CALTECH OPTICAL OBSERVATORIES / NASA JET PROPULSION LABORATORY
PALM-3000 PROJECT

PALM-3000
Error Budget Summary (EBS)

CIN #626

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Revision Sheet

Revision No.	Date	Revision Description
Rev. 0.1	11/07/07	Initial draft based on the spreadsheet file "Wavefront Error Budget Tool v1.30"
Rev. 0.2	11/09/07	Updated Appendix tables and added Performance Summary section

Contents

1 GENERAL INFORMATION

1.1 Purpose

This document is intended to outline the top-level wavefront error budget and associated detailed error budget flow-downs for the PALM-3000 system at different stages of its deployment (particularly for different TT WFS and guide star laser phases.)

1.2 Acronyms and Abbreviations

888Cam	The COO-built visible photon-counting camera (R. Dekany, PI) (named in honor of the successful June 2007 PALMAO + Cambridge LuckyCam experiments and a nod to the 2008 Beijing Olympic Summer Games)
AMNH	American Museum of Natural History
AO	Adaptive Optics
BTO	Beam transfer optics (for laser beam transport from Coude to Prime focus)
BVRIZ'YJHK	Johnson-Glass spectral bands (see table of definitions)
CCD50	E2V CCD model selected for PALM-3000 HO WFS
COO	Caltech Optical Observatories
CSFL	(University of) Chicago Sum-Frequency Laser
CW	Continuous Wave
CY	Calendar Year
DM	Deformable Mirror
EE	Ensquared Energy (never encircled energy in this document)
FoR	Field of Regard (usually the accessible sky patrol field of a sensor)
FoV	Field of View (usually the instantaneous field of view of a detector)
GS	Guide Star
HOWFS	High-order Wavefront Sensor
IAD	Instrument Architecture Document
IRD	Instrument Requirements Document
IRTT	Infrared Tip/Tilt Sensor
JPL	Jet Propulsion Laboratory
KBO	Kuiper Belt Object
LGS	Laser Guide Star
LOWFS	Low-Order Wavefront Sensor (for PALM-3000 indicating tip/tilt/focus sensing)
MASS/DIMM	A $C_n^2(h,t)$ profile and seeing measurement apparatus
MM	Macropulse/Micropulse
Na	Sodium
NGS	Natural Guide Star
NIR	Near Infrared (typically 0.9 to 2.5 microns)
P1640	The AMNH-built speckle-supression NIR integral field spectrograph (B. R. Oppenheimer, PI)
P18	The 18" telescope at Palomar, site of the P18 MASS/DIMM unit
P3K	An abbreviation of PALM-3000

PALAO	The original NGS AO system at Palomar commissioned in December 1999
PALM-3000	The visible light AO upgrade to PALMAO
PALMAO	Upgrades to PALAO, particularly after the April 2003 upgrade
PALM LGS	The LGS upgrade to PALMAO, with first science in Summer 2007
PALM LGS+	The (potential) PALM LGS sodium laser upgrade from 6-8 W to 20-50 W or more via new technologies
PHARO	The Cornell-built NIR imager/slit spectrograph/coronagraph (T. Hayward and B. Brandl, PI's)
PMP	PALM-3000 Management Plan
PSF	Point Spread Function
QE	Quantum Efficiency
SR	Strehl Ratio
SRD	Science Requirements Document
SoAD	Software Architecture Document
SOR	Starfire Optical Range (Kirtland Air Force Base, Albuquerque, NM)
SoRD	Software Requirements Document
SWIFT	The Oxford-built visible integral field spectrograph (N. Thatte, PI)
TT	Tip/Tilt
TTF	Tip/Tilt/Focus
TTFA	Tip/Tilt/Focus/Astigmatism (often synonymous with TTF when describing LOWFS)
TTWFS	Tip/Tilt Wavefront Sensor
TWFS	Truth Wavefront Sensor
u'g'r'i'Z'YJHK	SDSS spectral bands
VIS	Visible (typically 0.38 to 1.0 microns)
WFE	Wavefront Error

1.3 Definitions

$C_n^2(h,t)$	Index of refraction structure function constant, a function of height, h, and time, t, describing the strength of atmospheric turbulence at differing heights in the atmosphere.
Equivalent 12W MM Laser Return	Based upon our experience with the 5-8W macropulse/micropulse Chicago Sum Frequency Laser, which has demonstrated to date a yearly average ~50 photons/sec/cm^2/W unadulterated sodium return, we assume that a 12W MM laser would return a total of 600 photons/sec/cm^2. (This is believed to correspond to ~4e9 atoms/cm^2 sodium column density.) For total transmission to HOWFS = 0.28 (Section 2.2) and our CCD50 QE of 0.88, resulting in 148 e^-/sec/cm^2 in the HOWFS.
Equivalent 50W CW Laser Return	Based upon reported returns from the 50W-class SOR sum-frequency laser, yearly average ~100 photons/sec/cm^2/W unadulterated sodium return, we assume that a 50W CW laser would return a total of 5000 photons/sec/cm^2, where we assume no saturation, even for a small (1.7 arcsec FWHM) diameter sodium beacon. (This is believed to correspond to ~4e9 atoms/cm^2 sodium column density.) For total transmission to HOWFS = 0.28 (Section 2.2) and our CCD50 QE of 0.88, resulting in 1,232 e^-/sec/cm^2 in the HOWFS.
r_0	Fried's parameter, having median value at Palomar of 9.2 cm (based on CY2007 P18 DIMM data)
spaxel	An integral field spectrograph spatial element (analogous to a imaging pixel)
Unadulterated sodium return	The return from the sodium laser in photons/sec/cm^2/W where Watts are laser Watts reaching the mesospheric sodium layer, and photons are photons just departing the sodium layer, and cm^2 are cm^2 at the entrance pupil of the telescope.

1.4 Point of Contact

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2 AO SYSTEM ASSUMPTIONS

2.1 PALM-3000 Implementation Stages

2.1.1 Interim Layout (April 2008 – December 2009)

As described in the P3K IAD, PALM-3000 will during this period work with all the existing PALM-LGS hardware, but will be realigned to allow for inclusion of SWIFT and P1640 (one at a time) onto the PALM optical bench.

In this phase, we assume a 12W current equivalent MM pulse laser return (Section 1.3)

2.1.2 PALM-3000 Phase I (May 2010 – December 2010)

During this period, PALM-3000 will operate with upgraded deformable mirror(s), new control computer, new RTC, and some other improvements. However, the LOWFS at this time will be the existing LOWFS, perhaps improved slightly (by reducing dark current via better heat management). For this EBS, we do *not* assume a reduction from 3x3 subaperture sampling to 2x2 subaperture sampling in the LOWFS.

In this phase, we assume a 12W current equivalent MM pulse laser return (Section 1.3).

2.1.3 PALM-3000 Phase II (May 2011 – Onward)

In this final phase, the visible light LOWFS will be augmented (or perhaps replaced) by a NIR tip/tilt sensor which will allow guiding on AO-sharpened tip/tilt stars to improve sky coverage for a given WFE or EE specification.

In this phase, we assume two different possible laser situations, one in which a 12W current equivalent MM pulse laser return is obtained, and another using a current equivalent return of the SOR 50W CW laser return (Section 1.3).

2.2 Optical Transmission

We assume the following transmission values for PALM-3000:

Laser projection efficiency	
BTO	0.67 (assumes laser in Upper Coude Lab)
LLT	0.92
Overfilling LLT	0.95
Atmospheric Transmission	0.86 at 5 deg zenith angle
Total laser transmission to Na Layer	0.50 (half the power out of the laser itself)
HO WFS transmission	
Atmospheric Transmission	0.86 at 5 deg zenith angle
Telescope Transmission	0.64 (0.80 for both M1 and M2)
AO System Transmission	0.51 to CCD50
Total HOWFS transmission	0.28
TT WFS transmission	
Atmospheric Transmission	0.86 at 5 deg zenith angle
Telescope Transmission	0.64 (0.80 for both M1 and M2)
AO System Transmission	0.55 to IRTT sensor
Total HOWFS transmission	0.30

3 SCIENCE CASES

We elect to report our summary of error budget breakdown and performance predictions for a set of specific science programs that will be undertaken by the PALM-3000 system. We believe this is informative in identifying the individual limitations to science performance and provides guidance for particular cost/benefit decisions both in the implementation of the system and the long-term facility system maintenance and potential upgrade paths.

