

# NOTCam Calibration Plan v.2.0

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# 1 Introduction

The purpose of this document is to describe the content of the NOTCam Calibration Plan. This document is based on a previous draft “NOTCam Calibration Plan v.0.1” (Djupvik, 2006). That version included a large section about NOTCam performance in general, which has now been moved to another document.

In addition to the calibrations included in the 2006 version, we now include also calibration data and results of interest to the user community, not only the internal quality control of the system (telescope, instrument, detector). Calibration data and results of monitoring, processed calibrations and/or models are already available on-line through the NOTCam web pages, and fully described with links to the download archives from the NOTCam calibration page:

<http://www.not.iac.es:instruments/notcam/calibration.html>

- Nightly master flats, typically for WF-camera and JHKs filters
- Zero-pixel and cold-pixel masks
- Distortion correction models for WF-camera and JHKs filters
- Pixel by pixel non-linearity correction coefficients
- Monitoring of readnoise and gain etc.

The calibration plan defines the content of the NOTCam quality control, e.g. what should be monitored, how frequently, and how this is implemented in practice. Also, it includes how to manage the the calibration data obtained, potential post-processing, and storage of quality control results.

Section 2 gives an overview of the content of the calibration plan with a subsection describing each item more in detail. Section 3 describes the practical details of how to obtain the data, in what conditions and with which frequency. At last, in section 4 comes a description of the analysis of the various raw calibration data and information on the storage of the results.

## 2 Calibration plan content

The various parts of the calibration plan are listed briefly for an overview. See subsections below for a more thorough description.

The scripts **notcam.\*** mentioned below, are observing scripts to be run in the sequencer window of the NOTCam observing system. The reduction scripts **\*.cl** refer to scripts available in the IRAF package **notcam.cl**.

- **Detector Quality Control**

Read noise, gain, linearity, reset level, and dark level per quadrant per readout mode, as well as determination of zero pixels, cold pixels, and hot pixels. Performed in the afternoon with script **notcam.lintest** (takes 90 min), and analysed with the script **notcam.lintest-analyse** which sends results to the data base and updates the php files for online QC plots.

- **Imaging flat fields**

Differential twilight flats are obtained nightly as part of normal observing, by staff and/or the visiting observer, through the script **notcam.skyflat**, storing the raw flats in `/pub/service/calib/`. As a minimum, the JHKs filters with WF-camera are covered, and any additional filter/camera setups that are requested. To obtain a real master flat for any filter/camera combination, run the script **mkflat.cl** in the NOTCam IRAF package. Verified master flats are copied to the on-line NOTCam flatfield archive. These are also to be used for monitoring the flat field stability. Done by AAD.

- **NIR photometric standard stars**

In clear/photometric nights, if the observer agrees, photometric standard star fields are observed, typically by running purpose made scripts **notcam.as\*-jhk** that point, and make a 5-point dither in each filter JHKs (takes 9 minutes). The raw data is stored in `/pub/service/calib/`. The data is used to monitor the zeropoints and the sky backgrounds. Images are reduced with **reduce.cl**. Photometric analysis done by AAD.

- **Spectroscopy - flux standards**

During technical time, whenever specifically asked for, and else about once per year, in photometric/clear conditions, observe one of the flux standards at high altitude in all bands ZYJHK with the WF camera using both the 128  $\mu\text{m}$  slit (using ABBA) and the 1 mm pinhole (2 exposures on and 2 off). Take arcs and halogen with the slit setup, only halogen with the pinhole. Spectra are reduced and analysed by JHT or students.

- **Spectroscopy - flats and arcs**

Due to flexure, it is recommended to obtain wavelength calibration while pointing to target. Due to fringing it is recommended to take a few halogen flats at the same time. Flats and arcs are not taken at daytime, thus, as part of this plan. The custom made script **notcam.easy-calib** takes one Argon, one Xenon and three halogen lamp exposures per wavelength region requested. These data are *not* stored publicly. Should be used internally to monitor the slit position on the detector, and to provide a wavelength calibration to be used by **notcam.quick-spec**.

- **Darks**

The NOTCam darks are poorly understood, and there seem to be some excessive signal that is not due to dark current. Typically, however, it is not necessary to do specific dark subtraction in the reductions, since the dark is subtracted out with the sky. Nevertheless, we provide 10 raw darks obtained at the end of the night for each of the readout mode combinations used during the night. Done by running the script **notcam.notcam-calibs**. Raw data stored in /pub/service/calib/. Darks are also useful for making hot-pixel masks for longer exposures (since hot pixels depend on the exposure time).

- **Pinhole position monitoring**

Every time NOTCam has been mounted on the telescope, the pinhole position on the detector is measured for both cameras by running the script **notcam.pinholePosition**. You are asked to note down numbers and update web pages. In the future, the values should be sent by the same script directly to a data base.

- **Rotation centre monitoring**

Every time NOTCam has been mounted on the telescope, the rotation centre is found at night by running the script **notcam.rotation-centre**. You are asked to note down numbers and update web pages. In the future, the values should be sent by the script directly to a data base.

