DRAFT VASAO WAVEFRONT ERROR BUDGET

	Assume r_0 = 14 cm at 500 nm, D = 3592, 85 element DM							**PLGS fwhm = 0.7 arcsec**						**PLGS fwhm = 0.3 arcsec**			
	r_0 = 18.5 cm at 700 nm																
	Goal is 122 nm rms residual wavefront error for S = 0.3 at 700 nm	w.f. error nm		w.f.variance		w.f. error nm			w.f. variances			w.f. error nm			w.f. variances		
High order	LGS flux rates are linear extrapolations from Piques's 10 W case power delivered to the mesopshere	**PUEO** m=10	m=12			**10W**	**50W**	**100W**	**10W**	**50W**	**100W**	**10W**	**50W**	**100W**	**10W**	**50W**	**100W**
Atmosphere																	
1	Perfect DM-to-true-wavefront fitting error	185	185	34225	34225	47	47	47	2209	2209	2209	47	47	47	2209	2209	2209
2	Wavefront measurement error (photon, read noise …)	30.5	76.4	930.25	5837	94	43	30	8836	1849	900	94	43	30	8836	1849	900
3	Closed loop bandwidth error	31	31	961	961	46	46	46	2116	2116	2116	46	46	46	2116	2116	2116
4	Time delay bandwidth error	25.6	25.6	655.36	655.36	23	23	23	529	529	529	23	23	23	529	529	529
5	LGS cone effect - focal anisoplanetism	0	0	0	0	84	84	84	7056	7056	7056	84	84	84	7056	7056	7056
6	Scintillation at science instrument focal plane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Scintillation induced photon noise error on wfs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Angular anisoplanatism - LGS to science object separation	0	0	0	0	78	78	78	6084	6084	6084	78	78	78	6084	6084	6084
9	High to low spacial frequency wavefront signal aliasing	191	191	36481	36481	47	47	47	2209	2209	2209	47	47	47	2209	2209	2209
Dynamic																	
10	dynamic telescope errors (non-pointing / non-focus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Static																	
11	Primary mirror uncorrectable (high spatial frequency) errors	25	25	625	625	25	25	25	625	625	625	25	25	25	625	625	625
12	Secondary mirror uncorrectable aberrations	25	25	625	625	25	25	25	625	625	625	25	25	25	625	625	625
13	AOB optical design residuals	4.2	4.2	17.64	17.64	4.2	4.2	4.2	17.64	17.64	17.64	4.2	4.2	4.2	17.64	17.64	17.64
14	AOB uncorrectable aberrations - non-DM - non-design	33.5	33.5	1122.3	1122.3	33.5	33.5	33.5	1122.25	1122.25	1122.25	33.5	33.5	33.5	1122.25	1122.25	1122.25
15	Off-null static HOWFS errors	0	0	0	0	0			0	0	0	0	0	0	0	0	0
16	DM to Lenslet miscalibration	0	0	0	0	0			0	0	0	0	0	0	0	0	0
17	DM surface errors	34	34	1156	1156	34	34	34	1156	1156	1156	34	34	34	1156	1156	1156
18	DM hysterisis and non-linearlities	0	0	0	0	0			0	0	0	0			0	0	0
Tip/tilt																	
Atmosphere												plgs spot = 0.3 arcsec					
19*	differention tilt photon/read noise error (spot fwhm = 0.7; Tint = 140 ,80,65 ms)	0	0	0	0	236	139	109	55696	19321	11881	130	75	59	16900	5625	3481
20*	differential tip/tilt temporal error (Tint = 240,140,120 ms)	0	0	0	0	167	95	77	27889	9025	5929	101	60	47	10201	3600	2209
22	differential tip/tilt cone effect error - conic tilt error	0	0	0	0	66.4	66.4	66.4	4408.96	4408.96	4408.96	66.4	66.4	66.4	4408.96	4408.96	4408.96
Dynamic																	
23	uncorrected telescope vibration - residual signal within the siesmometer bandwid	0	0	0	0												
24	uncorrected telescope drift or very low frequency oscillation	0	0	0	0												
25	differential image separation after dispersion prism in PCWFS*	0	0	0	0												
26	science instrument drift	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Focus																	
27	residual Na layer focus error	0	0	0	0												
Science Instrument																	
28	science instrument optics	0	0	0	0	50	50	50	2500	2500	2500	50	50	50	2500	2500	2500
29	science instrument to AOB drift during exposure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	science instrument uncorrected infinte conjugate focus error	0	0	0	0												
Unaccounted errors		40	40	1600	1600	80	80	80	6400	6400	6400	80	80	80	6400	6400	6400
*	assumes maximum-likelihood or similar 'advanced' centroid algorithm			78399	83305				129478.9	67252.85	55767.85				72994.85	48131.85	43647.85
RSS Total	**Goal is 122 nm** rss residual wavefront error for S = 0.3 at 700 nm	279.997	288.63			359.832	259.332	236.152				270.1756	219.3897	208.9207			
			Strehl Ratio			2.9E-05	0.00443	0.01119				0.002792	0.020694	0.029699			
	note: Prism MUST move with the detector - otherwise image separation becomes a function of the PC detector focus position.																
				76799	81705				32584.89	25597.89	24648.89				32584.89	25597.89	24648.89
AOB RSS Total		277.125	285.84			180.513	159.993	157				180.5129	159.9934	156.9996			
			Strehl Ratio			0.07242	0.12715	0.13725				0.072418	0.127152	0.137255			

