On the calibration of WFCAM data from 2MASS

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1 Introduction

The requirement on VDFS is to photometrically calibrate WFCAM data to 2%.

Nikolaev et al. (2000) claim that the 2MASS all-sky point-source catalogue has photometry that is globally consistent to $\sim$ 1%. In Figure 7 of Nikolaev et al., the scatter in the differences between 2MASS and Persson/UKIRT standards is ± 0.02 mag, which includes some intrinsic scatter due to errors in the primary standards.

In this report, We address how well we can calibrate WFCAM images from 2MASS data alone.

All data discussed in this document have the same calibration as that released in UKIDSS DR1.

2 Method for routine calibration

The magnitude zeropoint is derived for each frame from measurements of stars in the 2MASS point source catalogue (PSC). We assume that there exists a simple linear relation between the mean J–H/J–K(2MASS) colour and the WFCAM–2MASS colour. This relation should go through (0,0), i.e. for an A0 star, Z=J=H etc. For each field observed with WFCAM, the pipeline derives the best fit relation to:

$$ZP_{\text{WFCAM}} + m(inst)_{\text{WFCAM}} + k\chi - m_{\text{2MASS}} = CT(J_{\text{2MASS}} - H_{\text{2MASS}}) + const \quad (1)$$

for each detector, solving for the zeropoint ZP. $m(inst)_{\text{WFCAM}}$ is the aperture corrected instrumental magnitude, $-2.5\log(\text{counts/sec})$. CT are the colour coefficients and have been solved for by combining data from many nights. k is a default value for the extinction (=0.05 in all filters) and χ is the airmass. The best fit ZP is combined across all four detectors to give a single, per-pointing, Zeropoint. The currently determined colour equations are listed below.

$$Z_w = J_2 + 0.95(J_2 - H_2) \quad (2)$$
$$Y_w = J_2 + 0.50(J_2 - H_2) \quad (3)$$
$$J_w = J_2 - 0.075(J_2 - H_2) \quad (4)$$
$$H_w = H_2 + 0.04(J_2 - H_2) - 0.04 \quad (5)$$
$$K_w = K_2 - 0.015(J_2 - K_2) \quad (6)$$

The actual step-by-step procedure is detailed below for completeness:

1. Search local version of 2MASS PSC for objects overlapping with a single detector and write a temporary file containing RA, DEC, J, H, K.

2. Select 2MASS sources with $0.0 \leq$ J–K ≤ 1.0 and SNR(2MASS) > 10, unless less than 25 2MASS sources, then don't use colour cut.

3. Distortion correct WFCAM photometry (using flux from the APER3 aperture: 1 arcsec radius), to account for the radially changing pixel scale and apply aperture correction to obtain instrumental magnitude.

4. Simple binary search in RA, DEC performed to find close matching 2MASS-WFCAM pairs. Only WFCAM sources which are stellar and unsaturated are used for the object matching

5. For a match, the 2MASS photometry is converted into the WFCAM system using the latest version of the colour equations (see Equations 1–5). A nominal extinction correction is applied (assuming default extinction of 0.05 mags/airmass in all passbands) to the WFCAM magnitude.

6. The WFCAM ZP for each star is then simply calculated from the difference between the reference (corrected 2MASS) and instrumental magnitudes. The detector ZP is calculated as the clipped median of all the per-star ZPs.

7. THE WFCAM ZP for the pointing is the median over all 4 detectors: MAGZPT. The error on the ZP is 1.48 * MAD (ZPDET): MAGZRR.

8. The pipeline also estimates the nightly zeropoint and an associated error which can be used to guage the photometricity of a night. NIGHTZPT is simply the median of all ZPs measured within the night, and NIGHTZRR is the interquartile range for the night.

3 Calibration of the JHK bands: observations of the UKIRT faint standards

The UKIRT faint standards[1] represent a homogenous sample of photometric calibrators with a good pedigree. Currently, observations with WFCAM are interspersed, approximately two-hourly, with observations of UKIRT faint standard stars. In this section we compare published photometry for the UKIRT faint standards with photometry derived from the pipeline using the 2MASS calibration.

19 photometric nights from semesters 05A and 05B were identified by visual examination of the DQC plots[2] from a total sample of 103 nights. A number of frames, identified by isolated significantly discrepant zeropoints in a plot of MAGZPT versus time, were found to be of poor quality, and were rejected from further analysis. Typically they show streaking (the telescope was moving during the exposure), or other artefacts. The photometric zeropoints for these nights all have $\sigma \leq 0.03$ mag (derived from the median absolute deviation), see Figure 1.

We restrict the analysis to a study of the UKIRT Faint Standards measured on these 19 nights. In summary, the data comprise 600 images (catalogues) in J, H and K filters spread over 19 nights containing 46 unique standard stars. The UFTI standards have published photometric errors in the range 0.01–0.02 mag for most stars.

