# OmegaCAM

## OmegaCAM Data Flow System - All CP and Data reduction related item

TO SUIT THE CONTACT GROUP

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*Prepared by:* Valentijn, Boxhoorn, Deul, Kuijken, Rengelink

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| Estimated time needed | • |
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| Recipe | • |
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# CHANGE RECORD

Changes between Version 1.0–FINAL DESIGN REVIEW and Version 1.1–FINAL DESIGN REVIEW

Additions

New section on 2-3 day cycle specifications – 2.2 DFS requirements.
Specify all three levels of TSF's, as given in VST-SPE-OCM-23100-3064, in requirements.
Detailed estimates of observing times for photometric checks – 2.2 DFS requirements, **req.**562, **req.**563, **req.**564.
Include tilt determination – **req. 571** *Camera focus/tilt.*
**CalFile– 562S** *Sky brightness* – **req.**562.
Reference to **req.**563 in CA – **req.**564.
OmegaCAM DID – 1.2 Applicable documents.
Once/year dark dome test – **req.**533.
Processing of calibration data follows telescope schedule – 2.2 DFS requirements, 6.1 Data reduction software requirements.

Updates

Clarify fast recipe for Technical Specifications conformance – **req.**562, **req.**563.
Erroneous references to darkcurrent check for **req. 547** *Quick detector responsivity check* removed.
Nonexistent **CalFile– 561** removed – **req.**533.
Stars have to be observed during the night – **req.**525.
**req. 571** *Camera focus/tilt* is no longer a workhorse/*doit* – 1.4 Abbreviations and Acronyms, 5.10 On site quick look analysis.
Exposure times TBC during commissioning – **req.**561.
More accurate description of the algorithm – **req.**523.
Lamp procedure TBC. – 5.4 Detectors operational specific calibrations.
Removed reference to QCO – **seq.– 631**.
Mention acceptance of multi-extension FITS files – **seq.– 631**.
Target-related template parameters (only) where applicable – 4.4 Observ-

ing Templates.
Reworded sentence about DFS-pipeline – 5.10 On site quick look analysis.
Reworded sentence about modules – 6.1 Data reduction software requirements.
Rotator $offset$ angle – 4.4 Observing Templates.
Use plots for analysis – **req.**571.

# TABLE of CONTENTS

1 INTRODUCTION ..... 8
2 SCIENTIFIC REQUIREMENTS ..... 9
2.2 DFS requirements ..... 9
3 INSTRUMENT CONCEPT- Summary ..... 13
3.1 Description ..... 13
3.2 Focal plane geometry ..... 13
3.3 CCD details ..... 15
3.4 Filters ..... 15
3.5 Control electronics ..... 16
3.6 Instrument Software ..... 16
4.0 OBSERVING MODES and STRATEGIES ..... 17
4.1 Observing Modes ..... 18
4.2 Observing Strategies ..... 20
4.3 Filtering ..... 21
4.4 Observing Templates ..... 21
4.5 Field correctors ..... 22
5 BASELINE CALIBRATION REQUIREMENTS ..... 23
5.0 Documentation system, **Odoco** ..... 23
5.1 Functional Checks ..... 27
5.2 Detector Electronics specific Calibrations ..... 28
5.2.1 Req.– *CCD read noise - doit* ..... 29
5.2.2 Req.– *Hot pixels* ..... 31
5.2.3 Req.– *CCD gain* ..... 33
5.2.4 Req.– *Electromagnetic Compatibility* ..... 36
5.2.5 Req.– *Electrical cross talk* ..... 38
5.3 Detectors specific calibrations ..... 39
5.3.1 Req.– *CCD Dark Current - doit* ..... 40
5.3.2 Req.– *CCD Particle Event Rate* ..... 43
5.3.3 Req.– *CCD Linearity* ..... 44
5.3.4 Req.– *CCD Charge Transfer Efficiency* ..... 47
5.3.5 Req.– *CCD Cold Pixels* ..... 49
5.3.6 Req.– *CCD Hysteresis, strong signal* ..... 51

5.4 Detectors operational specific calibrations ..... 53
5.4.1 Req.– *Bias - doit* ..... 58
5.4.2 Req.– *Flat-field - dome key bands + user bands - doit* ..... 61
5.4.3 Req.– *Flat-field - twilight* ..... 64
5.4.4 Req.– *Flat-field - night sky* ..... 67
5.4.5 Req.– *Flat-field - Fringing* ..... 70
5.4.6 Req.– *Flat-field - master flat and weight map* ..... 72
5.4.7 Req.– *Quick detector responsivity check-doit* ..... 75
5.4.8 Req.– *Illumination correction* ..... 76
5.5 Astrometric Calibration ..... 78
5.5.1 Req.– *Position of Camera in focal plane* ..... 80
5.5.2 Req.– *Telescope Pointing and offsetting* ..... 82
5.5.3 Req.– *Telescope and Field Rotator tracking* ..... 83
5.5.4 Req.– *PSF Anisotropy* ..... 86
5.5.5 Req.– *The astrometric solution for templates - doit -see 6.3.4* 88
5.5.6 Req.– *The astrometric solution for Guide CCD's* ..... 88
5.6 Photometric Calibration ..... 90
5.6.1 Req.– *Shutter Timing* ..... 94
5.6.2 Req.– *Photometric Calibration - monitoring* ..... 97
5.6.3 Req.– *Photometric Calibration - zeropoint keybands - doit* . 102
5.6.4 Req.– *Photometric Calibration - zeropoint user bands* ..... 107
5.6.5 Req.– *Filter band passes - user bands vs key bands* ..... 109
5.6.6 Req.– *Dependency on angle - ADC, rotator/ reproducibility* 110
5.6.7 Req.– *Linearity (as a function of flux)* ..... 111
5.6.8 Req.– *Detection limit and ETC calibrations* ..... 113
5.6.9 Req.– *Secondary Standards* ..... 114
5.7 Internal alignments, optics etc ..... 116
5.7.1 Req.– *Camera focus/tilt* ..... 116
5.7.2 Req.– *Ghosts - ADC* ..... 118
5.8 Effect of Telescope ..... 119
5.9 Workhorses and End to end tests ..... 120
5.10 On site quick look analysis ..... 121
Fig 6. Data Flow of Science and Calibration data ..... 123
6 DATA REDUCTION SOFTWARE SPECIFICS ..... 124

6.1 Data reduction software requirements . . . . . 124
6.2 Estimate of data volumes . . . . . 133
6.3 Baseline Requirements for the Image Pipeline . . . . . 135
6.3.1 Seq.– *Ingestion and image statistics* . . . . . 138
6.3.2 Seq.– *Trim, de-bias, flatfield* . . . . . 141
6.3.3 Seq.– *Construct weigths, determine seeing* . . . . . 142
6.3.4 Seq.– *Astrometric calibration* . . . . . 144
6.3.5 Seq.– *Apply photometric calibration* . . . . . 147
6.3.6 Seq.– *Dedithering/dejittering* . . . . . 148
7 NEEDED FUNCTIONALITIES . . . . . 151
7.1 Image manipulation . . . . . 152
7.2 Catalog manipulation . . . . . 156
7.3 Header manipulation . . . . . 162
7.4 Miscellaneous functionalities . . . . . 163
A1 LIST of CALIBRATION REQUIREMENTS . . . . . 164
A2 LIST of RAW CALIBRATION DATA . . . . . 166
A3 LIST of DFS I/O CALIBRATION FILES . . . . . 167
A4 LIST of DFS INPUT REFERENCE CATALOGUES . . . . . 169
A5 LIST of SEQUENTIAL STEPS in IMAGE PIPELINE . . . . . 170

# Lay-out of the sections

| URD | OmegaCAM |
|---|---|

| | |
|---|---|
| 1.0 | **Introduction** |
| 2.0 | **Scientific Requirements** |
| 3.0 | **Instrument Concepts** |
| 4.0 | **Observing Strategies** |
| 5.0 | **Calibration requirements** |
| 6.0 | **Data reduction** |
| 7.0 | **Preparatory Programmes** |

# 1 INTRODUCTION

**OmegaCAM** is planned as the first instrument for the VLT Survey Telescope (VST) on ESO's Paranal site. It is expected to operate for a period of ten years, and at least during the first 3-5 years of operations of the VST the **OmegaCAM** is foreseen to be the only instrument on this telescope. **OmegaCAM** is a 16,384 x 16,384 pixel (16k x 16k) imaging camera which will image a field of 1 square degree of sky.

