignment errors typical of segmented telescopes in both cases (TMT and Keck respectively).
Values: 43 nm / 32 nm
Commentary: TMT has learned from Keck experience and specified the telescope static error accordingly. Keck values are from the representative Phasing Camera system (PCS) measurements. The NFIRAOS values for telescope errors are from simulation of segment alignment errors done by JPL.

2.2. Uncorrectable dynamic telescope aberrations (Telescope: dynamic M1 segments)

Definition: These higher order errors result from the dynamic motion of the M1 segments. Both NGAO and NFIRAOS groups have found that these errors are the results of other telescope phase errors interacting with discontinuities caused by M1 segments resulting in wavefront sensor spatial aliasing.
Values: 31 nm / 14 nm (17 nm)
Commentary: The Keck values assume a worst-case vibration environment at the observatory, based on measured historical data.. The NFIRAOS input error is 45 nm rms which is corrected to 14 nm. These errors are the result of high spatial frequency wind-buffeting of M1 causing the misalignment. (Note from meeting at TMT November 14, 2008: looks like mechanical vibrations, for which an additional 10 nm rms was intended to be included, was left out. Should be 14 nm here added in quadrature with 10nm resulting in 17 nm residual wavefront error)

2.3. NGAO does not calculate (Telescope: dome seeing)

Definition: A phase screen representing additional atmospheric OPD variations in the telescope dome is added to the NFIRAOS AO simulations.
Values: NA / 16 nm
Commentary: NGAO includes this term as part of the ground layer turbulence in its standard atmospheric phase screens that are based on historically reported seeing at observatories on Mauna Kea. NFIRAOS: doesn't assume Kolmogorov turbulence within the dome. Since the NFIRAOS phase screen, and the computational fluid dynamics (CFD) analysis that generated it, is sampled rather coarsely with 5 points/meter, further modeling with higher resolution screens is planned to confirm that the high-spatial frequency components of dome seeing have not been overlooked in these results.

2.4. NGAO does not calculate (Telescope: mirror seeing)

Definition: A phase screen representing additional atmospheric OPD variations caused by the telescope mirror is added to the NFIRAOS AO simulations.
Values: NA / 14 nm
Commentary: NFIRAOS: does not assume Kolmogorov turbulence for mirror seeing. NGAO includes this in the ground layer of its standard turbulence profiles (see comments dome seeing above). Analysis of the impact of mirror seeing effects on NFIRAOS is awaiting high resolution CFD modeling of the magnitude of this effect and the current numbers are an allocation. Mirror seeing is more computationally challenging to model than dome seeing because of the smaller cell sizes required near the mirror. The initial estimates of mirror seeing are lower in amplitude than the dome seeing phase screen used above, but with greater high spatial frequency content.

2.5. NGAO does not calculate (AO: pupil misregistration)

Definition: This error results from telescope pupil mis-registration on wavefront sensors due to various optical motions in telescope and AO system. Typically, the reconstructor is recalculated as the illumination level changes on the various wavefront sensors; however, latency in this computation will cause the reconstructor to be "stale". The effect is most pronounced when observing near zenith.
Values: NA / 12 nm
Commentary: For NFIRAOS Telescope pupil mis-registration due to M3 pointing errors was simulated for a single conjugate AO system with a single ground-layer turbulence phase screen by misregistering (in translation) a single on-axis LGS WFS and a single DM by a common amount equal to 0.3% of the pupil diameter which is the TMT observatory requirement on input pupil misregistration. The resulting error was found to vary between 6 and 12 nm depending upon pupil rotation angle.

2.6. Static WFS zero-point calibration error (AO: NCPA calibration)

Definition: This error results from erroneously correcting wavefront errors that exist only in the optical path of the higher order WSF. This error is the residual after calibration of the AO system to minimize these errors. Current systems can calibrate out between 80-90% of this error.
Values: 25 nm / 35 nm
Commentary: NGAO number is an allocation based on experience with Keck and Palomar AO systems. NFIRAOS allocation assumes the ability to calibrate away 80% of an error that could be as large as 175nm (the 175nm was given to the optical designers as a requirement for uncorrected NCP errors). For example, this error includes NCP errors when the HO LGS WFS in NFIRAOS changes to track the long-throw in focus when Na layer distance varies from 90km to 180km.

