VISTA DATA FLOW SYSTEM (VDFS)

for VISTA & WFCAM data

WSA Photometric Recalibration Design Document

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number
VDF-WFA-WSA-00?
issue
Draft 0.1
date
12 May 2005
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1 SCOPE

The WFCAM Science Archive (WSA) photometric re-calibration design document describes how we use the standard star and overlap region data in the database and the standard star tables to fit a photometric model and update the data in the database with the final zero-points and extinction values calculated from this new photometric solution. It discusses the methodology used to solve the problem, the reasoning behind the design and the expectations of values, and computing time.

This document describes how the photometric calibration module (Curation Unit 8; CU 8) is organised and broken into component modules. It describes the task and the inputs and outputs of each module, starting from the top down.

Most of the data taken by WFCAM will be part of the UKIRT Infrared Deep Sky Survey (UKIDSS). This is utmost in our minds when we consider the calibration of the archive data and how this affects survey strategy. Finally the WSA will be the forerunner of the VISTA Science Archive. Therefore it is important to consider the needs of VISTA too. This document will concentrate on calibrating a wide field near-IR camera, although it is hoped that money will raised to provide VISTA with an optical camera in addition to the near-IR camera that is being built. There will also be additional concerns about the increased data rates from VISTA. These issues will be addressed in future documents.

2 OVERVIEW

CU 8 is a curation unit that is designed to be run infrequently, at intervals of several weeks. We find the best fit global photometric solution using all the available data - standard stars for absolute calibration on any given night and overlap regions for relative calibration between nights and for bootstrapping to non-photometric nights. We will make use of the metadata extracted from the image headers and numerical data from the image catalogues.

To extract the relevant data, calculate the best fit solution and then update the correct parts of the database needs a methodical approach. We have broken it into steps as shown in Fig 1. The first module links the observations of standard fields to tables listing the values of the standard stars. The second module produce lists of sources in the overlap regions. The third module uses all the data to find the best fit solution. The fourth module moves the values that were in the calibration tables before CU 8 was run to tables of old values. The fifth module updates the calibration tables with the just calculated values and the sixth module updates all the science metadata and numerical data with the new calibrations and version numbers. These modules are described further in the following subsections.

Below we will discuss the overall model that we have decided to base our global photometry on. To discuss this we must first define a few quantities.

The final calibrated magnitude of a star or galaxy in the WFCAM data is defined as:

$$m^{final} = ZP + m^{inst} - A \tag{1}$$

where ZP is the zero-point, which depends on instrumental effects and A is the extinction which depends on atmospheric effects. m^{inst} is the instrumental magnitude, defined using the luptitude measurement [1].

$$m^{inst}(f) = -a[\sinh^{-1}\frac{f}{2b} + \ln\, b] \tag{2}$$

where $a = 2.5\log_{10} e$, f is the flux of the star and b is the softening parameter, which is chosen to reduce the variance at low flux levels. Luptitudes behave like traditional magnitudes for large fluxes, in which case $m^{inst} \sim -2.5\log_{10} f$, but behave linearly for small fluxes, $m^{inst} = -1.09((f/2b)+\ln(b))$. Rearranging Eqn. 1, we get:

$$m^{inst} = m^{final} - ZP + A \tag{3}$$

We must sensibly model the zero-point and extinction so as to explain the variation seen in the fewest parameters possible. When we consider the zero-point, the main term is a constant, but we also expect there to be variation on short time-scales [2], and on long time-scales due to degradation of the detectors. Both of these effects will probably be non-linear and will most likely vary from detector to detector and could be wavelength dependent. Therefore the following model is suitable for the zero-point:

$$ZP_{\rm knfd} = a_{\rm 0fd} + a_{\rm 1fd}(t_{\rm kn}) + a_{\rm 2fd}(t_{\rm kn})^2 + a_{\rm 3fd}(T_{\rm n}) + a_{\rm 4fd}(T_{\rm n})^2 \tag{4}$$

where $a_{\rm 0fd}$ is the constant term. $t_{\rm kn}$ is the time of the kth observation on the nth night, measured in hours from midnight, and $a_{\rm 1fd}t_{\rm kn} + a_{\rm 2fd}(t_{\rm kn})^2$ is the short term variation. $T_{\rm n}$ is the Julian Date of the nth night and $a_{\rm 3fd}T_{\rm n} + a_{\rm 4fd}(T_{\rm n})^2$ is the long term variation. These variations are independent of each other.

The zero-point is likely to be function of position within each detector too, since flat-fielding using twilight flats does not remove the spatial dependence completely [3]. A polynomial series in x and y is suggested as a function to fit [4]. The spatial map will be characterised independently to the main night-to-night calibration by multiple stepped observations of a star cluster. This spatial map must be applied to all the observations. This should remove the dependence of the zero-point on the detector.

The extinction on the other hand is completely independent of the detector or position in the detector, but does depend on the filter, the airmass that the observations are viewed through and the colour of the star being observed, since blue light is scattered and absorbed more than red light. Therefore:

$$A_{\rm knf} = A_{\rm 0nf}(\chi_{\rm kn} - 1) + A_{\rm 1nf}(\chi_{\rm kn} - 1)^2 + A_{\rm 2nf}C_{\rm if}(\chi_{\rm kn} - 1) \tag{5}$$

The extinction is modelled as a quadratic variation in airmass ($A_{\rm 0nf}(\chi_{\rm kn} - 1) + A_{\rm 1nf}(\chi_{\rm kn} - 1)^2$) and a colour-airmass variation ($A_{\rm 2nf}C_{\rm if}(\chi_{\rm kn} - 1)$). The fth colour, of the ith star, $C_{\rm if}$, is defined as:

$$C_{\rm if} = m^{final}_{\rm if} - m^{final}_{\rm i(f+1)} \tag{6}$$

unless the fth filter is the reddest filter K. Then $C_{\rm if} = m^{final}_{\rm i(f-1)} - m^{final}_{\rm if}$.

We allow the extinction parameters to change from night-to-night, since the weather and therefore the amount of water vapour and dust in the atmosphere which contribute to extinction can change on these time scales.

When we take all this into account,the photometric model that we use is:

$$\begin{aligned} m^{model}_{\rm iknfd} = & m^{cal}_{\rm if} - a_{\rm 0fd} - a_{\rm 1fd}(t_{\rm kn}) - a_{\rm 2fd}(t_{\rm kn})^2 - a_{\rm 3fd}(T_{\rm n}) - a_{\rm 4fd}(T_{\rm n})^2 \\ & + A_{\rm 0nf}(\chi_{\rm kn} - 1) + A_{\rm 1nf}(\chi_{\rm kn} - 1)^2 + A_{\rm 2nf}C_{\rm if}(\chi_{\rm kn} - 1) \end{aligned} \tag{7}$$

where $m_{\rm iknfd}^{model}$ is the calculated magnitude of the ith standard star observed during the kth standard observation on the nth night through the fth filter and observed on the dth detector. $m_{\rm if}^{cal}$ is the actual magnitude of the ith standard star observed through the fth filter, and is therefore time and detector independent.

The model magnitude should be equal to the instrumental magnitude $m_{\rm iknfd}^{inst}$ within the measurement errors if the model is good. The same should be true for m_{iknfd}^{final} and m_{if}^{cal}:

$$\begin{aligned} m_{\rm iknfd}^{model} &= m_{\rm ikfnd}^{inst} \pm \sigma_{iknfd}^{inst} \\ m_{\rm iknfd}^{final} &= m_{if}^{cal} \pm \sigma_{iknfd}^{inst} \end{aligned} \tag{8}$$

where σ_{iknfd}^{inst} is the measurement error of the observation of the ith star at the kth time on the nth night, through the fth filter and measured on the dth detector

Some of the typical values that we might expect for calibration parameters are based on what has been found in previous surveys. For instance, the typical extinction values in the J, H and K bands at Mauna Kea Observatory are $A_{0J} = 0.10$, $A_{0H} = 0.05$ & $A_{0K} = 0.07$ [5]. The typical z-band extinction measured by the Sloan Digital Sky Survey is $A_0 z = 0.06$ [8] and their typical colour-extinction term was $A_{2z} = 0.003$. The typical values for a_1 from 2MASS in the H and K bands are ~ 0.001 and ~ 0.0004 respectively [6].

Within UKIDSS, there are five distinct surveys, the Large Area Survey (LAS), the Galactic Plane Survey (GPS), the Galactic Clusters Survey (GCS), the Deep Extragalactic Survey (DXS) and the Ultra Deep Survey (UDS). The LAS, GPS and GCS are shallow, wide area surveys, with one or two observations in each filter in each pointing, but with many pointings over a large area. In contrast the DXS and UDS are very deep and narrow surveys which have multiple stacked observations in each pointing and much fewer different pointings.

In each case we will have overlap regions between pointings, although this will only be about 3% of the field of view and will be between two different detectors and with different x and y positions. Within the DXS and UDS, we will have overlap within the stacks where the overlap will be $\sim$ 100% of the field of view, the same detectors will overlap each other and there will be almost no difference in the x and y positions. However, time and atmospheric differences will still apply. Both can be treated in a similar way, with a few more terms dropping out in the case of overlap between stacks. Within the LAS, GPS and GCS, there will be a few cases of stacks, when one or two filters are repeated at later times for proper motion studies, whereas in the DXS and UDS all filters have many repeat observations in all pointings. The standard fields that we observe are also stacks, so the following discussion applies to the standard observations too.

To properly calibrate a stack, all observations must be calibrated individually, before calculating the final magnitude. The flux, $f_{\rm iof}$, of the oth observation of the ith star through the fth filter may be very different from $f_{\rm i\theta f}$, the flux of the θ^{th} observation, but the calibrated magnitude $m_{\rm iof}^{final}$ will be the same within the errors as long as the star is not variable:

$$\begin{aligned} m_{\rm if}^{cal} &= m_{\rm iof}^{final} \pm \sigma_{iof}^{inst} = m^{inst}(f_{\rm iof}) + ZP_{\rm of} - A_{\rm of} \pm \sigma_{iof}^{inst} \\ &= m_{\rm i\theta f}^{final} \pm \sigma_{i\theta f}^{inst} = m^{inst}(f_{\rm i\theta f}) + ZP_{\theta \rm f} - A_{\theta \rm f} \pm \sigma_{i\theta f}^{inst} \end{aligned} \tag{9}$$

If there are N observations in each stack then, the final combined magnitude is:

$$m_{\rm if}^{final,comb} = \frac{1}{N}\sum_{o} m_{\rm iof}^{final} \tag{10}$$

with the error reduced to:

$$\sigma_{\rm if}^{final,comb} = \frac{1}{N}\sqrt{\sum_{o}(\sigma_{iof}^{inst})^2} \tag{11}$$

The stacks will also demonstrate if an object is variable. We define the deviation $\delta\, m_{\rm iof}^{dev}$ to be the difference between the final combined magnitude and the final calibrated magnitude of the observation, weighted by the measurement error:

$$\delta\, m_{\rm iof}^{dev} = \frac{m_{\rm iof}^{final} - m_{\rm if}^{final,comb}}{\sigma_{iof}^{inst}} \sim \frac{m_{\rm iof}^{inst} - m_{\rm iof}^{model}}{\sigma_{iof}^{inst}} \tag{12}$$

If the deviations do not have a standard normal distribution, then there is some additional error not accounted for. If most stars in a field have a standard normal distribution, then the stars that do not are variables. If most stars do not, and they all have outliers in the same observations, then those observations have not been properly calibrated. We will use these tests to understand both the science stacks and the standard stacks.