The instrument is envisaged to execute dedicated observing programmes defined by individual users or teams. About 2/3 of the available observing time will be allocated by ESO's OPC. The remaining time is labeled as guaranteed time for the consortia involved in the construction of the telescope and the camera. Both small dedicated programmes, and bulk wide field sky surveys, are expected.

The VST and **OmegaCAM** are built to provide an observing facility for the purpose of selecting targets for follow-up observations at the VLT, but also to conduct stand-alone observing programmes that require wide-field imaging. The camera and its associated data reduction will facilitate accurate photometry and astrometry over its entire field of view, following the requirements on the VST and its instrumentation. Primary Performance Characteristics for the VST wide-angle CCD camera are laid out in the Memorandum of Understanding (MoU) between **OmegaCAM** and ESO in Section A.4.1, while guidelines for its implementation in ESO's Data Flow System (DFS) are given in A.4.2 of the MoU which in turn refers to VLT-SPE-ESO-19000-1618.

# 2 SCIENTIFIC REQUIREMENTS

## 2.2 DFS requirements

### GENERAL

The Science requirements (Section 2.1) 15, 16, 17, 18 (see also Notes 15i, 15ii) propagate directly to requirements on the DFS pipeline infrastructure and the DFS peripheral infrastructure (housing operators manually running tools) and are not repeated here.

Prominent derivatives from these requirements include:

- Provide a quality control on all observational data– this task is matched by ESO's QC0 and QC1
- Provide a quality control on all results of the processing of **OmegaCAM** data, such as Calibration files and image data— this is provided by a **trend analysis**. Trend analysis is used as a tool to monitor the behaviour of the instrument. The results of trend analysis are not used to interpolate (calibration) results to be fed back to the pipeline.
- Parallel processing of image data
- Distribution of administration and calibration data to National data centers/Users facilitating further source extraction re-processing and error bar evaluation.
  The Interface Control Document [VST-PLA-OCM-23100-3551] specifies the essential data items for this distribution.

### QUICK ACCESS - 2-4 DAY CYCLE

The use cases:

- Supernova/ Optical transients
- Microlensing
- Kuiper Belt objects and fast moving asteroïds

require some fast follow-up observations within typically a few days (1-2 lensing) to 3-4 days (supernova). For brevity we call this the **2-4 day cycle**.

In the near future it is unlikely that the data transfer rates required to electronically transfer the raw image data to Europe will be available to the VST observers, but this might become possible in a couple of years, since the technology already exists.

For the time being, it appears that a 2-4 day cycle involves some data reduction to take place at, or near, Paranal. For most observing programmes it is enough to provide the user with the raw data and some calibration data. The user would then have to run some quick data reduction steps to identify the events which require fast follow-up observations.

As an indication how frequently and with what kind of data volumes the 2-4 day cycle would be loaded, the Consortium has made a small inventory on the estimated usage for the GT programmes. This might be used as an indication for the total usage, but beware individual programmes which might ask for exceptional data rates and we advise the OPC to include this as a consideration in the allocation procedures for any (also non 2-4 day cycle) programme.

**Supernova IA searches: GT about 10 nights per year (10 times 40 frames).**

For the search with OmegaCAM, typical exposure time could be 45-60 min (splitted in 3-5 dithered exposures). This makes 30-40 science frames per average night. For the search, image processing through archive calibration files (master flats and bias) is sufficient.

**Micro-lensing: GT about 15 nights/year**

We would spend (GT) two 1-week campaigns a year on monitoring the bulge, but there could also be a more extensive effort by combining with open time or other partners. This programme will mostly be useful for generating tighter limits on the optical depth in very short-duration events, which do not require follow-up per se. However, there are microlensing events all the time in each field, and it is likely some of these will be useful to study in real time with VLT (spectroscopically). In that case it is necessary to search for these events, which requires to analyse ALL data of those 2 weeks in near-real time. The

programme could combine a microlensing search for brown dwarfs with a transit search for hot jupiters in the same fields.

**Solar system Objects: Open Time up to 2-3 nights/month with 60 frames/night.**

As already indicated by the several SSO oriented use cases described in Section 2.1 there are a number of programmes which need a fast turn around time.

Although the interest for such programmes is great we have not assigned much GT time to this and it is very difficult to estimate the usage or anticipate on OPC allocations for this mode. One possible OT proposal relayed to us asks for typically 5 nights/month for this mode for which roughly half of the data require the 2-4 day cycle.

Two SSO programs that need fast follow-up:

(1) Search for Near-Earth asteroids: this has 2 levels of turn-around time. The objects really nearby and not yet discovered need immediate follow-up observations, basically during the same night or within 1-2 nights after discovery. Somewhat more distant objects objects in the asteroid belt require a turn - around time of around two weeks.

The searches must be done in both cases on the whole data set. The exposures will have 5-10 min integration time. The shorter the turn-around cycle time is the better.

(2) Search for Kuiper Belt Objects and MBOSSes: a few epochs per object need to be observed. Turn-around times up to the order of one month could be allowed, but it is preferably done within one week; this also depends on the survey method (one or two exposures per field) and how one combines the survey with other scientific programmes. Typical exposure times for this search will be 10-15 min with few images per field per night.

**SUM-UP 2-4 day cycle**

The present rough estimate indicates that the consortium would want to make use of a **2-4 day cycle** for a maximum of 25 nights/year with on average about 60 frames/night of its GT. The supernovae search (10 nights) has a high priority on our programme. Regarding open time, only for the SSOs one might

expect of the order of 24 nights/year (also with on average 60 frames/night). Some of these programmes can be optimized by combining these programmes. As the lower priority programmes will not all run year after year we estimate that in practice the 2-4 cycle would be used for a fraction ranging from 10% to 20% of the total time.

# 3 INSTRUMENT CONCEPT- Summary

This Section summarizes those characteristics of the camera which potentially can have an impact on the User requirements on calibration and data reduction. Particularly relevant are the focal plane geometry, the cosmetics of the CCD's and the chosen set of both narrow and wide band filters.

## 3.1 Description

**OmegaCAM** is a wide field optical imager, featuring a 4 $\times$ 8 mosaic of 4k $\times$ 2k pixels CCD's for a total imaging area of 16k $\times$ 16k pixels. It will cover the VST field of view of $1^\circ \times 1^\circ$ and at the same time it will adequately sample the best seeing foreseen at Paranal. The standard observing mode is with a two-lens field corrector. In addition, a single lens plus atmospheric dispersion corrector can be used.

The instrument features a two-blade photometric shutter. An exposure is started by moving the blade that obscures the CCD's to a rest position, and finished by moving the other blade from its rest position to the position that obscures the CCD's.

The focal plane geometry of the CCD's is given in section 3.2 and the **OmegaCAM** filters are described in section 3.4.

## 3.2 Focal plane geometry

The layout for the CCD array is sketched in Fig 3.2. It consists of a, roughly square, **science array** of 16384$\times$16384 pixels, and four **auxiliary CCD's** for guiding and image analysis.

With the preferred LL,RR arrangement for orientations of the CCDs' readout ports the gaps between sensitive areas are 6.0 and 2.0 mm. Vertically there will be 7 2.0mm gaps, leading to a total gap of 14mm vertically.

16384 pixels of 15$\mu$m comprise 246mm. Adding in the gaps, the total light-sensitive part of the science array is thus 259 x 260mm in size. The full unvi-

gnetted field of the VST is 1.47 degrees, or 372mm in diameter. The planned array with gaps fits in the field.

**Fig 3.2** Sketch of layout of CCD arrays. Units of X and Y axes are in mm.

## 3.3 CCD details

An extensive description of the CCDs is given in VST-TRE-OCM-23100-3042

## 3.4 Filters

The **OmegaCAM** filters are to be decided on jointly by the VST, **OmegaCAM** consortium and ESO. ESO has set up a VST/**OmegaCAM** Instrument Science Team (IST) for advise on such issues.

