Keck Adaptive Optics Note 051

Keck Adaptive Optics Error Budget

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The purpose of this note is to summarize the expected error sources which will contribute to the degradation of images on a science instrument fed by an Adaptive Optics (AO) system on the Keck II telescope, and to compare the resultant performance to the requirements. A second purpose for tabulating the error sources is to provide a quick reference in the process of evaluating potential engineering trade-offs. The calculations of Natural Guide Star magnitudes (made in May 1997) were added in the February 1998 revision.

Summary Tables:

The telescope and AO error sources are detailed in Chapters 3 and 4 of KOR 208 (KAON 012). These error sources are tabulated in Table 1, along with their equations or expected value, and a brief list of means for reducing each error term. The total rms error impacting the science image, as listed at the top of the table, is the square root of the quadratic sum of four categories of errors. The categories include the errors assigned to AO and the AO system, the uncorrected telescope errors, the science instrument aberrations and stability, and field dependent errors. Not included in this total rms error is a fifth category, which impacts the image position on the science detector.

The total at the top of each error category is itself the quadratic sum of the error terms listed in that category. The error terms which only impact the Laser Guide Star Facility are indicated with a LGS in parenthesis. All other terms effect both the Natural Guide Star (NGS) and LGS Facilities (note that in general there will be no isoplanatic angle error for the LGS).

The two Strehl ratio calculations after the total rms error reflect how the error sources impact the image quality. The first four categories degrade the image by spreading energy from the diffraction-limited core into the surrounding seeing limited halo. The fifth error category, image motion, acts to broaden the diffraction-limited core. Two terms, bandwidth error and isoplanatic error, whose rms errors are larger than their actual impact on the Strehl ratio, are treated differently in the Strehl calculation, as indicated in Table 1.

The atmospheric parameters for the conditions and zenith angles for which the AO system requirements were written are listed in Table 2 (from Chapter 5 of KOR 208 (KAON 012)). These are intended to represent good, average and poor observing conditions.

The flux from the laser guide star (LGS) that enters the telescope is a function of seeing conditions and zenith angle. The numbers in Table 3 are from Don Gavel.

Spreadsheets:

The equations and values listed in Tables 1 and 2 were used to generate an Excel spreadsheet, and several sample spreadsheets are attached. The first column of the spreadsheet is essentially the same as the first column of Table 1. The next 6 columns list the values for the NGS and LGS Facilities, respectively, under the 3 sets of observing conditions defined in Table 2. The final column lists all the variables used for the calculations.

The spreadsheet, Error budget 1(a), is intended to represent the best case scenario. The parameters used in this spreadsheet reflect some of the engineering assumptions that have been made (thanks to LLNL for specifying many of these numbers):

A D=10 m aperture divided into d=0.56 m Shack-Hartmann subapertures.
The fitting and bandwidth coefficients are μ=0.3 and β=1, respectively.
A closed loop bandwidth of f_c=90 Hz, with an integration time of t_i=1 ms.
A return laser beacon signal (LGS) of S_0=2000 photons/ms-m^2 (V mag = 9.3).
An infinite NGS signal.
A wavefront sensor quantum efficiency of 0.8; n=4 CCD pixels are used for centroiding, with a read noise of NR=11 electrons, and no dark ND or background NB noise.
A telescope + AO system + wavefront sensor optics thruput of 0.3.
A reconstructor noise propagator E=0.75 and a control loop averaging factor χ=0.524.
The LGS wavelength is λ=0.589 μm.
The NGS mean wavelength is λ=0.7 μm.
The projected laser spot size is θ_{proj}=0.7 arcsec.
The laser projection telescope is 6 m off-axis ε=0.65.
The NGS and science object are on-axis, θ=0.
The tilt closed loop frequency is $f_{c\text{-}t}$=90 Hz.
An infinite tilt star signal.
The tilt sensor QE=0.8; n=4 APD pixels are used with no noise.
The centroid anisoplanatism temporal averaging coefficient is minimized, F_{ca}=0.00037.

Parameters in this spreadsheet can be varied to explore the impact of various design choices or observing conditions. Some sample cases are presented below:

On-axis laser projection. If ε in error budget 1(a) is changed from 0.65 to 0.26, representing the case of moving the laser projection telescope from the edge of the Keck primary to its center, the measurement elongation error is reduced to 23, 39 and 138 nm for cases A, B and C, respectively. The case B Strehl is increased from 0.56 to 0.57 at 2.2 μm.

Increased laser power, lower noise CCD. If S_0(LGS) in error budget 1(a) is changed from 2000 to 4000 photons/ms-m^2 then the sum of the measurement error terms is reduced from 98 to 54 nm for case B. The result is that the Strehl ratio for case B is increased from 0.07 to 0.09 at 1 µm and from 0.56 to 0.60 at 2.2 µm. If instead the CCD read noise is reduced from 11 to 6 electrons, the measurements terms are reduced to 65 nm and the case B Strehl at 2.2 µm is increased to 0.59.