The key parameters for each of the considered science cases are shown in Table 1.

	Io surface geology	**Hot, young exo-Jupiter NGS**	**Faint NGS science**	**Hot, young exo-Jupiter LGS**	**Dynamics of z = 1-2 galaxies**	**30% sky coverage science**
HO GS Type	NGS	NGS	NGS	LGS	LGS	LGS
HO GS Brightness	m_V 5.0	m_V 7.0	m_V 16.0	12 W MM (50 W CW)	12 W MM (50 W CW)	12 W MM (50 W CW)
TT GS Distance (")	--	--	--	On-axis	16.8 (19.1)	38.6 (38.5)
TT GS Brightness (m_H)	--	--	--	9.2	14.6 (14.2)	16.9 (16.9)
Zenith Angle (degrees)	33	30	10	10	5	5
Galactic Latitude	--	--	--	30	30	60
NGS Color	G	M	K	M	M	M
NGS WFS Bands	g'r'i'Z	g'r'i'Z	g'r'i'Z	YJH	YJH	YJH
HO GS Intrinsic Diameter (")	1.1	--	--	1.0 Projection only[1]	1.0 Projection only	1.0 Projection only
HO WFS Spot Diameter for Centroiding (")	2.27	1.97	0.73	1.71	1.70	1.70
Field of View (evaluated at FoV edge)	0.5 arcsec	1.0 arcsec	5 arcsec	1.0 arcsec	4.0 arcsec	5.0 arcsec
Instrument	888Cam	P1640	PHARO	P1640	SWIFT	PHARO
Science Band	g'	H	K	H	Z	H
Max Exposure Time (sec)	10	2	30	300	1800	300
Optimizations	HO Int Time	HO Int Time	HO Int Time	HO Int Time TT Int Time	HO Int Time TT Int Time TT GS Brightness TT GS Distance (maximize EE_Z)	HO Int Time TT Int Time TT GS Brightness TT GS Distance to (maximize SR_H)

Table 1. Science case and observation parameters. For a list of acronyms, see Section 1.2.

[1] This size represents the combination of the intrinsic laser beam quality, beam transfer and launch telescope aberrations. It does not include atmospheric aberrations on the uplink or downlink, WFS subaperture diffraction, or charge diffusion (these are included in the subsequent table row "Spot Diameter for Centroiding"

4 PERFORMANCE SUMMARY

	Io surface geology	Hot, young exo-Jupiter NGS	Faint NGS science	Hot, young exo-Jupiter LGS	Dynamics of z = 1-2 galaxies		30% sky coverage science (galactic b = 60)	
Science Band (nm)	g'	H	K	H	Z 882 nm		H	
Number of Subapertures per Pupil	64	64	8	16 (32)	16 (32)		16 (32)	
TT WFS Type	HOWFS	HOWFS	HOWFS	IRTT	IRTT	Visible LOWFS	IRTT	Visible LOWFS
Optimal Frame Rates (2000 Max)								
HO WFS	2000	1755[2]	182	437 (826)	434 (815)	430 (796)	446 (894)	443 (839)
TT WFS	2000	1755	182	500 (500)	184 (234)	82 (86)	25 (32)	12 (12)
Strehl Ratio								
g' 467 nm	**22**	23	--	--	--	--	--	--
r' 616 nm	41	42	--	--	--	--	--	--
i' 747 nm	55	56	--	-- (06)	--	--	--	--
Y 1031 nm	72	73	--	13 (37)	-- (12)	--	--	--
J 1250 nm	80	81	--	25 (51)	11 (22)	-- (06)	--	--
H 1635 nm	87	**88**	8	**45 (67)**	25 (39)	09 (13)	**-- (09)**	**--**
K 2200 nm	92	93	**23**	64 (80)	45 (58)	20 (24)	11 (18)	--
Ensquared Energy (EE) in Science Band								
80 mas	48	63	13	33 (49)	05 (16)	-- (06)	05 (10)	--
160 mas	49	88	28	48 (70)	08 (24)	06 (17)	19 (33)	06 (07)
240 mas	50	89	34	50 (73)	**12 (27)**	**11 (25)**	33 (53)	12 (15)
Optimizations	HO Int Time (Maximize $SR_{g'}$)	HO Int Time (Maximize SR_H)	HO Int Time (Maximize SR_H)	HO Int Time TT Int Time (Maximize SR_H)	HO & TT Int Time TT GS Brightness & Distance (Maximize EE_Z)		HO & TT Int Time TT GS Brightness & Distance (Maximize SR_H)	

Table 2. PALM-3000 Performance Summary. Table values for LGS cases are for 12W MM equivalent return[3] laser and for 50W CW equivalent return[4] laser guide star (results in parentheses). The rightmost column shows that 30% sky coverage is not obtained with equivalent 12W MM laser return and the interim LOWFS. For a full list of acronyms, see Section 1.2.

[2] System settings that optimize contrast will differ from those that minimize residual wavefront error (shown here). PALM-3000 has set an IRD goal of 3,000 Hz operation because it is believed this will help mitigate relatively long-lived 'system latency speckles' that evolve only with wind-crossing time.

[3] Unadulterated sodium return of 600 photons/sec/cm^2; 148 e$^-$/sec/cm^2 detected in HOWFS.

[4] Unadulterated sodium return of 5,000 photons/sec/cm^2; 1,232 e$^-$/sec/cm^2 detected in HOWFS (see Sections 1.3 and 2.2.)

5 PARAMETRIC STUDIES

5.1 Performance vs. r_0

One of the features of LGS AO systems that surprise astronomers familiar with NGS AO systems is the stronger dependency of performance on seeing. To first order, because the LGS spot size is degraded in poor seeing conditions, wavefront sensing quality degrades with seeing, leading to a double degradation of the wavefront correction (which itself degrades with seeing, even given perfect wavefront information.) For a sufficiently large surface brightness beacon, some robustness of performance can be achieved, but for a 12 W equivalent MM laser return performance degrades rapidly at worse than median seeing conditions at Palomar, as shown in Figure 1.