- **Non-linearity of array (pixel by pixel map)**

Once every few years, a new set of data is used to calculate the non-linearity of the array, pixel by pixel. An IRAF script **getlincor.cl** was made to do this. In principle, there is no reason to believe that the non-linearity changes, but AAD checks the calibration.

- **Optical distortion correction (WF camera)**

Typically this is a once in a time calibration, but if things have been modi-

fied inside NOTCam, or if another internal focus is used, then the distortion correction must be re-mapped. The distortion model is not perfect, and it is not known to which degree the distortion may vary with altitude and rotation position, although no such tendency has been found so far.

- **Illumination correction**

Mapping the photometric response as a function of position on the array. A first surface correction has been made for the H-band, and mapping of a standard star in photometric conditions over the array is needed. Takes about 4 hours per filter. Does not need very good seeing.

- **Focus pyramid calibration**

Since it is not known how well the pyramid can stand thermal cycling, it is recommended to make a through-focus test about once a year in good seeing conditions. The sequencer script **notcam.through-focus** takes focus images with and without the pyramid, alternatingly. A script to analyse the data is to be made. So far only manual analysis.

## 2.1 The detector quality control

The detector Quality Control (QC) for NOTCam has been running since 2003, giving a database for each of the three arrays (SWIR1, SWIR2, and SWIR3) that have ever been used with NOTCam. The observations consist of daytime darks and domeflats obtained with a lamp, pointing the telescope towards the area of the upper hatch with least daylight leakage (to keep the light level as constant as possible).

Multiple darks and flats in each of the different integration times are obtained for both readout modes available with notcam: 1) the reset-read-read mode and 2) the sample-up-the-ramp mode, in order to cover the whole dynamical range, i.e. from a few hundred to 54000 ADU. For each of the read modes, the QC was designed to monitor: readnoise, gain, bad pixels (zero, cold, hot), reset level, dark counts as a function of integration time, and non-linearity. Since the IR-array is read out in four quadrants simultaneously, the quantities are calculated per quadrant.

A first version of the QC analysing script was programmed in IDL by Silva Järvinen in 2002-2003, and was running since January 2003. In 2009 the IDL code was translated to Python by Ricardo Cardenes, and a few additions and modifications as suggested in the NOTCam Calibration Plan, v.0.1 (Djupvik, 2006) were implemented, such as adding a monitoring of the reset level, and always discarding the first images of the 5 multiples. In short, the QC analysis calculates the following for each read mode:

- The gain and readout noise (with errors) per quadrant. Uses Janesick's method on short darks and bright domeflats. For the reset-read-read mode zero exposure darks are used, while for the ramp-sampling mode the shortest available are 4.2 second darks.

- For each quadrant the range of linear behaviour is calculated, i.e. the maximum number of ADUs which gives linear response. Two limits are calculated, linearity to within 1% and 3%.
- For each quadrant the reset level is monitored for jumps.
- The amount of bad pixels, given in percentage. Zero pixels, hot pixels, and cold pixels are monitored separately. Zero pixels are partly due to actually dead pixels, partly to a problem with the array controller giving rise to an apparently dead column which has nothing to do with dead pixels, and also depends on the voltage settings and the reset level selected. Cold pixels are usually groups of pixels with a lower sensitivity (20-80be caused by dust on the detector itself. These may change position. Hot pixels are highly non-linear pixels whose response is higher than the neighbouring pixels. The number of hot pixels depends critically on the integration time.
- A JPG image map of the zero pixels is produced.
- The detector temperature taken from fits header keyword
- The dark current as a function of exp time

More details regarding how the analysing script currently works are found in the web document

[http://www.not.iac.es/instruments/qc/notcam\\_document.html](http://www.not.iac.es/instruments/qc/notcam_document.html)

The analysing script is since 2009 run by giving the sequencer commands:

- **notcam.lintest-analyse rrr** filename
- **notcam.lintest-analyse rs** filename

The results for the calculation is partly output on the screen, and the user is asked if it is OK to send the results to the database. This action will automatically update the www pages:

<http://www.not.iac.es/instruments/qc/notcamqcrrr.php>  
<http://www.not.iac.es/instruments/qc/notcamqcrrs.php>

## 2.2 Imaging flat fields

### 2.2.1 Differential twilight flats

Differential twilight flats are used to flat field correct imaging NOTCam data. As part of the calibration plan, the stability of these flats should be monitored.

Whenever the weather permits, differential twilight sky flats should be obtained, as a minimum, in the filters *JHKs* with the WF camera. Any additional flats is a pre, for instance with the HR camera or in other filters.

The differential approach should cancel out the effects of the thermal emission as well as the dark, provided that the difference images are taken close in time. The timing is critical as the twilight window is narrow. It is recommended to start as early as possible and to use short integration times (typically 3-20 seconds). The NOTCam Cookbook gives instructions on how to best obtain differential flats. There is a sequencer script available called **notcam.skyflat** which takes the integration time in seconds as an input parameter. It is vital that the same integration time is used for the bright and the faint flats in each filter/camera combination, otherwise the differential approach breaks down.

Instructions on how to analyse these images are given in Section 4. Raw flats are always stored in `/pub/service/calib/`. Master flats are provided (by AAD) for download, available in the NOTCam flat field archive.