2.7. Leaky integrator zero-point calibration error (NFIRAOS does not calculate)

Definition: AO loop will attempt to converge to value that it consistent with the static optical aberrations in the AO system. This error term accounts for mistakes in this process. These errors result from slow changes in the optical system away from its calibrated state (i.e temperature, mechanical flexures, etc.). See also Dynamic WFS zero-point errors below.
Values: 15 nm / NA
Commentary: NGAO error is an allocation based on experience at Palomar.

2.8. Go-to control errors (NFIRAOS does not calculate)

Definition: Multi-Object AO (MOAO) implementations considered in the NGAO point design require operation of individual high-order deformable mirrors in a go-to control mode. By this, we mean that no wavefront sensor witnesses the effects of the correction; rather it is imprinted upon the astronomical science light alone.
Values: 0 nm / NA
Commentary: Current AO baseline assumes single DM correction at pupil conjugate. Science path is a multiple laser single corrector system. Therefore, this error is zero for science object error budget. Note that in the new baseline system the tip-tilt star will still be sharpened by MEMS deformable mirrors inside each tip tilt sensor arm.

2.9. Residual Na layer focus change (LGS WFS and Na laser variability: Na layer overall altitude tracking)

Definition: This focus error results because the LGS WFSs will not be precisely focused at the current height of the sodium layer centroid. The LGS WFSs can be refocused either electronically or mechanically by comparing the defocus measured on an NGS (Truth WFS) with the defocus measured on the LGSs. The conversion factor increases with the square of the diameter of the telescope.
Values: 31 nm / 10 nm
Commentary: NGAO error appears relatively large compared when considering the scaling of the error with aperture size. This should be checked closely by NGAO team. NFIRAOS error assumes an On Instrument WFS (OIWFS) sample rate of 100 Hz and a 30 m/s vertical motion of the Na layer centroid. For TMT, one meter of error in the focus adjustment at the range of the sodium layer results in a focus wavefront error of 4 nm RMS. Note that the error budget allocation of 9 nm RMS and the scale factor of 4 nm RMS per meter are both a factor of two smaller than the values quoted at the NFIRAOS CoDR, due to a discovery of a scale factor error by the NFIRAOS team.

2.10. DM finite stroke errors (deformable mirror: DM saturation)

Definition: This wavefront error results from finite actuator motion of the deformable mirror.
Values: 0 nm / 6 nm
Commentary: Needed stroke scales like diameter over r0 to the 5/6 power. NFIRAOS requires 10 microns peak to valley stroke (surface). Similar requirement for NGAO would be 4 microns stroke surface. The NGAO error is well within current the limits of current DM technology; hence the wavefront error from this effect is zero for NGAO.

2.11. DM hysteresis (deformable mirror: DM hysteresis)

Definition: Error made because DM actuators to not go exactly where commanded. Motion depends on the history of actuator commands.
Values: 13 nm / 24 nm
Commentary: NGAO number is an allocation scaled from the NFIRAOS AO model. The NFIRAOS hysteresis budget was derived from simulations assuming a 5% hysteresis as measured by CILAS on their TMT subscale DM demo at the NFIRAOS operating temperature.

2.12. DM drive digitization (NFIRAOS does not calculate this error)

Definition: Using a finite number of bits to convert the digital signal from real time computer (RTC) to an analogue drive signal results in an error in commanding the DM.
Values: 1 nm / NA
Commentary: NGAO error is based on digitizing 4 microns of surface stroke of the DM over 16 bits. Given its small size this error wasn't tracked by NFIRAOS.

2.13. Uncorrectable AO system aberrations (AO: uncorrectable errors)

Definition: This error results from wavefront errors in the AO system that cannot be corrected by the DM in the system. The error is the result of high frequency optical mounting and polishing errors that have a spatial frequency greater than the reciprocal of the DM interactuator spacing.
Values: 30 nm / 35 nm
Commentary: The NGAO number applies to all optical surfaces in the AO relay and WFS including the DM itself. The NFIRAOS system number excludes the DM, see deformable mirror: DM flattening below. Values are allocations for both NGAO and NFIRAOS.

