Next Generation Adaptive Optics

DAVINCI Background and Zero Point Estimates (KAON 764)

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May 11, 2010

INTRODUCTION

A revised background prediction spreadsheet has been developed for the NGAO DAVINCI instrument (DAVINCI_Backgrounds_2_2_NB_Spec) which provides predicted background magnitudes and zero point magnitudes for the imager in the NGAO photometric passbands and representative narrow bands for the integral field spectrograph (IFS). The spreadsheet also provides predictions for NIRC2 in the J, H, and K bands as a way of indicating the accuracy of the predictions made for DAVINCI.

METHODOLOGY

Zero Point Magnitude

To determine the zero point we use flux densities for Vega as given in Tokunaga and Vacca (2005), Table 1, and estimates for the NGAO I, Z, and Y bands as discussed in Appendix A of this document. The NGAO passbands defined in Adkins (2010) are used for DAVINCI's imaging and spectroscopic modes. For NIRC2 we use the NIRC2 filter specifications from the NIRC2 web page (W. M. Keck Observatory [WMKO], 2003).

The instrument's zero point magnitude m_z (where $m_{inst} = -2.5 \times \log(1) = 0$) can be calculated using equation 1.

$$
\begin{aligned}
& m_z = 2.5 \times \log\left(F_\nu \times P_F \times \frac{\Delta\lambda}{\lambda} \times A_{tel} \times T_{atm} \times T_{tel} \times T_{AO} \times T_{inst} \times QE \right) \\
& \text{where:} \\
& F_\nu = \text{flux in Janskys} \\
& P_F = \text{conversion from Janskys to photons/s/m}^2 \text{ where 1 Jansky} = 1.51 \times 10^7 \text{ photons/s/m}^2 \\
& \frac{\Delta\lambda}{\lambda} = \text{bandpass, filter FWHM divided by the central wavelength of the filter} \\
& A_{tel} = \text{collecting area of the telescope in m} \\
& T_{atm} = \text{transmission of the atmosphere at zenith} \\
& T_{tel} = \text{transmission of the telescope} \\
& T_{AO} = \text{transmission of the AO system} \\
& T_{inst} = \text{transmission of the instrument} \\
& QE = \text{the detector manufacturer's specified detective quantum efficiency} \\
& \text{i.e. a QE } of \text{ 1 means each interacting photon generates 1 electron of signal}
\end{aligned}
\qquad (1)
$$

The detector quantum efficiencies used in each DAVINCI passband are the corresponding minimum required values for a Hawaii-4RG detector (Adkins, 2009a). A gain of 1 is assumed for the detector readout system. The detector quantum efficiencies for NIRC2 are taken from the NIRC2 general specifications web page (WMKO, 2001).

Background Magnitudes

The background magnitudes are estimated for three sources, the sky, the telescope and the AO system.

To estimate the sky background, the sky flux in a given passband is taken from 1 to 2.5 μm infrared sky background data provided by Gemini Observatory (2009). These are models of the spectral emission from the night sky, starting with ATRAN (Lord, 1992) data, and assuming the emissivity is 1-transmission, and a blackbody temperature of 273 K. The OH emission spectrum was then added, along with oxygen lines around 1.3 μm, and zodiacal light assuming a 5800 K grey body scaled by the atmospheric transmission. As noted on the Gemini web page, this model can be expected to overestimate the thermal background, due in part to the assumption of a uniform temperature for the atmosphere. It is also important to note that the effect of the moon is not included in the model. For each passband the model flux densities are numerically integrated to produce the total flux density over the passband, F_{sky} in units of photons/s/arcsecond^2/m^2. Sky background for the wavelength range of 0.7 to 0.92 μm is taken from the same Gemini Observatory (2009) reference and is based on model optical sky spectrum developed using the methods of Krisciunas (1997) and Krisciunas and Schaefer (1991), scaled by broadband sky brightness for 50% dark time.