### 2.2.2 Flatfield stability

In order to monitor the flat field stability we use the master flats obtained from the differential twilight flats and make ratio flats for the same camera/filter/array setup. The ratio images will reveal any changes in the flat field.

Although this monitoring has not been regularly started yet, some preliminary results of the flatfield stability shows that there is a gradient in the ratio flats, probably due to stray light, in twilight images taken at different sky locations. Twilight flats taken towards the same blank field at more or less the same time, night after night, on the other hand, are much flatter, and the ratio images can reach a standard deviation of 0.1 %.

Monitoring of the flats will detect sudden changes due to dust particles and help us to localize the dust and decide when the system needs cleaning, i.e. in most cases the entrance window.

## 2.3 NIR photometric standard stars

NIR photometric standard stars observed with the WF camera in the filters *JHKs* obtained in photometric/clear conditions are useful for calibrating the *JHKs* images, for zero-point monitoring, and to monitor the sky backgrounds (e.g. as a function of moon illumination and angular distance, but also time-variability due to OH line emission from the mesosphere).

### 2.3.1 Zero-point monitoring

The zero point monitoring data for NOTCam is obtained with the WF camera through the broad band filters *JHKs*. A set of six standard star fields from Hunt et al. (1998) have been chosen as follows:

- to have standards available at the NOT at any time with zenith distances less than 40 degrees (airmass  $< 1.3$ )
- to have 2 or more standard stars per field
- standards have published photometric errors  $< 0.024$  mag and magnitudes in the range 9.4-13.5

One observing script is made per standard field (for instance **notcam.as05-jhk** for the standard field AS05). The script goes to target, starts guiding, sets up the instrument, and runs a 5-point dither per filter. This takes from 6-10 minutes. The exposure times have been chosen to avoid entering the non-linear regime (i.e. where the deviation from linearity is more than 1%), even for cases of very good seeing.

The zeropoint monitoring observations should be performed every NOTCam technical/service night which has clear/photometric weather. At least one standard field should be observed at three different airmasses, if possible.

### 2.3.2 Photometric calibration

If the target field contains a sufficient number of isolated and bright stars that do not saturate, the 2MASS point source catalogue Cutri et al. (2003) can be used to calibrate the JHKs magnitudes in the images. The accuracy obtained depends totally on the number of good calibrators.

If the sky conditions are clear/photometric, standard stars observed with the same system at several airmasses, will reveal the nightly zero-points and the atmospheric extinction.

### 2.3.3 Sky background monitoring

The sky backgrounds in the near-IR are highly variable. In the J and H bands this is mostly due to airglow, or OH emission lines. When ozone and hydrogen reacts in the mesosphere to form oxygen and  $\text{OH}^-$ , this is an exothermic process, leaving the hydroxyl radical in a vibrationally excited state. De-excitation happens radiatively or by collision and gives rise to line emission from the various levels producing the so-called Meinel bands, numerous sky lines in the near-IR. The lines are highly variable and strongest in the H band, where it may cause the background to vary by 10% in 5-15 minutes and by 50% over the night. The main contribution to the sky background in the K bands is the thermal emission from the sky, thus its intensity at night being a function of the ambient temperature.

With clear/photometric sky, the standard star images can be used to obtain the back-ground level in each filter, and due to the repeated measurements on several fields one can monitor the scatter with position on sky, moon distance and with time. The moon is not expected to affect the backgrounds in the near-IR, but there could be a slight contribution in J and bluer bands when the moon is near enough. To

estimate properly the background levels, darks with the same integration mode/time must be obtained.

## 2.4 Spectroscopic calibrations

Due to flexure in NOTCam, arcs are always recommended obtained when pointing to the target. Because of fringing, the spectroscopic flats are also better obtained pointing to the target. As default, an in-situ mode for spectroscopic calibrations at night is obtained by running the script

**notcam.easy-calib**

which while pointing to your target, stops guiding, closes mirror covers, switches on lamps, and takes 1 argon, 1 xenon, and 3 halogen flats in the wavelength region(s) the user requests before re-opening mirror-covers and re-gaining guiding on the target. Any additional spectroscopic flats should be obtained by the user according to needs.

For the K band it may also be recommended to do lamp ON and lamp OFF flats in order to subtract out the thermal contribution, especially in longer integrations.

### 2.4.1 Check on system efficiency

Every now and then a check on the system efficiency is made by observing spectrophotometric flux standards. Since we do not have a broad slit, we use the 1mm pinhole (4.7" diameter) which is about 10 times the typical fwhm (0.5") in good conditions. All wavelength regions ZYJHK are measured. In order to do a proper wavelength calibration, the same standard is observed with the 128  $\mu$ m slit for which arcs are also taken.

## 2.5 Darks

The counts measured in the NOTCam darks are too high, and cannot be due to dark current. In addition, the intensity in the darks decrease with exposure time, ending up being negative for longer darks. This behaviour is quite repetitive, when the images are obtained in the same order, but it is not well understood. In typical observing conditions the "dark" is subtracted out with the "sky", and no separate master dark is needed. Darks are obtained, nevertheless, for completeness and for other purposes, such as making the hot pixel masks. For every exposure mode 10 darks are obtained at the end of the night. Remember to discard the first 1-3 of these, which have not stabilized and will be affected by higher count levels.