[1] http://www.jach.hawaii.edu/UKIRT/astronomy/calib/phot_cal/fs_izjhklm.dat
[2] http://casu.ast.cam.ac.uk/wfcam/

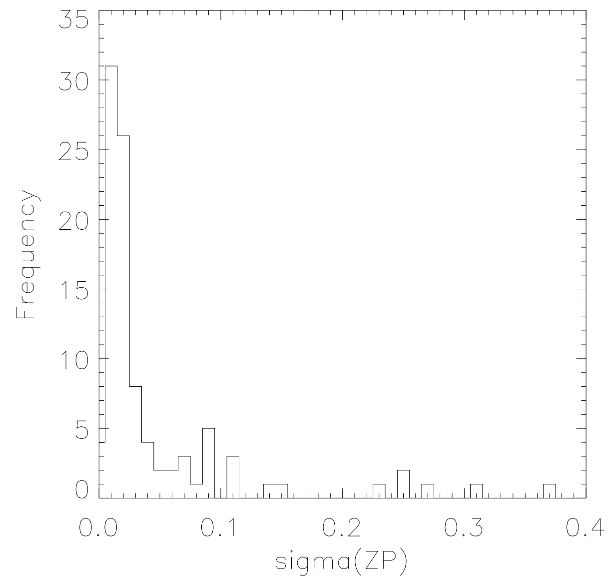

Figure 1: A histogram of the frequencey of photometric nights observed with WFCAM as measured by the standard deviation in the zeropoints for the nights. For each night we count the maximum of σ_J, σ_H, and σ_K. The entire sample comprise 103 nights of data measured in semesters 05A and 05B.

3.1 Comparison with UFTI measurements

In Figures 2, 3 and 4 we plot the differences between the 2MASS calibrated magnitudes and the UFTI magnitudes for the UKIRT Faint Standards. We show the by-night (a single median zeropoint is used for the entire night) and by-frame calilbrations on the same plots.

We make the following observations:

1. The per-frame calibration achieves 1σ errors of 2% for the UFTI standard stars.
2. The per-night calibration is slightly poorer, with 1-sigma errors of 2.5%. This slightly increased scatter could have a number of causes: (i) non-photometric behaviour within apparently photometric nights, (ii) residual contamination of the sample of images by some with trailing or other image quality issues.
3. The J-band calibration has no offset with respect to the UFTI system. There is no obvious trend with J-band magnitude, seeing, ellipticity or airmass. There is a hint that there may be a residual colour term in the second panel. Alternatively, looking at the first panel, we may actually be seeing small shifts between our measurements and the UFTI photometry on a star by-star basis. We note that the UFTI standards have quoted errors of around 1–2% and typically 2–4 measurements per star.
4. The H-band calibration is systematically off by 1%. We suggest that this is caused by a minor 1% error in the correction applied to the 2MASS stars (currently there is an H-band, colour-independent offset of 4% applied, this should probably be reduced to 3%)[3]. Again we see no obvious trend with colour, but there are systematic shifts between the stars.