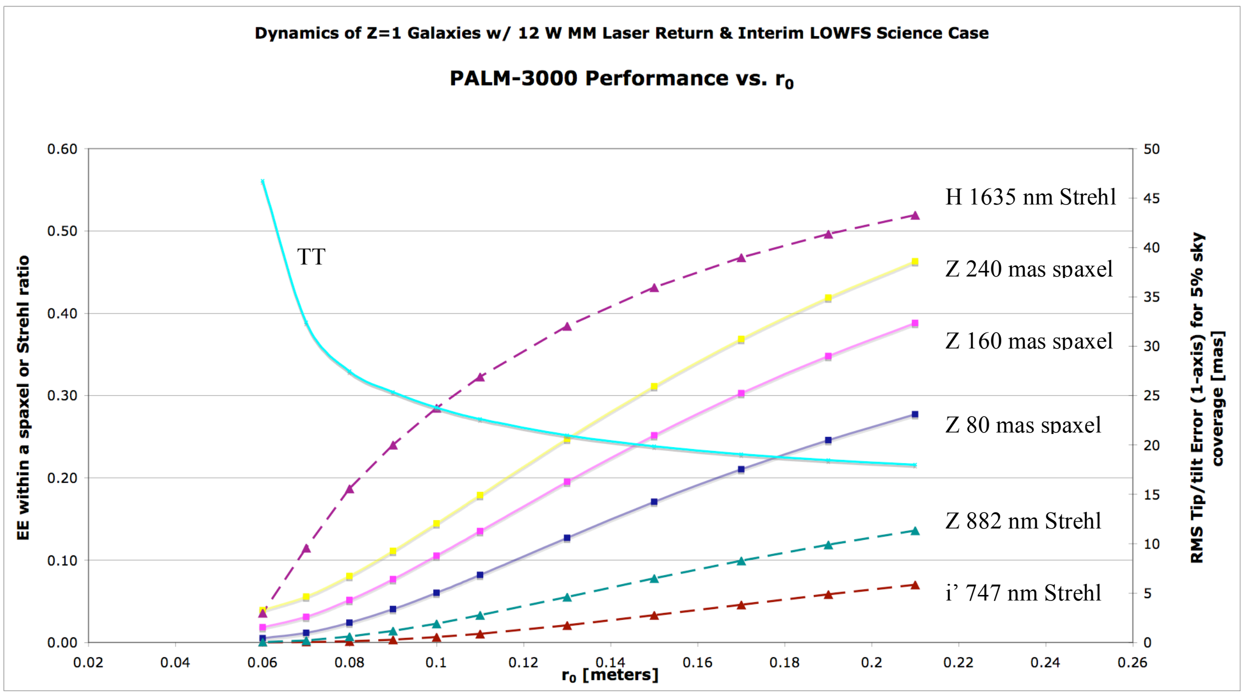

Figure 1. Ensquared Energy vs. r_0 for the science case 'Dynamics of Z=1 Galaxies w/ Equivalent 12 W MM Laser Return & Interim LOWFS', as will be seen in the Interim Layout phase of PALM-3000. Three curves show the EE for The descending curve (associated with the right axis) shows the residual RMS tip/tilt error in millarcseconds, which is seen to be generally small compared to SWIFT's set of spaxial sizes. As seeing improves, benefit to EE comes from both lower tip/tilt error and improved concentration of higher-order wavefront errors.

5.2 Performance vs. Month for CY 2007 Conditions

Given the careful recording of photometric and environmental conditions at Palomar during calendar year (CY) 2007, it is interesting to ask what PALM-3000 performance might have been expected to be obtained during each of the CY2007 LGS science and engineering runs. Similar to the result in Section 5.1, we find in Figure 2 that the PALM-3000 ensquared energy in a 240 mas spaxel with 12W equivalent MM laser return is largely insufficient for reliable science use in winter conditions, when seeing is typically worse than median (1.1 arcsec FWHM).

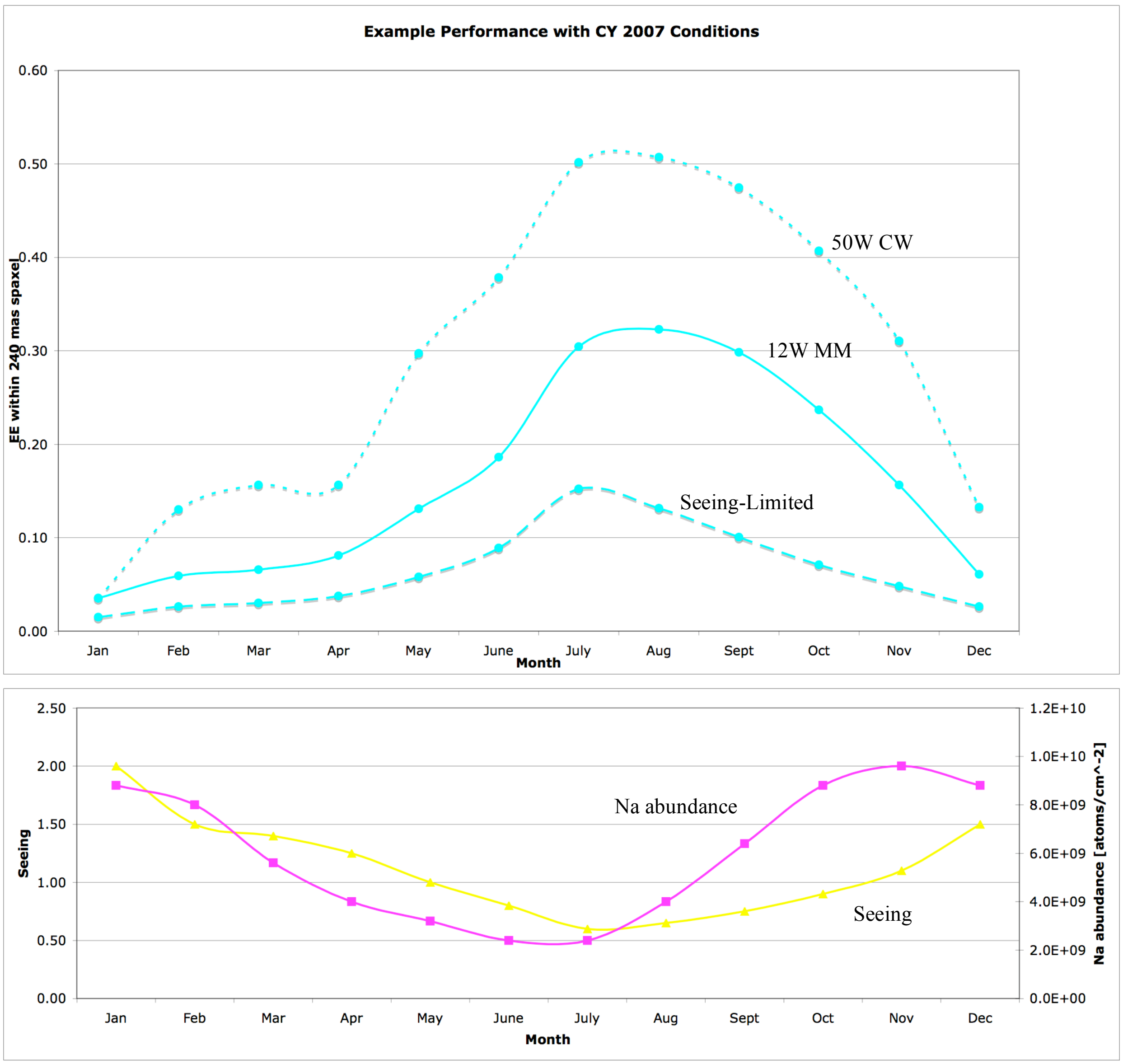

Figure 2. Example PALM-3000 + SWIFT Z-Band (882 nm) Performance vs. Month based upon CY2007 MASS/DIMM seeing and Na abundance estimated from measured CSFL mesospheric photoreturn[5]. The bottommost (dashed) curve represents the 240 mas spaxel EE for seeing-limited PSF. The middle (solid) curve represents what might have been seen in the same spaxel with PALM-3000 (interim LOWFS) with

[5] A. Bouchez, private communication – seeing estimates based on P18 DIMM data.

an equivalent 12W MM laser return. The topmost (dotted) curve represents what might have been seen with PALM-3000 (interim LOWFS) with an equivalent 50W CW laser return. Notice that even though P3K is laser photon starved with 12W MM laser return, expected performance depend more strongly upon the natural seeing than sodium abundance (Not only is AO NGS performance a strong function of seeing, but so is LGS spot size, making LGS performance particularly sensitive to seeing). In this simulation, there is no (optical pumping-based) spot-size dependency on photoreturn from the mesosphere.

Figure 3. Example PALM-3000 + SWIFT Z-Band (882 nm) Performance vs. Month under the same scenario as in Figure 2, but describing the Ensquared Energy in a 80 mas diameter spaxel.

5.3 Performance vs. Sky Fraction

PALM-3000 will be usable to some performance level over the entire viewable sky. However, the delivered performanced will be a function of the availability of sufficiently bright TT guide stars. A prediction of performance vs. sky fraction, along with the associated TT guide star parameters, is shown in Figure 4 using the planned IRTT sensor. The corresponding (lesser) performance curve using the interim LOWFS in shown in Figure 5.