Discussions between VST and **OmegaCAM** have resulted in the following list of filters:

- **Broad band** (6 filters)
  Given the importance of the Sloan survey in the North, the rather large width of g' for stellar work, and the desireability to maintain small colour terms with respect to the standard Johnson system for many applications, the top priority broad band filter set is:

– 2 Johnson B, V
– 4 Sloan u' g' r' i'

- **Narrow band** – current preferences in **bold**
  – O[III]/100Å (FWHM) at redshifts of 2000 and 6000 km/s.
  – H$\alpha$/**80**Å(FWHM) at redshifts of 2000 and 6000 km/s

The broad-band filters will be monolithic. The narrow-band filters are segmented, made up of two halves. A scheme where each half is made with a different passband is under investigation. Half the array would then be illuminated through one passband, half through the other. After a second exposure with the camera rotated through 180 degrees, the whole field will have been covered through both passbands, which can serve as each other's off-band image.

In addition a **composite filter**, comprising a u', B, V, and i' quadrant for rapidly obtaining photometry measurements is envisioned. For details see section 5.6

Note that the f/5.5 beam is transfered to f/6 in front of the filters due to the corrector optics.

Note that the fast beam makes it impossible to define truly rectangular filter profiles. A relative wavelength spread of at least 0.4% is unavoidable. At 5000Å, for instance, this represents a 20Å broadening of any filter profile. Thus, an O[III] filter with a FWHM of 50Å= 3000km/s, has a flat part of 40Å= 2400km/s. For H$\alpha$ filter with FWHM 60Å= 2600km/s, only 46Å= 2000km/s is flat.

For this reason it is not useful to define rectangular filter transmissivity profiles for the narrow-band filters. This may reduce the number of coatings, and hence the cost, of the filters.

## 3.5 Control electronics

The **OmegaCAM** subsystems to be controlled by the control electronics include:

- Filters Unit
- Shutter Drive Unit
- Filter identification system
- Instrument status and diagnostic system
- Interlock system

The design is given in Hardware Control Electronics, VST-TRE-OCM-23100-3043

## 3.6 Instrument Software

The Instrument Software shall be self-supporting and will internally verify whether commands have been successfully executed. Malfunctions or special status of the instrument will be displayed on the instrument monitor.

QC0 and the DFS-QC1 will not further check or double check these items.

The User requirements on the **OmegaCAM** instrument software are given in a separate document VST-SPE-OCM-23100-3060.

# 4.0 OBSERVING MODES and STRATEGIES

**OmegaCAM** employs a fixed set of observing **modes**. These observing modes use a particular dithering method (Section 4.1 URD) and either use a set of **key-filters** or **User-filters** (Section 4.3 URD). The observing modes shall be implemented in **observing templates** (Section 4.4 URD).

Supervising observing **strategies** subscribe additional instructions for the scheduling and pipeline data reductions (optional for ESO-pipeline, Section 4.2 URD).

The calibration procedures, often involving a **trend analysis** for qualification/quality control purposes, are designed to support the set of observing modes and employ as much as possible identical observing modes.

A prominent concept is the designation of **keyfilters**, which are used to monitor the behaviour of the instrument and atmospheric transparency: the observational data obtained with the keyfilters will be subject to extensive administration and trend analysis. Contrary to the keyfilters, the data obtained with userfilters, in so-called **user mode**, will not be subject to trend analysis. User-mode data are cross-calibrated nightly to the key-filters. Observations taken with the Atmospheric Dispersion Corrector are considered as user mode.

The information about strategies and modes shall be strictly carried through the DFS by, amongst others, FITS-header items.

### Glossary of OmegaCAM terms

| | |
|---|---|
| **Key filter** | Used for photometric calibration, instrument and atmosphere monitoring |
| **Key bands** | Sloan u' and i' and Johnson B and V |
| **Mode–** | Observing technique |
| **Mode– Dither** | Shifts larger than the gaps in the CCD mosaic |
| **Mode– Jitter** | Few pixels shifts between sub-exposures |
| **Mode– Stare** | Independent exposure(s) with identical pointing |
| **Mode– SSO** | Solar System Object / Non-Siderial tracking |
| **Strategy–** | Observing strategy |
| **Strategy– Deep** | Does deep integrations |

**Strategy– Freq** Frequently visits (monitors) the same field
**Strategy– Mosaic** Maps areas of the sky larger than $1^\circ$
**Strategy– Standard** Consists of a single observation

## 4.1 Observing Modes

In order to overcome:

i) the effect of the blank columns and rows in between individual CCD chips,

ii) bad (hot or cold) pixels (columns) of the CCD chips,

iii) the effect of cosmic ray events,

dithering (i.e. obtaining very slightly offset images of the same patch of sky) will play a prominent role in the data acquisition and its associated data reduction. Dithering can involve from N = 1 to 11 different positions on the sky.

There are two spatial domains to which the dithering can be optimized:

I **Dither** offsets matching the size of the largest gaps of the CCDs in the focal plane (= above item i).

II **Jitter** offsets matching the smallest gaps in CCDs, e.g. dead columns and bad pixels (= above items ii and iii).

While **dither mode** will provide maximum, complete, sky coverage with a minimum effect of the gaps in between the CCD's, its context map will be very heterogeneous (complex). Conversely, **jitter mode** will result in a very homogeneous context map, but the gaps in between CCDs will remain unobserved and sky coverage is incomplete. Depending on the scientific objectives of the observations the User can choose between **dither mode** with maximum sky coverage (completeness) and **jitter mode** with maximum homogeneity of the acquired data, which is expected to propagate as lower effective noise in the reduced data, as is desired for e.g deep fields.

Both **dither** and **jitter** observing modes will be supported. There will also be a **stare** mode, for which there are no offsets, and a **mosaic** mode, which is used to generate images larger than a single **OmegaCAM** field.

**Mode– Dither** N= will be operated with N pointings on the sky, with offsets matching the maximum gap between arrays, i.e. $\sim$ 380 pixels ($\sim$ 80 arcsec). In

standard observing mode N =5, maximum supported (pipeline!) value of N is 11. **Mode– Dither** N= covers all the gaps in the focal plane, thus the resultant image has no gaps within the field of view, but the context map describing the origin of the various pixels in the resultant map will be very complex. Dither mode is optimized for maximum sky coverage. **Mode– Dither** N= is used for general surveys, which want to achieve complete sky coverage.

**Mode– Jitter** N= will be normally operated with N=3-5 pointings, with quite small offsets ($\sim$ 5 pixels). Maximum N = 11. **Mode– Jitter** N= is optimized for observations which require maximum homogeneity of the context map, and for which the acquisition of information in the wide CCD gaps is not critical. **Mode– Jitter** N= will have a minimum of discontinuous variations of the PSF over the field of view; also all the data from a single sky pixel originate from a single CCD chip.

**Mode– Stare** N= will have one fixed pointing position, but the same position of the sky might be re-observed subsequently (N>1). **Mode– Stare** N= can be used to take all kinds of snapshots or calibration frames, but will also be the main workhorse for monitoring optical transients or fast moving objects. Facilities for direct on-line comparison of single **Mode– Stare** N=2 frames both for variable target monitoring and for instrument qualification monitoring will be an important aspect of this mode.

**Mode– Mosaic** N= will facilitate surveys that aim to image areas of the sky larger than $1^\circ$ diameter, or which for any other reason want to combine data from two adjacent partly overlapping fields. The prime characteristics of this mode are:

– the coordination of the definition of a set of pointings on the sky - in the OB planning
– the combination of the data from different fields into one data product

In principle, this mode should be handled by the de-dithering (=co-addition) process, (this can be interpreted as a requirement on the co-addition code, namely produce an output image which is the rectangle of the overlapping area of several input images). If the co-addition (particularly the set of quality

control parameters) and the source extraction methods are handled correctly, this mode will form a natural extension of the **dither mode** and does not require additional developments. Maximum image size supported for this mode is TBD; for mosaiced source lists the maximum covered sky area is unconstrained and data volumes could well run into the Tbyte regime. It is not planned for the standard DFS pipeline to produce mosaiced images.

