Calibration of Photometry from WFCAM

Author:	Simon Hodgkin
Document Number:	VDF-TRE-IOA-00008-0010
Version Number:	Draft 0.1
Date:	16th September 2005

Contents

1 Introduction

2 UKIDSS Calibration Goals

3 Manual Calibration

3.1 Throughput

The total throughput of the system is easily computed. I have assumed the following:

- The effective area of the UKIRT primary mirror is 10.5m^2 (i.e. outer diameter 3.802m with an inner diameter of 1.028m). No attempt has been made to allow for the shadowing of the primary by the secondary, nor for any obscuration caused by the forward mounted camera itself.
- The spectrum for Vega is interpolated over the flux values given at the UKIRT WWW pages[1]
- The filter transmissions are from Hewett et al. 2005 but renormalized to give the relative throughput as a function of wavelength, rather than absolute transmission (i.e. the peak value is 1.0)

Thus the table below gives the estimated number of photons that would be incident on the primary mirror, assuming no atmosphere, multiplied by the relative transmission of the filter in each band. These are converted to detector counts using an average gain of 5.1. This would then give the zeropoint of the system in each filter if there were no losses due to the atmosphere, telescope and the instrument. Comparison with the measured zeropoints then give us the throughput for WFCAM+UKIRT+atmosphere.

Filter	Photons (mag=0)	Counts (mag=0, gain=5.1)	ZP (100% throughput)	ZP (Measured)	Implied Throughput
Z	3.8e10	7.4e9	24.80	22.98	19%
Y	3.0e10	5.9e9	24.55	22.81	20%
J	2.9e10	5.6e9	24.50	23.00	25%
H	3.0e10	5.8e9	24.53	23.24	30%
K	1.6e10	3.1e9	23.83	22.55	31%

Still to do: Compare to predicted throughput (Hewett et al. 2005)

3.2 Relative detector sensitivities

The four detectors are not uniformly sensitive. Figure 1 shows the variation in sensitivity between the detectors as measured in the twilight flatfields. The assumption is that the twilight sky is flat. The detector-to-detector gain is measured from the average counts on each detector.

[1] http://www.jach.hawaii.edu/UKIRT/astronomy/utils/conver.html

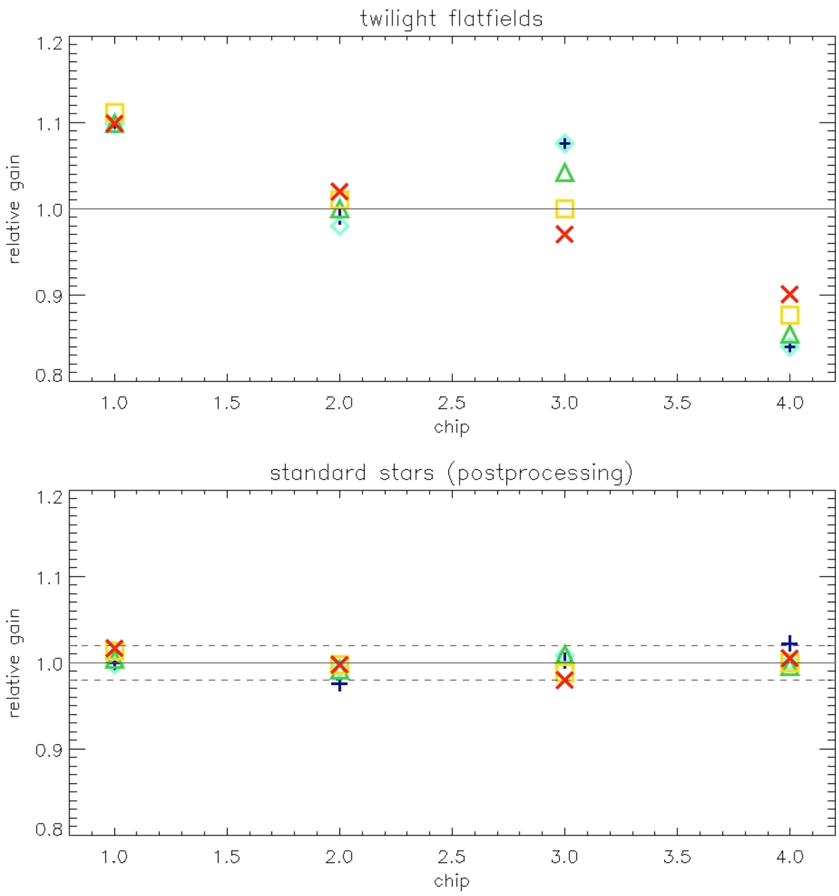

Figure 0: The top panel shows the detector-to-detector variation in gain, measured with respect to the mean of all 4 detectors, from twilight flatfield counts (ZYJHK).