To determine the background contribution from the telescope and AO system we assume that each source is a black body whose emissivity is equal to 1- transmission. We compute the spectral radiance L_λ (power per unit solid angle per unit projected area per unit wavelength) using square arcseconds instead of square radians for the telescope and AO system using equation 3, having used equation 2 to substitute photons/s for watts, resulting in units of photons/s/m^2/arcsecond^2/nm. The temperature of the telescope is 274.8 K (the average annual temperature at the summit of Mauna Kea for 2008 was 1.84 °C, see Adkins, 2009c) and the temperature of the AO system is set to 258 K (-15 °C) to match the emissivity of the telescope at the long wavelength end of the K band. We assume that operation of the instrument optics at 120 K reduces the instrument's background contribution to a negligible level for this analysis.

$$E = \frac{hc}{\lambda} \qquad (2)$$

The spectral radiance of the background source per unit wavelength is then integrated over the passband to determine the radiance L of each background source in photons/s/m^2/arcsecond^2. Since the radiance of the object is equal to that of the image (Smith, 2000, p. 227), we only have to account for the transmission losses to determine the radiance at the pupil plane using equation 4.

$$L_\lambda = \frac{2c}{\lambda^4} \times \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \times a_{sr}{}^2 \tag{3}$$

where:

c = the speed of light in m/s

λ = wavelength in m

h = Planck's constant

k = Boltzmann's constant

T = temperature in kelvin

$a_{sr} = 4.85x10^{-6}$ radians in 1 arcsecond

$$L_{pupil\_background\_tel} = L_{background\_tel} \times T_{AO} \times T_{inst} \tag{4}$$

For this analysis we note that the exit pupil seen by the detector is telecentric, as is the exit pupil from the AO system. The result is that the angular subtense seen by the detector is determined by the f-number at the detector. The irradiance at the detector $I_{detector\_tel}$ in photons/s/m^2 can be found using equation 5.

$$I_{detector} = \pi \times L_{pupil\_background\_tel} \times \sin^2\theta \tag{5}$$

where:

$\theta = \arcsin\left(\frac{1}{2 \times f\#}\right)$

$f\#$= f - number at the detector

Finally, the flux reaching one pixel on the detector, in photons/s is found using equation 6.

$$P_{background\_tel} = I_{detector} \times A_{pixel} \times QE \tag{6}$$

where:

A_{pixel} = area of a detector pixel in m^2

Using the same approach as that used for the telescope emissivity we compute the flux reaching the detector due to the emissivity of the AO system, but in this case we attenuate the radiance by only the instrument transmission. The total flux reaching the detector from the background sources is the sum of the telescope contribution, $P_{background\_tel}$, and the AO system contribution $P_{background\_AO}$.

The background flux ($m_{background}$) in magnitudes per square arc second as seen by the instrument is then given by equation 7.

$$m_{background} = m_z - \left[2.5 \times \log \left(\left(\left(F_{sky} \times \theta_{\text{pixel}}^2 \times A_{tel} \times T_{tel} \times T_{AO} \times T_{inst} \times QE \right) + P_{background\_tel} + P_{backkground\_AO} \right) \times \frac{1}{\theta_{\text{pixel}}^2} \right) \right]$$

(7)

Validation to NIRC2 Zero Points and Backgrounds

During the NGAO system design phase a report (Bouchez, 2007) was developed to evaluate emissivities for various AO relay designs. This report validated its methodology by modeling the current Keck II AO system and comparing the resulting backgrounds to the measured backgrounds for NIRC2 (WMKO, 2003). This is repeated in the DAVINCI backgrounds spreadsheet (DAVINCI_Backgrounds.xls). The NIRC2 J, H, and K broadband filter cut-on and cut-off wavelengths were used, although the effect of the differences with respect to the DAVINCI photometric passbands is small. In this evaluation the NGAO transmission values are used for telescope and atmosphere (see the next section). The AO transmission was based on the averages in each of the corresponding passbands as shown in Figure 2 of Bouchez (2007). The temperature of the telescope was set to match the value of 275.6 K used in Bouchez (2007). The transmission assumed for NIRC2 was adjusted to match the zero points used in the NIRC2 exposure calculator (WMKO, n. d.), and the temperature of AO system was then set to make the computed K band background match the measured values for NIRC2 (WMKO, 2003). This required the AO system to be at a temperature of 11.5 ºC, a value that does not seem unreasonable based on recent information that the Keck II AO system runs warmer than expected. Note that for NIRC2 we don't have information on the pupil geometry, so we simply add the AO and telescope background to the sky background. This may account for the need to increase the temperature of the AO system to match the measured K band background value since we do not model the background entendue correctly for NIRC2. The resulting backgrounds are summarized in Table 1.

	NIRC2 measured value	**Bouchez (2007), Table 1 "adjusted value"**	**DAVINCI background spreadsheet value**
J band	14.9	15.89	16.07
H band	13.6	13.71	13.76
K band	12.6	12.63	12.60

Table 1: NIRC2 background validation (mag./sq. arcsecond)

The results show reasonable agreement with measured values for H band. The values computed for the J band are very similar between those in Bouchez (2007) and the DAVINCI background spreadsheet, but the discrepancy with the NIRC2 measured values noted in Bouchez remains. It should also be noted that the H band background flux is higher than that for K band due to strong OH lines in the H band (Ramsay et al., 1992).