2.14. Uncorrectable instrument aberrations (science instrument: NCPA and uncorrectable errors)

Definition: This error results from aberrations in the science path above the spatial frequency cutoff of the deformable mirror. The NFIRAOS number also includes errors in calibration for NCP errors in the science path. The exact breakdown between uncorrectable errors and NCP errors for NFIRAOS/IRIS is yet to be determined.
Values: 30 nm / 30 nm
Commentary: These errors are allocations for both systems and are typical of state of the art instrument construction (OSIRIS and IRIS respectively).

2.15. DM-to-lenslet misregistration and DM-to-lenslet pupil scale error (AO DM/WFS pupil misregistration)

Definition: Error caused by misalignment of wavefront sensor subapertures relative to the DM actuator grid. AO control errors result from this misalignment.
Values: 22.1 nm / 16 nm
Commentary: The NGAO number is the quadrature some of pupil misregistration and pupil magnification errors. The NFIRAOS number represents both translation and rotation errors. The error budget for WFS pupil misregistration is allocated to be 16 nm RMS based upon averaging of the two effects.

2.16. NGA does not calculate (AO: DM/WFS pupil distortion)

Definition: The DM/WFS pupil distortion is primarily due to the design residuals in the LGS WFS optics. The resulting misalignment between WFS and DM results in AO control loop errors.
Values: 1NA / 12 nm
Commentary: NFIRAOS: pupil distortion map comes from a real optical design; these are used in closed loop simulation of the NFIRAOS system to estimate this error term as the quadrature difference between simulations with and without pupil distortion. The incremental wavefront error (WFE) caused by nominal DM/WFS pupil distortion at a 100 km LGS focus range is found to be 12.89 nm, the value of above was scaled to zenith.

2.17. NGAO does not calculate (deformable mirror: DM influence functions)

Definition: NFIRAOS uses a bilinear spline influence functions in all simulations. The true actuator influence function, with an interactuator coupling coefficient of about 25 per cent, is expected to slightly reduce the DM fitting error from current estimates.
Values: NA / 0 nm
Commentary: This error is a placeholder.

2.18. NGAO does not calculate (deformable mirror: DM flattening)

Definition: This wavefront errors in the AO system results from the sagging of the DM surface between actuator locations in the system and the ability to calibrate perfectly for the gain and offset of each individual actuator.
Values: NA / 45 nm
Commentary: The NFIRAOS DM flattening error is based upon measured performance of the CILAS subscale demo at an operating temperature of -35 C. The error has been multiplied by 21/2, since NFIRAOS is a dual-conjugate AO system. The NGAO error is carried as part of the overall AO system uncorrectable error term above.

2.19. NGAO does not calculate (control algorithm: algorithm precision)

Definition: Algorithm precision is defined as the best-to-worst case performance variation between the proposed candidate wavefront reconstruction algorithms as demonstrated in detailed AO simulations by NFIRAOS.
Values: NA / 15 nm
Commentary: NFIRAOS RTC engineers have the freedom to choose among several algorithms. This error is the difference between fielded algorithm and algorithm used in simulation to develop the error budget. Originally some fear that most accurate algorithm may not be realizable with available hardware or meet specification on compute update rate. Current design show that all proposed algorithms will meet specifications.

2.20. NGAO does not calculate (control algorithm: numerical precision)

Definition: Numerical precision refers to the error induced by the RTC finite precision arithmetic, tentatively set at 4 bytes.
Values: NA/20
Commentary: A 20 nm RMS allocation has been given to this term pending further simulation results. NFIROS team suggests this may be a conservative estimate (fearful guess).

2.21. NGAO does not calculate (control algorithm: turbulence profile mismatch)

Definition: Turbulence profile mismatch reflects the fact that the tomography algorithm will not be precisely optimized for the true turbulence profile.
Values: NA / 20 nm
Commentary: A 20 nm RMS allocation has been given to this term pending further simulation results. Based on "gut feeling" about how a typically stale Cn2 profile performs. This term includes layer quantization; this will be studied soon by NFIRAOS team.