Chip 1 is the most sensitive, while chip 4 is the least. Chip 3 shows the largest colour dependent scatter with a 10% change in relative sensitivity between Z and K (decreasing to the red). Chip 4 shows an increase to the red of about 8%.

The bottom panel shows the detector-to-detector gain variation measured post-pipeline processing, i.e. the residuals after gain correction (using the twilight flats). It is measured from the standard stars (their zeropoints). It illustrates that the gain correction calibrates each chip to within 2% of the mean, across all filters.

The ZPs derived for the night of 20050408 for each chip from the UKIRT faint standards are summarized in Table 1.

Filter	**Chip 1**		**chip 2**		**chip 3**		**chip 4**	
	ZP	**err**	**ZP**	**err**	**ZP**	**err**	**ZP**	**err**
Z	22.982	0.056	22.962	0.059	22.989	0.050	23.002	0.055
Y	22.810	0.018	22.803	0.016	22.821	0.015	22.810	0.020
J	23.003	0.021	22.998	0.020	23.005	0.026	23.005	0.021
H	23.241	0.017	23.238	0.016	23.226	0.019	23.246	0.014
K	22.557	0.016	22.547	0.021	22.535	0.021	22.557	0.016

3.3 *Extinction and night-to-night stability*

Two nights have sufficient standards to enable a good stab at measuring the extinction. The spread in airmass is not quite ideal. There is coverage up to χ=1.5 on April 8th and χ=1.7 on April 18th. All 4 detectors are combined to constrain a fit to

$$m_{MKO} - m_{inst} = ZP - k\chi$$

with the following results:

	20050408				20050418	
Filter	ZP	ΔZP	*k*	Δ*k*	ZP	*k*
J	23.003	0.015	0.036	0.012	23.004	0.055
H	23.237	0.024	0.031	0.021	23.236	0.033
K	22.548	0.024	0.050	0.020	22.535	0.024

These values are at the lower end of site testing results ***ref*** and maybe a figure. ** See comment on measurement of extinction from 2MASS.

