Title: Photometric Calibration for WFCAM data

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Document Number: VDFS-****-****-****
Version Number: 1
Date: 05/06/2003

1. Introduction

The purpose of this document is to discuss the photometric calibration of data from the planned UKIRT Wide Field Camera (WFCAM) in the context of the Vista Data Flow System (VDFS). The first draft of this document has been prepared to coincide with the WFCAM observing workshop (held at ROE during 12-13/6/2003).

The specific aims of the document are:

- to describe in detail factors which could affect the photometric calibration of data taken with WFCAM.
- to suggest techniques for investigating the photometric performance of the instrument and telescope during commissioning.
- to propose nightly observing strategies which will enable photometry to be measured to the accuracy required by the UKIDSS science programmes.

This document does not discuss in any detail post-facto calibration of WFCAM data via overlapping or bootstrapping techniques, although we do raise the issue. It is intended that this document will evolve to incorporate the results of discussion around the issues raised (and omitted!) herein.

2. State of Play

Hambly et al. (2001) have already written a detailed document discussing WFCAM calibration and in particular investigating the need to do preparatory observations with existing instrumentation. The resulting detailed discussion between the authors came to the following conclusions:

1. The majority of the UKIRT Faint Standards (Hawarden et al. 2001) will be observable by WFCAM. Standard fields can therefore be tied to this system. Also some of the Persson et al. (1998) standards have been re-observed with UFTI and put on the same system.

2. Standard fields are preferred to standard stars - more objects beats down the noise and allows for spurious variable objects. They also allow the investigation

of spatial systematics in the calibration and include a bigger colour range to enable determination of the colour equations.

3. The spatial systematic detector calibration effects are best modelled by 'meso-stepping' a dense stellar region across the detector. This region need not be a calibrated standard field.

4. There is not much to be gained from using the 2MASS standards – the filter pass bands are quite different (and this difference is variable over time as they include H_20 bands). The JHK filters on WFCAM are part of the MKO filter set – i.e. they are very similar to the UFTI filters and the sensitivity function will therefore depend only on QE differences between the detectors which look to be small (Casali ****).

5. There is no strong requirement to pre-observe fields with UFTI/UIST – all calibration can and should be done with WFCAM.

The suggested strategy was:

1. Check the spatial performance of the telescope + detector + reduction system, using a dense stellar region - e.g. a globular cluster.

2. Choose suitable calibration fields (spaced at suitable intervals in Right Ascension and covering a range of Declination), possibly centred on the UKIRT faint standards.

3. Observe UKIRT faint standards, and

4. Tie in calibration fields to the UKIRT FS system. Calibration fields should be observed on a minimum of 3 photometric nights (assuming there is already some photometric pedigree).

3. Photometric Calibration of Wide Field NIR Images

The WFCAM wide field of view, large pixels and four detectors add complexity to the issue of photometric calibration. The way in which the instrument will be used, being on the telescope for large blocks of time and running in predominantly a survey mode, mitigates these problems by providing a stable configuration and enabling us to take a long term approach. By defining routine calibration procedures at an early stage we should be able to maximise the accuracy of WFCAM data, and hence the scientific productiveness and legacy of the archive, for the minimum of fuss.

In **Appendix A1**, I briefly outline the photometric problem we are trying to solve. The accuracy to which we can calibrate WFCAM data depends crucially on our observing strategy. Effects which need to be accounted for during commissioning and the lifetime of the project include the following:
- spatial systematics (scattered light/flatfield errors)
- variable pixel spatial scale across the FOV

- extinction colour dependence
- differential extinction across the field
- chip-to-chip gain dependence
- chip-to-chip QE colour effects
- filter colour terms
- extinction time dependence
- geometrical/optical spatial effects (e.g. vignetting, secondary reflectivity function)

To get the most out of the pipeline processing, we need to define observing practices (MSBs) which should be rigorously adhered to by the WFCAM observers. In addition we need to ensure that time is set aside during commissioning and in every semester to characterise the performance of the instrument and to update the standard star fields.

4. Detailed Discussion of WFCAM Calibration

Following the initial document, I have revisited the WFCAM photometric calibration and highlight some important steps which need to be planned.