[3] http://www.ast.cam.ac.uk/vdfs/docs/reports/sv/index.html

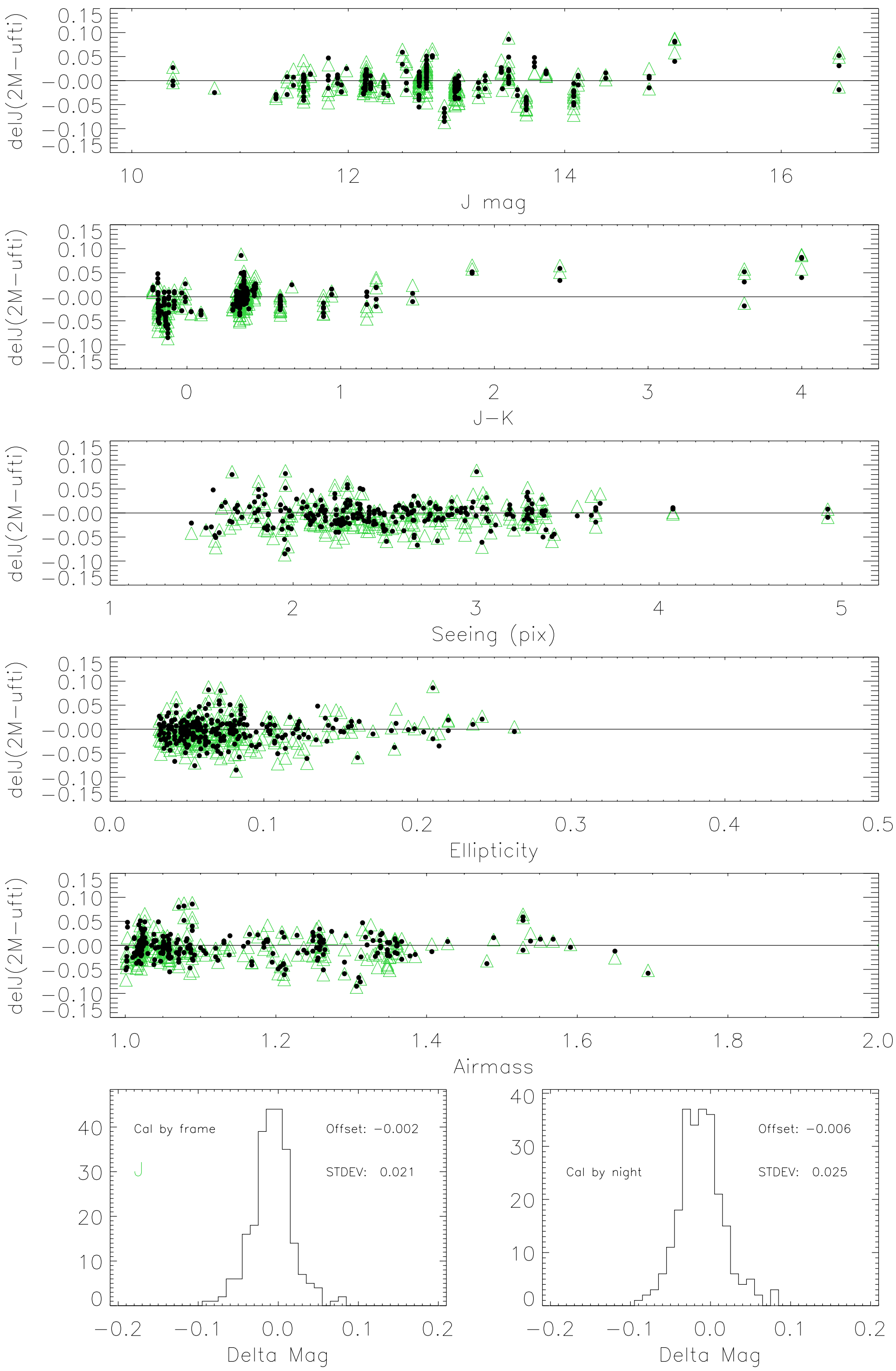

Figure 2: J-band Δmag (2MASS calibration–UFTI) for UKIRT faint standard stars observed with WFCAM. Measurements calibrated with a per-frame zeropoint, MAGZPT, are black dots, while measurements calibrated with a by-night zeropoint are green triangles. The histograms at the bottom collapse the data along the Y-axis for the by-frame (LHS) and by-night (RHS) calibrations.