**Mode– SSO** N= will support the data taking of Solar system objects with a non-siderial tracking of the telescope. No-autoguiding is required for this mode as in general the uncertainties of the predicted angular velocities of yet to be discovered objects are larger than the expected jitter of the telescope when the autoguiding is disabled. This mode resembles very much the **Mode– Stare** N=, however the wanted quick (<24 hour) data reduction for many fast moving targets implies that the DFS pipeline will not support the processing of these data fully. However, for observations which require a slower response (4 times 24 hour or longer) or which only require de-biasing and flatfielding, the standard pipeline can be configured to handle these data.

## 4.2 Observing Strategies

An **observing strategy** employs one of the basic **observing modes** and defines a number of additional instructions for specifically the scheduling of the observations. The observing strategy shall be recorded in the FITS headers of the observations. Optionally, this header information can be used in data reduction pipelines, particularly those operated by the Consortium when addressing the combination (e.g. stacking) of images. It is not expected that the ESO pipeline will recognize strategies, as the ESO pipeline will not combine various runs.

We discriminate strategy:

**Strategy– standard** which consists of a single observation (observation block),

**Strategy– deep** which does deep integrations, possibly taken at selected atmospheric conditions over several nights; the standard image pipeline will not combine images taken over several nights.

**Strategy– freq** which frequently visits (monitors) the same field on timescales ranging from minutes to months and has overriding priority on the telescope

schedule

**Strategy– Mosaïc** maps areas of the sky larger than $1^{\circ}$, which is essentially an item for the scheduling, as the pipeline has to produce uniform quality data anyway. The combination of various field centers into one image is not considered a standard pipeline task.

## 4.3 Filtering

**OmegaCAM** employs the following type of filters (see Section 3.4 for details):

- Broad-band filters (Johnson B,V and Sloan set)
- Intermediate band (e.g. Stromgren and deep sky filters 200A)
- narrow band ( e.g. O[III], H$\alpha$ )

A set of **keyfilters** will be defined which will be used for the photometric calibration. These **keybands** will be used for monitoring the instrument and the atmosphere at timescales from hours up to years. The keyfilters will be used for standard, beginning of the night checks, the monitoring of the atmospheric extinction and for a variety of trend analyses relating to the photometric calibration of the instrument. The photometric system of the instrument shall be continuously maintained at these **keybands**. One **composite keyfilter** will be available, which will contain in each quadrant a different passband, namely the four different keybands. The composite filter will be extensively used for quick checks, extinction measurements and other monitoring of the photometric system.

The observing modes related to the photometric calibration (**req.**'s 5.6) will employ the concept of keyfilters. The other filters (**Userbands**) will be cross calibrated versus the keyfilters (see **req.**5.6.5). Monitoring of the atmospheric extinction will be done with the keyfilters (**req.**562).

The 4 keyfilters are Sloan u' and i' and Johnson B and V.

## 4.4 Observing Templates

The Observing Templates for **OmegaCAM** are defined in Instrument Software Functional Specifications (VST-SPE-OCM-23100-3064). This definition is based

on the requirements as set out in the present document. The observation modes described in the previous section imply three basic OTs for science observations.

- **TSF– OCM_img_obs_dither**
  Observe with N pointings (default 5) in the sky, with offsets $>$ maximum gap between detectors ($>$ 750 pixels) between exposures.
- **TSF– OCM_img_obs_jitter**
  Observe with N pointings (2-5) in the sky, with small offsets ($\approx$ 5 pixels) between exposures.
- **TSF– OCM_img_obs_stare**
  Observe N (default 1) exposures with one fixed pointing position.

## 4.5 Field correctors

The VST and **OmegaCAM** employ two different field correctors:

**Two lenses field corrector:** In the U–I bands (0.320–1.014 $\mu$m) the worst case (edge of field) diffraction encircled 80% energy diameter is 1.33 pixel at Zenith. The transmission is 93%.

**One lens plus Atmospheric dispersion corrector - ADC:** In the B–I bands (0.365–1.014 $\mu$m) the ADC produces a diffraction encircled 80% energy diameter of 2.0 pixels (worst case at edge of field) at a Zenith distance of $50^\circ$. The transmission is 88%. At $70^\circ$ Zenith angle this is 2.88 pixel (2.63 average over the field). The ADC cannot be used in the U band.

For observations near Zenith the two-lens corrector will be preferred because of its higher throughput. At larger zenith distance (value depends on wavelength), the ADC will yield better imaging performance.

**The standard (=key) observing mode is with the two-lens corrector**.
The ADC observing mode is considered a User mode.

# 5 BASELINE CALIBRATION REQUIREMENTS

## 5.0 Documentation system, Odoco

The trajectory of the data through the DFS shall be guided by the **OmegaCAM** documentation system, **Odoco**. The set-up of the specifications of the calibrations and its data reduction is done in purely requirement driven fashion.

The calibration documentation system (**Odoco**) is a collection of files which contains a description of both the requirements on **OmegaCAM** calibrations, as well as detailed descriptions of the envisaged Calibration Observations (**CO's**) and their analysis and data-reduction. The **Odoco** is meant to avoid unnecessary duplication of work for the documentation of the various stages of the project; from the definition of basic requirements, to implementations and final operation and user manuals. It should also aid the documentation of development work. The **Odoco** was originally developed for ISO and provided a full uplink system (IOCD). The present version, adapted for **OmegaCAM**, contains essentially only the part which deals with text, pseudo code, recipe's and automatic document creation. The **Odoco** system is essentially a set of TeX macros, with LaTeX emulation, together with some supporting C routines. The whole present document is generated by **Odoco**, but particularly this section, listing the baseline calibration requirements, uses some more advanced **Odoco** options.

The very strict document control of the original IOCD will not be maintained, but **CVS** (Concurrent Versions System) will be used for local versioning control. Official versions of documents shall be filed separately.

The contents of the **Odoco** will be continuously evolving and fonts are chosen for optimal reading on a computer monitor screen.

In **Odoco**, calibrations are specified under requirement subsections (**req.**'s) which are labeled with 3-digit numbers. Each subsection contains a number of items: e.g. the **objective** of the requirement, a description of a specific Calibration Observation or a cross-reference to the use of a CO that has been defined under another requirement. Also, the end-results have been specified and the

text contains various descriptions for both Template Signature Files (**TSF**'s) which define the creation of the observation blocks (**OB**) and for the off-line data analysis. Overall priorities have been defined (essential, very important, desirable) and are specified under the item **priority**.

The chosen items for the descriptions of the requirements (**req.**'s) match well to the items needed for the **recipes** for DFS data reductions. In section 6.1 complete listings of both the **req.** items and the **recipe** items are given. The **req.**'s as listed in the **Odoco** will eventually evolve into the deliverable recipe's.

The **Odoco** is designed to provide a comprehensive and accessible documentation system of the various activities that relate to the **OmegaCAM** calibrations. It serves a variety of purposes, and facilitates the extraction of text from the **Odoco** data base into complete documents. The **Odoco** can provide the following documents:

1. **A listing of the Baseline OmegaCAM Calibration Requirements. Odoco** contains an up-to-date listing of all the baseline requirements for the **OmegaCAM** calibrations, i.e. for each requirement (**req.**) the text under the items: **Objective, When performed/frequency, Required accuracy, Priority**. See section 5 of the URD.
2. **Full documentation of the OmegaCAM calibration plan**. A detailed description of all the **OmegaCAM** calibration requirements and their implementations. See Section 5 of the Calibration Plan. Summary sections (two digit sections) have been introduced for a variety of calibration activities: e.g. detector specific calibrations, photometric calibrations etc. A general overview of the **OmegaCAM** calibrations can be obtained by printing the summary sections of the **Odoco**. In order to further ease the readability of this document, both each requirement and each calibration analysis procedure text item begins with a 'one-liner' stating the overall idea.
3. **A description of the Template Signature File necessary to produce observation blocks, TSF's.** When a requirement can not be fulfilled by means of data analysis of observations made for another requirement, **Odoco** contains a detailed description of the instrument configuration and procedures under the items **Sources, observations** and **TSF**, (TSF, Template Signature File). Note, the term **selfstanding** has an important meaning:

when a requirement is selfstanding, it will normally propagate as a single dedicated calibration observation, with a single dedicated data reduction task. Conversely, non-selfstanding requirements will have more complex dependencies and often involve a data reduction of data taken for another selfstanding requirement.
Under the item **TSF** the hierarchical structure of observation specifications is detailed (when applicable) on different lines:

- first line: observing **Strategy–**
- second line: observing **Mode–** N=
- third line: generic/base **TSF–**
- fourth line: specific/dependent == **TSF–**

4. **Description of Calibration Analysis (CA).** For each requirement, a specification of the data analysis related to the requirement is given under the item **CA**. Standard functionalities can be quoted in the optional item **Needed functionalities for CA**. A detailed description of the implementation, which could include guidelines for the data analysis or pseudo code is given under the items **CAP** (Calibration Analysis Procedure). **Inputs and Outputs** defines the various calibration tables. Thus a document listing all the text of the items **CA**, **CAP** and **Inputs and Outputs** gives a complete overview of the Calibration data reduction analysis.
5. **A reference document for timelining OmegaCAM Calibration observations.** The items **When performed/frequency and Estimated time needed** can be used to design a detailed **Schedule** of calibration observations both in the commissioning phase (**CP**) and during the Routine Phase (**RP**).
6. **A listing of the various requirements for an Astronomical Calibration Source data base, (ACS-dbase).**
7. The **recipes** belonging to the execution of requirements.