This gives us the criteria for an optimal solution. We must minimise the residuals of all observations of all stars over all filters:

$$\frac{\partial \sum_{\rm iof}(\delta\, m_{\rm iof}^{dev})^2}{\partial \underline{x}} = 0. \tag{13}$$

where $\underline{x}$ are the model parameters. Each filter can be solved separately. For good secondary standards with no intrinsic variation, all the variation between $m^{final,comb} = m^{cal}$ and $m^{final}(\underline{x})$ is due to the model.

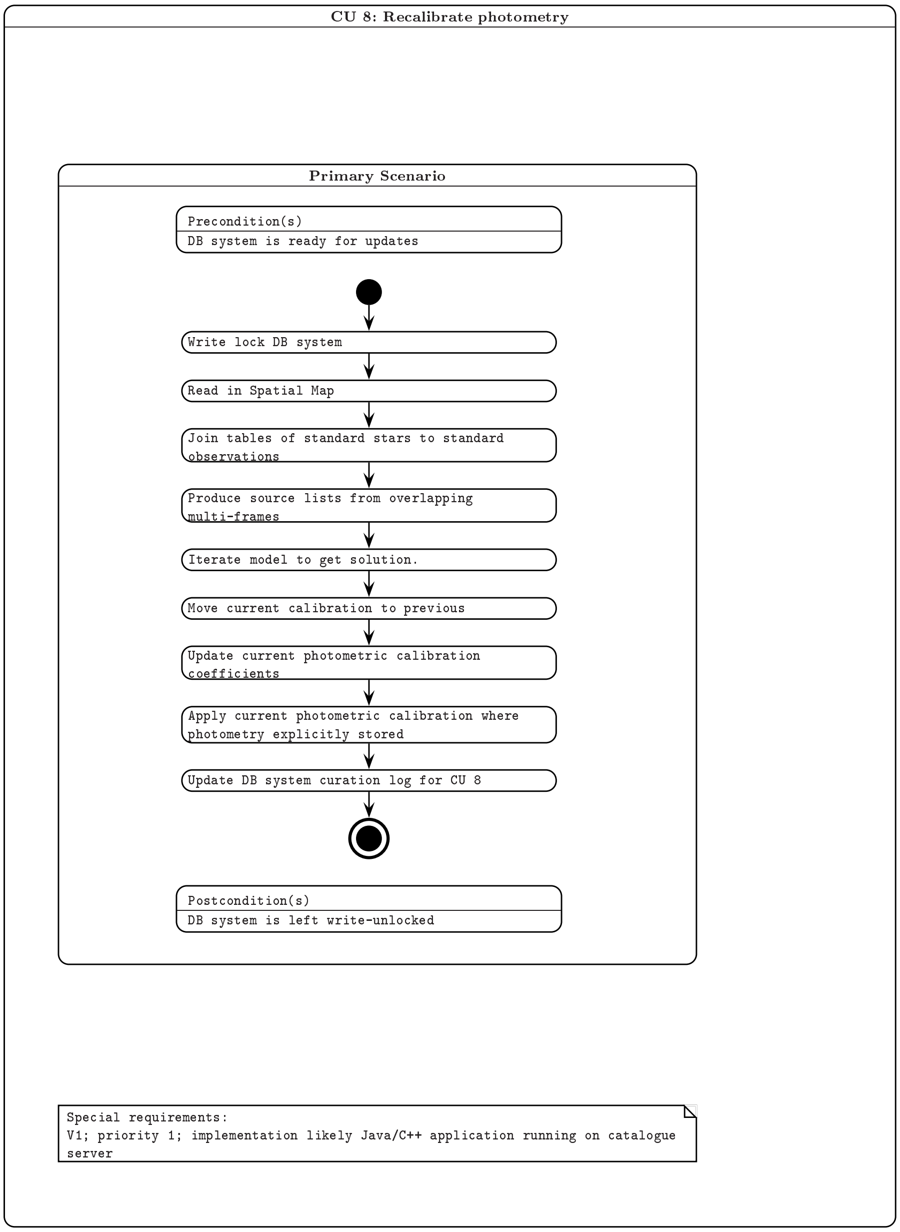

Figure 1: *Activity diagram for curation task CU 8.*

3 DETAILED DESIGN

In this section we will look at all the subunits of the curation unit and break these down into components.

3.1 Join tables of standard stars to standard observations.

To calibrate the UKIDSS and other data, several standard fields have been selected for observation. These are spaced at a variety of right ascensions and declinations throughout the equatorial and northern sky. These are targetted around existing UKIRT Faint Standards, which will be used as the initial primary standard stars. 48 stars in 43 fields have been selected by CASU [4] and are listed in Table 1. These are plotted on top of the UKIDSS fields in Fig 2.

The fields must be $14' \times 14'$ for WFCAM (each detector is $13.65' \times 13.65'$) and even larger for VISTA (which will need more southerly fields). The errors will be reduced by observing many secondary standards and minimising the variation seen, see Eqn 12. Even if several of the stars are variable, minimising the differences amongst the secondary standards will constrain variations between each field. The primary standards are necessary to put the calibration on an absolute scale. The schematics for joining the observations to the tables are shown in Fig 3.

The calibration strategy should not depend on the observing procedure adopted, and the model discussed above is very general. However it is worth discussing the observing strategy that UKIDSS observers are likely to adopt since it helps us to calculate the demands that will be made in terms of processing the data.

Throughout each night WFCAM will observe "Minimum Schedulable Blocks" (MSB): A 1 hour block of nearby fields that are observed in all the necessary filters. For instance a MSB in the Large Area Survey may consist of ~ 10 separate pointings taken in the Y, J, H and K filters. Between each MSB a standard field is observed in all five broadband filters and any narrow band filters that may be required that night. The standard field is observed 4 times, once for each detector; while the exposure time is short, 5s, there is a significant overhead, with readout (1-2s). Unfortunately it is not possible to readout one detector while exposing another as this leads to cross-talk between the detectors, increasing the noise, often systematically. If more than one standard field needs to be observed that night, then all of the necessary standard fields must be observed at many different times, so that one can understand the variation with time and airmass.

First of all the tables of primary and secondary stars are read in from the archive SQL, see Table 1 for example primary standard stars. We read in standardtableid, starid, ra, dec, and (filter, mag, magerr) for each filter. Initially, the magnitudes for the primary stars are in the filters $Z_{\rm UFTI}$, $J_{\rm MKO}$, $H_{\rm MKO}$ and $K_{\rm MKO}$, whereas the actual filters to be used are $Z_{\rm WFCAM}$, $Y_{\rm WFCAM}$, $J_{\rm WFCAM}$, $H_{\rm WFCAM}$, $K_{\rm WFCAM}$. The WFCAM filters are designed on the MKO system, but as always there will be some small variations with colour due to the throughput through the rest of the optics. The UFTI system is quite different. A colour transformation will be used to convert from the UFTI, MKO system to the WFCAM system [12], and this will be improved over time as more data is taken. Eventually we will have primary standard measurements in the WFCAM filters as well as UFTI/ MKO filters. The MKO system is much improved from the UFTI system since the filters are narrower and squarer. The UFTI and many previous near-IR filters suffered from water bands overlapping with the edges of the filters, and therefore the throughput would vary significantly with the amount of water vapour in the atmosphere on that particular night. This will make it difficult to go from the UFTI to MKO filters with a great deal of precision, so it will be a great improvement when we have standard measurements in $Z_{\rm WFCAM}$ and $Y_{\rm WFCAM}$.

For each night that we have observations, we locate all the standard fields that were observed, using the multiframe table which has details of each frame in the database. For each standard observed we

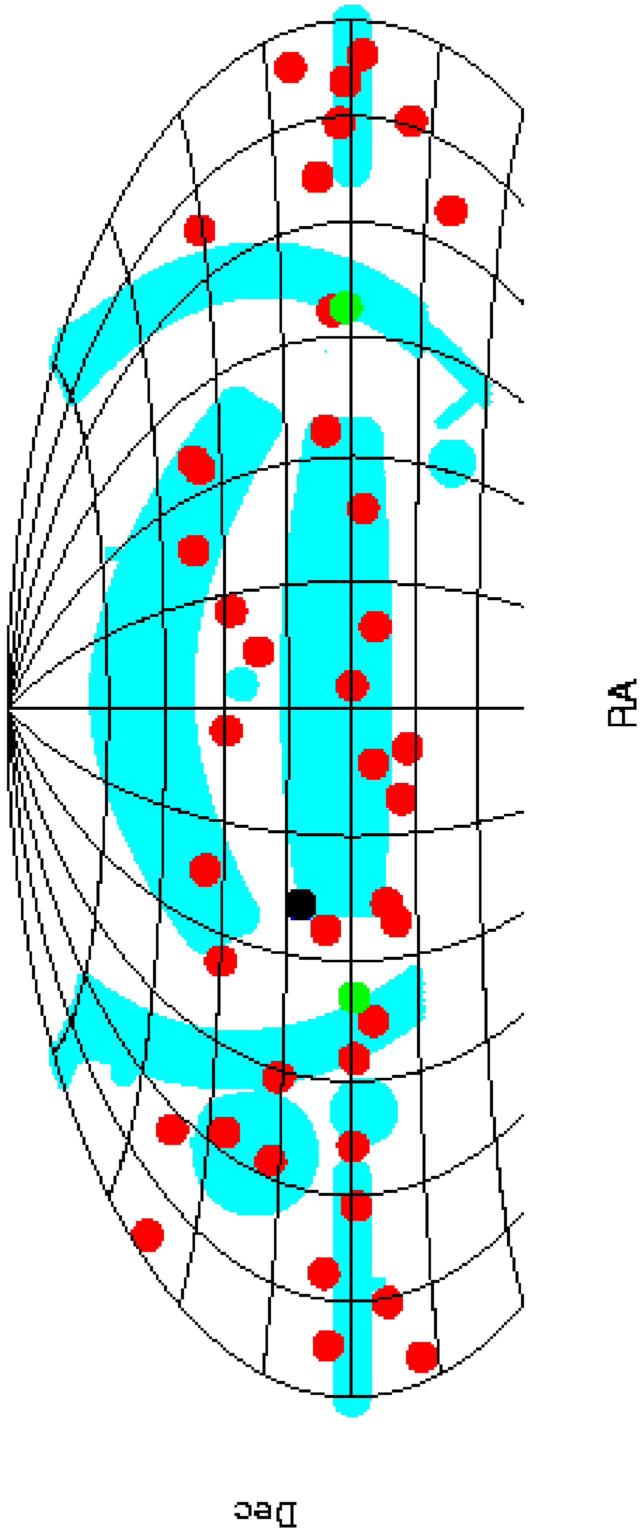

Figure 2: *Plot of standard fields selected for WFCAM calibration. The cyan area shows the 5 UKIDSS survey regions. The red circles show standard fields with one UKIRT faint standard, the green circles show standard fields with two faint standards and the black circle shows a standard field with 4 faint standards.*

extract the targetid, ra, dec, filter, epoch, airmass, exposure time and all information pertaining to the sky conditions from the metadata in the database. We then use the sky condition information for all the fields to decide whether the night was photometric or not.