2.22. NGAO does not calculate (LGS WFS and Na laser variability: offset calibration)

Definition: For NFIRAOS, the optimal matched filter gains and offsets used to estimate LGS centroid will depend upon the time-varying sodium layer profile. Updates will have measurement errors due to read and photon noise and will lag the actual variations in the sodium profile. These errors and delays will introduce wavefront reconstruction errors.
Values: NA / 10 nm
Commentary: The NFIRAOS RTC will adapt the filter coefficients in real time to compensate for these variations. A low bandwidth NGS "Truth" WFS is used to update offsets. The NGAO system deals with these effects in a simplified way as part of the LGS WFS noise term and as part of TBD truth wavefront sensor budget.

2.23. Dynamic WFS zero-point calibration error (LGS WFS and Na laser variability: gain calibration)

Definition: Static zero-point calibration errors can be accentuated in the presence of changing atmospheric and other conditions. The centroid offset values, for example, representing the closed-loop desired target point for the AO system depend on the subaperture centroid gain function mapping true wavefront tilt to measured centroid tilt (all slope sensors are to some degree non-linear meters of the instantaneous wavefront state). Shack-Hartmann sensor systems not designed to operate away from strict 'quad-cell' centers are particularly susceptible to this error. In the case of LGS, the calibration of the centroid for the effect of the sodium layer profile will be incorrect as the sodium layer evolves with time. These errors will be partially mitigated by using a NGS truth wavefront sensor operating at low bandwidth. These errors and delays will introduce wavefront reconstruction errors.
Values: 40 nm / 10 nm
Commentary: Although we have chosen to compare these errors, they emphasize different things in each system: NFIRAOS is looking at sodium profile fluctuations; NGAO is looking at residual error due to spot size variations (from all sources). For NFIRAOS the optimal matched filter gains and offsets used to estimate LGS centroid will depend upon the time-varying sodium layer profile. The NFIRAOS RTC will adapt the filter coefficients in real time to compensate for these variations. A low bandwidth NGS "Truth" WFS is used to update offsets and LGS line-of-sight "dithering" is used to update the pixel gains that determine the matched filter for subaperture gradient estimation. Both updates will have measurement errors due to read and photon noise and will lag the actual variations in the sodium profile.
NFIRAOS: gains updated from the TWFS about once per minute, currently based on changes in the Na layer. Brent Ellerbroek suggests that NFIRAOS should also look at changes in r0 i.e WFS spot size mismatch.

2.24. NGAO does not calculate (LGS WFS and Na laser variability: Na layer differential altitude variability

Definition: Each LGS in a multiple guide star constellation will propagate through different parts of the varying sodium layer. Variations in the sodium layer profile result in each LGS estimating a different focus error. If left uncorrected, these focus errors will propagate into the reconstructed wavefront. This error was estimated by the NFIRAOS team to be as large at ~50 nm RMS.
Values: NA / 5 nm
Commentary: The solution to this error is to use a reconstruction matrix that ignores the focus between the LGS beacons (measured differential focus). De-weighting the focus terms works because one cannot generate focus variations across the field in an MCAO system. The additional matrix operator also has only a small-to-negligible impact upon the computation and memory requirements for the NFIRAOS RTC. (Caution: In an MOAO system, the situation may be different and NGAO should be careful to understand the impact of differential focus).

2.25. NGAO does not calculate (LGS WFS and Na laser variability: Pt. source tomographic approximation)

Definition: The standard isoplanatic LGS subaperture imaging model is based upon the assumption that the uplink and downlink PSFs are effectively constant over the depth of the sodium layer. In fact, small focus aberrations will be present in the PSFs at both ends of the sodium layer, and the "downlink" optical path will shift across the atmospheric phase screens as the magnitude of the cone effect varies by approximately 10 per cent.
Values: NA / 0 nm
Commentary: The error resulting from the tomographic point source approximation was found to be entirely negligible for the NFIRAOS design parameters and performance requirements when this improved simulation model was exercised with 5-9 sodium sublayers. This NGAO is also negligible for NGAO.

2.26. NGAO does not calculate (LGS WFS and Na laser variability: Rayleigh)

Definition: Error that results from the changes in the background level from Rayleigh scatter from one LGS scattering into wavefront sensors assigned to adjacent laser beacons. Temporally stable backscatter will add additional background noise to the measurement of the WFS. Changes in Rayleigh scattering levels due to thin cirrus (sub visible) will add an additional background offset and noise.
Values: NA/40
Commentary: NGAO estimates this factor as an additional noise term in the centroid model used to estimate the overall LGS wavefront sensor noise term above. The current NFIRAOS error is an initial allocation the TMT projects hopes to use field data from Gemini South MCAO to anchor this estimate.