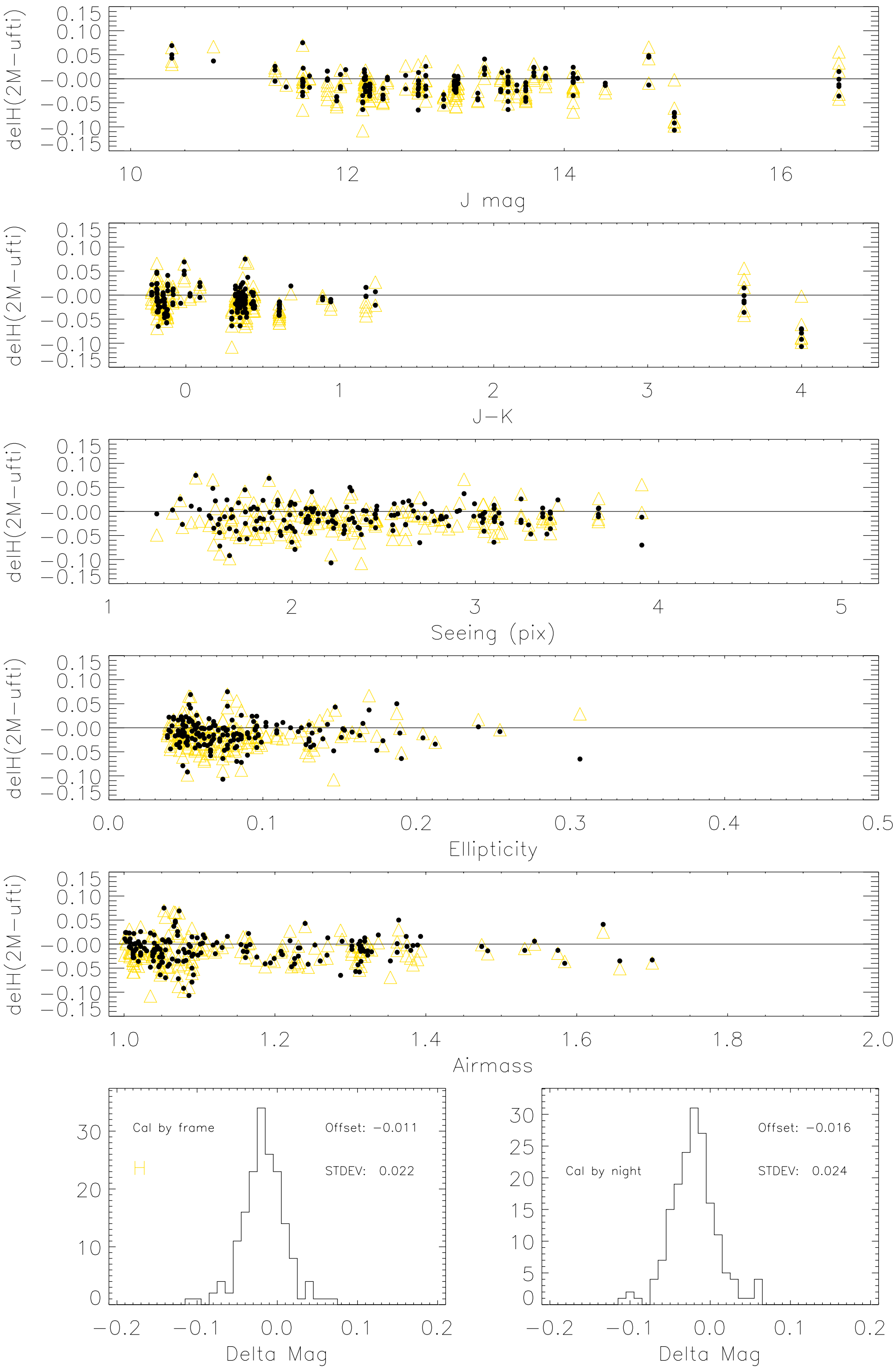

Figure 3: H-band Δmag (2MASS calibration–UFTI) for UKIRT faint standard stars observed with WFCAM. Measurements calibrated with a per-frame zeropoint, MAGZPT, are black dots, while measurements calibrated with a by-night zeropoint are yellow triangles. The histograms at the bottom collapse the data along the Y-axis for the by-frame (LHS) and by-night (RHS) calibrations.