For more about the NOTCam darks see:

<http://www.not.iac.es/instruments/notcam/staff/darks.html>

## 2.6 Non-linearity coefficients

The linearity of the current array used with NOTCam, SWIR3, is good to  $\sim 1\%$  for intensity levels up to 25000 ADUs. When reaching 45000-50000 ADUs, however, the average (over pixels) response is about 5% less than a linear response. The non-linearity has been mapped pixel by pixel by fitting a 3rd order polynomial to 10 measured values, obtaining three coefficients a,b,c per pixel, i.e. three coefficient images. These are reduced to two images by taking the ratios b/a and c/a.

The non-linearity correction, if applied, must be performed on the raw data. There is a task called `mklinco` in the IRAF NOTCam package that takes the two coefficient ratio images as input and corrects the selected image extension of an image (or list of images). The corrected image is appended as an extra MEF extension to the same raw data file.

## 2.7 Optical distortion model for the WF-camera

The WF-camera suffers from a strong optical distortion, leading to elongated stars in the corners of the detector. Gålfalk (2005) provided a first model of the distortion for the K band.

The HR camera has an excellent optical quality and the ellipticity of stars is typically 0.02 to 0.05 all over the field of view in good seeing conditions of  $\text{fwhm} = 0.44''$ . The pixel scale of the HR camera is  $0.078''/\text{pix}$ .

## 2.8 Illumination correction

The photometric response over the field of view may not be flat even after having divided by the nightly flat field. For many IR cameras a so-called photometric surface correction or illumination correction is needed. It is believed to originate in scattered light in the system. In order to map this, one needs repeated measurements of a standard star over many positions on the array in photometric conditions. A surface correction for the NOTCam WF-camera and the H-band (as well as one for NICS/TNG) was found and used by Janz et al. (2013). The spatial variation, about 10% across the array, mostly in the vertical direction, in agreement with previous preliminary results on star clusters.

It is not entirely clear whether this photometric surface correction is similar for different filters, neither whether it varies with time. We need to make a corresponding mapping for the J and Ks filters, and perhaps redo the analysis later to test stability.

## 2.9 Focus pyramid

The focus pyramid consists of 4 pieces of “Infrasil 302” cemented together and held in a spring-loaded metal frame. It was installed in November 2004 in the grism

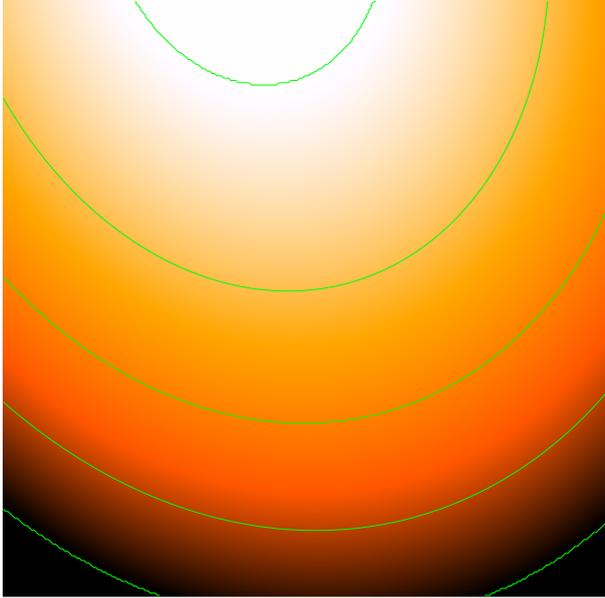


Figure 1: *The photometric surface of NOTCam WF-camera H-band. The response is higher at the upper centre. Contours go from 1.05 at the top through 1.02, 0.99, 0.96 to 0.94 at the bottom.*

wheel and a first calibration made. After a few re-calibrations it seems to be stable. Due to thermal cycling the calibration should be checked about once per year.

A full through-focus test for the WF camera should be made in good and stable seeing conditions (fwhm  $\sim 0.5''$ ) about once a year to monitor the focus pyramid and check its calibration. A suitable star at a good altitude is used to take alternating images with and without the focus pyramid (using the Ks-band) as the telescope focus is adjusted. A script is available for taking this data: **notcam.through-focus**, and it takes about 30 minutes.

For the HR-camera we do not need to check the focus-pyramid calibration since we only use the focus pyramid with the WF-camera and the K-band to actually determine each night's focus value. All other filter and camera settings have pre-determined focus offsets that are applied when using the NOTCam setup scripts **notcam.setup-ima** and **notcam.setup-spec** for changing the instrument configuration.

## 3 How and when the data is obtained

Instructions for how to obtain the calibration data is fully given in the NOTCam Cookbook and in the web documents for staff, related to the first night NOTCam goes on the telescope and the technical time tasks

<http://www.not.iac.es/instruments/notcam/staff/firstnighttests.html>

<http://www.not.iac.es/instruments/notcam/staff/techtimetasks.html>

### 3.1 Upon every NOTCam mounting on the telescope

These are the tasks to do right after having mounted NOTCam on the telescope.