Reduced NGS flux. Error budget 2(a) is for an NGS with the same flux as the LGS (significantly better NGS performance than for the LGS Facility). If the NGS flux is reduced by 4 the measurement errors increase from a total of 79 to 293 nm for case B and a 1 ms integration, reducing the 2.2 µm Strehl from 0.73 to 0.38. A factor of 10 (V~12), reduces the case A 2.2 µm Strehl from 0.83 to 0.20. A factor of 2000 (V~17.5) reduces the case A LGS 2.2 µm Strehl from 0.78 to 0.17.

Off-axis NGS. Error budget 3(a) demonstrates the impact of using a NGS 10 arcsec off-axis (flux = 2000 photons/ms-m^2). Compared to error budget 2(a) the NGS Facility case B Strehl is reduced from 0.73 to 0.62 at 2.2 µm due to the addition of 138 nm of isoplanatic error. When the NGS used for LGS tilt sensing is 50 arcsec off-axis the LGS Facility case A Strehl is reduced from 0.77 to 0.58 due to the addition of 57 nrad of isokinetic error.

Centroid anisoplanatism. The value of Fca used in error budget 1(a) assumes that temporal averaging of the coma term has significantly decreased this term. If no temporal averaging were assumed then Fca = 0.00304 and the centroid anisoplanatism term is increased from 30 to 86 nrad for case B thereby reducing the Strehl from 0.56 to 0.35.

Comparison to Requirements:

The requirements for the Natural Guide Star (NGS = Facility II) and Laser Guide Star (Facility III) Facilities are defined in Chapter 5 of KOR 208 (KAON 012). There are three image improvement requirements.

Error budget 1(a) is the case for which the image improvement requirement was written: an infinitely bright on-axis NGS, and an on-axis LGS. These cases are also presented as Figures 1 and 2. The calculated AO system errors should be compared to the NGS requirements of 70, 140 and 400 nm for case A at zenith, case B at 30E zenith angle, and case C at 60E, respectively. The corresponding numbers for the LGS Facility are 110, 210 and 500 nm, respectively. The predicted performance is seen to be slightly larger than the requirements in several cases. The achieved performance could be improved somewhat by balancing error terms such as the bandwidth and measurement errors.

The second requirement is that the Facility must reduce the sum of the static segment warping harness residual, the segment stacking errors, and the science instrument aberrations to < 70 nm. In Table 1 the rms sum of these three components is 72 nm.

The third requirement is that the wavefront, and tilt, sensor noise and quantum efficiency must not reduce the signal-to-noise ratio to < 10, assuming 400 incident photons/subaperture and a 100 ms integration. For a

0.56 m diameter subaperture, and a system throughput of 0.3, this works out to be a flux at the input to the telescope of S_0 = (400ph/subap)/[π(0.28m)^2*100ms*0.3] = 54.1 photons/m^2-ms. For a 10 m diameter subaperture, and a system throughput of 0.3 this works out to be a flux of S_0 = 0.17 photons/m^2-ms. Plugging these fluxes into the spreadsheet results in a SNR of 11.3 for the wavefront sensor, and a SNR of 17.9 for the tilt sensor.

Natural Guide Star Magnitudes:

The number of photoelectrons generated by a zeroth magnitude star is given by

$$f_0 = 10^{\log f} (\lambda/hc)\, \Delta\lambda\, A\, \eta\, t_i$$

where f is the flux in W cm^{-2} μm^{-1} and log f is from p. 202 of Allen's Astrophysical Quantities, λ is the wavelength, h is Planck's constant (6.63e-34 J-s), c is the speed of light (3e10 cm/s), $\Delta\lambda$ is the bandwidth, A is the subaperture collecting area, η is the system efficiency including optics and detector quantum efficiency, and t_i is the integration time. The first four rows of Table 4 are from Allen. The assumptions used in calculating the last two rows are given in the following sections.

NGS Wavefront Sensing

In the wavefront sensing case the subapertures correspond to an area on the primary mirror of A = (56.25 cm)^2. The system efficiency term consists of the telescope (T = 0.7) and AO system throughputs (T = 0.45) and the quantum efficiency of the wavefront sensor camera CCD (QE = 0.9 at V, 0.85 at R and 0.45 at I for the LL chip). The total flux per subaperture is 2.38e6 photons/ms for a zeroth V magnitude A0 star (V-R = V-I = 0). The total flux per subaperture for a zeroth V magnitude M0 star (V-R = 1.1, V-I = 2.2) is 7.00e6 photons/ms. Note that the average star is somewhere between K5 and M0.

For comparison, the 20W laser is supposed to produce a return signal of 0.3 photons/cm^2/ms at the primary mirror. Taking into account the subaperture size and the system efficiency the total flux per subaperture is predicted to be 269 photons/ms. This corresponds to a 9.9 V mag A0 star or an 11.0 V mag M0 star.

In order to calculate a rough limiting NGS magnitude assume that we need a SNR > 3 for wavefront sensing and that we allow a t_i = 10 ms integration. Note that SNR = f/sqrt(f + nN_r^2) where n = 4 is the number of pixels and N_r is the detector read noise. Assuming that the LL chip has N_r = 6 electrons we need f > 40 photons in order to achieve a SNR > 3. This gives a limiting V magnitude of 14.4 for an A0 star and 15.6 for a M0 star. A lower noise detector with N_r = 3 electrons would reduce the flux requirement to f > 23 photons for the same SNR, resulting in a limiting V magnitude of 15.0 for an A0 star and 16.2 for a M0 star; a magnitude limit gain of 0.6.