3. TOTAL NGS TIP/TILT AND PLATE SCALE ERRORS

3.1. Tilt measurement error one-axis (Tip/Tilt: median NGS WFS noise)

Definition: This part of the wavefront error budget is the contribution of the NGS detector measurement noise which includes the effects of photon noise, sky background, NGS Strehl ratio, detector read out noise, and dark current.
Values: 30 nm / 13 nm
Commentary: NFIRAOS tip tilt error from simulation, IRIS configuration of TTFA sensors. NGAO errors are typically larger because of smaller aperture to measure tip tilt errors (10 m compared 30 m).

3.2. Tilt bandwidth error one-axis (Tip/Tilt median atmospheric servo lag)

Definition: This error term is caused by the delay in applying the tip/tilt correction commands in closed loop operation of the AO system.
Values: 28 nm / 14 nm
Commentary: NFIRAOS tip tilt error from simulation, IRIS configuration of TTFA sensors. NGAO errors are typically larger because of smaller aperture to measure tip tilt errors.

3.3. Tilt anisoplanatism error (one-axis) (Tip/Tilt: median anisoplanatism)

Definition: Tilt anisoplanatism error is the inability to precisely estimate the tip/tilt error in the science directions using measurements from multiple NGS wavefront sensors. This term is caused by the atmospheric tip/tilt anisoplanatism modes.
Values: 48 nm / 8 nm
Commentary: NFIRIAOS error assumes 3 NGS used in tomographic estimation. NGAO assumes average of estimated anisoplanatism with classical formula for isoplanatic angle and average of typical separation of NGS guide stars from field center.

3.4. Residual atmospheric dispersion (NFIRAOS counts this error with the AO instrument IRIS)

Definition: This error results from the image smear resulting from uncorrected atmospheric dispersion in the AO system and instrument.
Values: 3 nm / NA
Commentary: Atmospheric dispersion is a chromatic effect that cannot be easily represent by the Marechal approximation. Despite this NGAO uses this approximation with its error budgets, adopting the residual atmospheric dispersion that would be present across the J-band, as this represents a worst case effect for near IR astronomy, the effect is smaller at longer wavelengths (H and K).

3.5. Induced plate scale deformations (Similar to but distinct from NFIRAOS NGS Plate scale mode below)

Definition: The plate scale modes are image magnification and two differential magnification modes rotated 45 degrees to each other. Errors in measuring and correcting these modes results in distortion of the science image
Values: 0 nm / NA
Commentary: NGAO is an MOAO system so these errors are by definition zero. However, NGAO must use multiple NGS to correct for the quadratic terms (focus and astigmatism) of focus anisoplanatism. Multiple LGS with no tilt information (tip tilt removed) fundamentally cannot reduce this error. So a new term needs to be added to the NGAO budget for these terms as they are not being counted now.

3.6. Science Instrument Mechanical Drift (NFIRAOS counts this error with AO instrument IRIS)

Definition: Due to typical non-common optical paths between the science focal plane and the NGAO tip/tilt sensor, slow thermal or gravitational drifts can cause blurring on the long-exposure science image.
Values: 42 nm / NA
Commentary: For the NGAO design, we assume 0.2 milli arc seconds as an allocation for the allowable non common-path mechanical drift for short exposures (e.g. 10 seconds) and 2.5 milli arc seconds for the long exposures (e.g. 0.5 hours).

3.7. Long exposure field rotation errors (NFIRAOS counts this error with AO instrument IRIS)

Definition: Imperfect field derotation science field relative to the science focal plane will result in a blurring of the science image.
Values: 83 nm / NA
Commentary: NGAO allocates 0.2 milli arc seconds for short exposure and 5 milli arc seconds for long exposures to these effects. Note that long-exposure in this case can represent any exposure that undergoes significant field derotation, including relatively short duration exposures need near zenith. For NGAO, this allocation is quite large. The NGAO team will consider that this term can be reduced by using information from the NGS TTFA sensors to provide feedback on the residual field rotation errors.