- Monitoring the pinhole positions (takes 5 min)
- Detector Quality Control (takes 90 min)
- Measuring the rotation centre for both cameras (at night, 10 min)
- Measuring the alignment of the instrument on the sky (at night, 10 min)

### 3.2 Daily calibration data

By *daily calibration data* we refer to those that are normally obtained, both by visiting observers and in service/technical nights, if sky conditions allow for it, on every night NOTCam is used. They sum up to:

- Differential twilight flats in given filter/camera combinations
- NIR photometric standard stars (JHKs filters, potentially ZY) if the sky is clear/photometric
- Darks

The instructions for how to obtain these data in the best way are given in the NOTCam Cookbook, available on our web pages.

It is noted that any spectroscopic calibration data needed by the projects are usually taken on target at night (due to flexure) and included in the observing blocks of the science program.

### 3.3 Additional Technical time calibrations

During technical nights, when conditions allow, and according to needs the following additional calibrations might be requested:

- Spectroscopic flux standards in clear/photometric conditions to check/monitor the throughput (instructions TBD).
- Mapping of the illumination correction (WF-camera, JHKs), only in photometric conditions, no seeing limits
- Optical distortion of WF camera (only in good seeing, needs a very crowded field, “Baade’s window” is recommended)
- Once a year a through-focus sequence (in 0.5” seeing conditions)
- Take a few really long darks (script `notcam.long-darks-test`)
- If NOTCam has been opened and the detector plate dismounted, check the alignment of the detector (instructions TBD).
- Check the alignment of optical components using the pupil imager. Especially the small stops are important to check after each opening and operation inside NOTCam.

## 4 Processing and storage of calibration data

The raw calibration data is in most cases stored for public download in `pub/service/calib/` at our ftp site.

Some of the calibration data, in particular flats and standard stars, are processed through a set of IRAF scripts made available in the NOTCam IRAF package called **notcam.cl**. The package is installed on florence and all NOT computers, and it is also publicly available for download. It is referred to as a quick-look reduction tool, not a pipe-line, but it is something in between. A data flow chart is shown in Fig 2.

### 4.1 Detector QC

The detector QC data is analysed with the two sequencer scripts (one for each read mode):

- **notcam.lintest-analyse-rrr** filename1
- **notcam.lintest-analyse-rs** filename1

The results for the calculation is partly output on the screen, and the user is asked if it is OK to send the results to the database. This action will automatically update the www pages:

```
http://www.not.iac.es/instruments/qc/notcamqcrs.php  
http://www.not.iac.es/instruments/qc/notcamqcrrr.php
```

The various quantities are calculated per quadrant. There is one database per array (SWIR1, SWIR2, SWIR3) and per readout mode. No processed images are stored.

### 4.2 Bad pixel masks

Every now and then the zero-pixel and cold-pixel masks are checked using domeflats from the QC data set or twilligh flats with the HR camera (which are flatter, in general).

The hot-pixel masks are derived from darks, and darks for each specific exposure time and mode are needed, since hot pixels increase with exposure time. The percentage of hot pixels is 0.5% for 42 sec integrations, 1.8% for 80 sec and 2.2% for 120 sec.

### 4.3 Flat field images

The skyflat data reduction is done with the dedicated script **mkflat.cl** which is run per filter/camera combination, searches for the available raw flats in the requested mode, processes them as described below, and outputs a master flat. It needs as input the zero-pixel mask image. For instance, running:

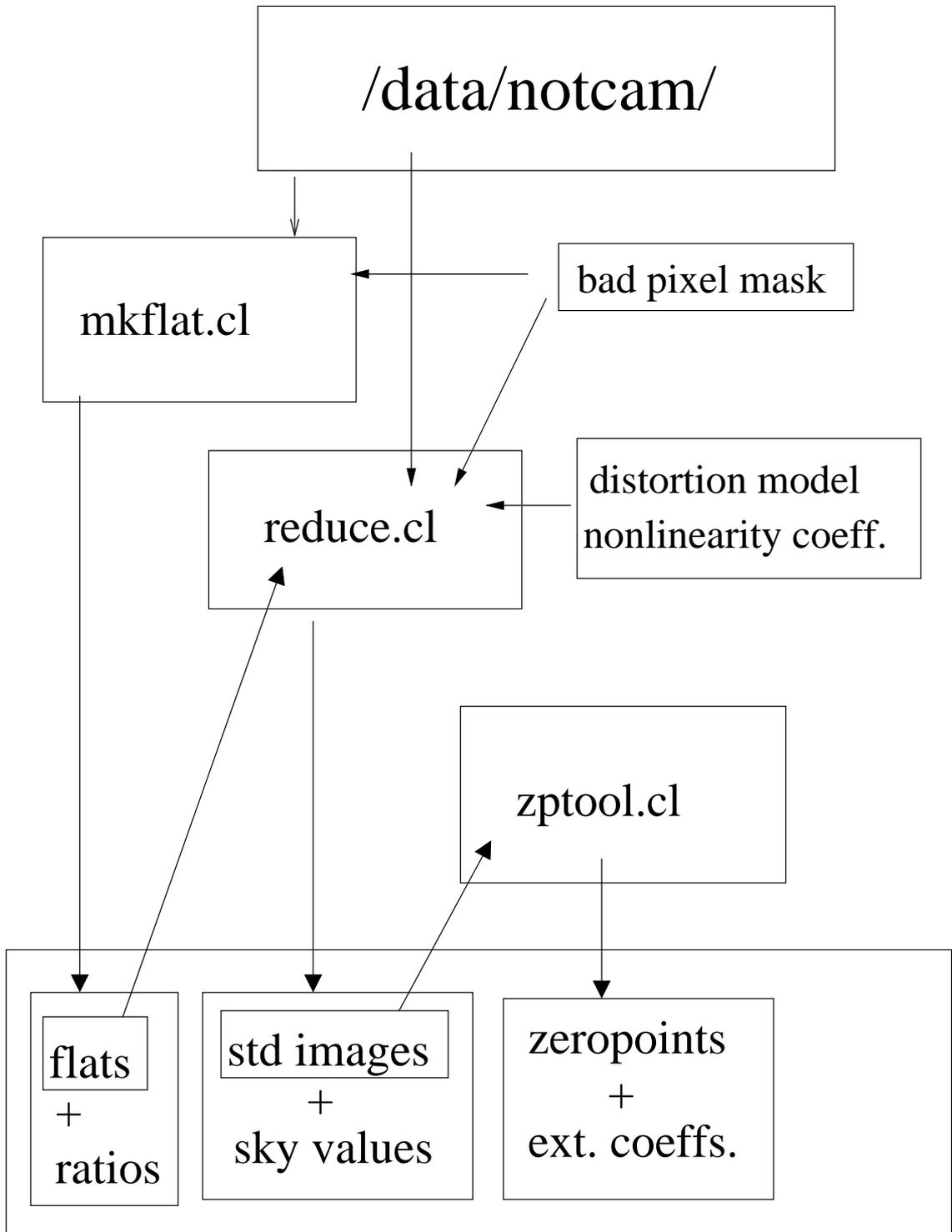


Figure 2: *Data flow chart for imaging.*

```
mkflat NCph28*[1] ph28_sf_wf_ks_sci bad_zero_sci wf ks yes
```

makes a WF camera Ks masterflat, searching among the “NCph28” files (using the NOT data file naming convention). NB! If there are raw flats for the same setup both from evening and morning twilight, it is necessary to separate the files into two blocks, evening twilight and morning twilight, otherwise the method will break down.

The script can be used for all differential raw flats, i.e. both dome lamp (on-off) as well as twilight (bright- faint) flats. The script searches for the requested camera/filter combination among images that have the keyword `IMAGETYP = FLAT`, checks that the exposure time is the same, checks that the count levels are below saturation (as default, or otherwise the max adu level set as a parameter by the user), corrects the raw images for zero-valued pixels using a mask, makes difference pairs, median combines these with an additive scaling to obtain a master flat, and normalises it. By setting `suppress=yes` the gradient produced in each quadrant by the reset-anomaly, see McLean (1997), and due to the continuously changing brightness level, will be suppressed by subtracting a collapsed median line by line. For more info type inside the NOTCam package in IRAF `help mkflat` and or read the NOTCam User’s Guide.

Master flats may also be obtained from the target images themselves, but then both the dark and the thermal component must be subtracted out.

The output master flat is displayed on a DS9 and the fits file is stored locally with the requested output image name. Some image statistics to quantify the small scale pixel to pixel flat quality, is output, together with a vector plot across two image diagonals to show the deviation from flatness over the FOV. The flat field quality can be determined based upon these numbers. The master flat is uploaded to the on-line **flatfield archive** if/when satisfactory result. See readme file in flatfield archive for naming conventions.

Non-satisfactory flats may be due to: cloudy sky, or non-removal of stars because dithering was not made (happens if the TCS access code was not set), or forgetting to turn off the dome lamps, etc. The reason why a cloudy sky is a problem for NIR flats is that the sky intensity jumps up and down and it is difficult to obtain a useful level (not too bright, not too faint) for the bright images.

### 4.3.1 Flat field stability

The stability of the flats from night to night and over longer timescales can be found by making ratio images of the master flats obtained in the different filter/camera combinations. The statistics of these ratio images will give an idea of the repeatability from night to night.

From a limited dataset of JHKs WF-camera flats from 4 consecutive nights in June 2012 and 5 consecutive nights in September 2012, it is found that the master flats from one night to the next typically agree to  $\sim 1\%$ , excluding the outer 40 pixels of the array (green square), which are otherwise much affected by bad pixels.