If the night was photometric we then read in the catalogue for each standard field. We extract the x,y, ra, dec, star/galaxy classification, flux and flux error for each source. Typically there will be many measurements of flux: the isophotal flux, the kron, the petrosian, various aperture fluxes and model fluxes, where exponential or de Vaucouleurs profiles are fitted. However we will be using stars to calculate the photometric model, so it is best to use PSF magnitudes, which assumes that the object is a point source and models the total flux. This will produce a flux measurement that is almost independent of seeing and optimal in terms of signal-to-noise. We use the exposure time to calculate the flux that we would get in 1s, since it is the zeropoints for a 1s exposure that we want to calculate.

The fluxes are converted to instrument magnitudes, using the method in [1]. The spatial map described in § 4.1 is applied to the x and y positions to find the expected difference in the magnitude at this position and the result is applied to the instrumental magnitude:

$$m_{\mathrm{iknfd}}^{inst} = m_{\mathrm{iknfd}}^{inst} + \Delta\, m_{\mathrm{fd}}^{SpMp}(x, y) \tag{14}$$

Using the metadata (targetid or ra and dec), we match the standard observation to a standard field. Then we match individual sources to secondary/ primary stars in the field. If no secondary standards have been identified, we take all stellar sources as potential secondary sources. Good secondary sources will be those with flux errors less than 5% on 90 per cent of all observations taken.

We save the measured magnitudes as a vector $\underline{m}$. This is the vector of measurements. We also form a matrix $\underline{\underline{C}}$, the design matrix which contains data on which calibration stars are used and at what times and airmasses. The time and night is calculated from the epoch. The design matrix is described in detail in § 6.1.

To test the residuals later, we save the data for each observation: UID, fieldid, ra, dec, altitude, azimuth, epoch, airmass, filter x, y, flux, flux error, m^{inst}, etc., in a data file. Since we have a lot of free disk space, but will be limited by memory in some of the calculations, in § 3.3, it is much better to produce a temporary working file to store this information.

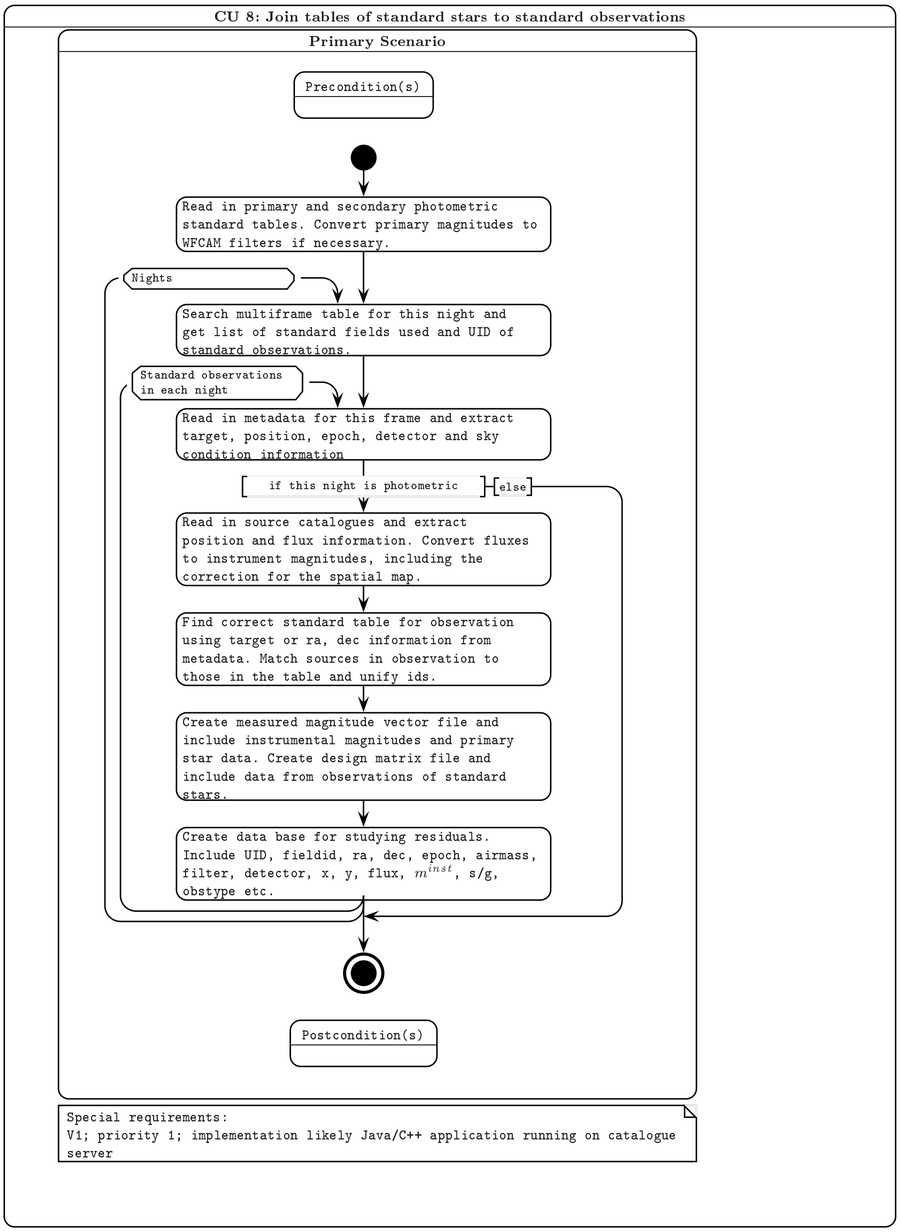

Figure 3: *Activity diagram for first module in CU8.*

3.2 Produce Source Lists from Overlapping Multi-Frames.

The WFCAM field of view consists of 4 separate detectors, spaced apart by 94% of the width. Other observations fill in the gaps or continue with the same spacing, giving a 3% overlap on either side. Generally speaking, each time there is overlap between two fields, each detector will have an area of overlap on one side, although in some cases it may be that only two detectors have the overlap.

While the overlap between each field is only 3% in each overlap region, even at the Galactic poles, we would expect almost 300 stars, $K < 17$ mag, in a $0.21\,\mathrm{deg}^2$ field [7], so we would expect ~ 8 stars in each overlap region at the poles, increasing to ~ 30 at $b = 30\,\mathrm{deg}$. These overlap regions are extremely important since they provide the only means to cross-calibrate between nights and calibrate data taken on non-photometric nights. The schematics of the breakdown of this module are shown in Fig. 4.

The first task is to read in the set of overlap regions found when merging source lists in curation unit 7. We then must find which two observations overlap in each region and get the frameids.

For each frame in each overlap region, we read in the metadata and extract the targetid, ra, dec, filter, epoch and airmass. We also read in the source catalogues and extract the objectid, ra, dec, x and y position and fluxes. Using the ra and dec, we match the objectids in each frame to each other, and give each pair a UID. We calculate measured magnitudes as in § 3.1 and find the difference between them and add this to the measurement vector $\underline{m}$.

$$\Delta\, m^{inst}_{\iota\beta\,\mathrm{b}\nu\,\mathrm{nfd}\delta} = m^{inst}_{\iota\beta\nu\,\mathrm{f}\delta} - m^{inst}_{\iota\,\mathrm{bnfd}} \tag{15}$$

where the ι^{th} star is observed through the f^{th} filter twice, once at the β^{th} time on the ν^{th} night on the δ^{th} detector and once at the b^{th} time on the n^{th} night on the d^{th} detector.

If this is overlap of the same pointing, in a stack, rather than two separate pointings, then $\mathrm{d} = \delta$.

We update the design matrix $\underline{\underline{C}}$ using the overlap information. We also store all the relevant information, for looking for other sources of variation in the residuals, in a data file. This is discussed in detail in § 6.1.

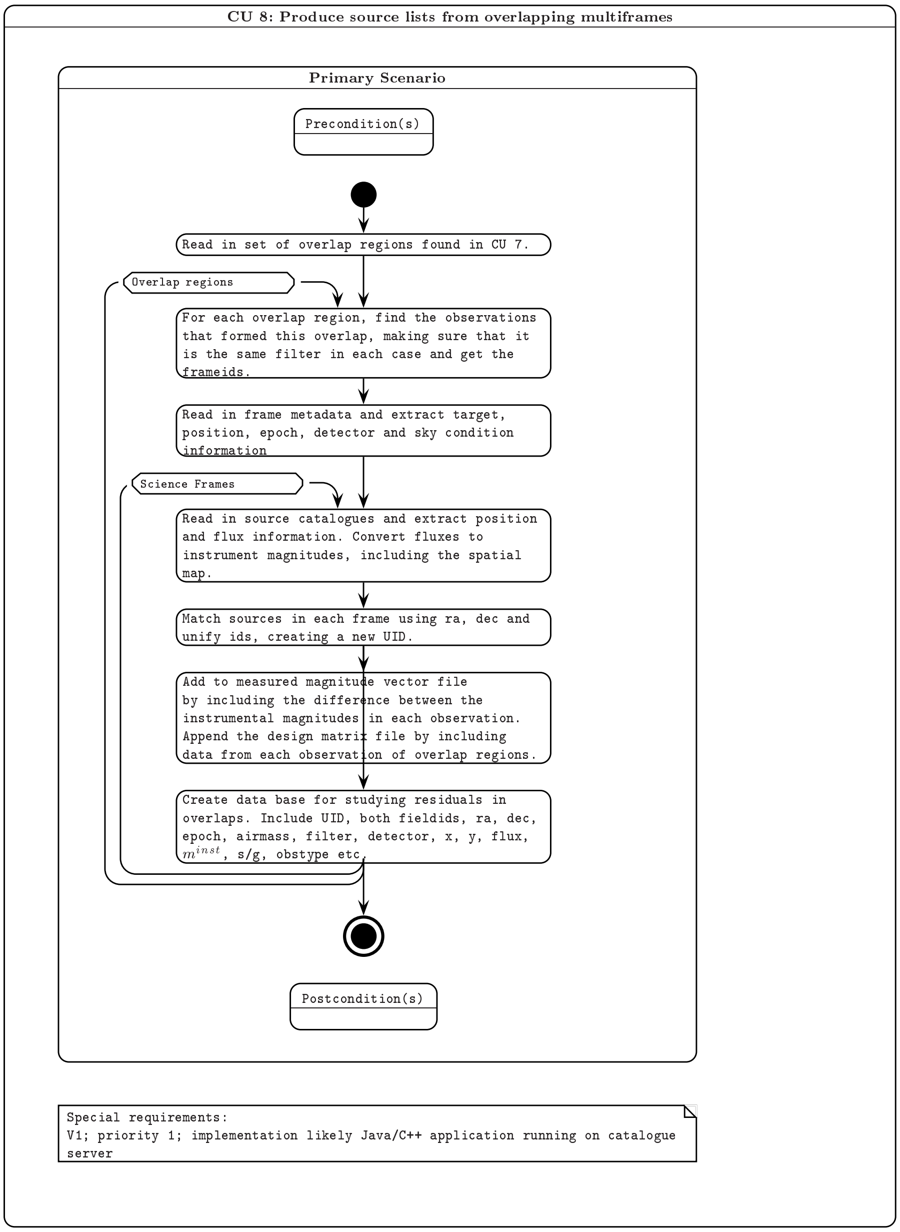

Figure 4: *Activity diagram for second module in CU8.*

3.3 Solve Model to get Solution

This module fits the global photometric calibration model, see Eqn. 7, to the current data that has been collected in the previous modules.