Tip/tilt Sensing

In the tip/tilt sensing case the entire primary is used, $A = \pi(500\ \mathrm{cm})^2$. The AO system throughput is slightly smaller (T = 0.4) and the quantum efficiency of the avalanche photodiodes must be considered (QE = 0.8 at V, 0.7 at R and 0.4 at I). The total zeroth V magnitude flux is 4.51e8 photons/ms for an AO star and 1.33e9 photons/ms for a M0 star. For essentially complete sky coverage we need an 19th V magnitude star which would provide a detected flux of 12.4 photons/ms for an A0 star and 36.6 photons/ms for an M0 star.

The SNR calculation for the tilt sensor is different since the sky background is a noise source and, although there is no read noise, the dark current is potentially significant. The full moon sky brightness is 19.4 mag/arcsec^2 in V, 18.6 in R and 17.5 in I; assuming 1 arcsec APD detectors (and 4 elements) the detected sky flux is 12.5 photons/ms in V, 32.9 in R and 34.5 in I for a total flux of 79.9 photons/ms. The dark current is < 0.1 electrons/ms. If we allow a 10 ms integration the resultant SNR is 4.1 for the 19th V mag A0 star and 10.7 for the M0 star.

Note that in the dark sky case the sky brightness is 1.7 magnitudes fainter so that the total detected sky flux is 16.8 photons/ms. A 10 ms integration then gives a SNR of 7.3 for the 19th V mag A0 star and 15.8 for the M0 star.

IR tip/tilt Sensing

In the dark cloud case there may not be a bright enough visible star to perform tip/tilt sensing with the quadrant APD sensor. In this case we may need a IR tilt sensor. The fluxes computed in the last row of the table above assume the telescope throughput is the same in the IR, the AO throughput to the IR tilt sensor is T = 0.35 (equal sharing of the science light; although could be smarter), and that the detector QE = 0.7.

The dark sky is brighter in the IR: 14.8 mag/arcsec^2 at J and 12.6 at K. However, we can use considerably smaller pixels for tilt sensing since the AO corrected image FWHM will be on the order of 0.04 arcsec at K. Assuming that we use four 0.05 arcsec pixels the total area on the sky is 0.01 arcsec^2. The expected detected sky flux is therefore 1.4 photons/ms at J and 2.8 at K; which is negligible, in a 10 ms exposure, compared to the expected detector read noise of 10 electrons/pixel. Assuming K band only tilt sensing and an 18th V magnitude star the detected star flux is 1.96 photons/ms for an A0 star and 30.6 for an M0 star (V-K ~ 3 for M0). The SNR in a 10 ms integration is therefore 1.0 for the 18th V mag A0 star and 11.5 for the M0 star.

Table 1. Summary of AO system error budget terms.

Error Term	**Equation or Value**	**How to reduce term**
TOTAL RMS (nm)	$\sigma_{total} = [\Sigma(\sigma_i^2)]^{1/2}$	i=AO, telescope, science instrument, field
Strehl Ratio (no tilt)	$SR = \exp[-(2\pi\sigma_{total}/\lambda)^2]$	
Strehl Ratio (with tilt)	$SR = \exp[-(2\pi\sigma_{total}/\lambda)^2]$ $*\sigma_D^2/(\sigma_{tilt}^2+\sigma_D^2)$ where $\sigma_D = 0.45\lambda/D$	
AO System + Atmosphere	$\sigma_{AO}(nm) = [\Sigma(\sigma_i^2)]^{1/2}$	i = fit,bw,wfs-MTF,wfs-spot, wfs-ε,fa,t-ca,LGS-foc,cal,unc
Fitting	$\sigma_{fit} = (\lambda/2\pi)\mu^{1/2}[d_{act}/r_0(\lambda,\theta_z)]^{5/6}$	- reduce actuator spacing d_{act} - reduce fitting coefficient
Bandwidth	$\sigma_{bw} = (\lambda/2\pi)\beta^{1/2}(f_g/f_c)^{5/6}$ $f_g = 0.135/\tau_0(\lambda,\theta_z)$ For Strehl, replace f_g with $f_{eff} = f_g[1+1/\log_{10}(D/r_0)]$	- increase f_c by increasing read rate & processor speed - optimize filter β
Measurement - MTF	$\sigma_{wfs\text{-}MTF} =$ $[4\int\tau_s(x)dx]^{-1}SNR^{-1}\lambda_{gs}E\chi$ $\int\tau_s(x)dx = 2/(3\pi)$ $*\{\exp[-0.115d/r_0(\lambda_{gs},\theta_z)]$ $+\exp[-0.115(d/r_0)^2]\}$ SNR= $S\{t_i/[S+n(N_B+N_D+N_R^2/t_i)]\}^{1/2}$ S(photons/sec/subaperture) $= \eta\ T\ S_0\pi(d/2)^2$	- increase SNR with brighter star or laser S_0, higher thruput T & quantum efficiency η, longer integration t_i, & lower noise (number of pixels n, read-noise N_R, dark noise N_D & background N_B) - subaperture diameter d - longer sensing wavelength λ_{gs} for NGS - reduce reconstr. algor. noise propagator E &/or control loop averaging factor χ
Measurement - spot size	$\sigma_{wfs\text{-}spot} = (\pi d\theta_{gs}/8)SNR^{-1}E\chi$ $\theta_{gs} = \{[\lambda_{gs}/r_0(\lambda_{gs},\theta_z)]^2+\theta_{proj}^2\}^{1/2}$	same as above + - reduce LGS projected spot size θ_{proj}