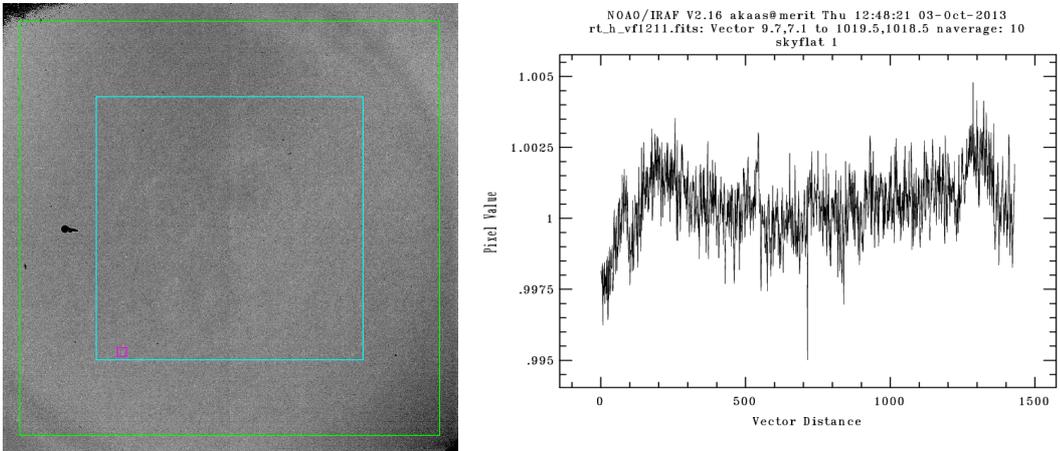


Figure 3: **Left:** Ratio image of WF-camera H-band master flats from one night to the next. Boxes indicate regions used for statistics. **Right:** A plot across the diagonal from lower left to upper right, averaging over 10 pixels to emphasize the structure.

That is, the standard deviation around the mean in the ratio image is  $< 0.015$  in all filters. Looking at small  $20 \times 20$  pixel areas that are free from bad-pixel groups (magenta square), we find that the standard deviation is always  $< 0.009$ . This accuracy is also in many cases maintained over timescales of weeks and sometimes months.

There seem to be, however, an influence on the flats from stray light that affect the images differently depending on telescope pointing with respect to the gradient on the twilight sky. When using the same blank field every night, we find that the standard deviation in the ratio images from one night to the next is as low as  $< 0.004$  in small areas, and  $< 0.007$  over the array (i.e. in the green box). It is believed that this improvement is mainly due to the same illumination gradient, such that stray light affect these flats in a similar manner and therefore cancel out. These results are, nevertheless, preliminary, and more systematic monitoring and studying of the flat field stability is requested.

## 4.4 Photometric standard stars

### 4.4.1 Image reductions

One standard star observation consists of 5 dithered images, but the first of these is discarded and only the latter 4 used. This is due to the time needed for the array to stabilize on a given intensity level. In order to reduce these images and produce one master frame, the script `reduce.cl` in the NOTCam IRAF package is used. In addition to the raw images also the bad-pixel mask and the master flat is needed. Assuming the 5 point dither of H-band images starts with file number NCwg140210.fits, then skip the first and reduce the latter 4 images. Note that the

image extension, here [1], but any extension can be selected, must be given in the input image name:

```
reduce NCwg140211[1] nim=4 std_h wg14_sf_wf_h_sci bad_zero_sci
```

For each of the 4 images this script interpolates over the zero-valued pixels, uses the supplied master flat to flat field each image, makes a sky template from the images by median combination and scaling, subtracts a properly rescaled sky from each image, makes an optional distortion correction of each image, and finally registers all images (using WCS in the header, or stars in the frame selected by the user), shifts and combines them to one result image, but stores also the individual images.

The FITS header of the output reduced images contain the keywords FLAT and SKY with the name of the flatfield and sky template image used.

#### 4.4.2 Non-linearity correction

If the peak intensity of the standards exceed 20000 ADUs it is recommended to make non-linearity correction on the raw data before reducing them. Make a list of the images that need non-linearity correction using **files** command in IRAF, and then run the script **mklinco**.cl in the NOTCam IRAF package, where you need the input coefficient ratio images *ba* and *ca*, that are downloadable from the NOTCam calibration archive.

```
files NCwg1403*% .fits% [1] % > mylist
mklinco @mylist lin_coeff_ba lin_coeff_ca
```

The script takes the input image (in the above example the input image is the one from extension [1]), produces its corrected image based on the non-linearity coefficients applied, and stores the corrected image in a new extension appended to the original MEF file. Needs write permission to the original data, but appends to, rather than alter, the original images. If using exp/mexp the new extension will always be extension [3], if using “frame t N” the new extension will be [N+3]. In the FITS header of the image three keywords: LINCOR-Y, LIN-C-BA, and LIN-C-CA to indicate which image extension has been corrected, and which files are used as the two coefficient ratio images BA and CA, respectively.

The corrected extension is now used in the subsequent data reduction, for instance when running the **reduce** script (see above).

#### 4.4.3 Aperture photometry

When all the standard star images are reduced, the photometric analysis of one night is made with the wrapper script **zptool**.cl which performs aperture photometry (with large apertures) on all standards, runs a fitting tool in IRAF to catalogue standard values, and outputs the zeropoints and the extinction coefficients (if calculated) to the user.