Unfortunately Eqn. 7 is non-linear since the term $A_{\rm 2nf}C_{\rm if}(\chi_{\rm kn}-1)$ includes the colour of the star $C_{\rm if}=m^{cal}_{\rm if}-m^{cal}_{\rm i(f+1)}$ and therefore the product of two parameters which are being solved for, so cannot be solved by simple linear algebra.

A non-linear term was not needed to calibrate 2MASS [2], since extinction in the near-infrared is almost colour-independent. However, WFCAM has bluer filters, Z and Y which may need small colour dependent terms, as were needed for the z-band filter in the SDSS [8]. If the term is sufficiently small it can be considered a small perturbation on the linear solution.

We calculate the solution in a two-step process, see Fig 6. Firstly we calculate the best fit linear solution using standard linear algebra techniques described in [9] to solve for the photometric parameters ($a_{\rm ofd}$, $A_{\rm enf}$) and the standard star magnitudes m^{cal}_{ijf}, which make up the vector $\underline{x}$:

$$\underline{\underline{C}}\,\underline{x}=\underline{m} \tag{16}$$

These different observations can be handled the same way, in the same design matrix $\underline{\underline{C}}$, see Appendix 6.1 for details. The measurements vector $\underline{x}$ contains the standard star and overlap regions measurements, described in more detail in Appendix 6.1. The parameter vector has N terms:

$$\mathrm{N}=N_{\rm std}+N_{\rm det}N_{\rm ZPpar}+N_{\rm ngt}N_{\rm Extpar} \tag{17}$$

where $N_{\rm std}$ is the number of standard stars in all standard fields, $N_{\rm det}$ is the number of detectors (4, for WFCAM), $N_{\rm ZPpar}$ is the number of zero-point parameters (5), $N_{\rm ngt}$ is the number of nights observed, and $N_{\rm Extpar}$ is the number of linear extinction parameters to solve for (2). For a set of observations taken over 200 nights, with 20 different standard fields, each with an average of 100 standard stars, we would be solving for 2420 parameters. The number of equations that are simultaneously solved to give these parameters is M:

$$\mathrm{M}=\sum_d\sum_n\sum_t\sum_j N_{\rm std,j,t,n,d}+\sum_j N_{\rm pri,j}+\sum_o N_{\rm str,o} \tag{18}$$

where $N_{\rm std,j,k,n,d}$ is the number of standard stars in the jth field, observed at time k on the nth night and on the dth detector. This is summed over all the standard fields j, times k, nights n and detectors d that are observed. These are the terms referred to Eqn. 27. Since any particular minimum schedulable block (MSB) will only need one standard field (observed at a range of times and airmasses) and therefore there will only be a limited number (up to half a dozen) of different standards observed on a particular night. At any particular time (i.e. within the same gap between two MSBs) only a few fields will be observed. Thus on a typical night with an MSB of 1 hour, and 8 hours of observing time, 16 standard fields may be observed (2 different ones observed 8 times, or 3 different ones observed at 6, 5 and 5 times). $N_{\rm pri,j}$ is the number of primary stars in each field, i.e. the number of previously calibrated stars, that have a well defined magnitude and do not show any variation. These are the terms referred to in Eqn. 28. At the beginning there is only likely to be one primary in each field, but as more observations are taken, we will have a better idea of which stars show variation or not and some additional stars maybe promoted to primaries. Finally $N_{\rm str,o}$ refers to the number of stars in each overlap region, see Eqn. 30. The overlap is not between stars in standard fields, but between stars in the science observations. The overlap could be between two fields observed on the same night, at different times, or observed weeks, months or years apart, when the calibration parameters are very different. In the above scenario, after 200 nights, of ~ 8 hours, with each observation being of length ~ 1 minute, there will be $\sim 100,000$ science observations, $25,000$ in each filter (assuming an average of 4 filters being used), reducing to $20,000$ assuming some loss due to weather, instrumental problems etc. Therefore, one would expect several 1000 overlap regions. Even if there are only average of a few stars per overlap region, that would produce a lot of constraining equations. Thus, after 200 nights, we might expect $\mathrm{M} = 1280000 + 20 + 40000 \sim 1300000$, although this could be many more. The number of overlap stars may be much greater in the DXS and UDS programmes where the overlap region will often be the whole field, not just a few per cent.

A design matrix with dimensions 1300000×2400 will take up 1.2Gb of memory if double precision is used, which it must be to reduce the chance that the matrix is ill conditioned, see § 6.1, a problem when there are rounding errors in nearly singular matrices. Running the singular value decomposition code requires two $\mathrm{M} \times \mathrm{N}$ matrices, amongst other items in memory. 2.4Gb of memory is beyond the limits of most machines, and this is after just 200 nights, i.e. 1 year. The full UKIDSS dataset could need up to 20Gb to solve it. Additionally the first 200 nights would take $11\mathrm{MN}^2 = 8 \times 10^{13}$ flops to solve if there was plenty of memory. On a 2GHz machine, this would take 11 hrs. VISTA would produce even greater challenges. Additionally, the matrix is sparse and so this is a very inefficient way to store it.

Using the method described in [10] (see § 6.1) we can convert this matrix to a square $\mathrm{N}\times\mathrm{N}$, $N = 2400$, matrix which is not so sparse. We solve the matrix using Singular Value Decomposition [9]. This would take $2\,\mathrm{MN}^2 + 11\,\mathrm{N}^3 = 1.5 \times 10^{13}$ flops to finish; on a 2GHz machine this would take 2hrs, over five times faster.

Once the linear solution has been found, we solve to get the non-linear part.

$$m_{\mathrm{iknfd}}^{inst} = m_{\mathrm{if}}^{cal} - ZP_{\mathrm{knfd}} + A_{\mathrm{knf}}^{lin} + A_{\mathrm{2nf}} C_{\mathrm{if}}(\chi_{\mathrm{kn}} - 1) \tag{19}$$

where:

$$A_{\mathrm{knf}}^{lin} = A_{\mathrm{0nf}}(\chi_{\mathrm{kn}} - 1) + A_{\mathrm{1nf}}(\chi_{\mathrm{kn}} - 1)^2 \tag{20}$$

The parameters that go into ZP_{knfd} and A_{knf}^{lin} have been estimated above. As long as the non-linear perturbation is small, the estimates will be reasonable. Based on the calibration of the SDSS [8] we expect $A_{\mathrm{2nf}} = 0.003$ in the z-band and so the typical colour-extinction term will be of the order 2×10^{-4} mag, but values of 3×10^{-3} mag will occur reasonably often. The colour can be estimated using Eqn. 6.

We can rearrange Eqn. 19 to estimate the non-linear term:

$$\Delta\, m_{\mathrm{iknfd}}^{nlin} = m_{\mathrm{iknfd}}^{inst} - m_{\mathrm{if}}^{cal} + ZP_{knfd} - A_{knf}^{\mathrm{lin}} = A_{\mathrm{2nf}} C_{\mathrm{if}}(\chi_{\mathrm{kn}} - 1) \tag{21}$$

However, systematic errors in the linear terms can lead to offsets in the above equation with respect to the mean colour and airmass, see Fig 5 and Eqn. 22. In this example we use $A_{\mathrm{2nf}} = 0.13$ and recovered this within 10%.

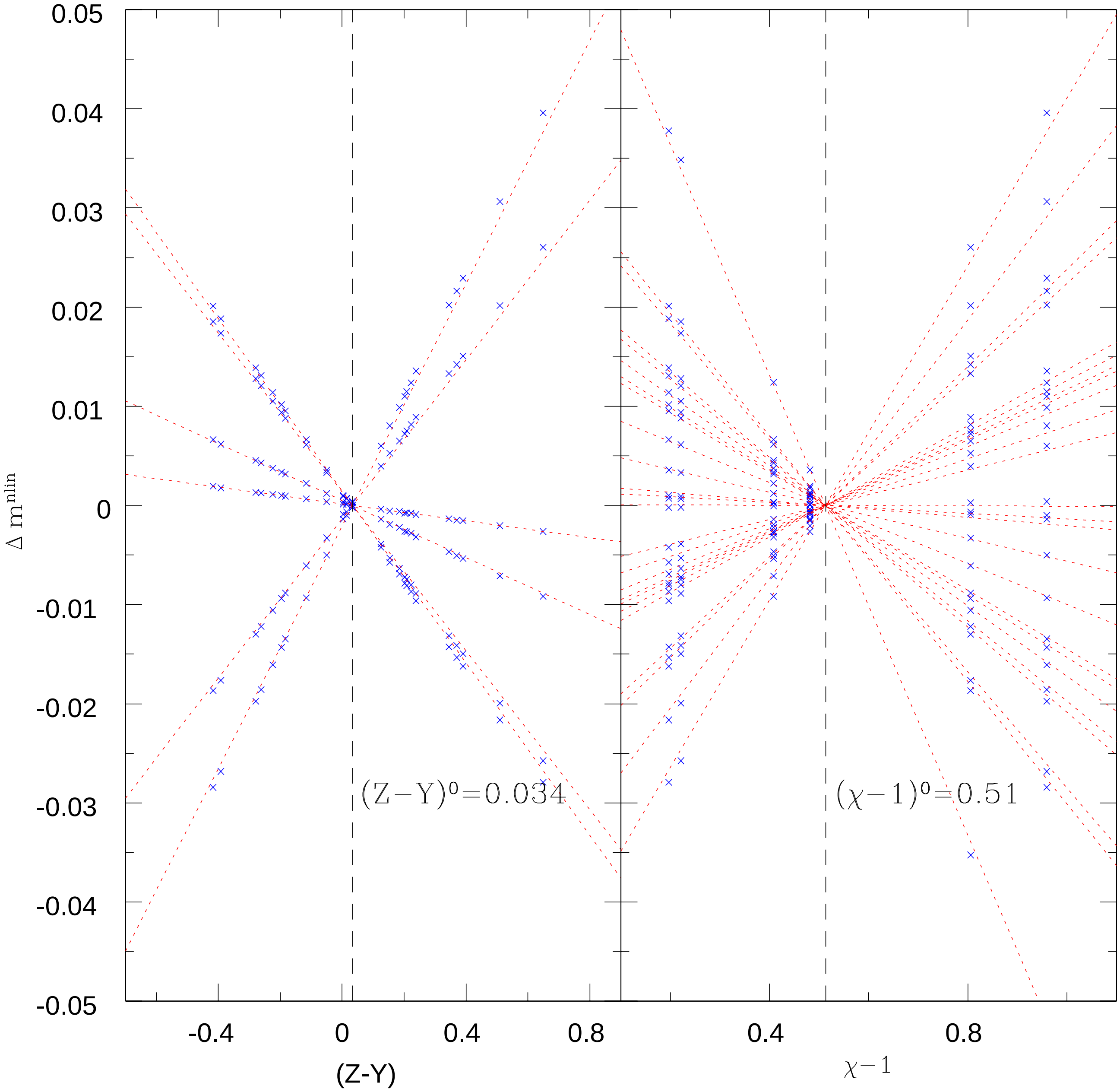

Figure 5: *Plot of residuals* Δm^{nlin} *versus colour and airmass. The blue crosses show the actual values of* Δm^{nlin} *vs* $(Z - Y)$ *in the left-hand plot, and* Δm^{nlin} *vs* $(\chi - 1)$ *in the right-hand plot for 150 observations: 25 stars at 6 different airmasses. Each star has a slightly different colour. The red dotted lines show the best fit solution using Eqn 22, with fixed airmass in the left-hand plot and fixed colour in the right-hand plot. We recovered* $A_{2\mathrm{nf}} = 0.14$*, but with additional offsets,* $C^0_{\mathrm{nf}} = 0.034$ *and* $\chi^0_{\mathrm{nf}} = 0.513$.

$$\Delta m^{nlin}_{\mathrm{iknfd}} = A_{2\mathrm{nf}}(C_{\mathrm{if}} - C^0_{\mathrm{nf}})(\chi_{\mathrm{kn}} - \chi^0_{\mathrm{nf}}) \qquad (22)$$

where C^0_{nf} and χ^0_{nf} are the reference colour and extinction values for that night. We use the Levenberg-Marquandt method ([9]) to solve for the non-linear term, separately for each filter and each night.