Measurement - elongation (LGS)	$\sigma_{wfs\text{-}\varepsilon}=[\varepsilon(\sigma_{wfs,MTF}^2+\sigma_{wfs,spot}^2)]^{1/2}$ ε(on-axis) = 0.26 ε(off-axis) = 0.65	same as above + - reduce elongation ε by going on-axis
Focal Anisoplanatism (LGS)	$\sigma_{fa} = (\lambda/2\pi)[D/d_0(\lambda,\theta_z)]^{5/6}$	- multiple laser beacons - reduce telescope diameter D
Focus (LGS)	$\sigma_{LGS\text{-}foc}$ = 35 nm	- more astigmatism
Calibration	σ_{cal} = 30 nm	- better calibration tools, alignment, focus & stability
Uncorrected Internal	σ_{unc} = 20 nm	- better optical design, fabrication & alignment
Telescope + AO + ACS	$\sigma_{tel} = [\Sigma(\sigma_i^2)]^{1/2}$ = 104.9 nm	i = res,ACS,phase,vib,stack
Warping residuals	σ_{res} = 62 nm	- better segments & setting
ACS noise	σ_{ACS} = 58 nm	
Segment phasing	σ_{phase} = 50 nm	- better characterization
Segment vibration	σ_{vib} = 30 nm	- reduce & isolate sources
Segment stacking	σ_{stack} = 20 nm	- feedback from WFS
Science Instrument + AO	$\sigma_{field} = [\Sigma(\sigma_i^2)]^{1/2}$ = 49.5 nm	i = int,align
Internal aberrations	30 nm	- better optics design/fab
Field Dependence	σ_{field}(nm) = $[\Sigma(\sigma_i^2)]^{1/2}$	i = t-iso,iso,f-AO,f-sci
Isoplanatic angle	$\sigma_{iso} = (\lambda/2\pi)[\theta/\theta_0(\lambda,\theta_z)]^{5/6}$ For Strehl, replace θ_0 with $\theta_{eff} = \theta_0[1+1/\log_{10}(D/r_0)]$	- find N/LGS closer to object - DM conjugate to layer - multi-conjugate AO
Telescope + AO field aber.	$\sigma_{f\text{-}AO}$ = (20nm)(θ/40arcsec)	- better AO optics design/fab.
Science instrument field aber.	$\sigma_{f\text{-}sci}$ = (20nm)(θ/40arcsec)	- better optics design/fab.
AO Tilt System +		i = t-bw,t-MTF,t-spot,t-ca,

Atmosphere (LGS)	σ_{tilt} (radians of tilt) = $[\Sigma(\sigma_i^2)]^{1/2}$	t-iso
Tilt Bandwidth	$\sigma_{t\text{-}bw} = (f_T/f_{c\text{-}t})(\lambda_T/D)$ $f_T = 0.0811[r_0(\lambda_T,\theta_z)/D]^{1/6} /\tau_k(\lambda,\theta_z)$	- increase closed loop bandwidth $f_{c\text{-}t}$ by decreasing read, processing, & integration times
Tilt Measurement - MTF	$\sigma_{t\text{-}MTF} = [4\int\tau(x)dx]^{-1}SNR^{-1}\lambda_T/D$ $\int\tau(x)dx$ $=4r_0(\lambda_T,\theta_z)/(3\pi D)$ for $D/r_0>20$ $=2/(3\pi)\exp(-0.115D/r_0)$ for $10<D/r_0<20$ S(phot/sec)= $\eta T S_0\pi(D/2)^2$	- increase SNR with brighter star, S_0, higher thruput T & quantum efficiency η, longer integration t_i, & lower noise (number of pixels n, read-noise N_R, dark noise N_D & background N_B) - longer sensing λ_T - reduce reconstr. algor. noise propagator E &/or control loop averaging factor χ
Tilt Measurement - spot size	$\sigma_{t\text{-}spot} = (\pi/8)\theta_T/SNR$ $\theta_T = \lambda_T/r_0(\lambda_T,\theta_z)$ for $\theta > \theta_0$ $\theta_T = \lambda_T/D$ for $\theta < \theta_0$	- increase SNR - longer sensing λ_T - find NGS close to object
Centroid Anisoplanatism	$\sigma_{t\text{-}ca} = [F_{ca}(f_{c\text{-}t})]^{1/2}\lambda/D *[D/r_0(\lambda,\theta_z)]^{5/6}$	-reduce F_{ca} thru temporal averaging by decreasing $f_{c\text{-}t}$ $(0.00037< F_{ca}<0.00304)$ - use more subapertures
Isokinetic angle	$\sigma_{t\text{-}iso} = 0.427[\theta/\theta_k(\lambda,\theta_z)] *\lambda/D[D/r_0(\lambda,\theta_z)]^{5/6}$	- find NGS closer to object - DM conjugate to layer - multi-conjugate AO
Science instrument alignment with AO tilt system	15 nrad	- improved stability, or measurement techniques, for non-common path tilt & piston errors