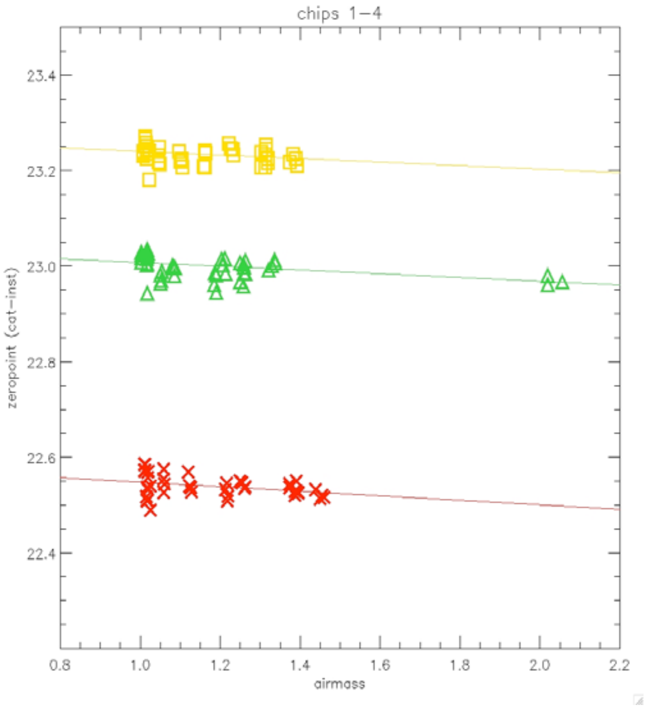

Figure 2: Extinction diagram for UT20050408

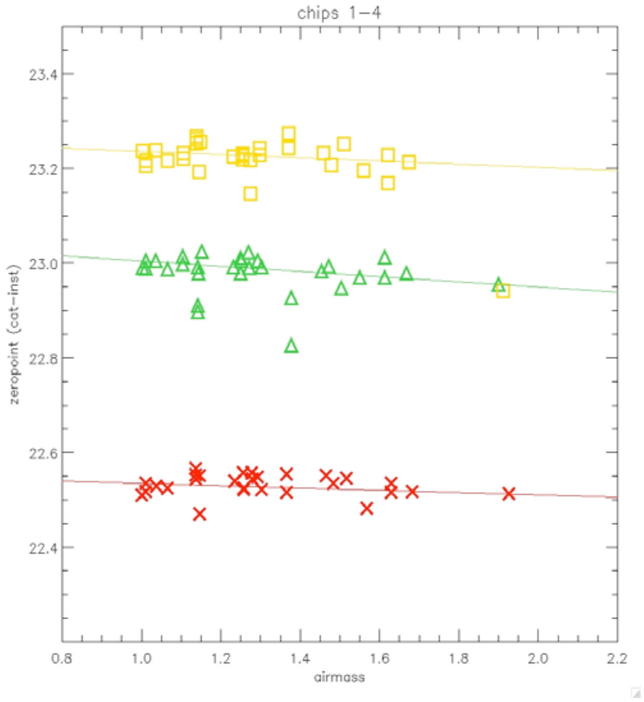

Figure 3: Extinction diagram for UT20050418

Note the very good agreement between the ZPs derived for these two nights.

3.4 *Nightly calibration*

In this section I plan to discuss the calibration we hope to get on a typical observing night. I will do this by analysing a couple of nights where we have observed hourly standards.

3.5 *WFCAM vs UFTI*

Figure * illustrates that there is essentially no colour term between the UFTI based UKIRT faint standard magnitudes, and the same objects measured through the WFCAM MKO filters and detector, as expected.