Once we have calculated all the calibration parameters, we can calculate the residuals at each time.

$$\Delta\, m_{\mathrm{iknfd}} = m_{\mathrm{iknfd}}^{inst} - m_{\mathrm{iknfd}}^{model} \tag{23}$$

These residuals will indicate if there are any bad nights, or poor standards. We eliminate bad nights and variable stars. Having solved for A_{2nf}, we recalculate the linear parameters, by setting:

$$m_{\mathrm{iknfd}}^{inst,new} = m_{\mathrm{iknfd}}^{inst} - A_{\mathrm{2nf}} C_{\mathrm{if}} (\chi_{\mathrm{kn}} - 1) \tag{24}$$

We can then recalculate the non-linear parameters and iterate until the residuals are no longer reducing significantly.

Once we have calculated the best solution, by minimising the residuals, we can use the overlap between photometric and non-photometric nights to calculate the combined zero-point and extinction for non-photometric fields.

Lastly we can try to simplify Eqn. 7 by looking for long/medium term trends in the calibration parameters. For instance, 2MASS found that the extinction varied seasonally [2]. We can eliminate terms where the contribution is less than the errors and look for other sources of variation that need to be added into the photometric model.

Other sources of variation could be instrumental effects: for example changes in the optics due to gravitational distortion may affect the zeropoint. This would depend on the altitude and azimuth of the telescope. Dust from Kilauea may also have a directional and time dependency, i.e. an eruption could add a significant additional component in southerly directions. The dust may also depend on the wind direction.

There may be additional detector related variations, such as imperfect distortion removal which leads to terms dependent on both colour and position. Over time tests on the residuals as a function of colour, x and y position, RA and Declination, altitude and azimuth, wind direction, time and any additional variables that we think could contribute will reveal any other important terms.

Other important tests that can be done in the future will be to compare the photometry to other near-IR data in the same part of the sky and to compare the optical and WFCAM-IR colours of star-clusters to the expected colours. In the former case, it would be best to do a three way test between UKIDSS, 2MASS and another near-IR data set, cf. [11]. Comparing WFCAM and 2MASS alone doesn't prove where the problems lie. A third data set will help to show where the problems lie, as long as all the data sets are calibrated independently in the first place.

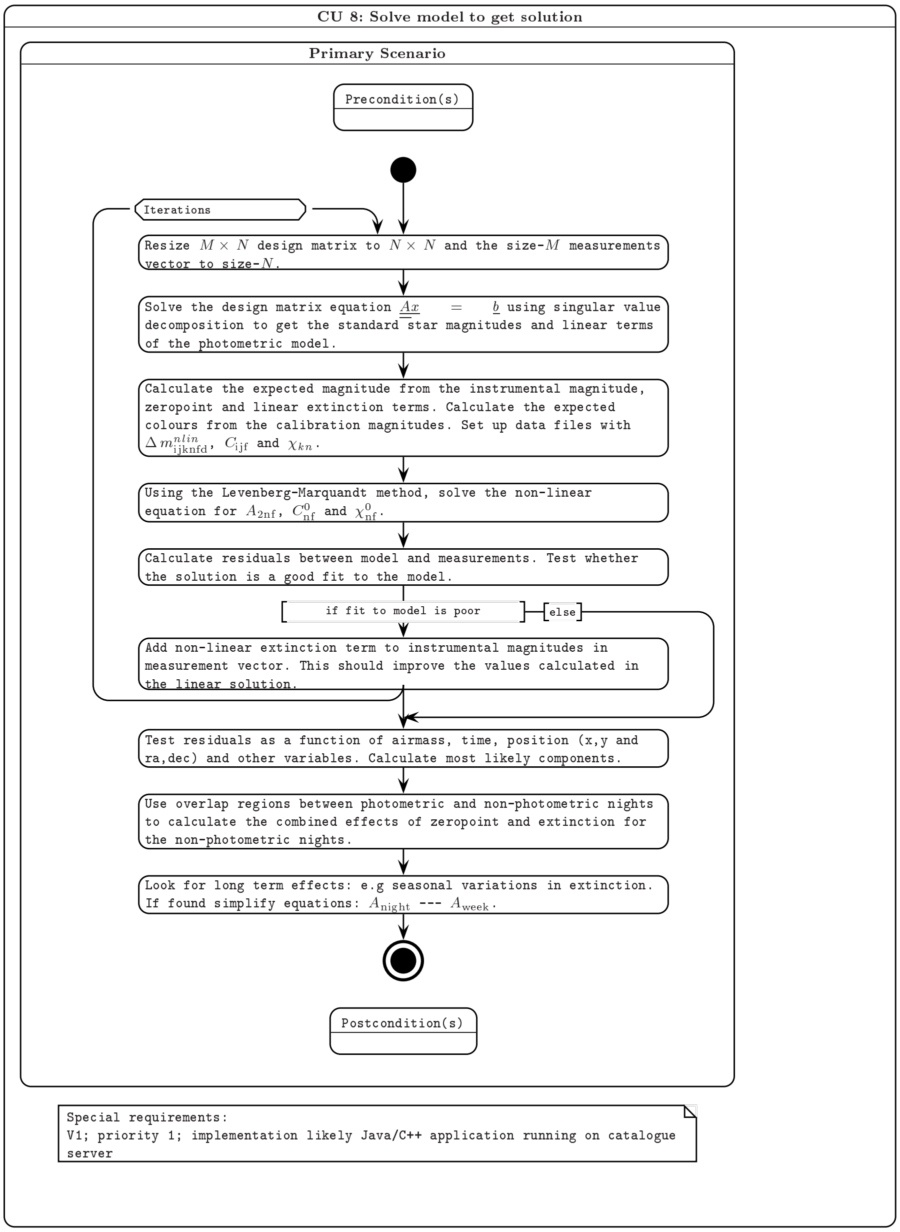

Figure 6: *Activity diagram for third module in CU8.*

3.4 Move Current Calibration to Previous

Once the new photometric calibration model parameters have been calculated, it is necessary to update the calibration tables. These tables include the zero-point table, i.e. $a_{0\mathrm{fd}}$, $a_{1\mathrm{fd}}$, $a_{2\mathrm{fd}}$, $a_{3\mathrm{fd}}$, $a_{4\mathrm{fd}}$: 5 coefficients in 5 broad band filters, and in one or two narrow band filters for each detector. This is 140 coefficients altogether. The nightly extinction table, which includes the coefficients $A_{0\mathrm{nf}}$, $A_{1\mathrm{nf}}$ and $A_{2\mathrm{nf}}$: 15 coefficients per night (upto 21 coefficients per night if the narrow band filters are used too).

Before updating the tables it is necessary to copy the current calibration coefficients to the previous calibration tables, so that we have a record of how the data were processed at any particular time. This will allow people to compare publications at various dates. First we move the current nightly zero-point and extinction tables to the previous nightly zero-point and extinction tables. Except for the first time these will already contain past zero-point and extinction values. The latest values will be appended at the end, with a timestamp and suitable annotation.

As well as the zero-point and extinction values, the current m_{if}^{cal} values must be moved to previous values, before the most recently calculated values are added. These values will be in 3 separate tables, which will be discussed further in the next subsection: primary, secondary and variable. However, in this case it is only necessary to append the current primary standards to the previous primary standards table with a suitable timestamp and annotation. Repeat this for the secondary and variable stars.

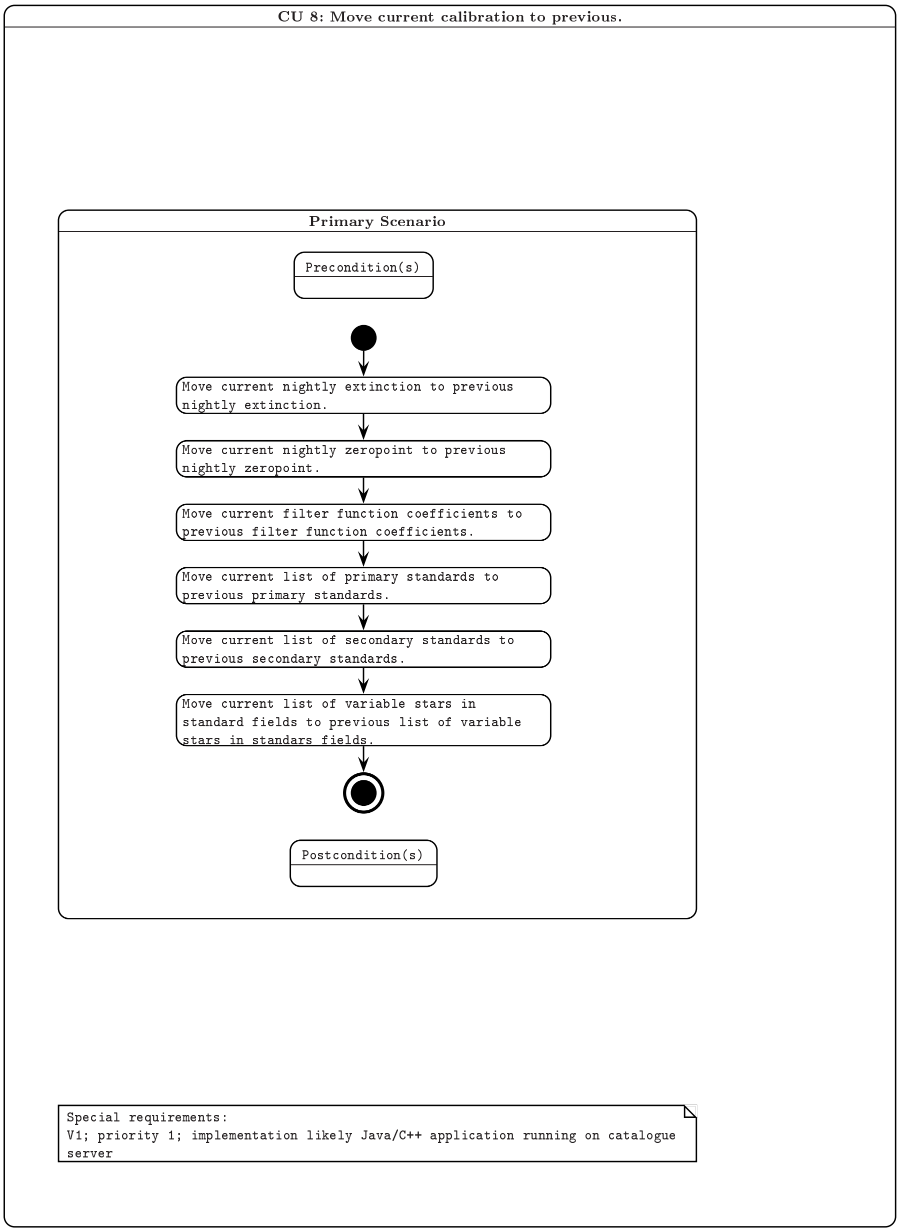

Figure 7: *Activity diagram for fourth module in CU8.*

3.5 Update Current Photometric Calibration Coefficients

Adding new values in is more complicated than copying the old values from the current to the previous tables. First the new values have to be extracted from the solution vectors (one for each filter) calculated in § 3.3. The solution vectors contain nightly calibration parameters and standard star solutions. The zero-point coefficients $a_{\rm ofd}$, where $o = 0, 1, 2, 3, 4$, and nightly extinction coefficients $A_{\rm enf}$, where $e = 0, 1, 2$, must populate the current zero-point and nightly extinction tables. When these tables are updated with the new values, the new version number must be included too.