4.1 Choice of Primary Standards

In a 5 (1) second exposure the detectors will saturate at magnitudes of J=11.5 (9.8), H=11.5 (9.8), K=11.1 (9.4) (Casali et al. 2003; numbers in brackets are the 1 second saturation limits). Which means that nearly all the UKIRT standard stars (http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/fs_izjhklm.dat) are in reach of WFCAM (defocusing can be used for brighter stars, but this should be avoided if possible).

Persistence effects have been measured and appear to be small ($2\ 10^{-4}$ after 20 seconds, Casali et al. 2003) therefore there should be no problem in observing the UKIRT faint standards, with the caveat that these are preliminary results from only one detector.

4.2 Spatial Calibration

Manfroid, Selman & Jones (2001) discuss the effect of scattered light in ESO WFI sky frames, i.e. by flatfielding a science image with data that contains an additive, spatially-dependent component, one will introduce a systematic calibration error across the field of view. However, the ESO WFI does seem to suffer a much larger effect than is seen in the INT WFC. There are two simple ways to check that the data reduction pipeline does not introduce an error of this nature.

- Observe a star (or star field) at many different positions on the science array during a photometrically stable night.

- Observe a previously calibrated star field which is dense enough to measure the spatial calibration.

In practice, at commissioning, it may be simplest to observe a single star and step it across the array. This will enable a quick (e.g. 64 pointings x 1s to give an 8x8 grid) and accurate check of any spatially dependent systematics. Using a dense star field will improve accuracy but will require a lot more analysis effort. Once a calibrated field is set up, this becomes a quick and simple routine check requiring only one image, providing the field contains enough stars.

4.3 Choice of Secondary Fields

These will become legacy fields for the calibration of WFCAM, VISTA and future IR projects. We consider the following as requirements:

- The field should extend over 14x14 arcminutes for WFCAM. VISTA fields need to be larger, but can be extended with VISTA itself.
- They should span 24 hours in RA, preferably spaced every 2 hours (1 hour?) eventually, maybe every 4 hours initially. Some fields to the North should be defined to enable observations at airmass 1.00, and to simultaneously span a rage of zenith distance.
- Similar fields should be chosen in the South for VISTA.
- The density of sources should be adequate to characterise the position dependent systematics in WFCAM. This is at least 100 stars with K magnitudes no fainter than 18 (otherwise prohibitively long exposures required)
- They should encompass a broad spread in colour so that we can determine colour terms.

Some suggestions for targets are:

1. Near or around existing UKIRT Faint Standards
2. In Open Clusters
3. On the edges of globular clusters
4. Fields selected purely on the basis of number density (e.g. from 2MASS)

[1] may not ensure a high enough stellar density to enable spatial analysis, which may also be true for [2]. Although 2MASS star counts (http://www.ipac.caltech.edu/2mass/releases/second/doc/sec6_7a.html) indicate that at high galactic latitude there are approximately 300 sources per square degree per magnitude at JHK=17. 2MASS data can be examined to investigate the colour properties of candidate fields. Figure 1 shows objects selected from a 7 arcminute radius around the UKIRT faint standard FS18 and indicates that this approach should work very well. However, this field, at least, shows a distinct lack of very blue stars which will limit the derivation of colour terms. Two more examples are shown in **Appendix A5**. Note that to achieve signal–to–noise=100 for J=16 requires an exposure of approx 30 seconds.

Globular clusters, [3], may have a strong gradient across the field, although the horizontal branch will ensure a good range of colour. The densest regions must be avoided and additional care taken with aperture photometry given the crowding