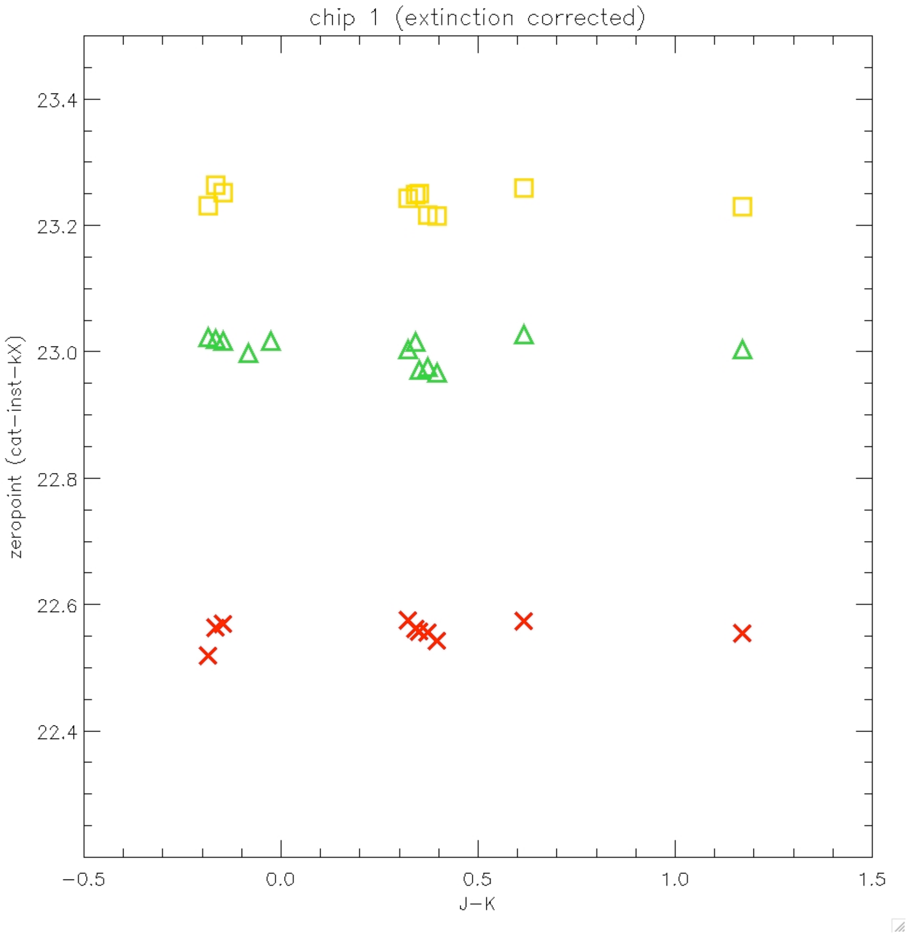

Figure 1 A plot of the offset between catalogue magnitude and (extinction corrected) instrumental magnitude for UKIRT faint standards on UT20050408 (JHK).

3.6 *Spatial Systematics*

3.6.1 From 2MASS

A simple analysis compares the WFCAM measured photometry against the 2MASS catalogue as a function of position. WFCAM sources are matched against 2MASS. The 2MASS photometry is converted to the WFCAM system using the colour equations listed elsewhere in this document. Only objects brighter than J=15,H=14.5,K=14 are used, they are also required not to be saturated in WFCAM. The offsets are combined for a whole night and averaged over a 5x5 grid in WFCAM pixel space. Each of these *jumbo-pixels* contains of order 100 stars. The rms scatter in each *jumbo-pixel* is about 0.025 mags and the standard error on the mean is about 0.0025 mag. The figure below shows the results for the analysis n the J-Band. H and K show similar results. The bottom line is I see no evidence for spatial variations at a level larger than 1%.