Note: - need to correct elongation measurement error; should only multiply the spot size term

Table 2. Atmosphere parameters scaled for zenith angle at $\lambda_0 = 0.55\ \mu$.
Wavelength and zenith angle dependence is $x_0(\lambda,\theta_z) = x_0(\lambda_0)(\lambda/\lambda_0)^{6/5}\sec^{-3/5}\theta_z$

	Set A **at zenith**	**Set B** **at 30 degrees**	**Set C** **at 60 degrees**
r_0 (m)	0.4	0.18	0.066
θ_0 (arcsec)	10	3.67	1.31
θ_k (arcsec)	300	147	52.8
τ_0 (ms)	10	2.75	0.99
τ_k (ms)	300	128	46.2
d_0 (m)	14	6.42	2.31
L_0 (m)	50	50	50

Table 3. Ratio of LGS return power as a function of observing conditions.

	Set A **at zenith**	**Set B** **at 30 degrees**	**Set C** **at 60 degrees**
Laser power ratio	0.95	1	0.75

Table 4. Number of photoelectrons generated and detected from a zeroth magnitude star.

Filter	**V**	**R**	**I**	**J**	**K**
λ (μm)	0.55	0.7	0.9	1.25	2.2
$\Delta\lambda$ (μm)	0.089	0.22	0.24	0.38	0.48
log f	-11.42	-11.76	-12.08	-12.48	-13.4
$10^{\log f}(\lambda/hc)\Delta\lambda$ (phot/s-cm^2)	935700	1346000	903300	790800	211400
f_0/t_i (phot/ms) for AOA/LL wfs camera	839300	1140000	405100		
f_0/t_i (phot/ms) for the APD tip/tilt sensor	164600000	207200000	79460000		
f_0/t_i (phot/ms) for IR tilt				106500000	28480000

sensor					

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Error Budget #1(a).	Best case scenario: bright NGS, everything on axis.							
	off-axis laser projection							
Error Term	NGS Facility			LGS Facility			**Parameters**	
	A	B	C	A	B	C		
	0 deg	30 deg	60 deg	0 deg	30 deg	60 deg	*Tel. & subaperture*	
							D(m)	10
Total RMS (nm)	133	173	321	163	239	559	d(m)	0.56
Strehl @ 1 um (no tilt)	0.50	0.30	0.02	0.35	0.10	0.00	*Fitting/bandwidth*	
Strehl @ 1 um (with tilt)	0.45	0.27	0.02	0.28	0.07	0.00	mu	0.3
Strehl @ 2.2 um (no tilt)	0.87	0.78	0.43	0.80	0.63	0.08	fc(Hz)	90
Strehl @ 2.2 um (with tilt)	0.85	0.76	0.42	0.77	0.56	0.05	beta	1
							SNR(LGS)	4.8
AO System (nm)	74	134	301	120	212	548	*S (LGS)*	118
Fitting	63	123	285	63	123	285	SO(LGS)	2000
Bandwidth	11	36	90	11	36	90	(ph/ms-m2)	
Measurement - MTF	0	0	0	35	52	185	*SNR(NGS)*	######
Measurement - spot	0	0	0	28	56	197	*S(NGS)*	######
Measurement - elong.				37	62	218	SO(NGS)	######
Focal Anisoplanatism				66	127	297	QE	0.8
Focus				35	35	35	T	0.3
Calibration	30	30	30	30	30	30	ti(ms)	1
Uncorrected Internal	20	20	20	20	20	20	n(pixels)	4
							NR(e-)	11
Telescope (nm)	105	105	105	105	105	105	ND(e-/ms)	0
Warping residuals	62	62	62	62	62	62	NB(e-/ms)	0
ACS noise	58	58	58	58	58	58	*Measurement*	
Segment phasing	50	50	50	50	50	50	E	0.75
Segment vibration	30	30	30	30	30	30	chi	0.524
Segment stacking	20	20	20	20	20	20	lambda(LGS)	0.589
							lambda(NGS)	0.7
Science Instr. (nm)	35	35	35	35	35	35	th(proj)(asec)	0.6
Internal aberrations	35	35	35	35	35	35	epsilon	0.65
							Field (arcsec)	
Field Depend. (nm)	0	0	0	0	0	0	th(NGS)	0
Isoplanatic angle	0	0	0				th(science)	0
Telescope + AO	0	0	0	0	0	0	*Tilt*	
Science Instrument	0	0	0	0	0	0	fc-t(Hz)	90
							SNR	######
AO Tilt (nrad)	15	15	15	22	34	71	*S*	######
Bandwidth				0	0	0	SO	######
Measurement - MTF				0	0	0	QE	0.8
Measurement - spot				0	0	0	T	0.3
Centroid anisoplan.				15	30	69	ti(ms)	1
Isokinetic angle				0	0	0	n(pixels)	4
Science Inst. alignment	15	15	15	15	15	15	NR(e-)	0
							ND(e-/ms)	0
							NB(e-/ms)	0
							Fca	0.0004