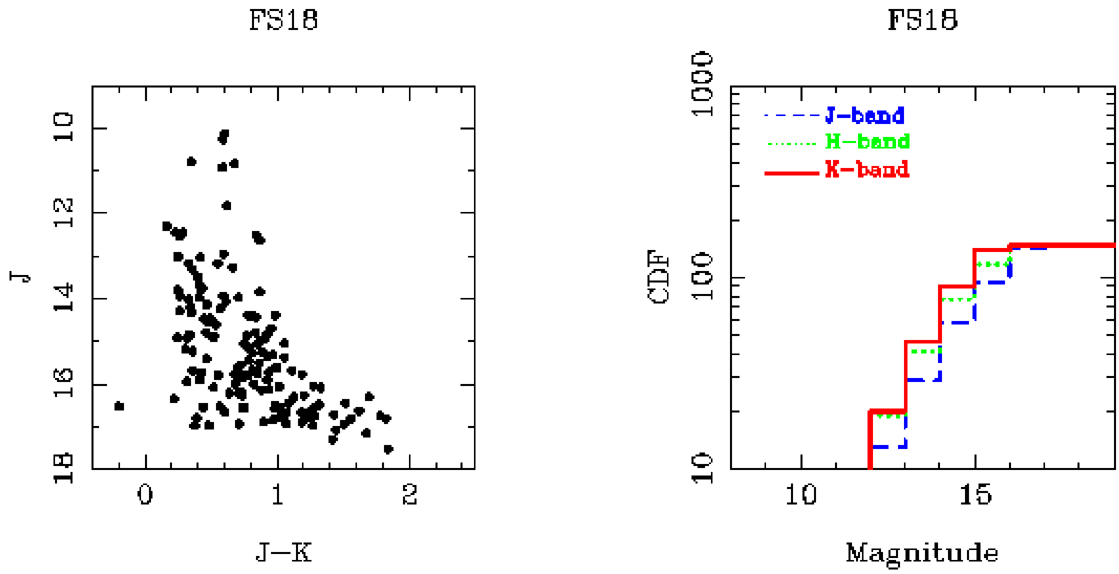

Figure 1. Sources extracted from the 2MASS point source catalogue from a 7 arcminute radius region centred on the UKIRT faint standard FS 18 (ά=8h51m δ=-00d25m, l=228, b=26). The left hand panel shows the J, J–K diagram, while the right hand panel shows the cumulative distribution function.

4.4 Narrow Band Filters

A clear strategy for calibration of the narrow band filters needs to be set in place. Three suggestions are

1. Use spectrophotometric flux standards.
2. Use normal standard fields and bootstrap the filters into the VEGA system.
3. Use a synthetic calibration.

Suggestion (3) seems unreliable. The preferred approach would be to tie the WFCAM standard fields into a system based on spectrophotometric standards if we can find any.

4.5 New broadband filters

Y and Z filters. SKL is setting up UKIRT Z-band standards, but this Z seems markedly different to the WFCAM Z filter. We need to define a consistent calibration method to put these filters in the same system as JHK. I propose to use the same technique as was used for the INT WFC z-band, i.e. tie the system into Vega by observing a stars of varying colour, a plot of e.g. Z-J vs J-K should pass through (0,0).

4.6 Definition of magnitude system

The WFCAM project needs to decide which magnitude system to work in. Stellar astronomers prefer Vega, while the extragalactic community prefer the AB system (allegedly). I propose to work in Vega and provide transformation coefficients for the AB system. I think we need to avoid releasing two sets of magnitudes, e.g. J_{WFCAM}^{Vega}, J_{WFCAM}^{AB}.

4.9 Science Requirement

The science requirement from UKIDSS is to achieve 2% accurate photometry. See Hambly et al. (2001) for some discussion of what this accuracy means.

References

- Hambly, Harwaden, Adamson, Casali, Warren, Leggett, 2001, http://www.ukidss.org/technical/technical.html (section 6), *Photometric calibration for WFCAM data.*
- Casali, 2003, WFCAM Performance *and Summary of Characteristics*.
- Hawarden, Leggett, Letawski, Ballantyne, Casali, 2001, MNRAS, 325, 563, *JHK standard stars for large telescopes 1. The UKIRT Fundamental and Extended Lists.*
- Manfroid, Selman, Jones, 2001, ESO Messenger (June), p.16, *Achieving 1% photometric accuracy with the ESO Wide Field Imager*.
- Nikolaev et al., 2000, AJ, 120, 3340, *A global photometric analysis of 2MASS calibration data*.
- Persson, Murphy, Krzeminski, Roth, Reike, 1998, AJ, 116, 2475, *A new system of faint near-infrared standard stars*.