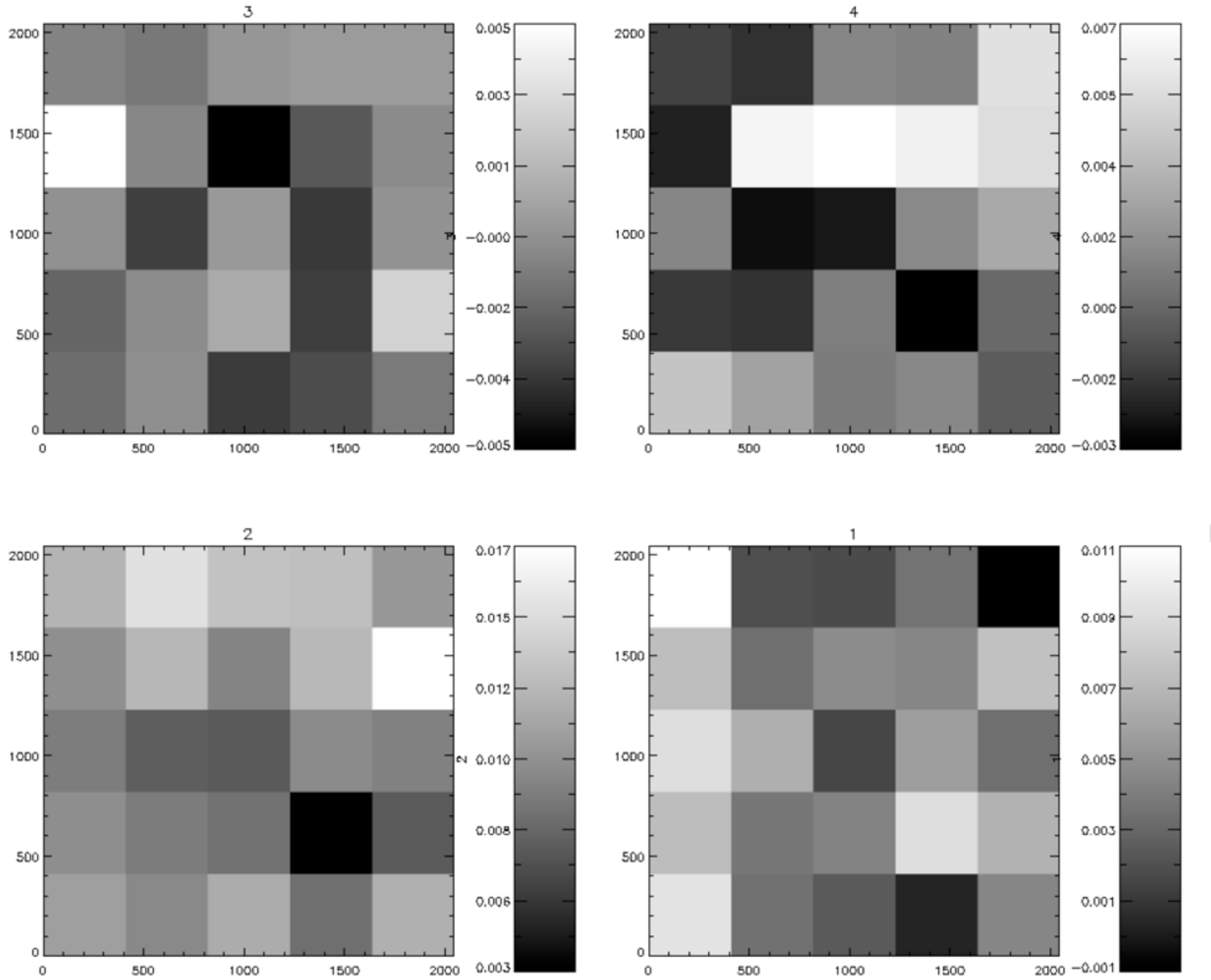

Figure 2 Spatial systematics in WFCAM in the J-band. For each chip this is the spatially-dependent difference between 2MASS and WFCAM magnitudes, binned into a 5x5 grid to improve statistics. The analysis is the stack of a whole night of observations (20050408). The scale is in magnitudes, and is WFCAM-2MASS, i.e. white=positive=the objects are fainter in WFCAM than 2MASS. The colorbars indicate the range of delta magnitudes for each chip.

3.6.2 From mesostep experiment

Not yet finished

4 Pipeline Calibration

4.1 Technique

The pipeline photometric calibration is currently based on 2MASS, via colour equations to convert to the WFCAM instrumental system. 2MASS solutions for every catalogued frame are generated and allow monitoring of effective ZPs at the ~few % level. The 2MASS–WFCAM colour equations are generated from a large number of catalogued 2MASS stars observed on the night of UT20050418. The solutions are average ones, and take no account of, for example, luminosity class. This has still been done via visual inspection.

$$Z_{WFCAM} = J_{2MASS} + 0.95(J-H)_{2MASS}$$
$$Y_{WFCAM} = J_{2MASS} + 0.50(J-H)_{2MASS}$$
$$J_{WFCAM} = J_{2MASS} - 0.075(J-H)_{2MASS} \quad \text{(dwarfs: -0.067 giants: -0.003)}$$
$$H_{WFCAM} = H_{2MASS} + 0.040(J-H)_{2MASS} \quad \text{(dwarfs: -0.080 giants: -0.065)}$$
$$K_{WFCAM} = K_{2MASS} - 0.015(J-K)_{2MASS} \quad \text{(dwarfs: -0.023 giants: +0.032)}$$

The shaded values are from Steve Warren's analysis of synthetic colours generated from template spectra (see Hewett et al. 2005) and Appendix B, which is a copy of an email circulated by Steve Warren.

The CASU derived system zero-points (corrected to unit airmass) for the main passbands are shown in the next table. Note also that in deriving these zero-points, all detectors have been gain-corrected to the *average* detector system. The CASU pipeline assumes a default extinction of 0.05 mags/airmass. Thus frame-to-frame variations in zeropoint include real variations in extinction.

Zero Point	Z	Y	J	H	K
WFCAM counts/s	22.8	22.7	23.0	23.3	22.6
WFCAM e^-/s	24.4	24.3	24.6	24.9	24.2
UFTI e^-/s	–	–	24.5	24.7	24.2

Table 1: WFCAM Zeropoints. The conversion to electrons assumes an average gain of 5.1.

4.2 Calibration of UKIRT faint standards

For the nights of 20050408 and 20050418 the difference between the published UFTI photometry for the UKIRT faint standards in the MKO system has been compared to the pipeline calibrated photometry. The idea is to see how good a job this first-pass photometric calibration is doing (Figure 3).