VASAO Wavefront Error Budget

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1. **DM to atmosphere fitting error: 40.8 nm**

Ref – JP Veran p. 33

The inability for the modes of the DM to fit the wavefront:

$$\sigma^2_{dmfit} = 0.2251 N^{-\frac{5}{6}} \left(\frac{D}{r_0} \right)^{\frac{5}{3}}$$

where: N is the number of effective subapertures (75)
D is the entrance pupil diameter (359.2 cm)
r_0 = 18.3 cm at 700 nm

gives: $\mathbf{s}_{dmfit}$ = 40.8 nm

2. **Wavefront measurement error: 94 nm (10 W), 43 nm (50 W), 30 nm (100 W)**

Ref: Roddier p.117

Wavefront sensor errors introduced by:

- Photon noise
- CCD read noise = 0
- CCD dark current = 0
- Sky background
- Rayleigh background = 0
- Spot elongation

$$\sigma_s^2 = \pi^2 \frac{1}{n_{ph}} \left(\frac{\theta_b d}{\lambda} \right)^2 \text{ and } \theta_b = \frac{\lambda}{d} \text{ if d < r0 and } \theta_b = \frac{\lambda}{r_0} \text{ if d > r0}$$

In its optimum (highest sensitivity) configuration, the stroke of the membrane mirror is set so that thetab*d/lambda = 1.

where: nph is the number of photons per integration time per subaperture
theta_b is the blur angle of the object lambda/r0
d is the subaperture diameter on the entrance pupil

and for the AOB, mag = 10 results in n_{ph} = 30.5 and
mag = 12 results in n_{ph} = 21

d ~ D/sqrt(19) = 824 mm

results in sigma =

Residual wavefront measurement error was derived in a detailed model by Olivier Lal grounded in established AOB performance. Residual wavefront estimation error ranges from 94 nm for 10W laser power delivered to the mesosphere, to 43 nm for 50 W delivered and 30 nm for 100 W delivered.

The model assumes zero read noise or dark current since the photon signal swamps both. Since excitation – and therefore Rayleigh scattering – takes place at 330 nm, while HOWFS signals are derived from the 589 nm cascade, Rayleigh scattering has also been ignored.