Appendices

A1 Definition of the problem

At any time (*t*), on any night (*n*), for any star (*i*), in any waveband (*b*),

$$m^{cal}_{ib} = m^{inst}_{ibtn} + ZP_{btn} - k_{btn} (X - 1),$$

where *ZP* is the Zero Point (i.e. the magnitude at airmass unity which gives 1 count/second at the detector), m^{cal} is the calibrated magnitude, m^{inst} is the measured instrumental magnitude *(-2.5 x log10[counts/sec]*), *k* is the extinction coefficient and *X* is the airmass of the observation. This assumes that second order extinction term and colour dependency of *k* are both negligible.

Typically, the Zero Point of the instrument + telescope system should be stable throughout the night. Long term decreases in the sensitivity of the instrument, and hence a decreasing *ZP*, could be caused by e.g. the accumulation of dust on the primary mirror.

The 2MASS project found extinction varied seasonally. They allowed the *ZP* to vary through the night, but fixed the extinction. One could reasonably allow the extinction to vary through the night, given that the dominant contributors are H_20 and CO. The *ZP* then becomes a measure of the system throughput and can be easily monitored with the pipeline summit using the 2MASS catalogue.

A2 Commissioning Calibration Plan

We propose to make the following observations **as soon as** the instrument is generating sensible images:

1. Investigation of spatial systematics (in a range of filters)
2. Observations of UKIRT standards (in all filters)
3. Observations of spectrophotometric standards (in narrowband filters)
4. Tie in of pre-selected secondary fields (in all filters)

This should be seen as a priority and given precedence as soon as conditions merit the observations.

[1] becomes routine and very quick when secondary standard fields are in place, and could be performed every night as a check on or correction to the standard 2D pipeline reduction. As confidence in the pipeline reduction is established, then the frequency can be reduced, perhaps only making the test every time the instrument is mounted.

[2-4] Will span the whole first year to cover the range in RA. Repeat observations throughout the lifetime of the instrument will be necessary to improve accuracy and identify variable stars.

A3 Nightly Calibration Plan

Currently this plan exists as a series of questions for discussion. This section will evolve to a firm plan and well defined MSBs.

1. What is the minimum number of measurements (fewest overheads on survey time) that are needed to achieve the Science Requirement accuracy?

2. What do we do about extinction? Do we know how MKO extinction behaves seasonally, or over the course of a night, in the infrared? Do we need to use the science arrays? For example the autoguider is monitoring in the V-band; it seems unlikely that we will be able to bootstrap the V extinction into JHK.

3. How frequently do standards need to be measured (time dependence)?

4. What range of colours do we want /require our standards to have?

5. Can we improve on the calibration by tying together groups of nights (how many) or should each night stand alone?

6. What about a global solution a la 2MASS (see Nikolaev et al. 2000)?

7. What other information will be available to us apart from WFCAM measurements (e.g. 2MASS measures, autoguider transmission, skyprobe, CSO Tau) and how can we make use of it?

8. Will we make PATT observers follow this procedure? Can we?

9. How do we tie in observations taken during non-photometric conditions? Observations taken in patchy cirrus will not be trivial to calibrate (since cloud structure could be smaller than the FOV).

A4 The 2MASS standard fields

The updated 2MASS standards table contains 32 standard fields. These are

16 equatorial fields, uniformly distributed in RA, and 8 each of North and South polar fields, in the range Dec=+/-30 to 60, i.e. fine for UKIRT and VISTA. More than 2000 standards are spread between these 32 fields, i.e. something like 100 stars per field. Field areas are around 1 degree x 8.5 minutes, i.e. width is 60% of a WFCAM field of view. Standards typically have few hundred up to 1500 hundred scans, RMS errors at the bright end are at the few percent level.

The filter profiles between 2MASS and MKO are significantly different, e.g. the 2MASS J filter contains significant water vapour lines. Hambly et al. (2001) suggest that these differences lead to huge uncertainties in the *ABSOLUTE* calibration of the photometry. They propose re-observing 2MASS fields in MKO filters – or defining new glob cluster field. WFCAM can then be used to extrapolate fields to larger range of RA, DEC.
Overall these fields do not seem to be useful - they are smaller then the FOV of the instrument. In their favour they do have a small photometric legacy, although the error on any measurement of an individual star is large. Additionally the transforms from a low, wet site to a high, dry site will compromise photometric accuracy. We probably would do better selecting our own fields.