As **Odoco** can provide various documents with a different filtering of the source of information, each printout contains a table, listing the selection criteria. Also, the status of the printout is marked (formal issue, or private workcopy). Each printout contains this section.

On the following pages a print-out is included which is believed to be relevant for the present document.

## 5.1 Functional Checks

The commissioning plan [VST-PLA-OCM-23100-3100] lists a large set of acceptance tests. Most of these test are engineering tests and need not to be repeated here. Those engineering tests which can be executed with requirements from the URD/CP contain the proper reference to the URD in the commissioning plan.

The technical operations and maintenance plan [VST-PLA-OCM-23100-3080] describes activities during **Routine Phase (RP)**. Both the URD, CP and the DRS specifies the requirements and the activities for fulfilling these requirements during RP. The label RP always points to activities that shall be followed in the technical operations and maintenance plan.

## 5.2 Detector Electronics specific Calibrations

Section 5.2 contains the requirements for the characterization of the detector system on electronics level, while Section 5.3 lists more detector specific calibrations. The separation between these Sections is somewhat artificial. In Section 5.4 more daily characterizations are listed, which involve the flatfielding and de-biasing. Requirements which are foreseen to become 'workhorses' are labeled with $doit$, e.g. a quick daily evaluation of the read noise serves as a daily health check.

The CCD's are operated at one port; **electrical cross talk** is not expected to significantly affect the observations. However, as a check, the absence of significant cross-talk is verified (**req.**525).

The **hot pixel** (**req.**522) and **cold pixel** (**req.**535) characterization are combined in the weight maps (**req.**546).

As the standard read-out time of the arrays is already very fast, $\sim$ 40 sec , no extra fast **read-out mode** is supported in the characterization.

CCD **rebinning mode** and **windowing mode** are not supported in the calibration and data reduction procedures.

### 5.2.1 Req. — *CCD read noise - doit*

**Objective:**

Measure the CCD read noise (in ADU's) as a standard health check.

Pairs of zero-second bias exposures are used. The rms scatter of the differences between two exposures is computed and divided by $\sqrt{2}$. Monitor variations with trend analysis. This is the first order daily health check.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

daytime- Commissioning, during all operations: daily health check.

**Inputs:**

2 raw bias frames

**CalFile– 521** *Readout noise* older versions

**Outputs:**

**CalFile– 521** *Readout noise* in ADU's

**Required accuracy, constraints:**

Readout noise less than $5e^-$.

Variation in readout noise w.r.t. previous readout noise less than $0.5e^-$.

These are lab values. The corresponding limits in ADU can be calculated using the $e^-$/ADU conversion factor from **req.**523.

**Estimated time needed:**

Observation: 5 min. Reduction: 1 min./CCD.

**Priority:**

essential

**TSF:**

**Mode– Stare** N=2

(**TSF– OCM_img_cal_bias,** N=2)

= **TSF– OCM_img_cal_readnoise**

**Recipe:**

**Recipe– Read_Noise**

**Needed functionality:**

image arithmetic; image statistics

**CA:**

Subtract the consecutive pairs of bias frames. Compute the rms in resulting frame. The readout noise is the mean of the measured rms devided by $\sqrt{2}$. Reject $3\sigma$ outliers.

**CAP:**

ADD trendanalysis

```
input: bias1, bias2, previous_read_noise

diff = bias1-bias2
imstat = diff.Stat(reject_method='sigma',
   reject_level=3, niter=2))
read_noise = imstat.rms/SQRT(2)
if abs(previous_read_noise/read_noise-1) > MAXIMUM_CHANGE:
    print 'WARNING - Large variation in read_noise'

output: read_noise
```

### 5.2.2 Req. — *Hot pixels*

**Objective:**

Determine CCD bad/hot pixels.

$5\sigma$ outliers in the master bias frame are bad-hot pixels. These pixels should be recorded and ignored (assigned a weight of 0) in dedithering and dejittering. For this purpose the bad/hot pixel map is used to assign a weight of zero to the affected pixels in the weight map (**req.**546). The search for hot pixels would also identify traps.

**Fulfilling or fulfilled by:**

Additional data reduction of **req. 541** *Master Bias frame* to determine cold pixels

**When performed/frequency:**

daytime- Commissioning, in RP twice per week.

**Inputs:**

**CalFile– 541** *Master bias*
**CalFile– 522** *Bad/hot pixel map* previous version

**Outputs:**

**CalFile– 522** *Bad/hot pixel map, number of hot pixels*

**Required accuracy, constraints:**

Number of hot pixels to be determined by experience/lab values. The total number of bad pixels (hot pixels + cold pixels) is less than 80000. Difference in number of hot pixels w.r.t. the previous version, less than 100.

**Estimated time needed:**

Observation: None.
Reduction: $<$ 1 min./CCD.

**Priority:**

essential

**TSF:**

Use master bias (**req.**541)

**Recipe:**

**Recipe– Bias,**see **req. 541** *Master Bias*

**Needed functionality:**

image - statistics; image - mask

**CA:**

Use the master bias to construct a bad pixel map, by assigning a value of 1 to output pixels for which the corresponding input pixel exceeds the mean bias level by $5\sigma$.

**CAP:**

```
input master_bias, prev_hot_pixel_map_stats
imstat        = master_bias.Stat()
hot_pixel_map = master_bias.Mask(val_in=0, val_out=1,
                    range_low=0, range_high = imstat.mean+5*imstat.r
imstat        = hot_pixel_map.Stat()
if imstat.total_flux > MAX_HOT_PIXELS:
    print 'WARNING - Too many hot pixels'
if imstat.total_flux-prev_hot_pixel_map_stats.total_flux >
    MAX_NEW_HOT_PIXELS:
    print 'WARNING - Too many new hot pixels'
output hot_pixel_map, imstat
```

### 5.2.3 Req. — *CCD gain*

**Objective:**

Determine CCD gain and variation with time

Determine the conversion factor between the signal in ADU's supplied by the readout electronics and the detected number of photons (in units $e^-$/ADU) and monitor variations in time.

The gain factors are needed to convert ADU's in raw bias-corrected frames to the number of electrons, i.e. detected photons.

Take two series of 20 dome flatfield exposures with wide range of exposure times. Derive the rms of the differences of two exposures taken with similar exposure (integration time). Exposure differences of pairs should not exceed 4%. The regression of the square of these values with the mean level yields the conversion factor in $e^-$/ADU (assuming noise dominated by photon shot noise). Compare with previous measurements, as a qualification (trend analyis).

**Fulfilling or fulfilled by:**

Selfstanding, also measures detector linearity (**req.**533).

**When performed/frequency:**

daytime- Commissioning, in RP once week.

**Sources, observations, instrument configurations:**

Dome flat field exposures on lamp, with $t_{int}$= 2, 60, 50, 4, 8, 40, 30, 1, 16, 24, 24, 16, 1, 30, 40, 8, 4, 50, 60 and 2 seconds.

**Inputs:**

**CalFile– 521** *Read noise*
**CalFile– 541** *Master bias frame*
**CalFile– 523** *Conversion factor* $e^-/ADU$ older versions.