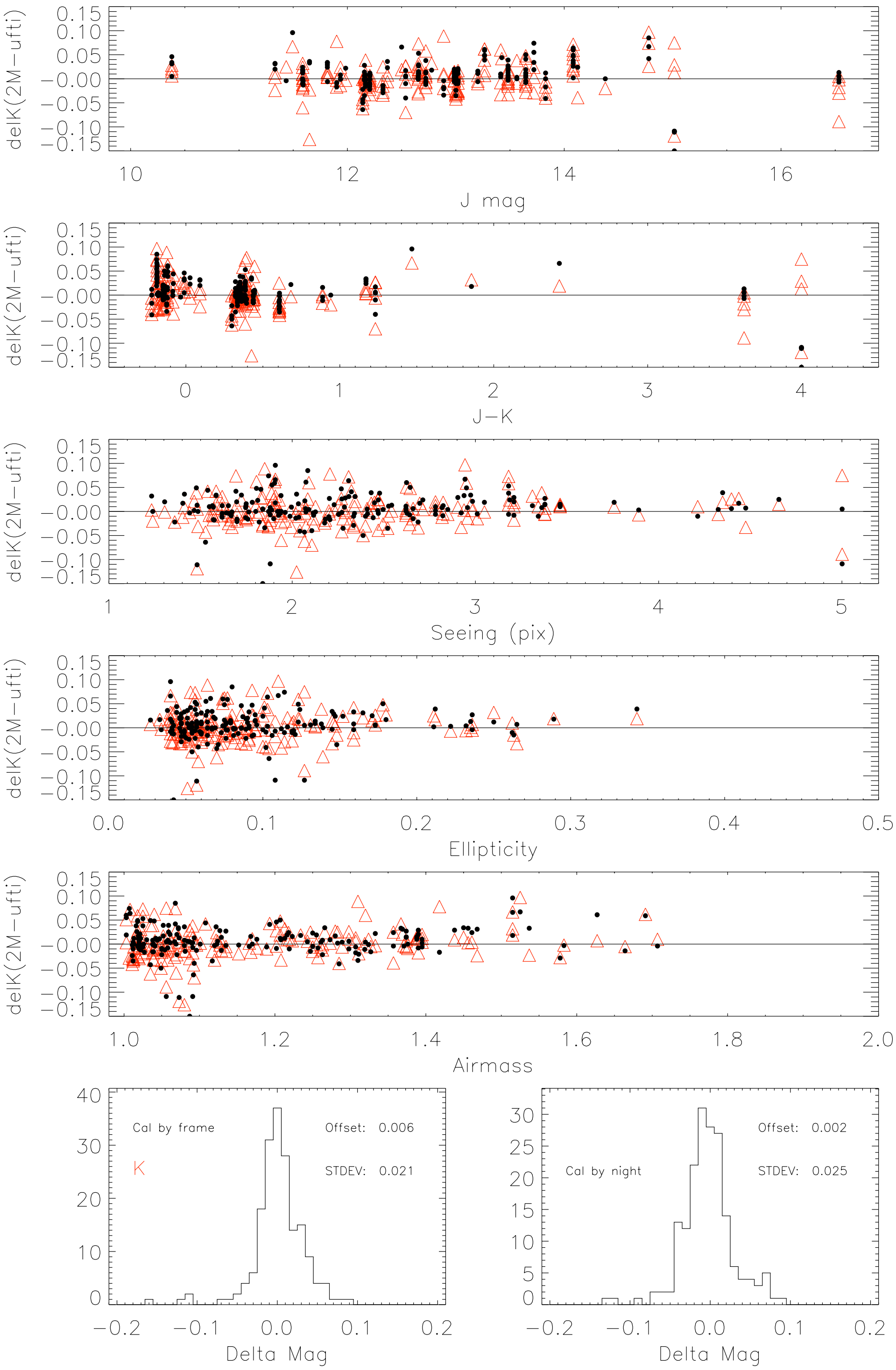

Figure 4: K-band Δmag (2MASS calibration–UFTI) for UKIRT faint standard stars observed with WFCAM. Measurements calibrated with a per-frame zeropoint, MAGZPT, are black dots, while measurements calibrated with a by-night zeropoint are red triangles. The histograms at the bottom collapse the data along the Y-axis for the by-frame (LHS) and by-night (RHS) calibrations.

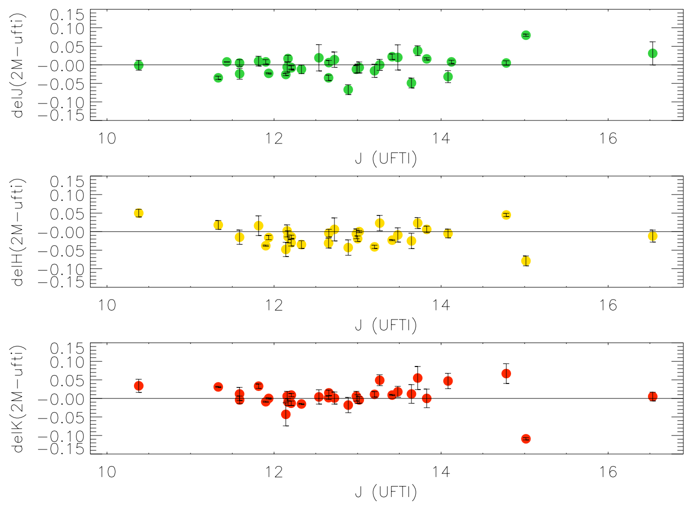

Figure 5: Median Δmag (2MASS calibration - UFTI published magnitude) plotted as a function of J(UFTI) for the J, H and K filters (top to bottom).

5. In the K-band we see no systematic offset nor colour-dependent trend. There are significant offsets in some of the UKIRT faint stanards.

In summary, this preliminary comparison with UFTI indicates that on photometric nights, a 2MASS calilbration can be used to calibrate WFCAM observations measure in J, H and K filters into the UFTI(MKO) system to 2%. This is very like the level of agreement found by Nikolaev et al., and as with their analysis, our analysis may be limited by errors in the fiducial measurements of the standard stars. In the next section we attempt to minimize these effects and see if we can do better than 2%.

3.2 Repeatability of fiducial stars

In the previous section, we found that there are offsets between the published UFTI(MKO) magnitudes for some of the UKIRT faint standards, and those we derived from an analysis based on observations of 2MASS stars using WFCAM(MKO).

In order to remove this effect from our analysis, and to examine the repeatability of the measurements of a set of fiducial starss, we corrected the magnitudes of the faint standards to minimise the dispersion in the WFCAM(MKO) system. UFTI J, H and K magnitudes were therefore re-calibrated from the measured offsets (only for stars with ≥ 3 measurements in the filter). The by-frame calibration was then re-analysed as previously. The results are shown in Figure 6.

This analysis shows a significant reduction in scatter in the 2MASS calibration of the UKIRT faint standards. After correcting the 2MASS faint standards, we can calibrate to $< 2\%$. Figure 6 displays the standard deviations measured from the distributions of Δmag (with no clipping); a robust estimate of the standard deviation, derived from the median absolute deviation, puts the standard deviation in each filter to be 0.010 mag.