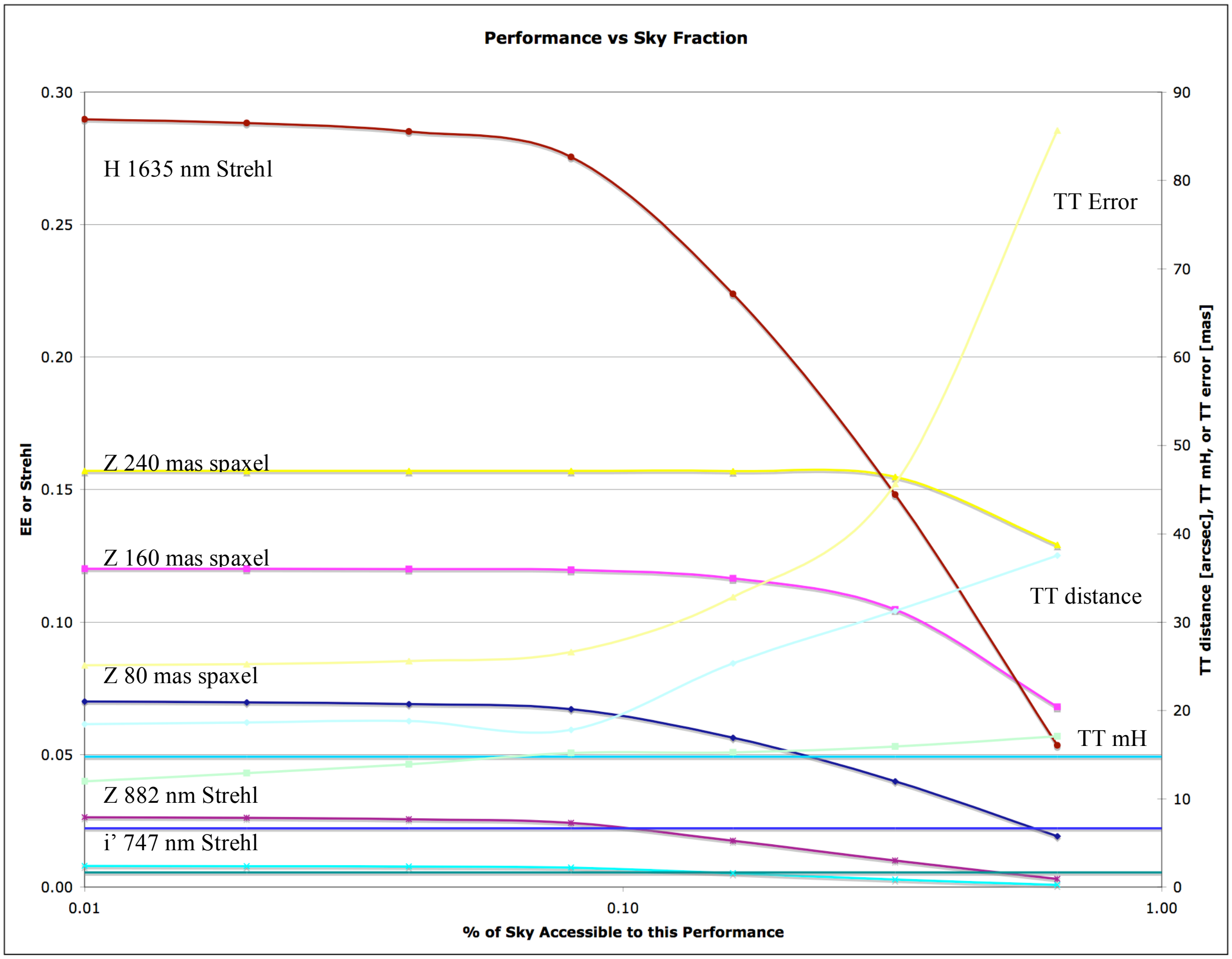

Figure 4. PALM-3000 performance vs. sky fraction r_0 for the science case 'Dynamics of Z=1 Galaxies w/ Equivalent 12 W MM Laser Return' using the IRTT sensor. The three horizontal lines represent the seeing-limited EE for 240 mas, 160 mas, and 80 mas spaxels (top to bottom).

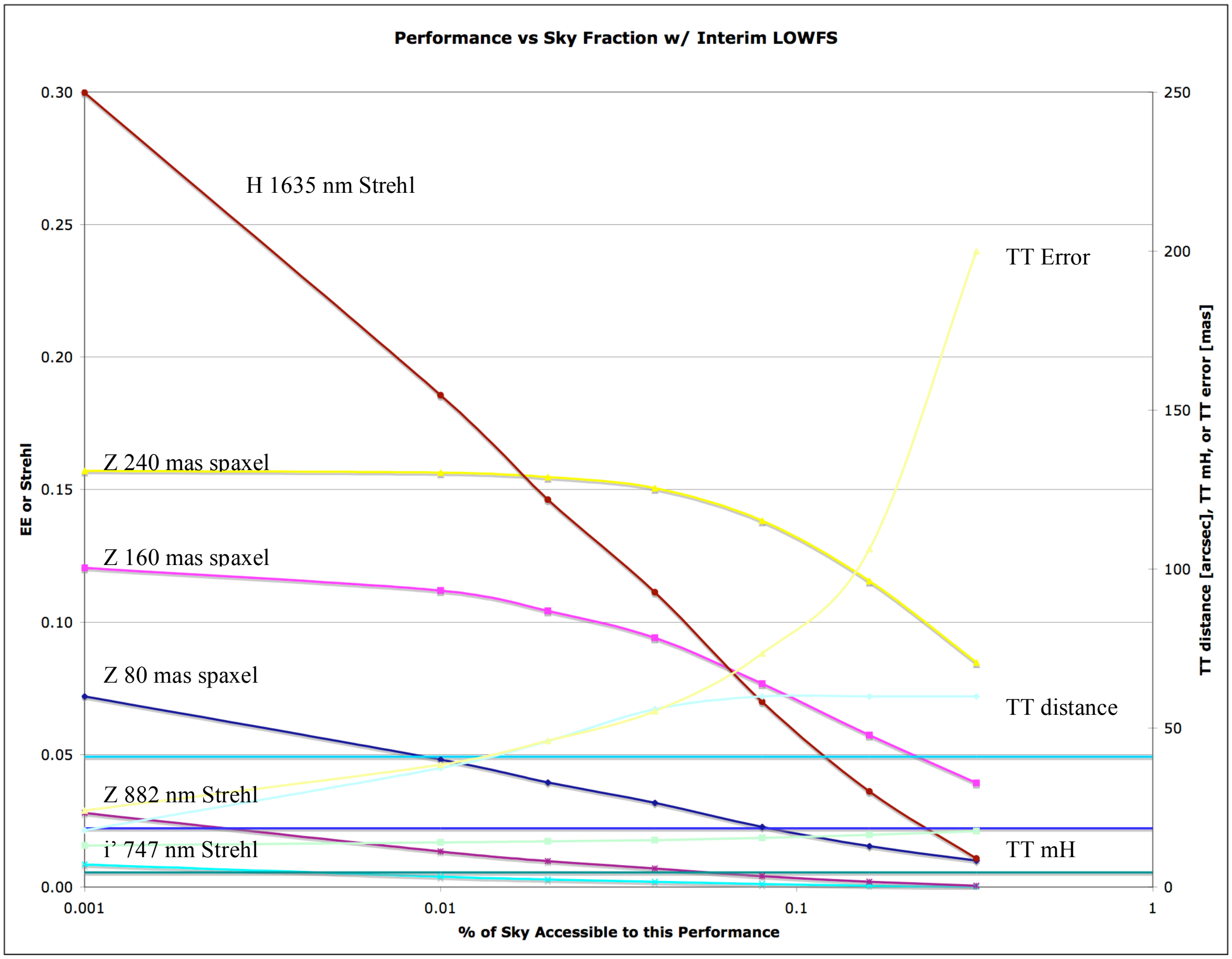

Figure 5. PALM-3000 performance vs. sky fraction r_0 for the science case 'Dynamics of Z=1 Galaxies w/ Equivalent 12W MM Laser Return' using the interim LOWFS sensor. The three horizontal lines represent the seeing-limited EE for 240 mas, 160 mas, and 80 mas spaxels (top to bottom).