3. Closed loop bandwidth error: 45.7 nm (f_s = 67 Hz), 32.7 nm (f_s = 100 Hz)

Errors due to the inability to correct the wavefront at temporal frequencies higher than the sample rate divided by two.

Ref: Hardy p 338

$$f_G = 0.427\frac{v}{r_0}$$

$$\sigma_{TR}{}^2 = \left(\frac{f_G}{f_S}\right)^{\frac{5}{3}}$$

where: v is the wind speed (10 m/s, 1000 cm/s)
r_0 is 18.3 cm
f_S is the servo bandwidth
@ 1/15 of sample frequency = 67 Hz
@ 1/10 of sample frequency = 100 Hz
for the AOB, the closed loop 0 db error transfer function frequency has been measured in the lab to be 104.3 Hz

gives: f_G = 23 Hz

s_{TR} = 45.7 nm @ f_s = 67 Hz
= 32.7 nm @ f_s = 100 Hz

4. Delay error: 26 nm

Ref: Roddier p 15 / Hardy p 339

Errors due to time delay in correcting errors within the operational bandwidth.

$$\sigma_{TD}{}^{2} = 28.4\left(\tau_S f_G\right)^{\frac{5}{3}}$$

where: $\mathbf{t_S}$ is a time delay (0.001s)

gives: $\mathbf{s_{TD}}$ = 26 nm

Note: Delay errors are not included in the closed loop bandwidth error and must be accounted for separately. (Hardy p 339)

5. Cone effect – focal isoplanetism 84 nm

Ref: Hardy p. 231 and p. 234 (atmospheric models ref p. 86)

Errors introduced by the fact that the cone of light coming from the LGS located at a finite height in the atmosphere only partially samples the cylinder of light from an object at infinity.

$$\sigma_{FA}{}^{2} = \left(\frac{D}{d_0}\right)^{\frac{5}{3}}$$

where: $\mathbf{s_{FA}}$ is the cone effect wavefront error
d_0 is a focal anisoplanetism parameter provided for Mauna Kea in Hardy – p 235
(5 m)

gives: $\mathbf{s_{FA}}$ = 84 nm

6. Scintillation at the science detector focal plane: 0.0 nm

Ref: none

A perfectly flat wavefront with only intensity variations will produce a point spread function whose width is larger than in the ideal case.

We assume no reduction in science image Strehl ratio resulting from time varying non-uniform pupil illumination induced by the atmosphere (scintillation).

7. Scintillation-induced photon noise errors on the wavefront sensor: 0.0 nm

Ref: none

If the pupil illumination – the illumination across the curvature wavefront sensor lenslet array – changes between samples of the extra-focal and intra-focal images, then the derived wavefront signal will be in error.

To avoid these errors the wavefront is sampled at 4 kHz in order to 'freeze' any scintillation-induced illumination non-uniformity.

We assume there are no errors introduced by scintillation at the wavefront sensor lenslet array.

8. Angular anisoplanetism – LGS to science object separation 78.4 nm

Ref: – spatial anisoplanetism models – Lai

The Strehl ratio of the science object degrades as the LGS-to-science object separation increases. In order to avoid leakage of the Na star beam into the science beam – assuming an imperfect Na rejection notch filter – at a minimum the defocused Na star should be sufficiently separated from the science object so that their images do not overlap on the science detector.

For a Na star at 81 km, the defocused Na spot is 3.15 mm in diameter at the f/20 (infinity) focus. In order not to overlap the science object, the defocused LGS should be at least 4.5 arcseconds distant.

Ref: Geometric ray calculations for the AOB.

At 700 nm, the angular anisoplanetism at 5 arcseconds separation introduces variance of 0.0892 radians^2 at H (1.65 microns), which corresponds at 700 nm to an equivalent rms wavefront error of 78.4 nm.