**Outputs:**

**CalFile– 523** *conversion factor* $e^-/ADU$

**Required accuracy, constraints:**

Accuracy: In units of $e^-$/ADU, from lab values or found empirically. Trend analysis better than 1%. On-site quality check.

Quality check: Difference with previous version less than 10%.

**Estimated time needed:**

Observations: 1 hour
Reduction: 10 min./CCD.

**Priority:**

essential

**TSF:**

**Mode– Stare** N=20
(**TSF– OCM_img_cal_domeflat,** $t_{exp}$= 2, 60, 50, 4, 8, 40, 30, 1, 16, 24, 24, 16, 1, 30, 40, 8, 4, 50, 60, 2 s.).
= **TSF– OCM_img_cal_gain**

**Recipe:**

**Recipe– Gain**

**Needed functionality:**

image - arithmetic; image - statistics; misc - regression

**CA:**

Assume bias corrected dome flats. Form sums and differences of pairs of exposures with same exposure time. Compute mean level $S_m$ in summed pairs. Compute rms in difference frames. Plot rms$^2$ versus $S_m$, compute second order regression, incl. error analysis and write to calfile.

**CAP:**

```
input gain_list, bias, shutter_map
sum_list  = []
diff_list = []

for i in range(no_gains/2)
    sum = gain_list[i]+gain_list[no_gains-1-i]
    imstat = sum.Stat()
    sum_list.append(imstat.mean)

    diff = gain_list[i]-gain_list[no_gains-1-i]
    imstat = diff,Stat()
    diff_list.append(imstat.rms**2)
```

```
regression_coeff = Regression(x=sum_list, y=diff_list, order=2)

output regression_coeff
```

### 5.2.4 Req. — *Electromagnetic Compatibility*

**Objective:**

Verify whether any external source (e.g. dome drives, control systems) is not interfering in the CCD overall detector system, leading to additional, mostly non-white noise.

Technical specifications require less than 20% effect on read-out noise, for external interference and less than 10% effect on read-noise for internal **OmegaCAM** interference.

If electronic interference occurs then this will put constraints on the operation of the instrument. For example, if interference occurs during movement of the telescope, one cannot read the CCDs and move the telescope at the same time,.

Interference is detected by measuring the read noise (**req.**521) under operational conditions. This means doing bias measurements while the telescope and/or dome are moving.

**Fulfilling or fulfilled by:**

repetition of CCD read noise calibrations **req.**521.

**When performed/frequency:**

Day time; Commissioning; once a year; every time a major system change has been made; To be determined by experience

**Sources, observations, instrument configurations:**

Raw bias frames obtained while the telescope/dome are moving.

**Inputs:**

raw bias frames, obtained when telescope/dome were moving.
**CalFile– 521** *CCD read noise*

**Outputs:**

OK/non-conformance flag.

**Required accuracy, constraints:**

Difference between read noise under operational conditions and the standard read noise measurement should be smaller than 20% for external and 10% for internal causes of interference.

**Estimated time needed:**
Observations: 4 hours. Reduction: 1 min./CCD.

**Priority:**
essential

**TSF:**
**Mode– Stare** N=2
**TSF– OCM_img_cal_bias** while telescope and/or dome are moving.

**Needed functionality:**
image arithmetic; image statistics

**CA:**
The operational read noise is compared to **CalFile– 521** $CCD\ read\ noise$ (see **req.**521 for implementation details). The difference should be measured with an accuracy of 5%.

**CAP:**
(see **req.**521 for implementation details)

### 5.2.5 Req. — *Electrical cross talk*

**Objective:**

Although crosstalk is not detectable in the WFI, and only one part per CCD is used, the sharing of one FIERA by 16 CCD's opens up the possibility of cross talk.

Observe a bright (mag 5-8) star at 16 different chips (1 FIERRA serves 16 chips).

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Nighttime Commissioning.

**Sources, observations, instrument configurations:**

Bright star, mag 5-8

**Outputs:**

Conformance flag

**Required accuracy, constraints:**

$10^{-5}$

**Estimated time needed:**

5 minutes

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=1

(**TSF– OCM_img_obs_stare,** N=1, filter=key band)

## 5.3 Detectors specific calibrations

### 5.3.1 Req. — *CCD Dark Current - doit*

**Objective:**

Measure CCD dark current (in ADU/pixel/sec) for qualification purposes of the detector chain (qualification and trend analysis). The particle event rate will be determined on the fly.

Repeating the test with the dome lights on will provide information on possible light leaks.

Three one hour exposures are taken with the shutter closed. After rejection of the cosmic ray events, the signal above the bias level is the dark signal.

For the reduction of the science observations the subtraction of the sky brightness will include the dark current, and a separation of both contributions is normally not required.

Do a trend analysis.

**Fulfilling or fulfilled by:**

Selfstanding, also used to compute the particle event rate.

**When performed/frequency:**

Daytime (if dome and camera are proven to be light tight enough) - Commissioning; once per week. Alternatively, one dark frame per day could be taken, followed by a trend analysis once/month.

**Sources, observations, instrument configurations:**

Three 1 hour exposures with shutter closed. Dome lights on/off

**Inputs:**

Lab values

**CalFile– 531** *Dark count rate for each CCD* older versions.

**CalFile– 532** *Particle event rate* older version.

**Outputs:**

**CalFile– 531** *Dark count rate for each CCD* in ADU/pixel/hour

**CalFile– 532** *Particle event rate* in ADU/cm$^2$/hour

**Required accuracy, constraints:**

Dark count rate should be less than 3 e$^-$/pixel/hour excluding bad pixels.

Accuracy of determining particle event rate 1 ADU/cm$^2$/hour.

Particle event rates should be identical for each chip.

**Estimated time needed:**
Observation: 3 hour. Reduction: $<$ 1 min./CCD.

**Priority:**
very important

**TSF:**
**Mode– Stare** N=3
**TSF– OCM_img_cal_dark** exposure time 1 hour each, shutter closed. Dome lamp on-off-on

**Recipe:**
**Recipe– Dark_Current**

**Needed functionality:**
image - trim; image - median average, image - arithmetic, image - masking

**CA:**
Median average the 3 input frames. Subtract master bias level. The mean of the resulting images is the dark current in ADU/pixel/hour. The difference between the raw bias-corrected original frames and the mean contains the particle events. Use SExtractor with a cosmic ray detection filter to determine the number of particle events.

**CAP:**

```
input dark_list

dark_list = dark_list.OverscanCorrect()
dark_list = dark_list.Trim()

dark           = dark_list.Average(method='median')
imstat         = dark.Stat()
dark_count     = imstat.mean
particle_count = 0
for i in range(3):
    tmp    = dark_list[i]-dark
    cat    = tmp.Sextractor( filter='cosmic' )
    particle_count=len(cat)
```

```
particle_count=particle_count/3/detector_area
output dark_count, particle_count
```

### 5.3.2 Req. — *CCD Particle Event Rate*

**Objective:**

Determine CCD particle event rate by evaluating dark current measurements. Verify the absence of a local radiation source affecting the detector. The data will be inspected for significant differences of the rates on different chips, and will be screened for local effects.

**Fulfilling or fulfilled by:**

Data reduction of **req. 531** *Dark current*

**When performed/frequency:**

Commissioning and when dark current is measured.

**Outputs:**

**CalFile– 532** *Particle event rate* in ADU/cm$^2$/hour

**Required accuracy, constraints:**

better than 1 ADU/cm$^2$/hour

**Priority:**

desirable

**Recipe:**

**Recipe– Dark_Current,**see **req. 531** *Dark current*

**CA:**

See **req. 531** *Dark Current*

**CAP:**

See **req. 531** *Dark Current*

### 5.3.3 Req. — *CCD Linearity*

**Objective:**

Characterize the linearity of the system over the full dynamic range of the A/D converter.

Both the overall absolute linearity of the system and the pixel-to-pixel variation in linearity are of interest.

The overall linearity of the system can be obtained by measuring the counts as a function of exposure time for a series of dome flats. The data to use for this can be the same as for the measurement of the Gain (**req.**523, q.v.)