`zptool @imagelist`

The interactive `zptool.cl` script does the following:

- For each image, display on the DS9 with the standard star catalogue overlaid, for easy identification of the actual stars to measure
- For each image makes a call to the IRAF task “digiphot.apphot.phot” to do aperture photometry through a number of different apertures
- Sorts the output magnitude files
- Calculates the measured photometric scatter over the FOV
- Makes the obsfile and sets up the aperture correction files etc.
- Finds image shifts between repeated observations
- Calculates zeropoints and extinction coefficients using fitparams

If there are too few data points to calculate the extinction coefficients, then we use the standard extinction coefficients 0.086, 0.065, and 0.08 for J, H and K, see Fuensalida & Alonso (1998).

## 4.5 Spectroscopic calibrations

No spectroscopic calibration data reduced.

## 4.6 Darks

Raw data stored in `pub/service/calib/`. Occasionally used for making masks.

## 4.7 Pinhole position monitoring

Measurement of pinhole position is updated on our web pages.

## 4.8 Rotation centre and alignment monitoring

Measurement of rotation centre and alignment is updated on our web pages.

## 4.9 Non-linearity coefficient images

Whenever new calibration data is obtained, new coefficients are calculated per pixel. The two coefficient ratio images are checked on a few datasets before they are made available in the NOTCam calibration archive, linked from the NOTCam Calibration web page.

## 4.10 Optical distortion model

To actually make the distortion model from a set of 9 dithered observations in 3 filters, using about 300 stars at 9 positions, giving 2700 reference points over the field of view, is a rather tedious procedure.

To correct for the distortion, using the available model that can be downloaded from our web pages, is simple and implemented in the reduction tasks **reduce.cl** and **reduce\_bs.cl** in the NOTCam IRAF package. In these tasks, if distortion correction is applied (it is available as an option only), it is performed *after* the basic image reductions such as bad-pixel correction, flat-fielding and sky subtraction, but *before* individual images are shifted. After distortion correction, the individual images are registred, shifted and combined. In the FITS header of distortion corrected images the keyword DISTCORR is added with a string giving the name of the distortion model applied.

## 4.11 Illumination correction

The construction of a photometric surface requires accurate aperture photometry of the calibration star at the N positions over the array as input to a surface fitting function. The illumination correction found by Janz et al. (2013) for the WF-camera and the H-band was based on calibrations obtained during their observing run in March 2012.

## 4.12 Focus-pyramid re-calibration

The observing script **notcam.through-focus**, always to be done in the Ks-band, supplies alternating images with the focus pyramid in and out while stepping the telescope focus value. The distance between the 4 images of the star split up by the pyramid is a function of the focus, and the reference distance for best focus is found from these calibrations. Offset images to be used for sky subtraction are supplied. A dedicated script to analyse these images is TBD. An example of the calibration of the reference distance for the HR camera is shown in Fig. 4.

## 4.13 Data storage

Apart from all the raw data, the processing of some of the calibration data requires some extra disk space, mainly on our web server, and the disk capacity needed is mainly that for the flat-field archive. The remaining stuff consists of few images.

NOAO/IRAF V2.12.2-EXPORT akaas@merit Mon 12:02:53 20-Nov-2006  
 func=legendre, order=4, low\_rej=3, high\_rej=3, niterate=0, grow=0  
 total=13, sample=13, rejected=0, deleted=0, RMS= 0.0273  
 hr\_dist.dat

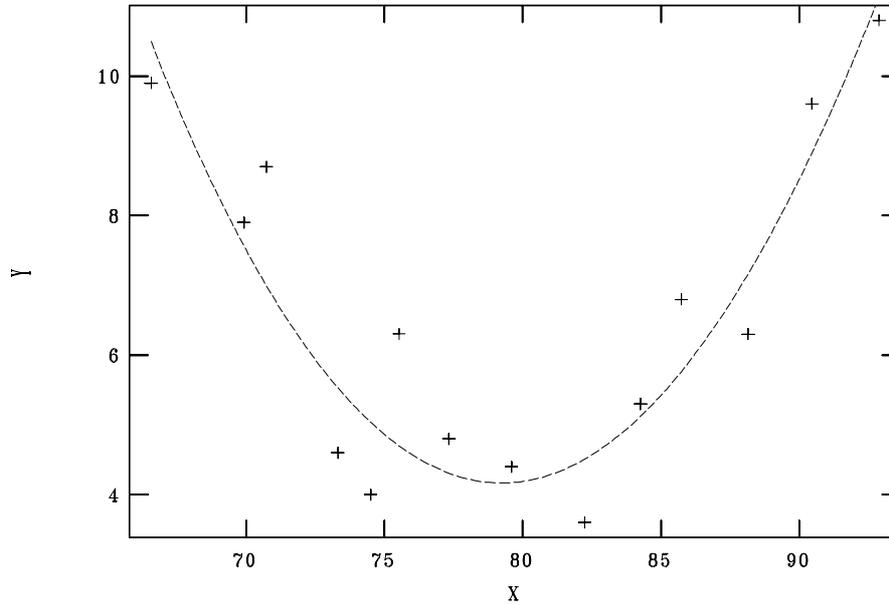


Figure 4: Calibration of the focus pyramid reference distance (x-axis) for the HR camera. The FWHM in pixels (4 pixels = 0.31") on the y-axis.

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