The calibration magnitudes for standard stars are more complicated, since these must be separated into primary, secondary and variable stars. Primary standard stars are those that do not show variation within the errors and have been measured over a long period (to be decided) and have been absolutely calibrated to the WFCAM/ MKO system. Variable stars are those that show significant variation (i.e. variation much greater than that expected given the random errors in the flux). All other stars which meet the criteria of being within the field of view, are neither too faint such that the measurement errors are larger than $\sim 10\%$, nor too bright such that the star is saturated are secondary standards.

To test the variation, we must look at the residuals between the measured magnitude and the model magnitude for each standard star observation on each night, through each filter.

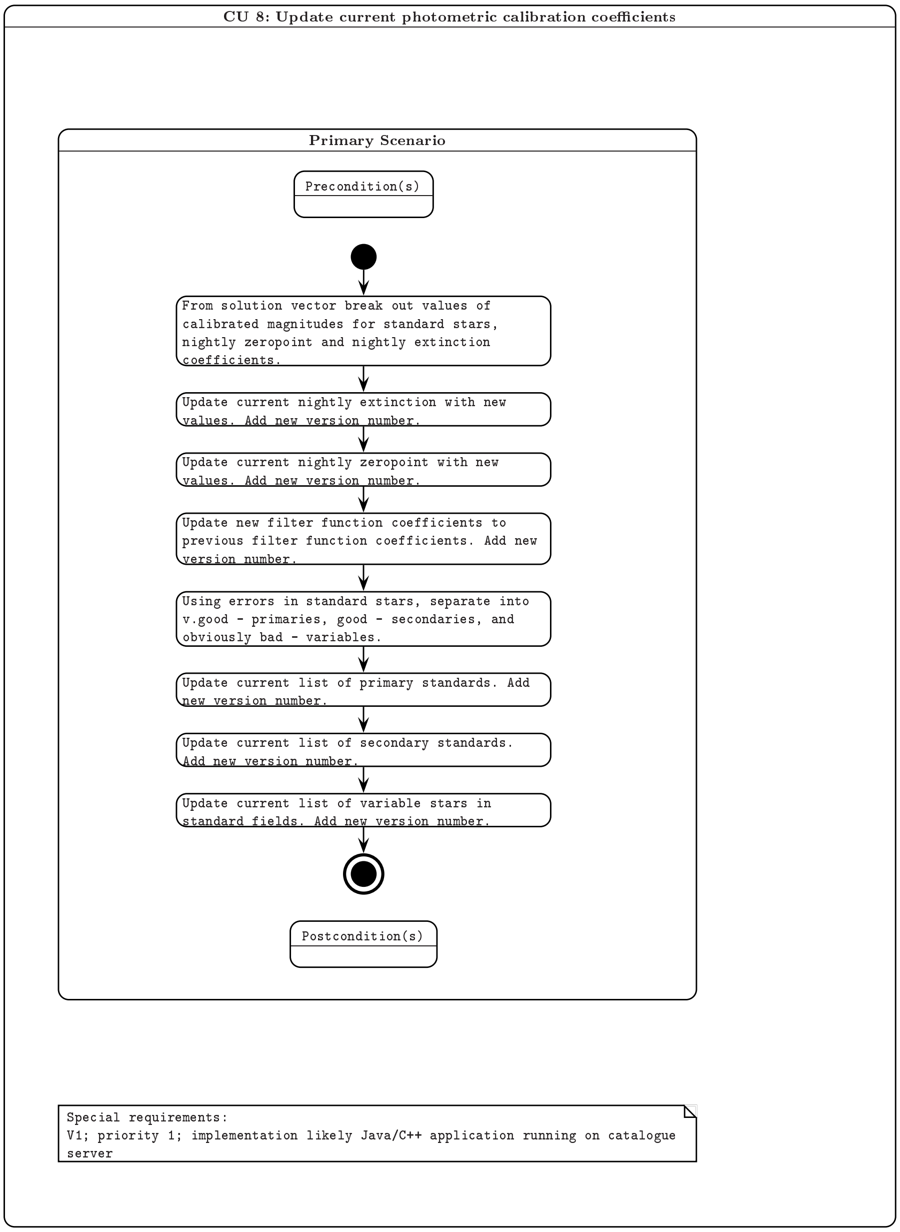

Figure 8: *Activity diagram for fifth module in CU8.*

3.6 Apply Current Photometric Calibration where Photometry Explicitly Stored

Once all the photometric calibration tables have been updated, we must update the catalogues in the database. For each science frame we extract the epoch and airmass from the metadata and calculate the full zero-point and extinction using the calibration coefficients in the current calibration tables.

We update the metadata with the new zero-point and extinction values and the new calibration version number. Once this has been completed we read in all the fluxes (isophotal, aperture, kron and petrosian for each filter), and use these to calculate instrumental magnitudes, see Eqn. 2 and then calculate the new magnitudes (isophotal, aperture, kron and petrosian for each filter). These replace the old magnitudes in the database. The old magnitudes are discarded, but can be recalculated using the previous calibration tables. The recalibrated magnitude ($m^{final}_{\rm abnfd}$) of the ath star at the bth time on the nth night observed through the fth and detected on the dth detector is defined in Eqn. 25.

$$m^{final}_{\rm abnfd} = m^{inst}_{\rm abnfd} + ZP_{\rm bnfd} - A_{\rm bnf} \tag{25}$$

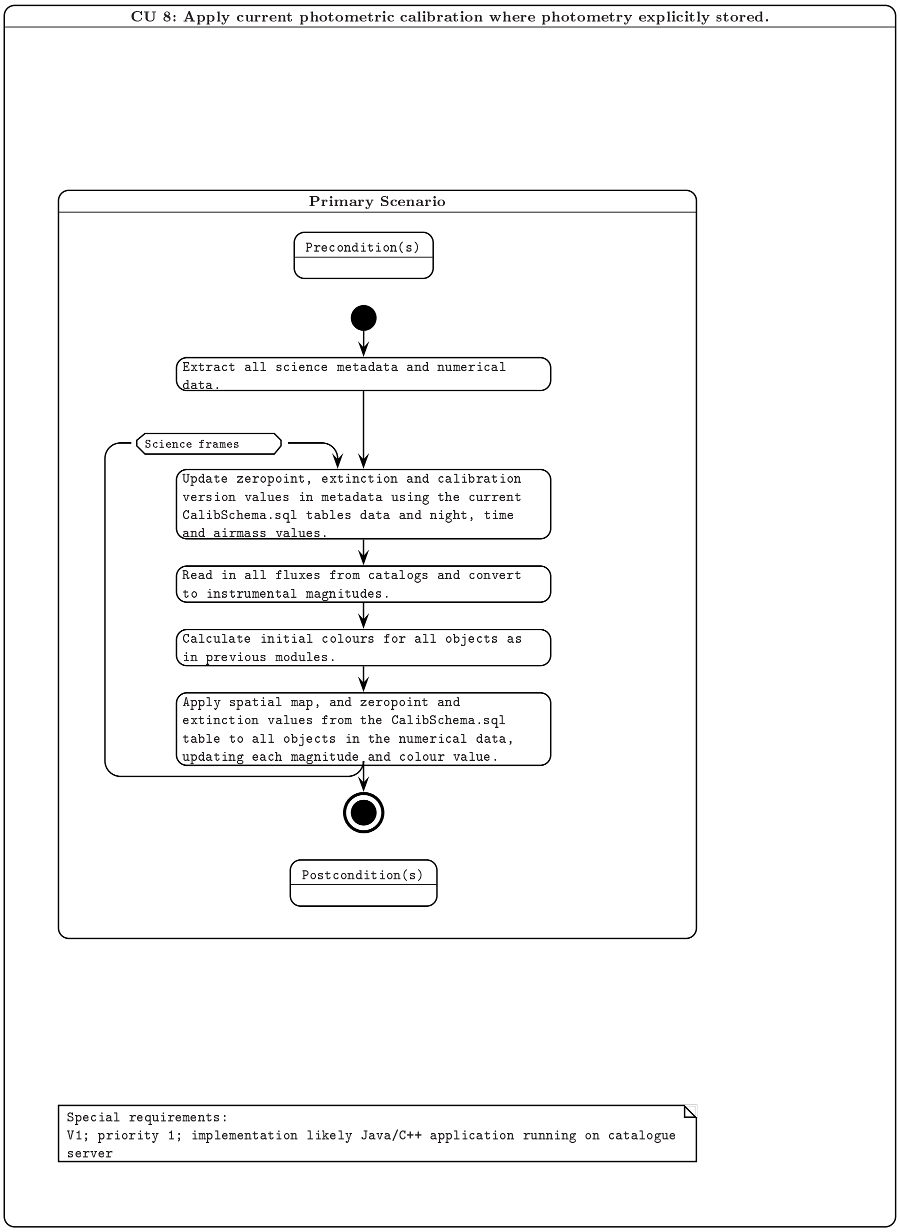

Figure 9: *Activity diagram for sixth module in CU8.*

4 Detector Effects

As well as global calibration, there is a need for calibration within each detector. While these issues are beyond the scope of CU 8, and will be properly investigated and solved further up the Data Flow Scheme (DFS), at CASU, we will discuss these issues briefly for completeness and because the results are used in CU 8.

4.1 Spatial Map

In Eqn 14, we state that the zero-point will probably vary across each detector due to an imperfect flat-fielding model. We can improve on this with measurements of a suitable star field measured at various different positions on each detector.

A polynomial surface:

$$\Delta\, m_{\rm fd}^{SpMp} = \sum_{hk} a_{hk} x^h y^k \tag{26}$$

has been suggested as a model [4], although more complicated terms may be needed.

4.2 Point Spread Functions

Since the best fluxes to use for stars are PSF corrected magnitudes, which are independent of the seeing, it is necessary to know the shape of the PSF, how this depends on the nightly seeing, and how it varies across the detectors. This requires photometry in multiple apertures to measure the growth curves for various stars at various positions, in all bands. These measurements are vital for both stellar photometry and can also be useful in extragalactic studies when you need to compare photometry in many different filters.