The pixel-to-pixel variation in the linearity is obtained by dividing a flatfield with a mean exposure level of more than 30000 ADU by a flatfield with an exposure level of less than 1000 ADU. Pixels that deviate more than $5\sigma$ from the mean, in this divided image, have an anomalously high nonlinearity. This map of nonlinear pixels may be used in conjunction with the hot and cold pixel maps to produce a map of bad pixels.

In addition, during a cloudy night, once per year, the linearity will be checked by taking various exposures with a variety of exposure times on the dome screen.

**Fulfilling or fulfilled by:**

Use same raw data as for **req.**523

**When performed/frequency:**

daytime- Commissioning, in RP once per month, dark dome test once/year

**Inputs:**

**CalFile– 541** *Bias*
**RawData– 523** *CCD Gain*
**RawData– 533** *CCD Linearity*

**Outputs:**

**CalFile– 533** *CCD Linearity* includes a measure of the overall nonlinearity and a map of the pixel-to-pixel variation of the linearity

**Required accuracy, constraints:**

better than 1% on the photometric scale

**Estimated time needed:**
Observation: None

**Priority:**
essential

**TSF:**
Use same raw data as for **req. 523** $CCD\ gain$

**Recipe:**
**Recipe– Gain,**see also **req. 523** $CCD\ Gain$

**Needed functionality:**
image - trim; mage - arithmetic; image - statistics

**CA:**
Assuming an input list of de-biased, shutter corrected dome flats with exposure times of 2, 60, 50, 4, 8, 40, 30, 1, 16, 24, 24, 16, 1, 30, 40, 8, 4, 50, 60 and 2 seconds, determine the mean value per flat, and plot as function of exposure time. Estimate the number of ADU's from where the plot becomes nonlinear.
Assuming that the CCD's are still linear with an exposure time of 40 seconds, divide the 40 second exposures by the 4 second exposures. $5\sigma$ outliers in the mean of this frame are pixels with an anomalous nonlinearity.

**CAP:**

```
input dome_list

mean_list = []
exposure_times = []
for i in range(len(dome_list)):
     imstat = dome_list[i].Stat()
     mean_list.append(imstat.mean)
     exposure_times.append(dome_list[i].exposure_time)

plot = Plot(x=exposure_times,y=mean_list)

non_linear_frame = (dome_list[6]/dome_list[4]+dome_list[14]/dome_lis
```

```
imstat = non_linear_frame.Stat()

non_linear_map = non_linear_frame.Mask(val_in=0, val_ou1=1,
           range_low=imstat.mean-5*imstat.sigma,
   range_hi=imstat.mean+5*imstat.sigma)

output plot, non_linear_map
```

### 5.3.4 Req. — *CCD Charge Transfer Efficiency*

**Objective:**

Characterize horizontal and vertical transfer efficiency (CTE) per single transfer (in units of the fraction of the charge actually transferred).
(taken from WFI@2.2m:) Ten flatfields are taken with 50 vertical and 50 horizontal overscan pixels and a mean exposure level of about 20000 ADU's. The mean is computed and corrected for the bias. Average signal levels are determined in the two overscan regions as well in the light sensitive pixels just preceeding the respective overscan pixels. Any signal found in the overscan pixels was due to non-unity CTE lost from the neighbouring light-sensitive pixels. The fractional charge still remaining in the light-sensitive pixels is the CTE.

**Fulfilling or fulfilled by:**

selfstanding but related to masks for **req. 541** *Bias - doit*, **req. 522** *hot pixels* and **req. 535** *CCD Cold Pixels*.

**When performed/frequency:**

daytime- Commissioning, in RP once half year

**Sources, observations, instrument configurations:**

Dome flat field- lamp.

**Inputs:**

**CalFile– 541** *Bias*

**Outputs:**

**CalFile– 534** *charge transfer efficiency factors*

**Required accuracy, constraints:**

CTE $>$ 0.999995 per parallel or serial shift.

**Estimated time needed:**

30 min.

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=10
(**TSF– OCM_img_cal_domeflat,** N=10)

= **TSF– OCM_img_cal_cte**

**Needed functionality:**

image – arithmetic; image – statistics

**CA:**

Ten flat fields are taken with 50 vertical and 50 horizontal overscan pixels and a mean exposure level of about 20000 ADU's. The mean is computed and corrected for the bias. Average signal levels are determined in the two overscan regions as well in the light sensitive pixels just preceeding the respective overscan pixels. Any signal found in the overscan pixels was due to non-unity CTE lost from the neighbouring light-sensitive pixels. The fractional charge still remaining in the light-sensitive pixels is the CTE.

### 5.3.5 Req. — *CCD Cold Pixels*

**Objective:**

Identify cold pixels.

From a set of 5 low-level flatfield exposures a mean image is computed. This mean image is smoothed. The smoothed mean is used to flatfield the mean image. In this flatfielded image, pixels that are smaller than the mean minus $5\sigma$, are taken to be cold pixels. Make sure to differentiate between hot and cold pixels.

Cold pixel maps are used, together with the hot pixel maps (**req.**522), to identify pixels that should be ignored (assigned a weight of 0) in further processing.

**Fulfilling or fulfilled by:**

Data reduction of master domeflat (**req.**542) or twilight (**req.**543) flat frames.

**When performed/frequency:**

daytime- Commissioning, in RP once per 3 months.

**Sources, observations, instrument configurations:**

Use master dome- or twilight flat

**Inputs:**

**CalFile– 535** *Cold pixel map* previous version
**CalFile– 546** *Master flatfield*

**Outputs:**

**CalFile– 535** *Cold pixel map*

**Required accuracy, constraints:**

Quality Check: Number of hot pixels to be determined by experience/lab values. The total number of bad pixels (hot pixels + cold pixels) is less than 80000. Difference in number of cold pixels w.r.t. the previous version, less than 100.

**Estimated time needed:**

Observations : None

**Priority:**

very important

**TSF:**

Use master dome- or twilight flat (**req.**546)

**Recipe:**

**Recipe– Dome_Flat** or **Recipe– Twilight_Flat**

**Needed functionality:**

image - trim; image - median average; image - convolution; image - arithmetic; image - statistics.

**CA:**

Compute a median of the input flatfields. This flatfield can be flatfielded by itself, using a 5x5 pixel median top-hat filter. Determine the mean of this flatfielded flat. Pixels more than $5\sigma$ below the mean, that are not hot pixels, are cold pixels.

**CAP:**

```
input flat_list, hot_map

flat1 = flat_list.Average(method='median')
flat2 = flat1.Convolve(method='median')
flat = flat1/flat2
imstat = flat.Stat()
cold_map = flat.Mask(in_val=0, out_val=1,
              range_low=imstat.mean-5*imstat.rms,
              range_hi=65000)
cold_map = cold_map*(1-hot_map)

output cold_map
```

### 5.3.6 Req. — *CCD Hysteresis, strong signal*

**Objective:**

Quantify the effect of CCD signal reminiscence.

Reminiscence of a strong signal (a saturated star) in subsequent observations ("ghosts") is a potentially debilitating problem for data reduction and interpretation. The absence of this effect should be verified by observations of very bright objects and subsequent dark exposures.

If "sources" are detected in the dark frames at the pixel positions of bright sources in the first field, signal reminiscence is a problem, which can characterized by the decay time of a strong signal.

The CCD readout mechanism means to cure for reminiscence.

**When performed/frequency:**

Commissioning.

**Sources, observations, instrument configurations:**

Observe a field containing very bright objects followed by a dark exposure.

**Outputs:**

**CalFile– 536** *CCD Hysteresis*, containing the signal decay time.

**Estimated time needed:**

30 minutes

**Priority:**

desirable

**TSF:**

**Mode– stare** N=2

**TSF– OCM_img_obs_stare**

**Recipe:**

**Recipe– Hysteresis**

**Needed functionality:**

catalog - associate; misc - plotting

**CA:**

Process the bright field as normal science data. Select the bright (saturated) objects from the catalog of the bright field. Use the pixel position of these sources to inspect the corresponding positions in the dark frame. Plot the

source magnitude as function of time (exposure number), and measure the decay time.
If reminiscence is detected, repeat the experiment with more dark frames and determine decay-times.

## 5.4 Detectors operational specific calibrations

In this Section **req.**'s are listed which are essential related to the daily operations of the acquisition of the science data.