6 APPENDIX: DETAILED ERROR BUDGETS

6.1 Near-IR TT WFS Budgets

6.1.1 Io surface geology with P3K NGS

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K NGS
Instrument:	888Cam
Observation:	Io

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (NGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		41 nm	64 Subaps
Bandwidth Error		32 nm	133 Hz (-3db)
High-order Measurement Error		31 nm	5 mV
LGS Tomography Error		0 nm	1 natural guide star
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		22 nm	33 zenith angle, H band
Scintillation Error		18 nm	0.46 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	68 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		20 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		0 nm	30 m/s Na layer vel
DM Finite Stroke Errors		29 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		9 nm	64 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		20 nm	888Cam Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	60 nm		
Angular Anisoplanatism Error		12 nm	0.5 arcsec
Total High Order Wavefront Error	91 nm	**92 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.11	0.28	0.47	0.60	0.69	0.76	0.83	0.89	0.93

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.60 mas	5 nm	3.5 mag (mH)
Tilt Bandwidth Error (one-axis)		2.26 mas	18 nm	36.4 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS x reduction
Residual Atmospheric Dispersion	r'	3.58 mas	31 nm	20 x reduction
Induced Plate Scale Deformations		0.28 mas	2 nm	-1500 m conj height
Science Instrument Mechanical Drift		0.08 mas	1 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.16 mas	1 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**4.3 mas**	36 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**92 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.69	0.80	0.87	0.91	0.93	0.95	0.97	0.98	0.99
Total Strehl (%)	0.08	0.22	0.41	0.55	0.64	0.72	0.80	0.87	0.92

Spaxel Diameter (mas)	50	70	80	160	240	480	1000		880
Ensquared Energy r'	0.45	0.48	0.48	0.49	0.50	0.57	####		0.80

Sky Coverage	Galactic Lat. 30 deg		
Corresponding Sky Coverage		**0.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.083 m	at this zenith	Wind Speed	9.54 m/s	Zenith Angle	33 deg		
Theta0_eff	1.49 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	2000 Hz	SH using	CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	6.5 e- rms		
Science Target:	SCAO		HOWFS Trans	0.23	HOWFS anti-aliasing	YES		
LOWFS Target:	NGS				LO WFS rate	2000 Hz	NGS using	CCD50
LOWFS Star Type:	G	Num TT 0	Num 3x3	0	LO WFS Noise	6.5 e- rms		
Max Exposure Time	10 sec	Num TTFA 0	Num HOWFS	1	Max mechanical tip/tilt rejection bandwidth	50 Hz		

Table 3. Error budget performance prediction for Io surface geology science case. This budget is dominated by the many uncorrectable internal aberration and calibration error terms, which might be reduced with optimized algorithms or calibration techniques.

6.1.2 Hot, Young Exo-Jupiters (NGS mode) with P3K NGS

Palomar Wavefront Error Budget Summary Version 1.30

Mode: **P3K NGS**
Instrument: **P1640**
Observation: **Exo Jup NGS**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (NGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		40 nm	64 Subaps
Bandwidth Error		35 nm	117 Hz (-3db)
High-order Measurement Error		37 nm	6 mV
LGS Tomography Error		0 nm	1 natural guide star
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		22 nm	30 zenith angle, H band
Scintillation Error		17 nm	0.44 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	71 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		20 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		0 nm	30 m/s Na layer vel
DM Finite Stroke Errors		29 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		9 nm	64 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		2 nm	P1640 Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	57 nm		
Angular Anisoplanatism Error		21 nm	1 arcsec
Total High Order Wavefront Error	91 nm	**94 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.10	0.26	0.45	0.58	0.68	0.75	0.82	0.88	0.93

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.69 mas	6 nm	2.2 mag (mH)
Tilt Bandwidth Error (one-axis)		2.39 mas	19 nm	35.0 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS x reduction
Residual Atmospheric Dispersion	*H*	0.34 mas	3 nm	20 x reduction
Induced Plate Scale Deformations		0.57 mas	5 nm	-1500 m conj height
Science Instrument Mechanical Drift		0.02 mas	0 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.16 mas	1 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**2.6 mas**	22 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**94 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.86	0.92	0.95	0.97	0.97	0.98	0.99	0.99	1.00
Total Strehl (%)	0.08	0.23	0.43	0.56	0.66	0.73	0.81	0.88	0.93

Spaxel Diameter (mas)		50	70	80	160	240	480	1000		110
Ensquared Energy	*H*	0.34	0.54	0.63	0.88	0.89	0.91	0.94		0.80

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage **0.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.084 m	at this zenith		Wind Speed	9.24 m/s	Zenith Angle	30 deg
Theta0_eff	1.57 arcsec	at this zenith		Outer Scale	75 m	HO WFS Rate	1755 Hz SH using CCD50
Sodium Abund.	4×10^9	atoms/cm^2		LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	6.2 e- rms
Science Target:	SCAO			HOWFS Trans	0.24	HOWFS anti-aliasing	YES
LOWFS Target:	NGS					LO WFS rate	1755 Hz NGS using CCD50
LOWFS Star Type:	M	Num TT	0	Num 3x3	0	LO WFS Noise	6.2 e- rms
Max Exposure Time	2 sec	Num TTFA	0	Num HOWFS	1	Max mechanical tip/tilt rejection bandwidth	50 Hz

Table 4. Error budget performance prediction for hot, young exo-Jupiters (NGS mode) science case. Here, we do include the potential calibration benefit of the JPL-built P1640 calibration unit, which could reduce all calibration errors (within frequencies of interest) to a few nm rms.

6.1.3 Faint NGS with P3K NGS

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K NGS
Instrument:	PHARO
Observation:	Faint NGS

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (NGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		213 nm	8 Subaps
Bandwidth Error		220 nm	12 Hz (-3db)
High-order Measurement Error		202 nm	16 mV
LGS Tomography Error		0 nm	1 natural guide star
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	10 zenith angle, H band
Scintillation Error		14 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	368 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		20 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		0 nm	30 m/s Na layer vel
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		47 nm	8 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		38 nm	PHARO Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	80 nm		
Angular Anisoplanatism Error		68 nm	5 arcsec
Total High Order Wavefront Error	376 nm	**382 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.12	0.30

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		19.49 mas	151 nm	12.8 mag (mH)
Tilt Bandwidth Error (one-axis)		9.27 mas	75 nm	9.8 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS x reduction
Residual Atmospheric Dispersion	K	0.05 mas	0 nm	20 x reduction
Induced Plate Scale Deformations		2.84 mas	23 nm	-1500 m conj height
Science Instrument Mechanical Drift		0.25 mas	2 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.59 mas	5 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**21.8 mas**	178 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**422 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.08	0.13	0.21	0.28	0.35	0.43	0.52	0.65	0.77
Total Strehl (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.23

		u'	g'	r'	i'	Z	Y	J	H	K
Spaxel Diameter (mas)		50	70	80	160	240	480	1000		1180
Ensquared Energy	K	0.06	0.10	0.13	0.28	0.34	0.45	0.72		0.80

Sky Coverage	Galactic Lat.	30 deg	
Corresponding Sky Coverage		**0.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.091 m	at this zenith	Wind Speed	8.12 m/s	Zenith Angle	10 deg			
Theta0_eff	1.92 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	182 Hz	SH	using	CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.0 e- rms			
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	YES			
LOWFS Target:	NGS				LO WFS rate	182 Hz	NGS	using	CCD50
LOWFS Star Type:	K	Num TT 0	Num 3x3	0	LO WFS Noise	4.0 e- rms			
Max Exposure Time	30 sec	Num TTFA 0	Num HOWFS	1	Max mechanical tip/tilt rejection bandwidth	50 Hz			

Table 5. Error budget performance prediction for faint NGS science case. This case may be overly pessimistic in bandwidth error as the WFE budget tool overestimates bandwidth error at low HOWFS frame rates. In practice, the existing PALMAO system with N=16 subapertures can provide, in median conditions with an m_V = 15 (not 16) star, SR_K ~ 15% and $EE_{K,\ 240\ mas}$ ~ 30%, even with a guide star some 10-20 arcsec off-axis[6].

[6] R. Dekany, private communication.