5 Tables*

References

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[11] The Millennium Galaxy Catalogue: the photometric accuracy, completeness and contamination of the 2dFGRS and SDSS-EDR/DR1 data sets, Cross et al. MNRAS, 349, 576 (2004)

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6 APPENDICES

6.1 Producing the design matrix to calculate the linear solution.

The matrix equation, Eqn. 16, combines all the simultaneous equations needed to solve the photometric calibration, assuming there are no non-linear terms. This is the most efficient way to solve the huge numbers of simultaneous equations with multiple parameters.

There are 3 types of simultaneous equations that are used to form the matrix equation. The first is the linear equation for all standard stars:

$$\begin{aligned} m^{inst}_{\mathrm{iknfd}} =& m^{cal}_{\mathrm{if}} - a_{0\mathrm{fd}} - a_{1\mathrm{fd}}(t_{\mathrm{kn}}) - a_{2\mathrm{fd}}(t_{\mathrm{kn}})^2 - a_{3\mathrm{fd}}(T_{\mathrm{n}}) - a_{4\mathrm{fd}}(T_{\mathrm{n}})^2 \\ &+ A_{0\mathrm{nf}}(\chi_{\mathrm{kn}} - 1) + A_{1\mathrm{nf}}(\chi_{\mathrm{kn}} - 1)^2 \end{aligned} \tag{27}$$

We use every standard star measurement taken at every time and on every photometric night, just separating the measurements into different filters and detectors.

The second type of equation uses the already calibrated primary standard star measurements to fix the degeneracy between m^{cal}_{ijf} and $a_{0\mathrm{fd}}$ using the following equation:

$$m^{std}_{\mathrm{if}} = m^{cal}_{\mathrm{if}} \tag{28}$$

where m^{std}_{if} is the calibrated primary standard star measurement of the i^{th} star observed through the f^{th} filter.

Finally we use measurements taken in overlap regions to constrain the linear model. In this case the difference in the measured magnitudes of stars in the overlap region is used to constrain the calibration parameters.

$$\begin{aligned} m^{inst}_{\iota\beta\nu\,\mathrm{f}\delta} - m^{inst}_{\iota\,\mathrm{bnfd}} =& [m^{cal}_{\iota\,\mathrm{f}} - a_{0\mathrm{f}\delta} - a_{1\mathrm{f}\delta}(t_{\beta\nu}) - a_{2\mathrm{f}\delta}(t_{\beta\nu})^2 \\ &- a_{3\mathrm{f}\delta}(T_{\nu}) - a_{4\mathrm{f}\delta}(T_{\nu})^2 + A_{0\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1) + A_{1\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1)^2] \\ &- [m^{cal}_{\iota\,\mathrm{f}} - a_{0\mathrm{fd}} - a_{1\mathrm{fd}}(t_{\mathrm{bn}}) - a_{2\mathrm{fd}}(t_{\mathrm{bn}})^2 \\ &- a_{3\mathrm{fd}}(T_{\mathrm{n}}) - a_{4\mathrm{fd}}(T_{\mathrm{n}})^2 + A_{0\mathrm{nf}}(\chi_{\mathrm{bn}} - 1) + A_{1\mathrm{nf}}(\chi_{\mathrm{bn}} - 1)^2] \end{aligned} \tag{29}$$

where the ι^{th} star, is observed twice at different times, b and β (either on the same night or different nights, n and ν), through the same filter, f and on detectors d and δ. The actual magnitude of the stars $m^{cal}_{\iota\,\mathrm{f}}$, drops out of the equation. The useful measurement is the difference in the measured magnitudes, $\Delta\, m^{inst}_{\iota\beta\,\mathrm{b}\nu\,\mathrm{nf}\delta\,\mathrm{d}} = m^{inst}_{\iota\beta\nu\,\mathrm{f}\delta} - m^{inst}_{\iota\,\mathrm{bnfd}}$. Eqn. 29 reduces to Eqn. 30.

$$\begin{aligned} \Delta\, m^{inst}_{\iota\beta\,\mathrm{b}\nu\,\mathrm{nf}\delta\,\mathrm{d}} =& [-a_{0\mathrm{f}\delta} - a_{1\mathrm{f}\delta}(t_{\beta\nu}) - a_{2\mathrm{f}\delta}(t_{\beta\nu})^2 - a_{3\mathrm{f}\delta}(T_{\nu}) \\ &- a_{4\mathrm{f}\delta}(T_{\nu})^2 + A_{0\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1) + A_{1\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1)^2] \\ &- [-a_{0\mathrm{fd}} - a_{1\mathrm{fd}}(t_{\mathrm{bn}}) - a_{2\mathrm{fd}}(t_{\mathrm{bn}})^2 - a_{3\mathrm{fd}}(T_{\mathrm{n}}) \\ &- a_{4\mathrm{fd}}(T_{\mathrm{n}})^2 + A_{0\mathrm{nf}}(\chi_{\mathrm{bn}} - 1) + A_{1\mathrm{nf}}(\chi_{\mathrm{bn}} - 1)^2] \end{aligned} \tag{30}$$

If the overlap is between two stacks, then d $= \delta$, and Eqn. 30 reduces further to Eqn. 31.

$$\begin{aligned}\Delta m^{inst}_{\iota\beta\,\mathrm{b}\nu\,\mathrm{nfd}} =&[-a_{1\mathrm{fd}}(t_{\beta\nu}) - a_{2\mathrm{fd}}(t_{\beta\nu})^2 - a_{3\mathrm{fd}}(T_\nu) \\ &- a_{4\mathrm{fd}}(T_\nu)^2 + A_{0\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1) + A_{1\nu\,\mathrm{f}}(\chi_{\beta\nu} - 1)^2] \\ &- [-a_{1\mathrm{fd}}(t_{\mathrm{bn}}) - a_{2\mathrm{fd}}(t_{\mathrm{bn}})^2 - a_{3\mathrm{fd}}(T_{\mathrm{n}}) \\ &- a_{4\mathrm{fd}}(T_{\mathrm{n}})^2 + A_{0\mathrm{nf}}(\chi_{\mathrm{bn}} - 1) + A_{1\mathrm{nf}}(\chi_{\mathrm{bn}} - 1)^2]\end{aligned} \tag{31}$$

To take account of the various measurement errors we weight each row of the measurement vector and the design matrix by the reciprical of the total noise in each measurement.

To illustrate how these equations go into the design matrix, we will give a simple example. We will simplify the problem by assuming that there is only one detector, instead of four, so we drop the d subscript. Our example contains just two nights of observations, and in which just a single standard field, (we can drop the j subscript) with 3 standard stars has been observed, of which one is a primary standard. This field is observed twice during each night, at different times and airmasses. This gives three values of m^{cal}, 5 values of a and 4 values of A to solve for - a total of 12 parameters.

In the course of the observations, there are 3 overlap regions, each with 1 star, one an overlap between two frames on night 1, one an overlap between two frames on night 2 and one an overlap between one frame on night 1 and one frame on night 2. The matrix $\underline{\underline{C}}$ and the vectors $\underline{x}$ and $\underline{m}$ are shown below. This gives one primary star simultaneous equation, Eqn. 28, twelve secondary star simultaneous equations, see Eqn. 27 and three overlap region simultaneous equations, see Eqn. 30, giving a total of 16 simultaneous equations. Thus the matrix has 16 rows and 12 columns.

In the normal course of events we would have 7 design matrices, one for each of the 5 broad band filters Z, Y, J, H, K and smaller ones for the 2 narrow band filters, since these will not be used as often. In this example we assume just one filter and therefore drop the f subscript. Finally we have not weighted this example by the standard error, for the sake of clarity.

Tables 6 & 5 show the first 3 simultaneous equations properly weighted by the errors.

Once the design matrix has been formed from the simultaneous equations as above, we convert it from a sparse rectangular (M $\times$ N) matrix to a square (N $\times$ N) matrix using the method in [10]. This is much quicker to solve, especially for large matrices after months of observation.

$$\begin{aligned}A_{ni} &= \sum_k C_{kn} C_{ki} \\ \underline{\underline{A}} &= \underline{\underline{C}}^T \underline{\underline{C}}\end{aligned} \tag{32}$$

$$\begin{aligned}b_n &= \sum_k C_{kn} m_k \\ \underline{b} &= \underline{\underline{C}}^T \underline{m}\end{aligned} \tag{33}$$

$$\underline{\underline{A}}\,\underline{x} = \underline{b} \tag{34}$$

We solve Eqn. 34 for $\underline{x}$, using Singular Value Decomposition (SVD [9]). SVD decomposes a matrix $\underline{\underline{A}}$ into 3 matrices $\underline{\underline{U}}$, $\underline{\underline{W}}$ and $\underline{\underline{V}}$, such that:

$$\underline{\underline{A}} = \underline{\underline{U}}\,\underline{\underline{W}}\,\underline{\underline{V}}^T \tag{35}$$

where $\underline{\underline{U}}$ is an $M \times N$ column-orthogonal matrix, $\underline{\underline{W}}$ is an $N \times N$ diagonal matrix with positive or zero elements (the singular values) and $\underline{\underline{V}}$ is an $N \times N$ orthogonal matrix. $\underline{\underline{U}}$ and $\underline{\underline{V}}$ are both orthogonal, since their columns are orthonormal:

$$\begin{aligned} \sum_{i=1}^{M} U_{\mathrm{ik}} U_{\mathrm{in}} &= \delta_{\mathrm{kn}} \\ \sum_{j=1}^{N} V_{\mathrm{jk}} V_{\mathrm{jn}} &= \delta_{\mathrm{kn}} \end{aligned} \tag{36}$$

Since $\underline{\underline{W}}$ is diagonal, it can be represented by a size N vector, with elements w_i. The condition of the matrix $\underline{\underline{A}}$ is the ratio w_i^{max}/w_i^{min}. This tells you if rounding errors are a significant problem for any particular parameter. If the condition is infinite (i.e. $w_i^{min} = 0.$) then the matrix is singular. The value of a parameter becomes unknowable when the value becomes dominated by roundoff error. For a double precision matrix, this occurs when $w_i^{max}/w_i^{min} > 10^{12}$. The errors in the parameters are found using the covariance matrix, which is the inverse matrix of $\underline{\underline{A}}$. The covariance matrix is easily found using the solutions from the SVD.

$$\underline{\underline{CM}} = \underline{\underline{V}}[\mathrm{diag}(1/w_i)]\underline{\underline{U}}^T \tag{37}$$

$$\sigma_i = \sqrt{CM_{ii}} \tag{38}$$

where $\underline{\underline{CM}}^T \underline{\underline{A}} = \underline{\underline{I}}$, and $\underline{\underline{I}}$ is the identity matrix.