Transmission Data

Transmission data for the sky and AO system are taken from the version of the NGAO PD Phase Flowdown Budgets spreadsheet released on March 5, 2010 by Rich Dekany, file name "NGAO PD Phase Flowdown Budgets v0_101 2003 Format.xls" (KAON 723). The averages over each passband used in the DAVINCI background and zero point calculations are the green values as summarized in Table 2.

Data for the telescope are for newly coated mirrors and are based on measurements made in August 2009 on coating witness samples (Panteleev, 2009) and are summarized in Table 3.

Transmission data is also used to predict emissivity of the telescope and AO system as 1-transmission as discussed in the background magnitudes section above.

	Cut-on, nm	Cut-off, nm	Atmosphere	Atmosphere, average	AO system	AO system, average
I band						
S, P	700		91.37%	92.26%	44.45%	51.05%
S, P		853	93.15%		57.64%	
Z band						
S	855		93.15%	96.56%	57.64%	57.98%
S		1050	99.97%		58.33%	
P	818		92.90%	96.04%	55.59%	57.57%
P		922	99.18%		59.54%	
Y band						
S	970		99.31%	92.02%	61.08%	59.84%
S		1120	84.74%		58.60%	
P	970		99.31%	99.63%	61.08%	60.51%
P		1070	99.96%		59.93%	
J band						
S	1100		98.72%	63.67%	58.65%	58.56%
S		1400	28.62%		58.47%	
P	1170		99.22%	97.76%	57.48%	57.90%
P		1330	96.30%		58.31%	
H band						
S	1475		96.58%	86.40%	59.59%	61.15%
S		1825	76.23%		62.70%	
P	1490		95.38%	97.10%	59.75%	60.76%
P		1780	98.82%		61.78%	
K band						
S	2000		63.46%	79.31%	62.81%	62.25%
S		2400	95.16%		61.69%	
P	2030		97.19%	90.73%	62.73%	62.23%
P		2370	84.27%		61.73%	

Table 2: Atmosphere and AO system throughput estimates
(Cut-on and cut-off wavelengths for spectroscopic (S) and photometric (P) bands shown in nm)

	Cut-on, nm	Cut-off, nm	R ave. %	3 ref. %
I band	700	853	86.99	65.82
Z band	855	1050	91.58	76.81
Y band	970	1120	94.42	84.18
J band	1100	1400	96.22	89.09
H band	1475	1825	97.13	91.62
K band	2000	2400	97.35	92.26

Table 3: Keck telescope transmission

Throughput Estimates

The throughput estimates for the current DAVINCI optical design are summarized in Table 6 for the imager and Table 7 for the IFS.

BACKGROUND AND ZERO POINT ESTIMATES

The resulting background magnitudes and zero point estimates for DAVINCI's imager and IFS are summarized in Table 4. The IFS narrowband filter passbands are shown in Table 5.

Passband	Cut-on, nm	Cut-off, nm	CWL, nm	Zero point	Background, mag./sq. arcsecond
Ia narrow band spectroscopic	700	784	742.1	25.71	19.57
I band photometric	700	853	776.5	27.34	19.33
Za narrow band spectroscopic	855	962	908.6	26.14	17.33
Z band photometric	818	922	870	27.16	18.45
Yb narrow band spectroscopic	1045	1120	1083	25.56	16.96
Y band photometric	970	1070	1020	26.92	17.28
Jb narrow band spectroscopic	1200	1310	1255	25.62	15.83
J band photometric	1170	1330	1250	26.96	16.04
Hc narrow band spectroscopic	1650	1746	1698	24.76	13.76
H band photometric	1490	1780	1635	26.95	13.76
K' band spectroscopic*	1956	2291	2124	25.45	14.08
K' band photometric	1956	2291	2124	26.39	13.86
Kc narrow band spectroscopic	2200	2310	2255	24.16	13.72
K band photometric	2030	2370	2200	26.35	13.42

Table 4: DAVINCI zero point and background estimates
(Cut-on and cut-off wavelengths at 50% transmission points, CWL = central wavelength,
** = no K' filter is planned for the IFS mode, values for reference only)*