A5 Proposed Standard Fields

This section will grow to include the proposed WFCAM and VISTA standard fields. I've currently included two candidate fields for the UKIRT standards FS 13 and FS 24, at low and high low galactic latitude respectively.

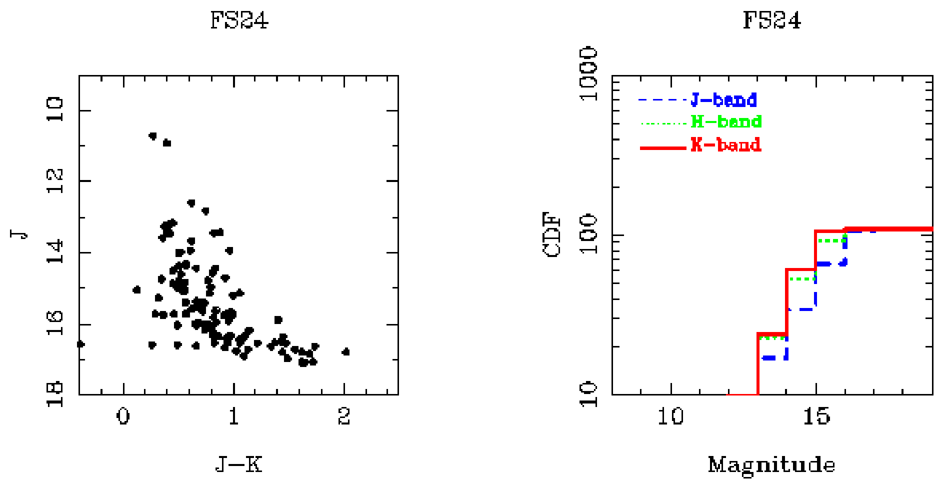

Figure 2. Sources extracted from the 2MASS point source catalogue from a 7 arcminute radius region centred on the UKIRT faint standard FS 24 (ά=14h37m δ=+00d14m, l=351, b=+53). The left hand panel shows the J, J–K diagram, while the right hand panel shows the cumulative distribution function.

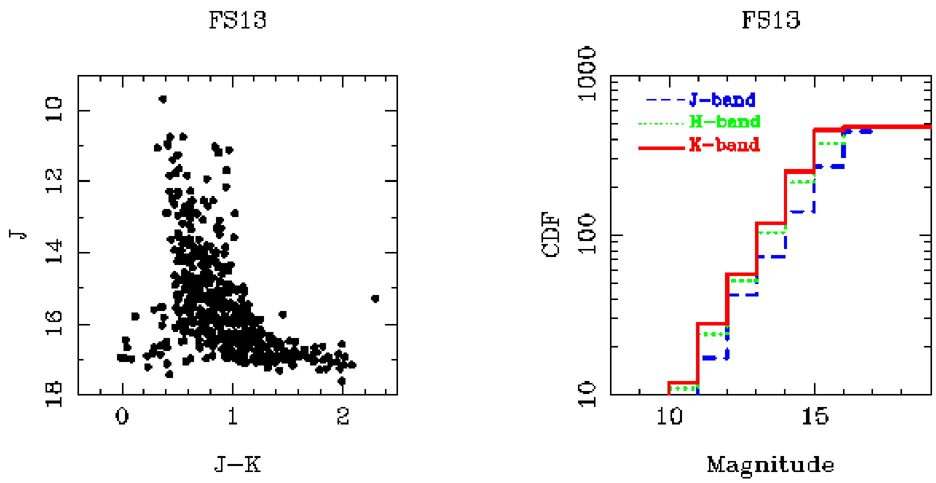

Figure 3. Sources extracted from the 2MASS point source catalogue from a 7 arcminute radius region centred on the UKIRT faint standard FS 13 (ά=05h54m δ=+00d00m, l=206, b=-13). The left hand panel shows the J, J–K diagram, while the right hand panel shows the cumulative distribution function.