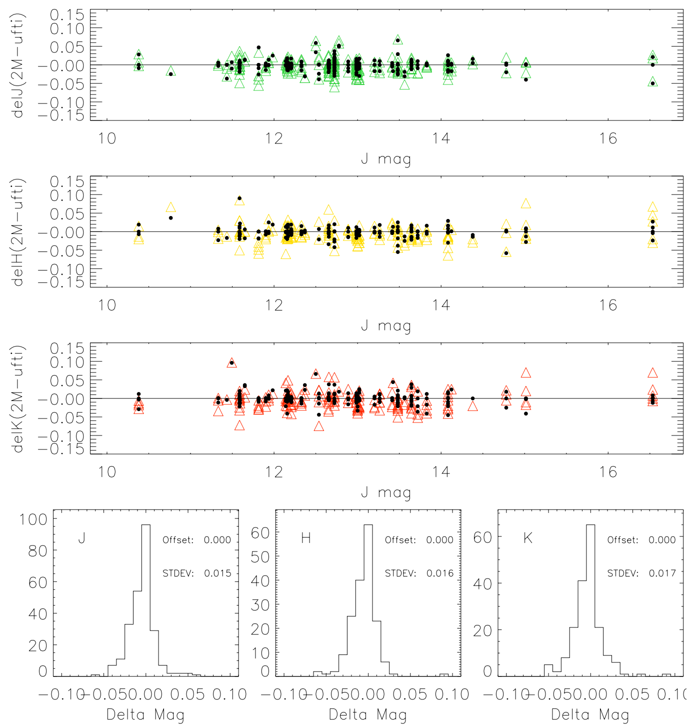

Figure 6: Δmag (2MASS calibration–recalibrated UFTI mags) for UKIRT faint standard stars, i.e. after applying the offsets shown in Figure 5. J, H and K from top to bottom. Measurements calibrated with a per-frame zeropoint, MAGZPT, are black dots, while measurements calibrated with a by-night zeropoint are coloured triangles. The histograms at the bottom collapse the data along the Y-axis. The standard deviation for each filter/histogram is shown on the plot.

4 Calibration of the Y and Z bands

Unlike J, H and K, there are no established standard stars for the Z and Y filters. The following analysis makes use of datasets extracted from the WFCAM Science Archive. For the Y-band analysis, the data are selected from the Large Area Survey with coverage in all 4 bands (YJHK). For the Z-band analysis, the data are selected from the Galactic Cluster Survey. Quality control cuts are enforced such that $\sigma(\mathrm{Y}-\mathrm{J}) < 0.04$, $\sigma(\mathrm{J}-\mathrm{H}) < 0.04$, and $\sigma(\mathrm{H}-\mathrm{K}) < 0.04$. We also require the source to be stellar (mergedclassstat= -1), unsaturated (J$>$ 13.0) and bright (J$<=$15.0).

4.1 The LAS Y-J vs J-H diagram

Plotting Y–J against J–H, there is a clear offset for the bluest stars; they don't go through $[0, 0]$. There is also a systematic shift between the data and the Hewett synthetic photometry (blue crosses).

The source of this can be traced back to the use of the linear colour relation between 2MASS and WFCAM instrumental (above) when deriving the Zeropoints: $Y_{\mathrm{wfcam}} = J_{\mathrm{2MASS}} + 0.50 * (J-H)_{\mathrm{2MASS}}$. A plot of $Y_{\mathrm{wfcam}} - J_{\mathrm{2mass}}$ vs $(J-H)_{\mathrm{2mass}}$ (Figure 7 (right panel)) demonstrates that the relation is not linear. The colour relation used in the conversion is overlaid on the

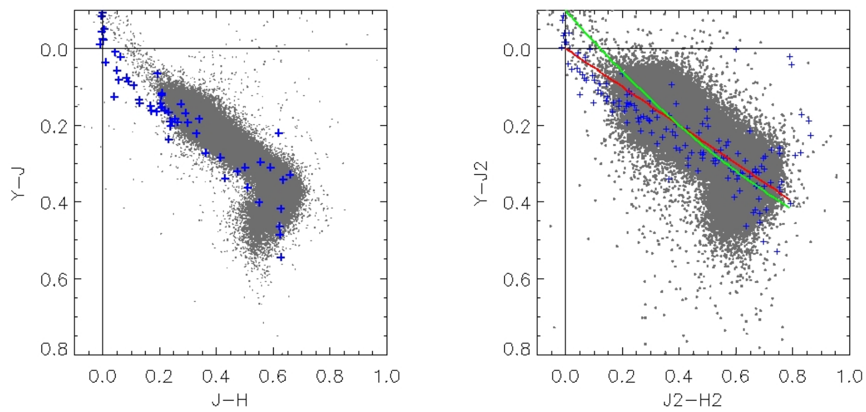

Figure 7: **Left:** The Y–J vs J–H diagram for bright point sources in the UKIDSS LAS. Synthetic photometry from Hewett et al. 2006 is plotted with a blue cross. **Right:** The $\mathrm{Y_{WFCAM}}$–$\mathrm{J_{2MASS}}$ vs $\mathrm{(J–H)_{2MASS}}$ diagram for bright point sources in the UKIDSS LAS. Synthetic photometry from Hewett et al. 2006 is plotted with a blue cross. The current colour equation used in the pipeline is shown in red: it is a very good fit to the red stars. A 'by-eye' polynomial fit is show in green ehich attempts to give more weight to the A0 stars.