The average offsets (and associated standard deviations) are given in table **. The two most significant findings are:

- There is a residual offset in the H-band measurements for the standards at the 4% level. A closer look at the H_{WFCAM} to H_{2MASS} conversion is probably warranted, although the synthetic photometry implies a larger colour term, which would lead to a bigger offset in Figure *.
- The scatter in all filters is rather larger than one might hope for. At 2-4% it may well represent the limit to how accurately the WFCAM photometry can be calibrated with 2MASS. Residual spatial systematics and chip-to-chip variation may also be contributing to this scatter

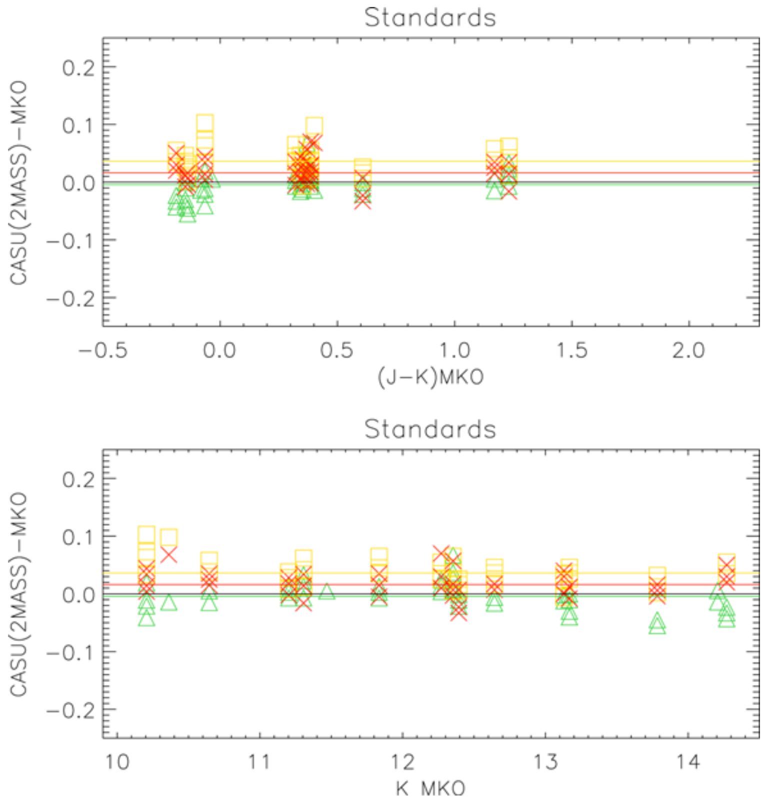

Figure 3 The differences between pipeline calibrated and UFTI magnitudes for UKIRT faint standards measured on 8th April 2005. J-band in green, H-band in yellow and K-band in red. Horizontal lines show the mean offset between the CASU and UFTI photometry.