6.1.4 Hot, Young Exo-Jupiters (LGS mode) w/ Equivalent 12 W MM Laser Return

Palomar Wavefront Error Budget Summary Version 1.30

Mode: **P3K LGS**
Instrument: **P1640**
Observation: **Exo Jup LGS**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		119 nm	16 Subaps
Bandwidth Error		106 nm	29 Hz (-3db)
High-order Measurement Error		118 nm	12 W
LGS Focal Anisoplanatism Error		87 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	10 zenith angle, H band
Scintillation Error		14 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	218 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		40 nm	16 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		2 nm	P1640 Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	69 nm		
Angular Anisoplanatism Error		18 nm	1 arcsec
Total High Order Wavefront Error	229 nm	**230 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.03	0.07	0.14	0.27	0.46	0.65

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.60 mas	5 nm	9.2 mag (mH)
Tilt Bandwidth Error (one-axis)		4.54 mas	37 nm	20.0 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		1.63 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	*H*	0.10 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		0.57 mas	5 nm	-1500 m conj height
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.29 mas	2 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**5.5 mas**	48 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**234 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.58	0.71	0.81	0.86	0.90	0.92	0.94	0.97	0.98
Total Strehl (%)	0.00	0.00	0.00	0.02	0.06	0.13	0.25	0.45	0.64

	Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1080
Ensquared Energy	*H*	0.18	0.28	0.33	0.48	0.50	0.60	0.78		0.80

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage **0.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.091 m	at this zenith	Wind Speed	8.12 m/s	Zenith Angle	10 deg				
Theta0_eff	1.92 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	437 Hz	SH	using	CCD50	
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.3 e- rms				
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO				
LOWFS Target:	SCAO				LO WFS rate	500 Hz	SH	using	H2RG	
LOWFS Star Type:	M	Num TT 1	Num 3x3	0	LO WFS Noise	4.5 e- rms				
Max Exposure Time	300 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth				50 Hz	

Table 6. Error budget performance prediction for hot, young exo-Jupiters (LGS mode) 12 W MM laser science case.

6.1.5 Hot, Young Exo-Jupiters (LGS mode) w/ Equivalent 50 W CW Laser Return

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K LGS
Instrument:	P1640
Observation:	Exo Jup LGS

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	32 Subaps
Bandwidth Error		63 nm	55 Hz (-3db)
High-order Measurement Error		67 nm	50 W
LGS Focal Anisoplanatism Error		87 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	10 zenith angle, H band
Scintillation Error		14 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	145 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		27 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		22 nm	32 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		2 nm	P1640 Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	64 nm		
Angular Anisoplanatism Error		18 nm	1 arcsec
Total High Order Wavefront Error	159 nm	**160 nm**	**High Order Strehl**

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.44 mas	4 nm	9.2 mag (mH)
Tilt Bandwidth Error (one-axis)		4.54 mas	37 nm	20.0 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	0.0 arcsec
Residual Centroid Anisoplanatism		1.63 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	*H*	0.10 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		0.57 mas	5 nm	-1500 m conj height
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.29 mas	2 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**5.5 mas**	48 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**165 nm**	**Total Strehl (%)**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.18	0.29	0.40	0.53	0.69	0.81
Tip/Tilt Strehl	0.58	0.71	0.81	0.86	0.90	0.92	0.95	0.97	0.98
Total Strehl (%)	0.00	0.01	0.06	0.15	0.26	0.37	0.51	0.67	0.80

Spaxel Diameter (mas)	50	70	80	160	240	480	1000		500
Ensquared Energy *H*	0.26	0.42	0.49	0.70	0.73	0.79	0.89		0.80

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage **0.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.091 m	at this zenith	Wind Speed	8.12 m/s	Zenith Angle	10 deg	
Theta0_eff	1.92 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	826 Hz	SH using CCD50
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.9 e- rms	
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO	
LOWFS Target:	SCAO				LO WFS rate	500 Hz	SH using H2RG
LOWFS Star Type:	M	Num TT 1	Num 3x3	0	LO WFS Noise	4.5 e- rms	
Max Exposure Time	300 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz	

Table 7. Error budget performance prediction for the hot, young exo-Jupiters (LGS mode) science case. The benefit of more LGS return compared to 12W MM is to achieve 165 nm WFE, compared to 234 nm, delivering between 4x – 8x higher Strehl ratio in Z-band (882 nm).

6.1.6 Dynamics of Z = 1 Galaxies w/ Equivalent 12 W MM Laser Return

Palomar Wavefront Error Budget Summary Version 1.30

Mode: **P3K LGS**
Instrument: **SWIFT**
Observation: **Z = 1 Galaxies**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		119 nm	16 Subaps
Bandwidth Error		107 nm	29 Hz (-3db)
High-order Measurement Error		115 nm	12 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	216 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		40 nm	16 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		62 nm	SWIFT Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	93 nm		
Angular Anisoplanatism Error		56 nm	4 arcsec
Total High Order Wavefront Error	235 nm	**242 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.02	0.05	0.12	0.23	0.43	0.62

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		11.13 mas	83 nm	14.6 mag (mH)
Tilt Bandwidth Error (one-axis)		9.32 mas	71 nm	9.9 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		12.41 mas	91 nm	16.8 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	Z	0.14 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		2.27 mas	18 nm	-1500 m conj height
Science Instrument Mechanical Drift		15.00 mas	105 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.58 mas	5 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**24.5 mas**	154 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**285 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.07	0.11	0.17	0.24	0.30	0.37	0.46	0.60	0.73
Total Strehl (%)	0.00	0.00	0.00	0.00	0.02	0.04	0.11	0.25	0.45

Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1330
Ensquared Energy (Z)	0.02	0.04	0.05	0.08	0.12	0.27	0.63		0.80

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage **5.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith		Wind Speed	8.03 m/s	Zenith Angle	5 deg
Theta0_eff	1.96 arcsec	at this zenith		Outer Scale	75 m	HO WFS Rate	434 Hz SH using CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2		LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.3 e- rms
Science Target:	SCAO			HOWFS Trans	0.28	HOWFS anti-aliasing	NO
LOWFS Target:	SCAO					LO WFS rate	184 Hz SH using H2RG
LOWFS Star Type:	M	Num TT	1	Num 3x3	0	LO WFS Noise	4.5 e- rms
Max Exposure Time	1800 sec	Num TTFA	0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz

Table 8. Error budget performance prediction for dynamics of Z = 1 galaxies w/ equivalent 12 W MM laser return science case, optimized for Z-band ensquared energy.

6.1.7 Dynamics of Z = 1 Galaxies w/ Equivalent 50W CW Laser Return

Palomar Wavefront Error Budget Summary — Version 1.30

Mode:	P3K LGS
Instrument:	SWIFT
Observation:	Z = 1 Galaxies

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	32 Subaps
Bandwidth Error		63 nm	54 Hz (-3db)
High-order Measurement Error		65 nm	50 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	144 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		27 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		22 nm	32 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		62 nm	SWIFT Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	89 nm		
Angular Anisoplanatism Error		56 nm	4 arcsec
Total High Order Wavefront Error	169 nm	**178 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.04	0.11	0.21	0.32	0.46	0.63	0.77

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		7.61 mas	59 nm	14.2 mag (mH)
Tilt Bandwidth Error (one-axis)		7.73 mas	60 nm	11.9 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		14.04 mas	100 nm	19.1 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	Z	0.14 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		2.27 mas	18 nm	-1500 m conj height
Science Instrument Mechanical Drift		15.00 mas	105 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		0.48 mas	4 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**23.4 mas**	150 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**231 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.07	0.12	0.19	0.25	0.32	0.39	0.49	0.62	0.75
Total Strehl (%)	0.00	0.00	0.01	0.03	0.07	0.12	0.22	0.39	0.58

Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1540
Ensquared Energy (Z)	0.09	0.14	0.16	0.24	0.27	0.41	0.66		0.80

Sky Coverage	Galactic Lat.	30 deg
Corresponding Sky Coverage	**5.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith	Wind Speed 8.03 m/s	Zenith Angle	5 deg
Theta0_eff	1.96 arcsec	at this zenith	Outer Scale 75 m	HO WFS Rate	815 Hz SH using CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad. 0.00 arcmin	HO WFS Noise	4.8 e- rms
Science Target:	SCAO		HOWFS Trans 0.28	HOWFS anti-aliasing	NO
LOWFS Target:	SCAO			LO WFS rate	234 Hz SH using H2RG
LOWFS Star Type:	M	Num TT 1	Num 3x3 0	LO WFS Noise	4.5 e- rms
Max Exposure Time	1800 sec	Num TTFA 0	Num HOWFS 0	Max mechanical tip/tilt rejection bandwidth	50 Hz

Table 9. Error budget performance prediction for dynamics of Z = 1 galaxies w/ equivalent 50 W CW laser return science case, optimized for Z-band ensquared energy.