plot for illustration (in red), as well as a by-eye estimate of a polynomial relation (in green). The result would be a shift of approximately 0.1 to the Y-band zeropoint, between the instrumental WFCAM system, and a VEGA system, whereby the colours of an A0 star are 0.0 between all passbands. Thus the WFCAM system is currently offset in the Y-band by 0.1 with respect to Vega.

4.2 The GCS Z-J vs J-H diagram

In Figure 8 we plot the Z–J vs J–H diagram for the UKIDSS GCS survey, selecting only fields with E(B-V)<= 0.2 in order to remove the effects of reddening. As with the Y-band, we see an offset for the bluest stars, of around 0.05 magnitudes.

5 Internal consistancy of the photometry

A simple way to test the homogneneity of the photometric calibration is to look at the dispersion in the median colours of high galactic latitude WFCAM survey fields. In Figure 9 we plot the per-frame offset in colour from the median for all UKIDSS GCS colours. We plot it as a function of E(B–V) for the Y–J, J–H and H–K colours. The frame colour is highly dependent on the galactic reddening. On the right hand side we plot the frequency histograms for high and low reddening cases. Where reddening is low, $\sigma_{\mathrm{colour}} < 0.03$ in all colours, showing the uniformity of the WFCAM photometry.

6 Effect of galactic extinction

Although we have attempted to mitigate againt the pernicious effects of interstellar reddening on the WFCAM calibration, by employing a colour restriction to the calibrators,

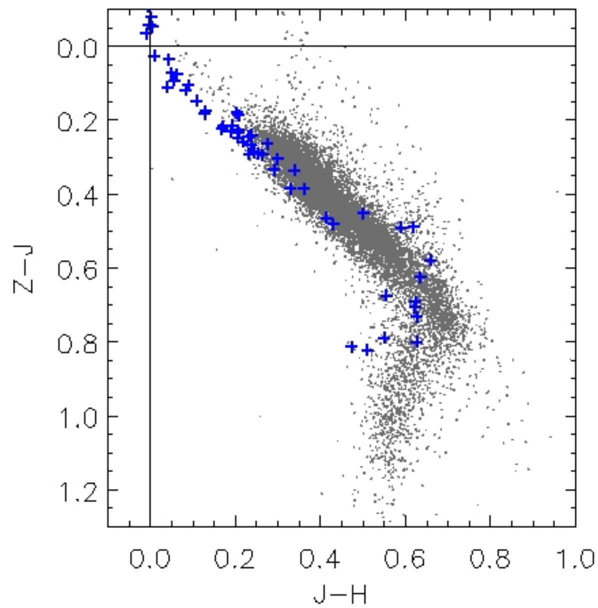

Figure 8:

we might expect residuals to exist. This is largely because the stellar population sampled by 2MASS varies quite significantly as we move to low galactic latitudes. In Figure 10 we plot the deviation in zeropoint (from the median) versus E(B–V) (corrected according to Bonifacio et al. 2000) for the Z, Y and J filters. A significant, E(B-V) dependent, correction will be required for the Z and Y filters. The effect is less than 1% in the J, H and K filters. These corrections have been tested and will be introduced into the next iteration of the calibration.

7 Summary

A photometric calibration based on 2MASS offers the following advantages:

- It meets the requirements for the UKIDSS surveys.
- The calibration is homgenous across all WFCAM observations.
- The system is well matched to existing external JHK photometric systems (e.g. the UFTI photometry of the UKIRT faint standards).
- A per-frame calibration derived from the science images is less sensitive to variations in the photometricity of the night.
- The calibration is simple to derive and apply.