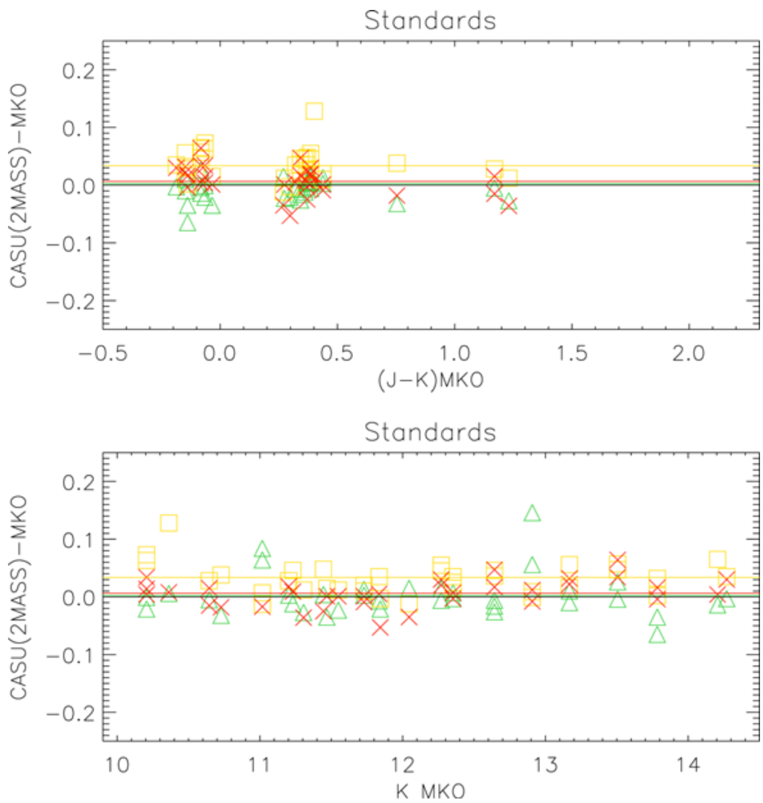

Figure 4 The differences between pipeline calibrated and UFTI magnitudes for UKIRT faint standards measured on 18th April 2005. J-band in green, H-band in yellow and K-band in red. Horizontal lines show the mean offset between the CASU and UFTI photometry.

	20050408		20050418	
FILTER	$WFCAM_{2MASS}$-MKO	σ	$WFCAM_{2MASS}$-MKO	σ
J	-0.004	0.022	0.002	0.036
H	0.036	0.022	0.034	0.028
K	0.016	0.020	0.006	0.023

Table 2: UKIRT faint standards calibrated by the WFCAM pipeline using 2MASS; differences with published photometry.

Still to do: direct comparison between UFTI and 2MASS systems for UKIRT faint standards. Is there an inherent offset in the 2MASS photometry?

4.3 Calibration of T dwarfs

Figure ** shows the differences between UFTI and WFCAM photometry for a series of L and T dwarfs. These stars were observed over a series of nights. Table ** summarises the numbers. As with the previous section, these stars were calibrated via the WFCAM pipeline using 2MASS stars measured simultaneously.

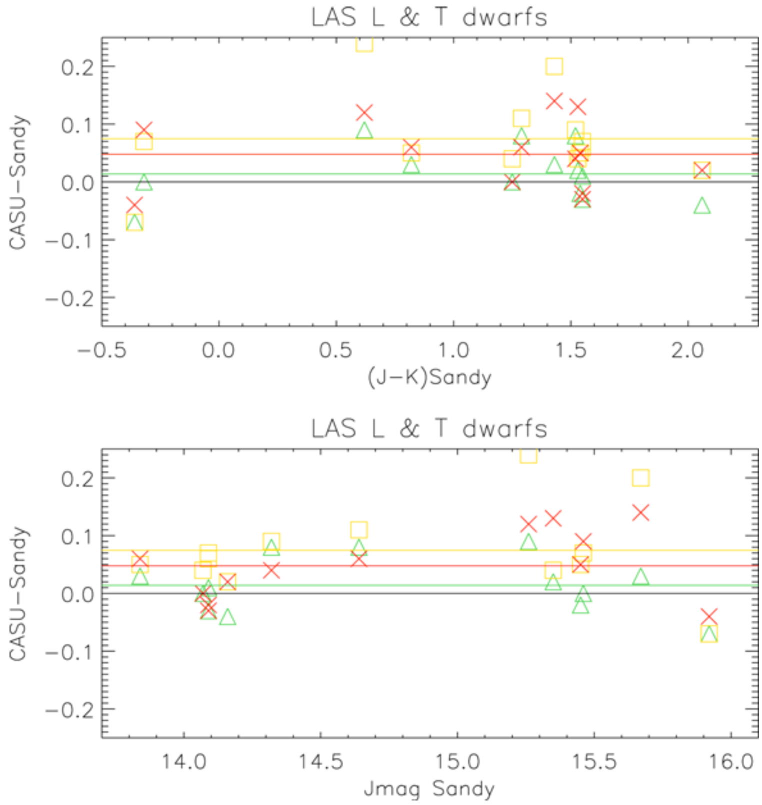

Figure 5 The differences between UFTI and WFCAM pipeline photometry for a series of L and T dwarfs measured as part of SV, as a function of colour (top) and J magnitude (bottom). J-band is green, H-band is yellow, K-band is red.