Error Budget #2(a).	NGS = LGS flux, everything on-axis.							
	off-axis laser projection							
Error Term	**NGS Facility**			**LGS Facility**			**Parameters**	
	A	B	C	A	B	C		
	0 deg	30 deg	60 deg	0 deg	30 deg	60 deg	*Tel. & subaperture*	
							D(m)	10
Total RMS (nm)	141	191	386	163	239	559	d(m)	0.56
Strehl @ 1 um (no tilt)	0.46	0.24	0.00	0.35	0.10	0.00	*Fitting/bandwidth*	
Strehl @ 1 um (with tilt)	0.41	0.21	0.00	0.28	0.07	0.00	mu	0.3
Strehl @ 2.2 um (no tilt)	0.85	0.74	0.30	0.80	0.63	0.08	fc(Hz)	90
Strehl @ 2.2 um (with tilt)	0.83	0.73	0.29	0.77	0.56	0.05	beta	1
							SNR(LGS)	4.8
AO System (nm)	87	155	370	120	212	548	*S (LGS)*	118
Fitting	63	123	285	63	123	285	SO(LGS)	2000
Bandwidth	11	36	90	11	36	90	(ph/ms-m2)	
Measurement - MTF	39	55	148	35	52	185	*SNR(NGS)*	4.8
Measurement - spot	26	57	156	28	56	197	*S(NGS)*	118
Measurement - elong.				37	62	218	SO(NGS)	2000
Focal Anisoplanatism				66	127	297	QE	0.8
Focus				35	35	35	T	0.3
Calibration	30	30	30	30	30	30	ti(ms)	1
Uncorrected Internal	20	20	20	20	20	20	n(pixels)	4
							NR(e-)	11
Telescope (nm)	105	105	105	105	105	105	ND(e-/ms)	0
Warping residuals	62	62	62	62	62	62	NB(e-/ms)	0
ACS noise	58	58	58	58	58	58	*Measurement*	
Segment phasing	50	50	50	50	50	50	E	0.75
Segment vibration	30	30	30	30	30	30	chi	0.524
Segment stacking	20	20	20	20	20	20	lambda(LGS)	0.589
							lambda(NGS)	0.7
Science Instr. (nm)	35	35	35	35	35	35	th(proj)(asec)	0.6
Internal aberrations	35	35	35	35	35	35	epsilon	0.65
							Field (arcsec)	
Field Depend. (nm)	0	0	0	0	0	0	th(NGS)	0
Isoplanatic angle	0	0	0				th(science)	0
Telescope + AO	0	0	0	0	0	0	*Tilt*	
Science Instrument	0	0	0	0	0	0	fc-t(Hz)	90
							SNR	194.2
AO Tilt (nrad)	15	15	15	22	35	76	*S*	37699
Bandwidth				0	0	0	SO	2000
Measurement - MTF				4	10	26	QE	0.8
Measurement - spot				0	0	0	T	0.3
Centroid anisoplan.				15	30	69	ti(ms)	1
Isokinetic angle				0	0	0	n(pixels)	4
Science Inst. alignment	15	15	15	15	15	15	NR(e-)	0
							ND(e-/ms)	0
							NB(e-/ms)	0
							Fca	0.0004

Error Budget #3(a).	NGS = LGS flux, NGS is 10 arcsec off-axis.							
	off-axis laser projection							
Error Term	**NGS Facility**			**LGS Facility**			**Parameters**	
	A	B	C	A	B	C		
	0 deg	30 deg	60 deg	0 deg	30 deg	60 deg	*Tel. & subaperture*	
							D(m)	10
Total RMS (nm)	152	236	519	163	239	559	d(m)	0.56
Strehl @ 1 um (no tilt)	0.40	0.11	0.00	0.35	0.10	0.00	*Fitting/bandwidth*	
Strehl @ 1 um (with tilt)	0.36	0.10	0.00	0.27	0.04	0.00	mu	0.3
Strehl @ 2.2 um (no tilt)	0.83	0.64	0.11	0.80	0.63	0.08	fc(Hz)	90
Strehl @ 2.2 um (with tilt)	0.81	0.62	0.11	0.76	0.47	0.01	beta	1
							SNR(LGS)	4.8
AO System (nm)	87	155	370	120	212	548	*S (LGS)*	118
Fitting	63	123	285	63	123	285	S0(LGS)	2000
Bandwidth	11	36	90	11	36	90	(ph/ms-m2)	
Measurement - MTF	39	55	148	35	52	185	*SNR(NGS)*	4.8
Measurement - spot	26	57	156	28	56	197	*S(NGS)*	118
Measurement - elong.				37	62	218	S0(NGS)	2000
Focal Anisoplanatism				66	127	297	QE	0.8
Focus				35	35	35	T	0.3
Calibration	30	30	30	30	30	30	ti(ms)	1
Uncorrected Internal	20	20	20	20	20	20	n(pixels)	4
							NR(e-)	11
Telescope (nm)	105	105	105	105	105	105	ND(e-/ms)	0
Warping residuals	62	62	62	62	62	62	NB(e-/ms)	0
ACS noise	58	58	58	58	58	58	*Measurement*	
Segment phasing	50	50	50	50	50	50	E	0.75
Segment vibration	30	30	30	30	30	30	chi	0.524
Segment stacking	20	20	20	20	20	20	lambda(LGS)	0.589
							lambda(NGS)	0.7
Science Instr. (nm)	35	35	35	35	35	35	th(proj)(asec)	0.6
Internal aberrations	35	35	35	35	35	35	epsilon	0.65
							Field (arcsec)	
Field Depend. (nm)	56	138	348	0	0	0	th(NGS)	10
Isoplanatic angle	56	138	348				th(science)	0
Telescope + AO	0	0	0	0	0	0	*Tilt*	
Science Instrument	0	0	0	0	0	0	fc-t(Hz)	90
							SNR	194.2
AO Tilt (nrad)	15	15	15	25	57	302	*S*	37699
Bandwidth				0	0	0	S0	2000
Measurement - MTF				4	10	26	QE	0.8
Measurement - spot				0	0	0	T	0.3
Centroid anisoplan.				15	30	69	ti(ms)	1
Isokinetic angle				11	45	292	n(pixels)	4
Science Inst. alignment	15	15	15	15	15	15	NR(e-)	0
							ND(e-/ms)	0
							NB(e-/ms)	0
							Fca	0.0004