6.1.8 30% Sky Coverage w/ Equivalent 12 W MM Laser Return

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K LGS		**Science Band**								
Instrument:	PHARO			u'	g'	r'	i'	Z	Y	J	H	K
Observation:	30% Sky	λ (μm)		0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
		δλ (μm)		0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
		λ/D (mas)		15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%)
Atmospheric Fitting Error		119 nm	16 Subaps	
Bandwidth Error		104 nm	30 Hz (-3db)	
High-order Measurement Error		117 nm	12 W	
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)	
Asterism Deformation Error		0 nm	0.50 m LLT	
Multispectral Error		19 nm	5 zenith angle, H band	
Scintillation Error		13 nm	0.34 Scint index, H-band	
WFS Scintillation Error		10 nm	Alloc	
	216 nm			
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts	
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D	
Static WFS Zero-point Calibration Error		25 nm	Alloc	
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc	
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc	
Go-to Control Errors		0 nm	Alloc	
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel	
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke	
DM Hysteresis		7 nm	from TMT	
High-Order Aliasing Error		40 nm	16 Subaps	
DM Drive Digitization		1 nm	16 bits	
Uncorrectable AO System Aberrations		20 nm	Alloc	
Uncorrectable Instrument Aberrations		38 nm	PHARO Instrument	
DM-to-lenslet Misregistration		15 nm	Alloc	
DM-to-lenslet Pupil Scale Error		15 nm	Alloc	
	79 nm			
Angular Anisoplanatism Error		67 nm	5 arcsec	

Total High Order Wavefront Error	230 nm	**240 nm**	**High Order Strehl**	0.00	0.00	0.00	0.02	0.06	0.12	0.24	0.43	0.63

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)
Tilt Measurement Error (one-axis)		59.35 mas	318 nm	16.9 mag (mH)	
Tilt Bandwidth Error (one-axis)		56.00 mas	308 nm	1.6 Hz (-3db)	
Tilt Anisoplanatism Error (one-axis)		28.49 mas	199 nm	38.7 arcsec	
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction	
Residual Atmospheric Dispersion	*H*	0.05 mas	0 nm	20 x reduction	
Induced Plate Scale Deformations		2.84 mas	23 nm	-1500 m conj height	
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min	
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min	
Residual Telescope Pointing Jitter (one-axis)		3.50 mas	28 nm	3 Hz input disturbance	

Total Tip/Tilt Error (one-axis)	**86.6 mas**	390 nm	**Tip/Tilt Strehl**	0.01	0.01	0.02	0.02	0.03	0.04	0.06	0.11	0.18
Total Effective Wavefront Error		**457 nm**	**Total Strehl (%)**	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.11

		Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1140
Ensquared Energy	*H*		0.02	0.04	0.05	0.19	0.33	0.56	0.76		0.80

Sky Coverage	Galactic Lat.	60 deg	
Corresponding Sky Coverage		**30.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith	Wind Speed	8.03 m/s	Zenith Angle	5 deg			
Theta0_eff	1.96 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	446 Hz	SH	using	CCD50
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.3 e- rms			
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO			
LOWFS Target:	SCAO				LO WFS rate	25 Hz	SH	using	H2RG
LOWFS Star Type:	M	Num TT 1	Num 3x3	0	LO WFS Noise	4.5 e- rms			
Max Exposure Time	300 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz			

Table 10. Error budget performance prediction for 30% sky coverage w/ equivalent 12 W MM laser return science case, optimized for H-band Strehl ratio.

6.1.9 30% Sky Coverage w/ Equivalent 50 W CW Laser Return

Palomar Wavefront Error Budget Summary Version 1.30

Mode: **P3K LGS**
Instrument: **PHARO**
Observation: **30% Sky**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	32 Subaps
Bandwidth Error		58 nm	60 Hz (-3db)
High-order Measurement Error		69 nm	50 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	144 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		27 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		22 nm	32 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		38 nm	PHARO Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	74 nm		
Angular Anisoplanatism Error		67 nm	5 arcsec
Total High Order Wavefront Error	162 nm	**175 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.05	0.12	0.22	0.33	0.47	0.64	0.78

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		48.53 mas	285 nm	16.9 mag (mH)
Tilt Bandwidth Error (one-axis)		44.82 mas	271 nm	2.0 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		28.37 mas	198 nm	38.5 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	H	0.05 mas	0 nm	20 x reduction
Induced Plate Scale Deformations		2.84 mas	23 nm	-1500 m conj height
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		2.80 mas	23 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**72.1 mas**	361 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**401 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.01	0.01	0.02	0.03	0.05	0.06	0.09	0.15	0.24
Total Strehl (%)	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.09	0.18

Spaxel Diameter (mas)		50	70	80	160	240	480	1000		670
Ensquared Energy	H	0.04	0.08	0.10	0.33	0.53	0.75	0.86		0.80

Sky Coverage Galactic Lat. 60 deg

Corresponding Sky Coverage **30.0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith	Wind Speed	8.03 m/s	Zenith Angle	5 deg	
Theta0_eff	1.96 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	894 Hz	SH using CCD50
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	5.0 e- rms	
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO	
LOWFS Target:	SCAO				LO WFS rate	32 Hz	SH using H2RG
LOWFS Star Type:	M	Num TT 1	Num 3x3	0	LO WFS Noise	4.5 e- rms	
Max Exposure Time	300 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz	

Table 11. Error budget performance prediction for 30% sky coverage w/ equivalent 50 W CW laser return science case, optimized for H-band Strehl ratio.

6.2 Visible Interim LOWFS Budgets

6.2.1 Dynamics of Z = 1 Galaxies w/ Equivalent 12 W MM Laser Return & Interim LOWFS

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K LGS
Instrument:	SWIFT
Observation:	Z = 1 Galaxies

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		119 nm	16 Subaps
Bandwidth Error		107 nm	29 Hz (-3db)
High-order Measurement Error		114 nm	12 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	216 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		40 nm	16 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		62 nm	SWIFT Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	93 nm		
Angular Anisoplanatism Error		56 nm	4 arcsec
Total High Order Wavefront Error	235 nm	**242 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.02	0.05	0.12	0.23	0.43	0.62

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		31.15 mas	169 nm	14.9 mag (mV)
Tilt Bandwidth Error (one-axis)		18.60 mas	123 nm	4.9 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		44.22 mas	200 nm	60.0 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	Z	0.14 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		2.27 mas	18 nm	-1500 m conj height
Science Instrument Mechanical Drift		15.00 mas	105 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		1.16 mas	9 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**59.2 mas**	230 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**332 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.01	0.02	0.03	0.05	0.07	0.09	0.13	0.20	0.31
Total Strehl (%)	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.09	0.20

	Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1330
Ensquared Energy	Z	0.01	0.02	0.02	0.06	0.11	0.27	0.63		0.80

Sky Coverage	Galactic Lat.	30 deg	
Corresponding Sky Coverage		**5.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith	Wind Speed	8.03 m/s	Zenith Angle	5 deg			
Theta0_eff	1.96 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	430 Hz	SH	using	CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.3 e- rms			
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO			
LOWFS Target:	SCAO				LO WFS rate	82 Hz	SH	using	CCD39
LOWFS Star Type:	M	Num TT 0	Num 3x3	1	LO WFS Noise	4.3 e- rms			
Max Exposure Time	1800 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz			

Table 12. Error budget performance prediction for dynamics of Z = 1 galaxies w/ equivalent 12 W MM laser return & interim LOWFS science case. Through comparison with the nearly equivalent EE per spaxial seen with the NIR TT sensor in Table 8, we see that the interim LOWFS does not degrade this science case (which benefits most from more laser power). We do note, however, that using the interim visible LOWFS, the optimal TT GS will typically be found further away from the science object (compare 59 arcsec distance here with 38 arcsec distance in Table 8.)