9. High to low spatial frequency wavefront signal aliasing 40.8 nm

Ref: Veran p. 104

High spatial frequency wavefront errors are aliased into sensor mode signals. For Shack Hartmann sensors, aliasing error has been shown to be on the order of 6 times less than mirror fitting error, while for curvature systems it is on the same order as the fitting error. (see 1 above)

For the AOB (19 actuators)

$$\sigma_{\vartheta}{}^{2} = 0.021\left(\frac{D}{r_0}\right)^{\frac{5}{3}}$$

Note from O.Lai:

With r_0(700nm) = 0.185 meters and using r_0 proportional to $\lambda^{6/5}$, we get r_0(2.2um) = 0.723m. From Roddier fig 9.4 page 222, AOB performance should be S ~ 0.5, which, using Marechal's approximation, gives a phase variance = 0.693 radians^2, s_{opd} = 291 nm. Using fig 9.8 of Roddier (page 226), the Strehl attenuation for magnitude 12 in K band is 0.95, so S ~ 0.475, thus phase variance is = 0.744 radians^2 and s_{opd} = 302 nm.

Note the large error bars on Fig 9.4.

10. Dynamic telescope errors (non-pointing, non-focus): 0.0 nm

We identify none.

11. Primary mirror uncorrectable (high frequency) wavefront errors: 25 nm

Ref: Report on the Optical Quality of the Primary Mirror – Fouere and Ratier, 1978

These highly qualitative estimates come from mirror acceptance test reports dating from the 1970s. A guestimate of the uncorrectable mirror wavefront errors – largely zonal polishing errors - is 25 nm.

12. Secondary mirror uncorrectable (high frequency) wavefront errors: 25 nm

A guestimate of the uncorrectable mirror wavefront errors – largely zonal polishing errors - is 25 nm.

13. AOB optical design residuals: 4.2 nm (on-axis), 11.0 nm (@ 22.5 arcsec), 91.6 nm (@ 45 arcsec)

Ref: Zemax AOB design model
file: aob wfs_vasao_bschange_science.zmx

The residual wavefront error in the AOB optical design assuming a perfectly flat input wavefront and perfect optical components.

With beamsplitter radii changed from the nominal values of 2237.8 mm / 2217.4 mm to shorter radii 1508.4 mm / 1495.5 mm needed to focus the LGS on the membrane mirror, and keeping the LGS in the field center due to lack of telecentricity in the HOWFS feed, the on-axis residual wavefront error for the science beam is 4.2 nm. This value increases to 11.0 nm at 22.5 arcsecond field radius, and to 91.6 nm at a radius of 45 arcsec.

14. AOB uncorrectable aberrations – non DM, non-design: 33.5 nm

Ref: calculation

The residual alignment and optical fabrication errors in the AOB science path, for optics other than the DM.

Assuming an rms wavefront smoothness of 12.65 nm for each of M1, F/8 collimator, the F/20 tip/tilt mirror, and M2, (surface lambda/100 rms at 632.8 nm) and the same errors for the transmitted wavefronts of each of the 2 ADC prisms and the beamsplitter, the total contribution is 33.5 nm

No account has been made of residual alignment errors

15. Off-null static HOWFS errors: 0.0 nm

We identify none. We plan to use the HOWFS at null.

16. DM to lenslet misalignment 0.0 nm

Because for other reasons we are forced to keep the LGS images centered in the science field, this error is assumed to be one which can be driven to zero, or close to zero, through correct alignment of the wavefront sensor optics.

17. DM surface errors: 34 nm

Ref: AOB DM acceptance test at Laserdot – 1995

In-lab iterative DM surface correction and measurements of the 19-element AOB DM alone using a phase-shift interferometer face-on provided on the order of 7000 points over the DM's illuminated surface. After four successive iterations, the wavefront residual was 34 nm. We assume residuals on an 85 element DM will be comparable.

Note: The need to make four successive corrections to attain this level of correction should be modeled as an additional phase error in the error budget.

18. DM hysterisis and non-linearities: 0.0 nm

These are assumed to be included in 17) – DM surface errors. No further contributions are assumed.

