DAVINCI Background and Zero Point Estimates

By Sean Adkins and Elizabeth McGrath

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INTRODUCTION

A spreadsheet has been developed for the NGAO DAVINCI instrument (DAVINCI_Backgrounds.xls) which provides predicted background magnitudes for the imager and integral field spectrograph (IFS) in each of the NGAO passbands, and also predicts the zero point magnitude for each passband.

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.

$$m_z = 2.5 \times \log\left(F_\nu \times P_F \times \frac{\Delta\lambda}{\lambda} \times A_{tel} \times T_{atm} \times T_{tel} \times T_{AO} \times T_{inst} \times QE \right) \qquad (1)$$

where:

F_ν = flux in Janskys

P_F = conversion from Janskys to photons/s/m^2 where 1 Jansky $= 1.51 \times 10^7$ photons/s/m^2

$\frac{\Delta\lambda}{\lambda}$ = bandpass, filter FWHM divided by the central wavelength of the filter

A_{tel} = collecting area of the telescope in m

T_{atm} = transmission of the atmosphere at zenith

T_{tel} = transmission of the telescope

T_{AO} = transmission of the AO system

T_{inst} = transmission of the instrument

QE = the manufacturer's specified detective quantum efficiency

i.e. a QE of 1 means each interacting photon generates 1 electron of signal

The detector quantum efficiencies used in each 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.

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.

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

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

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

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.

$$L_{pupil\_background\_tel} = L_{background\_tel} \times T_{AO} \times T_{inst} \qquad (4)$$

The irradiance at the detector $I_{detector\_tel}$ in photons/s/m^2 can be found using equation 5.

$$\begin{aligned} &I_{\det ector} = \pi \times L_{pupil\_background\_tel} \times \sin^2(\alpha) \\ &\text{where:} \\ &d = \text{the distance from the detector to the exit pupil} \\ &r = \text{the radius of the exit pupil} \\ &\alpha = \text{atan}\left(\frac{\text{r}}{\text{d}}\right) \end{aligned} \qquad (5)$$

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

$$\begin{aligned} &P_{background\_tel} = I_{\det ector} \times A_{pixel} \times QE \\ &\text{where:} \\ &A_{pixel} = \text{area of a detector pixel in m}^2 \end{aligned} \qquad (6)$$

Note that equation 5 applies for an exit pupil at a finite conjugate. For a telecentric system, where the pupil is at infinity the solid angle is equal to the subtense of the pixel on the sky, and the radiance is the same for all points in the image plane. The result is that we substitute equation 7 for equations 5 and 6 for a telecentric exit pupil like that provided for DAVINCI's imager and IFS.

$$\begin{aligned} &P_{background\_tel} = L_{pupil\_background\_tel} \times \theta_{\text{pixel}}{}^2 \times A_{pixel} \times QE \\ &\text{where:} \\ &\theta_{\text{pixel}} = \text{angular size of each pixel on the sky in arcseconds} \end{aligned} \qquad (7)$$

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 8.

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

(8)

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, 2004). 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 these differences is small. In this version the NGAO transmission values are used for telescope and atmosphere (see the next section) and the temperature of the telescope was set to match the assumptions in KAON-501. The transmission assumed for NIRC2 was adjusted to match the zero points used in the NIRC2 exposure time calculator (WMKO, n. d.), and the temperature of AO system was then set to make the computed K band background match the measured values. This required the AO system to be at a temperature of 13.8 ºC, a value that does not seem unreasonable based on recent information that the Keck II AO system runs warmer than expected. The resulting backgrounds are summarized in Table 1.

	NIRC2 measured value	**KAON-501, 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

The agreement for H band is reasonable, and the J band values are similar for KAON-501 and the DAVINCI background spreadsheet, but the discrepancy with the value measured for NIRC2 in J band remains. Also, 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.

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". 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 5 for the imager and Table 6 for the IFS.

BACKGROUND AND ZERO POINT ESTIMATES

The resulting background magnitudes and zero point estimates for each of DAVINCI's observing bands are summarized in Table 4.

Passband	Cut-on, nm	Cut-off, nm	CWL, nm	Zero point	Background, mag./sq. arcsecond
I band spectroscopic	700	853	776.5	26.48	22.13
I band photometric	700	853	776.5	27.42	22.13
Z band spectroscopic	855	1050	952.5	26.90	20.68
Z band photometric	818	922	870	27.24	21.28
Y band spectroscopic	970	1120	1045	26.49	17.05
Y band photometric	970	1070	1020	26.97	17.28
J band spectroscopic	1100	1400	1250	26.89	16.33
J band photometric	1170	1330	1250	27.05	16.04
H band spectroscopic	1475	1825	1650	26.40	13.79
H band photometric	1490	1780	1635	27.07	13.76
K band spectroscopic	2000	2400	2200	25.85	14.62
K band photometric	2030	2370	2200	26.52	14.78

Table 4: DAVINCI zero point and background estimates
(Cut-on and cut-off wavelengths at 50% transmission points, CWL = central wavelength)

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%	92.00%	92.00%	98.00%	98.00%						
Filter	90.00%	90.00%	80.00%	88.00%	85.00%	95.00%						
OAP2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM4 (hole to IFS)							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
FM5 (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%	69.34%	76.98%	78.94%	89.40%						
%R							84.68%	90.18%	91.80%	93.17%	93.40%	94.33%
Combined	73.99%	78.79%	63.66%	71.73%	73.73%	84.33%						

Table 5: DAVINCI Imager Throughput Budget

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%	92.00%	92.00%	98.00%	98.00%						
Filter	90.00%	90.00%	80.00%	88.00%	85.00%	95.00%						
OAP2							97.65%	98.53%	98.79%	99.00%	99.03%	99.17%
Scale changer	84.93%	84.93%	84.93%	84.93%	84.93%	84.93%						
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 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%
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	70.49%	70.50%	55.95%	62.12%	63.69%	72.13%						
%R							44.22%	49.25%	50.78%	52.09%	52.31%	53.20%
Combined	31.17%	34.72%	28.41%	32.35%	33.32%	38.38%						

Table 6: 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 7 lists the flux densities in Janskys for each NGAO passband.

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