Issues which are currently being addressed include:

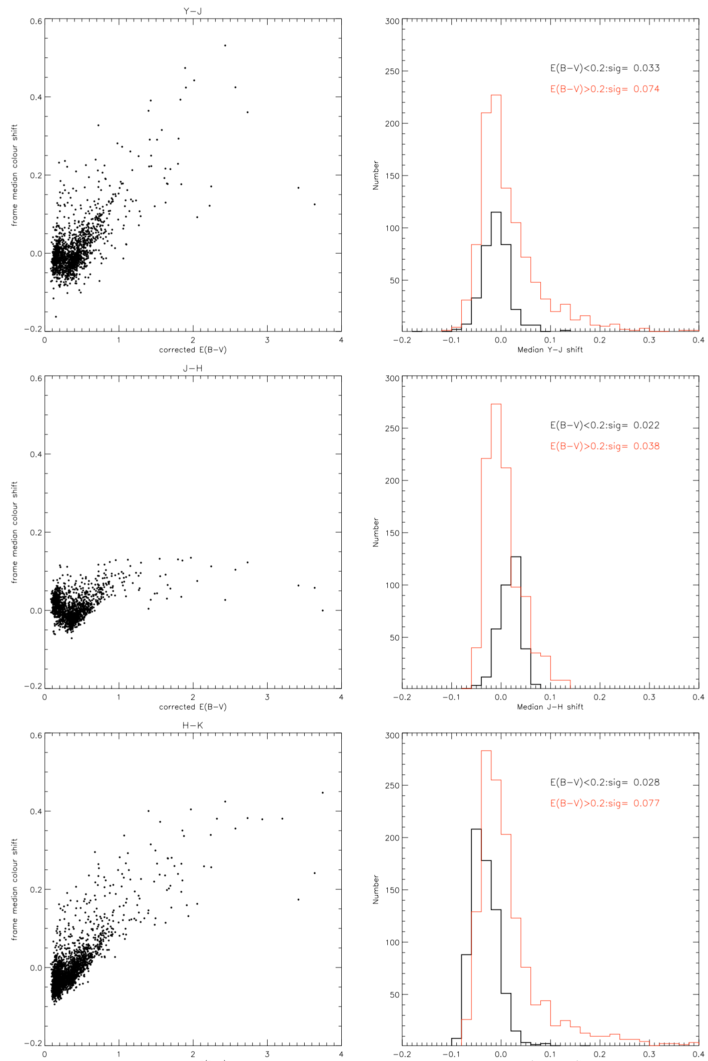

Figure 9: Frame-by-frame colour shifts (from the median frame) in the UKIDSS GCS pltted as a function of E(B–V). On the right, frequency histograms are shown for samples selected above (red) and below (back) E(B–V)=0.2.

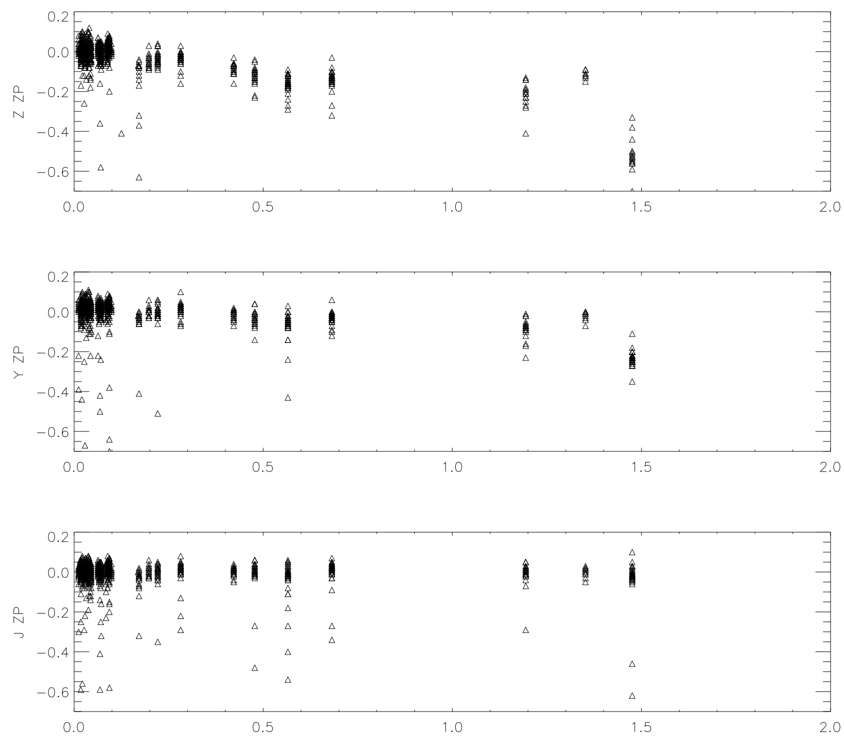

Figure 10: Δ zeropoint versus corrected E(B–V) for the ZYJ filters for all photometric nights in 05A and 05B.

- The external calibration of the Z and Y bands currently shows offsets of 0.05 and 0.10 magnitudes for the bluest stars in colour-colour diagrams. Future calibrations will offset the Z and Y zeropoints to bring them in line with the Vega system.
- The 2MASS calibration is sensitive to the effects of interstellar reddening. A first order correction has been derived and tested and will be implemented in future calibrations. Note that this effects a very small fraction of the WFCAM survey area.