19. Differential tip/tilt photon/read noise error*: 236,139,109 nm (10,50,100 W)

- assuming a maximum-likelihood centroid estimator with variance on centroids five times better than from center-of-mass calculation.

Ref: A new concept for polychromatic laser guide stars: one photon excitation of 4P3/2 level of sodium atom – J.P. Pique et al. – JOSA – submitted 12/24/2005. and Pique – private CFHT communications.

Ref: Centroid Mathcad model, file: Vasao_pc_tip_tilt.xmcd

This estimate accounts for the effects of photon noise and CCD read noise when using a polychromatic LGS to derive atmospheric tip/tilt. The rms wavefront error of the tip/tilt estimate is based on the use of simple center of mass calculations to determine differential tilt between the two chromatic LGS images. The calculation assumes 2 e readnoise and a 16 pixel read area. The flux rates for the 3 laser powers (10,50 and 100 W) come from linear extrapolation of J.P. Pique's models for 10 W delivered to the mesosphere at 330 nm.

The LGS image size at the detector is not expected to be better than 1.0 arcsecond without adaptive correction of the uplink. The best reported values for similar (50 cm diameter) beam sizes at Keck and Gemini are on the order of 1.1 arcseconds, while the best reported in the literature using a bright NGS for uplink wavefront correction is on the order of 0.8 arcseconds. We have assumed in the error budget that we can obtain 0.7 arcsec fwhm.

Ref: - Keck, Gemini LGS spot size

- Beam focusing of a laser guide star – Chueca et al. - SPIE Vol 4839 p 412 (0.8 to 1.99 arcsecond at the mesosphere)

- Simultaneous Measurements of the Sodium Column Density and Laser Guide Star Brightness – Ge et al. – http://caao.as.arizona.edu/publications/publications/mcguire/98lgs1.pdf (best ever at MMT - 0.57 x 0.95 arcsec at the mesosphere, deconvolved from 0.8 x 1.1 arcsec image)

- Sky tests of a Laser-pumped Sodium Guidestar With and Without Beam Compensation – Drummond et al. – SPIE vol 5490 p.12 (best LGS size at Starfire using NATURAL guide star uplink compensation – 0.85 arcsec fwhm).

A better centroid position estimator, possibly base on cross-correlation, Kalman filter, and maximum likelihood techniques, is clearly needed.

20. Differential tip/tilt correction temporal error*: 167,95,77 nm (10,50,100 W)

Ref: Roddier, p 309

The temporal error associated with the integration time given by :

$$\sigma_{bwtt}{}^2 = \left(\frac{f_{tilt}}{f_c}\frac{\lambda}{D}\right)^2 \text{ radians on the sky}$$

$$f_{tilt} = \frac{0.08 v_{tilt}}{r_0^{\frac{5}{6}} D^{\frac{1}{6}}}$$

$v_{tilt\text{-}effective}$ = 23 m/s

where:

f_{tilt} is the tip tilt correlation frequency
fc is the 3 db tip/tilt servo bandwidth
D telescope diameter
$v_{tilt\text{-}effective}$ is an effective tilt wind speed derived by Roddier

Gives f_{tilt} = 6.06 Hz

Since the decorrelation time constant for tip/tilt is long compared to that for high-order correction, VASAO can effectively take advantage of this increase time to integrate on the return beam and beat down the associated photon-limited measurement error.

The combined effects of 19) and 20) above are summarized below. The integration times correspond to that for which the summed variance is minimized.