7 ACRONYMS & ABBREVIATIONS

ADnn : Applicable Document No. nn
API : Application Program Interface
BLOB : Binary Large OBject
CASU : Cambridge Astronomical Survey Unit
Combiframe: WSA parlance for any image that is a combination of two or more Multiframes
CSV : Comma Separated Value
CVS : Concurrent Versions System
DBI : Data Base Interface
DBMS : DataBase Management System
DXS : Deep eXtragalactic Survey (UKIDSS)
ERM : Entity–Relationship Model
ESO : European Southern Observatory
FITS : Flexible Image Transport System
GCS : Galactic Clusters Survey (UKIDSS)

GPS : Galactic Plane Survey (UKIDSS)
HDU : Header Data Unit (FITS nomenclature)
HEALPix : Hierarchical Equal Area isoLatitude PIXelisation
HTM : Hierarchical Triangular Mesh
JAC : Joint Astronomy Centre
LAS : Large Area Survey (UKIDSS)
MEF : Multi–Extension FITS
Multiframe : WSA parlance for any frame consisting of several distinct device images
OODBMS : Object–Oriented DBMS
RDBMS : Relational DBMS
SDSS : Sloan Digitial Sky Survey
SQL : Structured Query Language
UID : Unique IDentifier
UDS : Ultra Deep Survey (UKIDSS)
UKIDSS : UKIRT Deep Infrared Sky Survey
UKIRT : United Kingdom Infrared Telescope
VISTA: Visible and Infrared Survey Telescope for Astronomy
WCS : World Co-ordinate System
WFAU : Wide Field Astronomy Unit (Edinburgh)
WSA : WFCAM Science Archive
2MASS : 2 Micron All–Sky Survey

Table 1: UKIRT WFCAM photometric standard fields:

FS	Name	RA (J2000)	Dec(J2000)	J	H	K	Nchp	YZ
1	G158-100	00 33 54.48	-12 07 58.1	13.414	13.063	12.968	84	x
103	p241-g	00 36 29.60	+37 42 54.3	12.328	11.833	11.722	270	x
3	F11	01 04 21.63	+04 13 36.0	12.653	12.739	12.833	104	x
5	F16	01 54 34.65	-06 46 00.4	12.369	12.336	12.342	75	est
6	F22	02 30 16.64	+05 15 51.1	13.265	13.311	13.383	119	est
x	P247-U	03 32 03.00	+37 20 40.0	11.901	11.614	11.507	505	x
10	GD50	03 48 50.20	-00 58 31.2	14.780	14.830	14.969	102	est
114	Hy214	04 19 41.72	+16 45 22.4	14.379	13.860	13.438	207	x
116	b216-b7	04 23 50.18	+26 40 07.7	12.777	11.517	10.922	224	x
11	SA96-83	04 52 58.92	-00 14 41.6	11.332	11.267	11.241	170	est
12	GD71	05 52 27.66	+15 53 14.3	13.720	13.818	13.910	966	x
x	S842-E	06 22 43.70	-00 36 30.0	11.650	11.324	11.224	800	syn
121	s772-g	06 59 46.82	-04 54 33.2	11.984	11.436	11.302	1136	syn
14	Rubin149	07 24 14.40	-00 33 04.1	14.124	14.145	14.206	689	x
x	RU149D	07 24 15.36	-00 32 47.9	11.435	11.445	11.469	689	syn
x	P309-U	07 30 34.50	+29 51 12.0	11.816	11.492	11.445	250	syn
x	P545-C	08 29 25.10	+05 56 08.0	11.823	11.588	11.549	219	syn
x	S705-D	08 36 12.50	-10 13 39.0	12.315	12.102	12.045	370	syn
15	M67-I-48	08 51 05.81	+11 43 46.9	12.723	12.415	12.353	408	x
123	p486-r	08 51 11.88	+11 45 21.5	10.141	10.157	10.206	456	est
16	M67-IV-8	08 51 15.01	+11 49 21.2	12.986	12.694	12.643	502	x
17	M67-IV-27	08 51 19.31	+11 52 10.4	12.656	12.345	12.270	508	x
124	lhs254	08 54 12.60	-08 05 03.0	11.482	11.072	10.728	245	syn
125	p259-c	09 03 20.60	+34 21 03.9	10.764	10.432	10.362	110	syn
19	G162-66	10 33 42.75	-11 41 38.3	13.645	13.698	13.784	130	x
20	G163-50	11 07 59.93	-05 09 26.1	13.424	13.453	13.506	121	est
129	lhs2397a	11 21 48.95	-13 13 07.9	11.815	11.182	10.645	112	x
21	GD140	11 37 05.15	+29 47 58.4	13.020	13.064	13.168	66	syn
132	s860-d	12 21 39.36	-00 07 13.3	12.157	11.875	11.835	81	x
33	GD153	12 57 02.30	+22 01 52.8	14.083	14.165	14.270	46	x
x	S791-C	13 17 29.60	-05 32 37.0	11.592	11.274	11.231	119	x
23	M3-193	13 41 43.57	+28 29 49.5	13.001	12.494	12.393	537	x
x	P272-D	14 58 33.10	+37 08 33.0	11.587	11.262	11.202	84	x
x	T868-110639	15 10 17.00	-02 41 05.0	12.537	11.868	11.306	156	x
137	p565-c	16 26 42.72	+05 52 20.3	12.141	11.893	11.843	243	x
138	p275-a	16 28 06.72	+34 58 48.3	10.380	10.377	10.391	144	est
27	M13-A14	16 40 41.56	+36 21 12.4	13.482	13.196	13.130	222	x
35	fs35	18 27 13.52	+04 03 09.4	12.167	11.830	11.729	2071	x
143	Ser-EC68	18 29 53.79	+01 13 29.9	16.534	14.271	12.908	1206	x
144	Ser-EC84	18 29 56.90	+01 12 47.1	15.016	12.563	11.017	1212	x
34	EG141	20 42 34.73	-20 04 34.8	12.888	12.927	13.013	262	est
x	P576-F	20 52 47.30	+06 40 05	12.207	11.928	11.867	406	x
151	p340-h	21 04 14.75	+30 30 21.2	12.205	11.938	11.870	1057	x
29	G93-48	21 52 25.36	+02 23 20.7	13.203	13.248	13.323	181	est
x	BRI2202	22 05 36.00	-11 04 27.0	11.588	11.088	10.700	128	x
30	SA114-750	22 41 44.72	+01 12 36.5	11.936	11.972	12.021	138	est
31	GD246	23 12 21.60	+10 47 04.1	13.828	13.935	14.050	115	x
32	F108	23 16 12.37	-01 50 34.6	13.563	13.649	13.730	118	x

Table 2: Example Solution Vector, $\underline{x}$

m_0^{cal}	m_1^{cal}	m_2^{cal}	a_0	a_1	a_2	a_3	a_4	A_{00}	A_{01}	A_{10}	A_{11}

Table 3: Example Measurement Vector, $\underline{m}$

m_0^{std}	m_{000}^{inst}	m_{100}^{inst}	m_{200}^{inst}	m_{010}^{inst}	m_{110}^{inst}	m_{210}^{inst}	m_{001}^{inst}
m_{101}^{inst}	m_{201}^{inst}	m_{011}^{inst}	m_{111}^{inst}	m_{211}^{inst}	$\Delta\, m_{00}^{inst}$	$\Delta\, m_{10}^{inst}$	$\Delta\, m_{20}^{inst}$

Table 4: Example Design Matrix, $\underline{\underline{C}}$

1	0	0	0	0	0	0	0	0	0	0	0
1	0	0	-1	$-t_{00}$	$-(t_{00})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{00}-1)$	0	$(\chi_{00}-1)^2$	0
0	1	0	-1	$-t_{00}$	$-(t_{00})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{00}-1)$	0	$(\chi_{00}-1)^2$	0
0	0	1	-1	$-t_{00}$	$-(t_{00})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{00}-1)$	0	$(\chi_{00}-1)^2$	0
1	0	0	-1	$-t_{10}$	$-(t_{10})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{10}-1)$	0	$(\chi_{10}-1)^2$	0
0	1	0	-1	$-t_{10}$	$-(t_{10})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{10}-1)$	0	$(\chi_{10}-1)^2$	0
0	0	1	-1	$-t_{10}$	$-(t_{10})^2$	$-T_0$	$-(T_0)^2$	$(\chi_{10}-1)$	0	$(\chi_{10}-1)^2$	0
1	0	0	-1	$-t_{01}$	$-(t_{01})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{01}-1)$	0	$(\chi_{01}-1)^2$
0	1	0	-1	$-t_{01}$	$-(t_{01})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{01}-1)$	0	$(\chi_{01}-1)^2$
0	0	1	-1	$-t_{01}$	$-(t_{01})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{01}-1)$	0	$(\chi_{01}-1)^2$
1	0	0	-1	$-t_{11}$	$-(t_{11})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{11}-1)$	0	$(\chi_{11}-1)^2$
0	1	0	-1	$-t_{11}$	$-(t_{11})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{11}-1)$	0	$(\chi_{11}-1)^2$
0	0	1	-1	$-t_{11}$	$-(t_{11})^2$	$-T_1$	$-(T_1)^2$	0	$(\chi_{11}-1)$	0	$(\chi_{11}-1)^2$
0	0	0	0	$-\Delta\mathbf{t}^{*}_{10,00}$	$-\Delta(\mathbf{t})^{2,**}_{10,00}$	0	0	$\Delta(\chi)_{10,00}$	0	$\Delta(\chi)^2_{10,00}$	0
0	0	0	0	$-\Delta\mathbf{t}_{11,01}$	$-\Delta(\mathbf{t})^2_{11,01}$	0	0	0	$\Delta(\chi)_{11,01}$	0	$\Delta(\chi)^2_{11,01}$
0	0	0	0	$-\Delta\mathbf{t}_{12,02}$	$-\Delta(\mathbf{t})^2_{12,02}$	$-\Delta\mathbf{T}_{1,0}$	$-\Delta(\mathbf{T})^2_{1,0}$	$\chi_{02}-1$	$-(\chi_{12}-1)$	$(\chi_{\mathbf{02}}-1)^2$	$-(\chi_{12}-1)^2$

* $\Delta\mathbf{t}_{bn,\beta\nu}$ is the difference between the bth time on the nth night (t_{bn}) and the β^{th} time on the ν^{th} night ($t_{\beta\nu}$). ** $\Delta(\mathbf{t})^2_{bn,\beta\nu}$ is the difference between the square of the bth time on the nth night ($(t_{bn})^2$) and the square of the β^{th} time on the ν^{th} night ($(t_{\beta\nu})^2$).

Table 5: Example Measurement Vector, $\underline{m}$

$\frac{m_0^{std}}{\sigma_0^{std}}$	$\frac{m_{000}^{inst}}{\sigma_{000}^{inst}}$	$\frac{m_{100}^{inst}}{\sigma_{100}^{inst}}$

Table 6: Example Design Matrix, $\underline{\underline{C}}$

$\frac{1}{\sigma_0^{std}}$	0	0	0	0	0	0	0	0	0	0	0
$\frac{1}{\sigma_{000}^{inst}}$	0	0	$\frac{1}{\sigma_{000}^{inst}}$	$\frac{t_{00}}{\sigma_{000}^{inst}}$	$\frac{(t_{00})^2}{\sigma_{000}^{inst}}$	$\frac{T_0}{\sigma_{000}^{inst}}$	$\frac{(T_0)^2}{\sigma_{000}^{inst}}$	$\frac{\chi_{00}-1}{\sigma_{000}^{inst}}$	0	$\frac{(\chi_{00}-1)^2}{\sigma_{000}^{inst}}$	0
0	$\frac{1}{\sigma_{100}^{inst}}$	0	$\frac{1}{\sigma_{100}^{inst}}$	$\frac{t_{00}}{\sigma_{100}^{inst}}$	$\frac{(t_{00})^2}{\sigma_{100}^{inst}}$	$\frac{T_0}{\sigma_{100}^{inst}}$	$\frac{(T_0)^2}{\sigma_{100}^{inst}}$	$\frac{\chi_{00}-1}{\sigma_{100}^{inst}}$	0	$\frac{(\chi_{00}-1)^2}{\sigma_{100}^{inst}}$	0