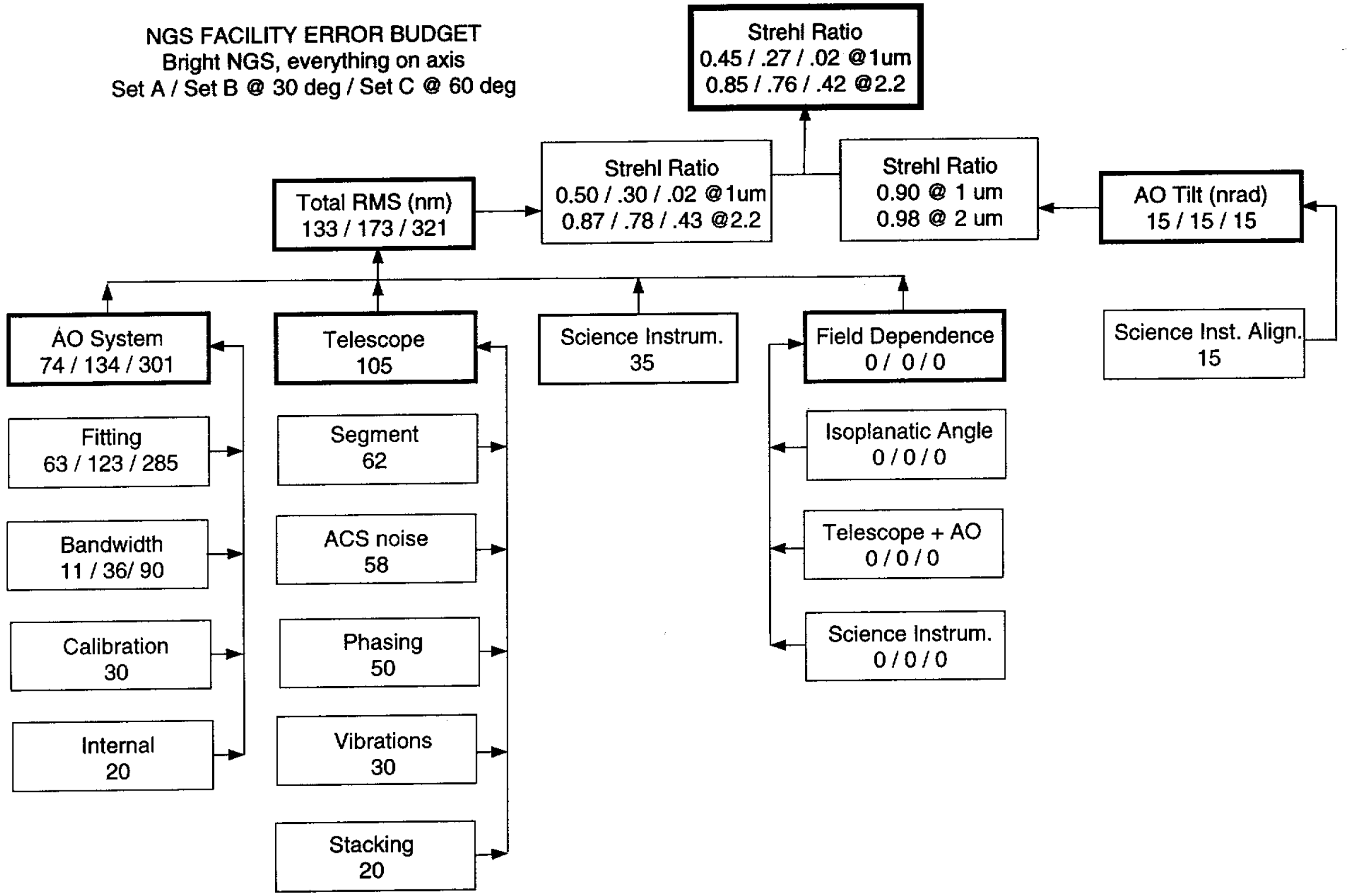
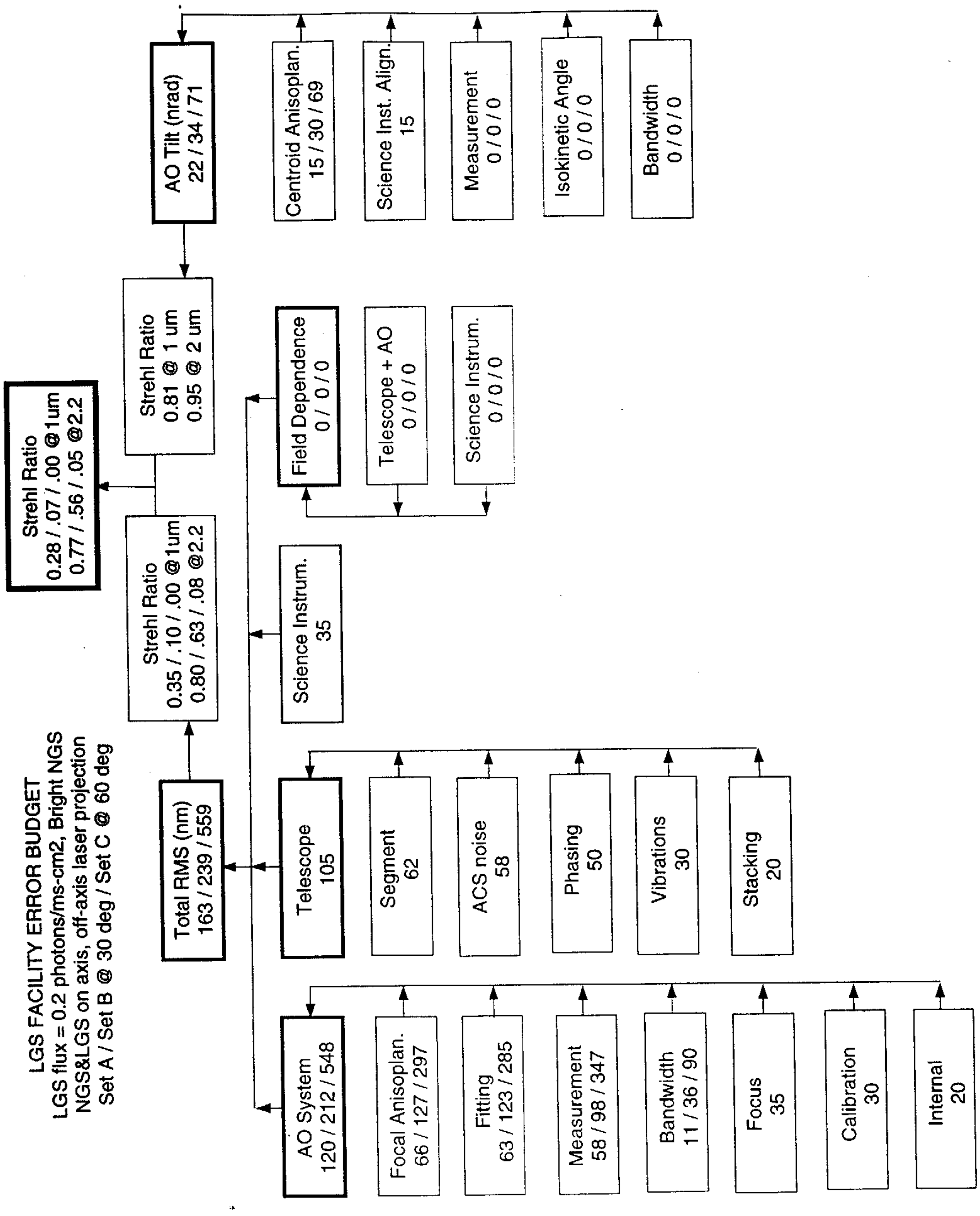

NGS FACILITY ERROR BUDGET
Bright NGS, everything on axis
Set A / Set B @ 30 deg / Set C @ 60 deg
Strehl Ratio
0.45 / .27 / .02 @1um
0.85 / .76 / .42 @2.2
Total RMS (nm)
133 / 173 / 321
Strehl Ratio
0.50 / .30 / .02 @1um
0.87 / .78 / .43 @2.2
Strehl Ratio
0.90 @ 1 um
0.98 @ 2 um
AO Tilt (nrad)
15 / 15 / 15
AO System
74 / 134 / 301
Fitting
63 / 123 / 285
Bandwidth
11 / 36/ 90
Calibration
30
Internal
20
Telescope
105
Segment
62
ACS noise
58
Phasing
50
Vibrations
30
Stacking
20
Science Instrum.
35
Field Dependence
0/ 0 / 0
Isoplanatic Angle
0 / 0 / 0
Telescope + AO
0 / 0 / 0
Science Instrum.
0 / 0 / 0
Science Inst. Align.
15

Figure 1.


LGS FACILITY ERROR BUDGET
LGS flux = 0.2 photons/ms-cm2, Bright NGS
NGS&LGS on axis, off-axis laser projection
Set A / Set B @ 30 deg / Set C @ 60 deg