Passband	Narrowband 1				Narrowband 2				Narrowband 3				Narrowband 4			
	Cut-on	Cut-off	CWL	Bandpass	Cut-on	Cut-off	CWL	Bandpass	Cut-on	Cut-off	CWL	Bandpass	Cut-on	Cut-off	CWL	Bandpass
Ia, Ib	700.00	784.15	742.08	84.15	776.50	853.00	814.75	76.50								
Za, Zb	855.00	962.25	908.63	107.25	952.50	1050.00	1001.25	97.50								
Ya, Yb	970.00	1052.50	1011.25	82.50	1045.00	1120.00	1082.50	75.00								
Ja, Jb, Jc	1100.00	1210.00	1155.00	110.00	1200.00	1310.00	1255.00	110.00	1300.00	1400.00	1400.00	100.00				
Ha, Hb, Hc, Hd	1475.00	1571.25	1523.13	96.25	1562.50	1658.75	1610.63	96.25	1650.00	1746.25	1698.13	96.25	1737.50	1825.00	1781.25	87.50
Ka, Kb, Kc, Kd	2000.00	2110.00	2055.00	110.00	2100.00	2210.00	2155.00	110.00	2200.00	2310.00	2255.00	110.00	2300.00	2400.00	2350.00	100.00

Table 5: DAVINCI IFS narrowband filter passbands
(Cut-on and cut-off wavelengths at 50% transmission points, CWL = central wavelength)

	%T						%R					
Surface	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**
Dewar Window												
Infrasil 302, 25 mm thick	99.23%	99.23%	99.23%	99.23%	99.23%	99.23%						
Coating, 2 surfaces	97.83%	97.84%	94.95%	95.83%	95.50%	96.77%						
Coronagraph Mask												
Infrasil 302, 2 mm thick												
Coating, 2 surfaces												
FM1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Cold stop	100.00%	100.00%	97.00%	97.00%	97.00%	97.00%						
Filter	90.00%	90.00%	80.00%	85.00%	85.00%	92.00%						
OAP2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM3 (hole to IFS)							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM4 (periscope)							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP3							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP4							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Totals												
%T	87.37%	87.37%	73.11%	78.40%	78.13%	85.69%						
%R							84.68%	90.18%	91.80%	93.17%	93.40%	94.33%
Combined	73.99%	78.79%	67.12%	73.05%	72.98%	80.84%						

Table 6: DAVINCI Imager Throughput Budget

	%T						%R					
Surface	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**	**I band**	**Z band**	**Y band**	**J band**	**H band**	**K band**
Dewar Window												
Infrasil 302, 25 mm thick	99.23%	99.23%	99.23%	99.23%	99.23%	99.23%						
Coating, 2 surfaces	97.83%	97.84%	94.95%	95.83%	95.50%	96.77%						
FM1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
OAP1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Cold stop	100.00%	100.00%	97.00%	97.00%	97.00%	97.00%						
Filter	90.00%	90.00%	80.00%	85.00%	85.00%	92.00%						
OAP2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Scale changer	78.47%	78.47%	78.47%	78.47%	78.47%	78.47%						
FM2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Lenslet	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%						
Reformatter							91.26%	93.75%	94.47%	95.07%	95.18%	95.58%
Collimator asphere							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM5							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Grating							60.00%	60.00%	60.00%	60.00%	60.00%	60.00%
Camera TMA												
1							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
3							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
%T	65.13%	65.14%	54.50%	58.45%	58.25%	63.88%						
%R							44.22%	49.25%	50.78%	52.09%	52.31%	53.20%
Combined	28.80%	32.08%	27.68%	30.44%	30.47%	33.99%						

Table 7: DAVINCI IFS Throughput Budget

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APPENDIX A: FLUX DENSITY ESTIMATES

The flux densities for the photometric passbands in J, H, and K are taken from Table 1 of Tokunaga and Vacca (2005). Values for the Bessel I and R bands are from Bessel (1979).Flux densities for the NGAO spectroscopic bands and the NGAO I, Z, and Y bands have been calculated using the model flux standard data set "alpha_lyr_stis_005.ascii" from the Space Telescope Science Institute (2009). Table 8 lists the flux densities in Janskys for each NGAO passband (Adkins, 2010).

Passband	**CWL, nm**	**Flux, Jy**
Bessel R band	640.00	3080
I band	776.50	2556
Bessel I band	790.00	2550
Z band spectroscopic	952.50	2232
Z band photometric	870.00	2301
Y band spectroscopic	1045.00	2077
Y band photometric	1020.00	2121
J band spectroscopic	1250.00	1596
J band photometric	1250.00	1560
H band spectroscopic	1650.00	1035
H band photometric	1635.00	1040
K band spectroscopic	2200.00	648
K band photometric	2198.00	645

Table 8: Passband central wavelength (CWL) and zero magnitude flux densities for Vega