<u>Mesospheric lgs image size at detector = 1.0 arcsec</u>

Tip/tilt wavefront error (photon and read noise / temporal error - nm)

Optimum sample time	10 W	50 W	100 W
300 ms	513 / 357		
180 ms		295 / 214	
150 ms			229 / 179
total wavefront error	624 nm	364 nm	290 nm

<u>Mesospheric lgs image size at detector = 0.7 arcsec</u>

Optimum sample time	10 W	50 W	100 W
240 ms	402 / 286		
140 ms		234 / 167	
110 ms			187 / 131
total wavefront error	493 nm	287 nm	228 nm

<u>Mesospheric lgs image size at detector = 0.5 arcsec</u>

Optimum sample time	10 W	50 W	100 W
190 ms	323 / 226		
115 ms		185 / 137	
90 ms			147 / 107
total wavefront error	394 nm	231 nm	181 nm

These values are known to be biased toward greater than expected errors in tip/tilt for two reasons. In the case of the longer integration times (> 50 ms) the estimated bandwidth error is too large since atmospheric tilt coherence times approach the system bandwidth. This correction is not however expected to be significant at the flux levels and shorter integration times needed for VASAO operation.

The second bias comes from the use of center-of-mass as a centroid estimator. Much better maximum likelihood estimators exist which should be able to reduce the variance of centroid errors by a large factor. Entries assuming an improvement of a factor of 5 in variance are provided in the error budget and are provided below.

<u>'Improved' Centroid and Mesospheric lgs image size at detector = 1.0 arcsec</u>

Tip/tilt wavefront error (photon and read noise / temporal error - nm)

Optimum sample time	10 W	50 W	100 W
180 ms	297 / 214		
110 ms		169 / 131	
85 ms			136 / 101
total wavefront error	366 nm	213 nm	169 nm

<u>'Improved' centroid and Mesospheric lgs image size at detector = 0.7 arcsec</u>

Optimum sample time	10 W	50 W	100 W
140 ms	236 / 167		
80 ms		139 / 95	
65 ms			109 / 77
total wavefront error	289 nm	168 nm	133 nm

<u>'Improved' centroid and Mesospheric lgs image size at detector = 0.5 arcsec</u>

Optimum sample time	10 W	50 W	100 W
115 ms	186 / 137		
65 ms		110 / 77	
55 ms			84 / 65
total wavefront error	231 nm	134 nm	106 nm

22. Differential tip/tilt cone effect error – conic tilt error: 66.4 nm

Ref: Hardy p232 and p239 - 242

The cone effect error on the tip/tilt error is given by:

$$\sigma_{ct}{}^{2} = \left(\frac{D_B}{d_1} \right)^{\frac{5}{3}}$$

where: Db is the aperture of the receiving telescope

d1 = 4.46 m @ 500 nm, 6.68 m @ 700 nm, 26.4 m @ 2200 nm for Mauna Kea, zenith observation, average turbulence profile including ground layer turbulence and beacon height of 92 km.

Gives 66.4 nm at a wavelength of 700 nm

23. Uncorrected telescope vibration:

24. Uncorrected telescope drift:

25. Differential tip error due to Na layer focus drift (telecentricity error):

26. Science instrument drift: 0.0 nm

This is drift/motion entirely within the science instrument.
We assume no drift

27. Residual Na layer focus error

Focus of the Na layer is sensed by the focus signal from the HOWFS.

Focus models from MegaPrime have a 42 microns rms error at f/4.2. Since tracking focus of an object at infinity through focus derived from a model of Na layer range / zenith distance will at some point rely on a model, it is unlikely that this model will do better than that from MegaPrime. As a first estimate therefore we include the wavefront error inherent in the MegaPrime focus model which is 171 nm.

28. Science instrument optics: 50 nm

Imperfect optics of the science instrument are expected to contribute at a level similar to those of the AOB. We assume therefore a total 50 nm rms error.

29. Science instrument to AOB drift during exposure: 0.0 nm

We assume no relative drift between the AOB tip/tilt wavefront sensor and the science instrument.

30. Science instrument uncorrected infinite conjugate focus error:

31. Unaccounted errors: 80 nm

The error budget cannot account for, nor operationally can we identify the sources of all wavefront errors. A sizeable allowance ought to be made for these unaccounted errors. We assume an (optimistic) 80 nm residual.

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