3.8. Residual telescope pointing jitter one-axis (Tip/Tilt: telescope mechanical vibration)

Definition: Mechanical vibration telescope line of sight that is not well corrected by the AO tip tilt system results in this error term.
Values: 10 nm /10 nm
Commentary: NGAO allocation from estimate of 29 Hz vibration left uncorrected by NGAO. NFIRAOS allocation awaiting confirmation from structural analysis of telescope vibration modes.

3.9. NGAO does not calculate (Tip/Tilt: telescope windshake)

Definition: Wind driven line of sight motion of the telescope that is not well corrected by the AO tip tilt system results in this error term.
Values: NA/ 17 nm
Commentary: NGAO does not account for a separate windshake term in the tip tilt error budget as the mechanical vibrations appear to be the dominant term. The TMT telescope wind shake model used in the NFIRAOS sky coverage simulations has been updated to reflect the results of recent telescope structural analysis of wind shake.

3.10. Residual Centroid Anisoplanatism (Tip/Tilt: Physical Optics Effects)

Definition: Physical optics effects in the NGS wavefront sensors, including spatial aliasing of high-order wavefront errors and speckle noise. Ideally, tip/tilt sensors would measure wavefront tilt, but in practice they usually measure centroid motion as a surrogate to true tilt in the Zernike sense. Because other wavefront aberrations (notably coma) can also displace the wavefront centroid, a centroid anisoplanatism error is introduced.
Values: 18 nm / 35 nm
Commentary: The NGAO term is from the conventional centroid anisoplanatism scaling law. NFIRAOS term is an allocation at present. The NFIRAOS planned modeling includes more than just coma-related centroid anisoplanatism effect. They also hope to include effects from pupil shape, M2 shape, M2 spiders, LGS errors coupling to NGS loop; simulation errors in calculating the actual "sharpening" and centroid error on real "sharpened" images. This study is funded by CfAO Y10 and part of their plan is to model the Keck NGAO system as a starting point.

3.11. NGAO does not calculate these terms (NGS Plate scale: Atmospheric Errors and NGS WFS noise)

Definition: The plate scale modes are image magnification and two differential magnification modes rotated 45 degrees to each other. Errors in measuring and correcting these modes results in distortion of the science image. In NFIRAOS, six modes are controlled by the NGS wavefront sensors: image rotation handled by the instrument rotator; the two global tip/tilt modes considered above; and three so-called “plate scale” modes. These modes are image magnification, differential magnification in X versus Y, and differential magnification at 45 degrees. In an MCAO system, plate scale modes result from focus and astigmatism distributed on both DMs, which are scaled so that the wavefront propagated from a LGS at finite range to the aperture-plane consists of pure T/T, which is invisible to the T/T-removed LGS WFS. For a science object at infinity, the propagated wavefront contains focus/astigmatism aberrations due to the cone effect, which de-weights the effect of the quadratic aberration applied to the upper DM. These modes must be measured with the NGS low order wavefront sensors. Measurement noise and delay in correction will cause errors in the correction.
Values: NA / 15 nm
Commentary: As a MOAO system NGAO is immune to these modes, but see comments above on error term “Induced plate scale deformations”. For NFIRAOS these “plate scale” modes are estimated in the sky coverage simulations as the quadratic difference between the total wavefront error in the modes controlled by the NGS and the field averaged tip/tilt wavefront error.

3.12. NGAO does not calculate (NGS Plate scale: telescope windshake)

Definition: Windshake can induce low order aberrations in the primary and secondary mirror, mostly collimation type errors, astigmatism and coma.
Values: NA / 5 nm
Commentary: In the case of NFIRAOS, the impact of low-order M1 figure distortions and telescope misalignments were analyzed using a separate low-order modal simulation of the NFIRAOS system. The baseline case was 75 % telescope windshake model and an 80 Hz NGS control loop sampling rate. This sampling rate is the median NGS WFS sampling rate determined by the Monte Carlo sky coverage simulations. Optical sensitivity matrices and cross-spectra of the telescope dynamic errors provided by HIA and Nightsky Systems Inc. were used as input to the low-order modal simulation. The dominant impact of these dynamic telescope misalignments is to introduce TT errors as described above, and an additional RMS WFE of approximately 5 nm in the plate scale modes (The additional wavefront error in the LGS-controlled wavefront modes was found to be negligible, presumably on account of the higher control bandwidth).