6.2.2 Dynamics of Z = 1 Galaxies w/ Equivalent 50W CW Laser Return & Interim LOWFS

Palomar Wavefront Error Budget Summary Version 1.30

Mode: **P3K LGS**
Instrument: **SWIFT**
Observation: **Z = 1 Galaxies**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	32 Subaps
Bandwidth Error		64 nm	53 Hz (-3db)
High-order Measurement Error		64 nm	50 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	144 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		27 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		22 nm	32 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		62 nm	SWIFT Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	89 nm		
Angular Anisoplanatism Error		56 nm	4 arcsec
Total High Order Wavefront Error	169 nm	**178 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.04	0.11	0.21	0.32	0.46	0.63	0.77

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		31.88 mas	171 nm	14.9 mag (mV)
Tilt Bandwidth Error (one-axis)		17.87 mas	120 nm	5.1 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		44.22 mas	200 nm	60.0 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	Z	0.14 mas	1 nm	20 x reduction
Induced Plate Scale Deformations		2.27 mas	18 nm	-1500 m conj height
Science Instrument Mechanical Drift		15.00 mas	105 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		1.12 mas	9 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**59.4 mas**	230 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**289 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.01	0.02	0.03	0.05	0.07	0.09	0.13	0.20	0.31
Total Strehl (%)	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.13	0.24

	Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1530
Ensquared Energy	Z	0.02	0.04	0.06	0.17	0.25	0.41	0.66		0.80

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage	**5.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith	Wind Speed	8.03 m/s	Zenith Angle	5 deg	
Theta0_eff	1.96 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	796 Hz	SH using CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2	LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.8 e- rms	
Science Target:	SCAO		HOWFS Trans	0.28	HOWFS anti-aliasing	NO	
LOWFS Target:	SCAO				LO WFS rate	86 Hz	SH using CCD39
LOWFS Star Type:	M	Num TT 0	Num 3x3	1	LO WFS Noise	4.8 e- rms	
Max Exposure Time	1800 sec	Num TTFA 0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz	

Table 13. Error budget performance prediction for dynamics of Z = 1 galaxies w/ equivalent 50W CW laser return & interim LOWFS science case.

6.2.3 30% Sky Coverage w/ Equivalent 12 W MM Laser Return & Interim LOWFS

Palomar Wavefront Error Budget Summary Version 1.30

		Science Band								
Mode:	P3K LGS	u'	g'	r'	i'	Z	Y	J	H	K
Instrument:	PHARO λ (µm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
Observation:	30% Sky δλ (µm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
	λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		119 nm	16 Subaps
Bandwidth Error		105 nm	30 Hz (-3db)
High-order Measurement Error		116 nm	12 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	216 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		19 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		40 nm	16 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		38 nm	PHARO Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	79 nm		
Angular Anisoplanatism Error		67 nm	5 arcsec
Total High Order Wavefront Error	230 nm	**240 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.02	0.06	0.12	0.24	0.43	0.63

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		162.01 mas	472 nm	17.6 mag (mV)
Tilt Bandwidth Error (one-axis)		114.30 mas	422 nm	0.8 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		66.33 mas	336 nm	90.0 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	H	0.05 mas	0 nm	20 x reduction
Induced Plate Scale Deformations		2.84 mas	23 nm	-1500 m conj height
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		7.15 mas	58 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**209.2 mas**	515 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**568 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.04
Total Strehl (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02

	Spaxel Diameter (mas)	50	70	80	160	240	480	1000		1160
Ensquared Energy	H	0.01	0.01	0.01	0.06	0.12	0.38	0.75		0.80

Sky Coverage	Galactic Lat.	60 deg	
Corresponding Sky Coverage		**30.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith		Wind Speed	8.03 m/s	Zenith Angle	5 deg		
Theta0_eff	1.96 arcsec	at this zenith		Outer Scale	75 m	HO WFS Rate	443 Hz	SH using	CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2		LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.3 e- rms		
Science Target:	SCAO			HOWFS Trans	0.28	HOWFS anti-aliasing	NO		
LOWFS Target:	SCAO					LO WFS rate	12 Hz	SH using	CCD39
LOWFS Star Type:	M	Num TT	0	Num 3x3	1	LO WFS Noise	4.3 e- rms		
Max Exposure Time	300 sec	Num TTFA	0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz		

Table 14. Error budget performance prediction for 30% sky coverage w/ equivalent 12 W MM laser return & interim LOWFS science case. For this case, we have expanded the search radius for visible TT GS out to 90 arcsec radius (the P3K goal specification), which dramatically improves TT error.

6.2.4 30% Sky Coverage w/ Equivalent 50W CW Laser Return & Interim LOWFS

Palomar Wavefront Error Budget Summary Version 1.30

Mode:	P3K LGS		
Instrument:	PHARO		
Observation:	30% Sky		

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	15	20	27	32	38	45	54	71	95

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		67 nm	32 Subaps
Bandwidth Error		62 nm	56 Hz (-3db)
High-order Measurement Error		66 nm	50 W
LGS Focal Anisoplanatism Error		86 nm	1 beacon(s)
Asterism Deformation Error		0 nm	0.50 m LLT
Multispectral Error		19 nm	5 zenith angle, H band
Scintillation Error		13 nm	0.34 Scint index, H-band
WFS Scintillation Error		10 nm	Alloc
	144 nm		
Uncorrectable Static Telescope Aberrations		14 nm	64 Acts
Uncorrectable Dynamic Telescope Aberrations		0 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Alloc
Dynamic WFS Zero-point Calibration Error		30 nm	Alloc
Leaky Integrator Zero-point Calibration Error		15 nm	Alloc
Go-to Control Errors		0 nm	Alloc
Residual Na Layer Focus Change		4 nm	30 m/s Na layer vel
DM Finite Stroke Errors		27 nm	5.5 um P-P stroke
DM Hysteresis		7 nm	from TMT
High-Order Aliasing Error		22 nm	32 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		20 nm	Alloc
Uncorrectable Instrument Aberrations		38 nm	PHARO Instrument
DM-to-lenslet Misregistration		15 nm	Alloc
DM-to-lenslet Pupil Scale Error		15 nm	Alloc
	74 nm		
Angular Anisoplanatism Error		67 nm	5 arcsec
Total High Order Wavefront Error	162 nm	**175 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.05	0.12	0.22	0.33	0.47	0.64	0.78

Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		162.22 mas	472 nm	17.6 mag (mV)
Tilt Bandwidth Error (one-axis)		114.03 mas	421 nm	0.8 Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		66.33 mas	336 nm	90.0 arcsec
Residual Centroid Anisoplanatism		1.62 mas	13 nm	10 x reduction
Residual Atmospheric Dispersion	H	0.05 mas	0 nm	20 x reduction
Induced Plate Scale Deformations		2.84 mas	23 nm	-1500 m conj height
Science Instrument Mechanical Drift		2.50 mas	20 nm	Alloc 0.25 mas / min
Long Exposure Field Rotation Errors		0.00 mas	0 nm	Alloc 0.25 mas / min
Residual Telescope Pointing Jitter (one-axis)		7.13 mas	57 nm	3 Hz input disturbance
Total Tip/Tilt Error (one-axis)		**209.3 mas**	515 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**544 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.04
Total Strehl (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03

Spaxel Diameter (mas)	50	70	80	160	240	480	1000		880
Ensquared Energy H	0.01	0.01	0.02	0.07	0.15	0.46	0.84		0.80

Sky Coverage	Galactic Lat.	60 deg	
Corresponding Sky Coverage		**30.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.092 m	at this zenith		Wind Speed	8.03 m/s	Zenith Angle	5 deg			
Theta0_eff	1.96 arcsec	at this zenith		Outer Scale	75 m	HO WFS Rate	839 Hz	SH	using	CCD50
Sodium Abund.	4 x 10^9	atoms/cm^2		LGS Ast. Rad.	0.00 arcmin	HO WFS Noise	4.9 e- rms			
Science Target:	SCAO			HOWFS Trans	0.28	HOWFS anti-aliasing	NO			
LOWFS Target:	SCAO					LO WFS rate	12 Hz	SH	using	CCD39
LOWFS Star Type:	M	Num TT	0	Num 3x3	1	LO WFS Noise	4.9 e- rms			
Max Exposure Time	300 sec	Num TTFA	0	Num HOWFS	0	Max mechanical tip/tilt rejection bandwidth	50 Hz			

Table 15. Error budget performance prediction for 30% sky coverage w/ equivalent 50W CW laser return & interim LOWFS science case. For this case, we have expanded the search radius for visible TT GS out to 90 arcsec radius (the P3K goal specification), which dramatically improves TT error. Through comparison with Table 10, we see the tip/tilt error associated with 30% sky coverage is much worse with the interim LOWFS than with the IRTT.