Principally, there may again be an offset at H, and perhaps at K. However these results are dominated by the very large scatter in all filters. It's not clear why the scatter should be as large as 5-8%, given that these stars are not significantly fainter than the standards. However there are a couple of factors which may come into play:

- They are observed across a number of nights. It's important to exclude potentially non-photometric data from this analysis (not yet done).
- They have spectra that are significantly different from the standard stars.
- There is a trend for increasing scatter with increasing magnitude (do we have any estimate for the errors on the original photometry?)

FILTER	$WFCAM_{2MASS}$-MKO	σ
J	0.014	0.049
H	0.075	0.078
K	0.048	0.061

Table 3: L and T dwarfs calibrated by the WFCAM pipeline using 2MASS; differences with UFTI photometry.

4.4 Extinction

In this section I will attempt to measure the extinction from the 2MASS data to compare with my derivation from the UKIRT faint standards.

5 Towards a system of WFCAM secondary standards

This section will describe how the WFCAM secondary standards will be calibrated from the UKIRT faint standards and collected together to form a community resource. Ultimately a paper.

6 Summary

6.1 Remaining uncertainties

6.2 Proposed changes to observing strategy?

A. List of Standards

B. Synthetic Photometry

Hi Mike

Here are some comments on your WFCAM-2MASS colour equations, based on an analysis of the synthetic colours. I get mostly pretty good agreement for dwarfs, but with a few odd effects to note.

Steve

I confined myself to objects of luminosity class III and V in the BPGS, as well as the additional M dwarfs from Sandy, in Hewett et al. (2005).

1. Regarding the Z equation you got:

$$Z\_wfcam - J2 = 0.95*(J2 - H2)$$

where J2, H2 are 2MASS. Below I have plotted dwarfs as crosses and giants as green circles. The red line is your relation, which is mostly a good fit. But two comments i) the relation goes very badly wrong for M dwarfs cooler than M3 (become way redder in Z-J2), ii) you can see from the plot that it seems to turn down very sharply at A0, so this is something to watch out for. Some of these colours seem quite odd e.g. A stars with negative Z-Y or Y-J:

Z-Y	Y-J	class	BPGS no.	name
-0.069	-0.120	B9V	13	HD189689
-0.027	-0.094	A0V	14	THETA-VIR
-0.023	-0.084	B9V	15	NU-CAP
-0.056	-0.021	A2V	16	HR6169
-0.022	-0.010	A1V	17	HD190849A
-0.013	-0.044	A2V	18	69-HER
-0.009	0.037	A3V	19	HD190849B
-0.001	-0.050	A0V	20	58-AQL
-0.029	-0.025	B9V	21	78-HER
-0.015	0.127	A7V	22	HR6570
0.028	0.009	A2V	23	HD187754
0.012	0.083	A5V	24	THETA1-SER
0.020	0.087	A5V	28	HD190192

2. For the Y band you got

$$Y\_wfcam - J2 = 0.50*(J - H)$$

The analogous plot is below, and you see the same behaviour i.e. cool M dwarfs very red in Y-J2, and a turndown at zero colour. However in this plot the scatter looks worse, and the dwarfs and giants may follow different relations.

I think it would be justified to worry about the usefulness of the synthetic analysis for the Y band which is probably the band where the BPGS calibration is worst. Nevertheless there is a hint that the relation for dwarfs is somewhat steeper than your value.

3. J band, you got

$$J\_wfcam - J2 = -0.075*(J2 - H2)$$

I get somewhat different behaviour for dwarfs and giants

```
    J_wfcam  - J2 =   0.01-0.067*(J2-H2) dwarfs
    J_wfcam  - J2 =   -0.01-0.003*(J2-H2) giants
```

4. H band, you got

```
    H_wfcam  - H2 =  0.075*(J2 - H2)
```

I get pretty good agreement with that (0.080 for dwarfs and 0.065 for giants)

5. K band, you got

```
      K_wfcam  - K2 = - 0.015*(J2 - K2)
```

The K band is the band where the giants and dwarfs differ the most.

I get

```
K_wfcam  - K2 = - 0.023*(J2 - K2) (dwarfs)
K_wfcam  - K2 =  -0.01 + 0.032*(J2 - K2)    (giants)
```

These relations are somewhat non-linear, and so the colour term depends on the colour range selected.