For all detector and photometry related calibrations each CCD is characterized independently of the others. (Only in the case of astrometric solutions, data of various chips is combined).

A **set of calibration lamps** together with a **dome screen** is used to monitor the health of the instrument and to measure the fine structure of the flatfield.

The calibration lamp system contains two **sets** of 4 commercial 12-24V halogen lamps each. Each set is operated independently. Each set is stabilized in current supply (one unit for whole set). Lamps are switched on/off with a gradual increase/decrease of the current over a timespan of 3-5 minutes. Implementation TBC. When operated this way, the nominal lamp instabilities are expected to be of the order of 0.05%/hour for a timespan of 200 hours of lamp operations (private comm. Philips Labs). For a nominal 1-2 hour/day of operations the lamp instability is expected to be of the order 1.5-3 % per month. The lamp instabilities are expected to be strictly linear after 100 hours of operations. When operating two sets at different rates, say one set 1 hour/day the other set at say 1 hour/two weeks a full characterization of the lamp stability can be achieved at accuracies better than a few percent on a monthly basis. Also continuity after failiure of one lamp can be obtained. The accuracy is better than required as also other factors, like dust on the lamps and background light will affect the effective illumination of the screen. Altogether, the system is expected to provide control over the illumination of the screen with an accuracy better than 5-10%, which will be used for a daily health check on the overal throughput/health of the detectors (**req. 547** *Quick detector responsivity and health check*). This activity provides a deliberate redundancy with flatfield measurements on the dome screen (**req. 542** *Flat field – dome key bands–doit*), in order to provide the necessary cross-check in the off-line calibration analysis procedures. Next to the health checks taken during the night, a standard health check using a photometric standard field (also providing the absolute photometry is specified in **req. 562** *Photometric Calibration – Monitoring*). The system of lamps, flatfields measurements, quick checks

using the lamps and health checks on the sky on photometric standard fields is designed to support the photometric calibration of a Survey System, for many years to come. The system provides redundancy faciltating cross-checks and has a typical maintenance/update frequency once/month.

The calibration of science data can be divided in three steps.

1 Removing the effects of bias and differential gain.

2 Relating the overall gain, and hence counts $S(x, y)$ to a photometric scale

3 Relating the $x, y$ coordinates to an astrometric reference system.

The raw science and standard images record $S(x, y)$ counts in pixel $x, y$, that are related to the incident photon flux $I(x, y, \lambda)$ by:

$S(x, y) = b(x, y) + G \int g(x, y, \lambda) I(x, y, \lambda) d\lambda$,

with $G$ the ADU conversion factor, $g(x, y, \lambda)$ the quantum efficiency or **gain** as function of position and wavelength, and $b(x, y)$ the bias offset.

The photometric and astrometric calibration (steps 2 and 3) are the subject of Sections 5.5 and 5.6, respectively. Here we list the calibration data necessary to remove the effects of bias and gain variation over the image. These calibration data include:

- **Bias** to subtract residual pattern in the bias offset.
- **Flatfields** to correct for non-uniform gain.
- **Fringe maps** to remove the fringe-patterns
- **Weight maps** to determine the relative contribution of each pixel when image data are combined,

A first-order approximation of the bias level in an image is provided by the median of the overscan region. A more accurate determination of the bias offset takes into account the following two effects: i) the bias level grows to its asymptotic level in the first few hundred lines, and ii) the bias level depends on the total signal in a given line. Therefore, an initial bias correction—the **overscan correction**, is applied by averaging the overscan pixels for each line, and subtracting this value from that line. Also, experience with the WFI has shown the presence of residual patterns in the bias offset over the image area. Under the assumption that these patterns are also present in **OmegaCAM** data its characterization by means of a master bias frame is specified in **req.**541.

The gain, $g(x, y, \lambda)$, incorporates the wavelength-dependent pixel-to-pixel variation in transmissivity of the different lightpaths through the telescope optics, filters and detectors. The gain can be approximated with

$g(x, y, \lambda) = g_{DQE}(\lambda) g_{ff}(x, y)$,

with $g_{ff}(x, y)$ the pixel-to-pixel variation in the gain, and $g_{DQE}(\lambda)$ the overall detector quantum efficiency (zeropoint), at $g_{ff} = 1$, which is subject to photometric calibration (Section 5.5).

The characterization of the pixel-to-pixel variation of the gain, the **flatfield**, is obtained by observing a spatially uniform source of illumination. A normalized version of such an image provides a measure of the relative variation of the gain over the image area, $g_{ff}(x, y)$. Note that this flatfield measures a combination in the pixel-to-pixel gain variation and the variation in transmissivity of the different light paths through the telescope optics and filters.

The ideal flatfield observation is:
i) uniformly illuminated
ii) bright, to minimize errors due to photon noise,
iii) of constant color, preferably a color that is the same as the night sky.

Several methods to determine a flatfield will be operational. However, each method suffers from different drawbacks. The various characterizations of the flat field, the **dome**, **twilight**, and **night sky** flats, are specified under the **req.**542-545, while the eventual **master flatfield** to be applied to science and standard field observations, is constructed from a suitable combination of the dome, twilight and night sky flat fields (**req.**546).

Dome flats (**req.**542) are obtained by observing in **telescope screen park position** a fixed **domescreen** *relatively* uniformly illuminated by the **calibration lamp** with a stabilizing power supply. The illumination is not sufficiently uniform to measure large scale variations, and the color is very different from the night sky.

Twilight flats (**req.**543) are based on a bright, uniform source of illumination (twilight sky), that is unfortunately not of constant brightness and color. Unfortunately the 'twilight gradient' precludes measurement of the largest scale gain variation. Also bright objects may be visible even at twilight, which provides an additional complication.

Night sky flats (**req.**544), obtained by combining a large number of science observations, most closely mimic the illumination properties of the science frames themselves. These are the only flatfields usable for measuring the largest scale gain variations. Unfortunately, the assumption that the illumination is uniform (except for astronomical sources of course), has proven to be invalid on WFI (e.g Manfroid et al, 2000). It remains to be seen how large this problem of "sky concentration" will be for **OmegaCAM**. Computing the night sky flat is also a computationally expensive process, both because of the large numbers of frames involved, and because the need for a proper masking of bright objects in the field. Fortunately, this measurement may also be usable for the fringe correction.

The master flatfield (**req.**546), to be applied to science and standard field observations, is constructed from a suitable combination of the dome, twilight and night sky flat.

The approximation that the pixel-to-pixel variation in the gain is independent of wavelength is in fact incorrect. Interference effects, mainly in the filters and thinned silicon layers of the CCDs, introduce wavelength dependent gain variations that vary on small angular scales. Since most sources are continuum sources, and only the convolution $\int g(\lambda)I(\lambda)d\lambda$ is measured, this effect can be ignored when measuring source fluxes. However, due to variable strength of several sky lines, mostly apparent at the long wavelengths, the background will exhibit so-called **fringing** patterns, which can change during the night. This requires an additional calibration step for bands redward of R: the construction of suitable fringed background images (**req.**545).

The weight map is an important auxiliary file, which is used in several image processing steps. The weight map is intimately linked to the flatfields and therefore its construction is also addressed in this section.

Whenever individual pixels are combined, either in constructing source lists necessary for photometric and astrometric calibration, or in the coaddition of different frames, the **OmegaCAM**-reduction pipeline uses variance weighting (weight$= 1/\sigma^2$). The inverse variances are recorded in **weight maps**.

The debiased images record $S(x, y)$ counts in pixel $x, y$, that are related to the photon flux $I(x, y)$ by:

$S(x,y) = Gg_{DQE}g_{ff}(x,y)I(x,y)$,
Since photon shot-noise is much larger than the read-out noise, the rms-noise in the raw data is given by:
$\sigma_S(x,y) = G(g_{DQE}g_{ff}(x,y)I(x,y))^{1/2} = (GS(x,y))^{1/2}$.
Once data has been flatfielded ($S' = S/g_{ff}$), the counts are given by:
$S'(x,y) = Gg_{DQE}I(x,y)$,
and the rms-noise by:
$\sigma_{S'}(x,y) = G(g_{DQE}g_{ff}(x,y)I(x,y))^{1/2})/g_{ff} = (GS'(x,y)/g_{ff})^{1/2}$
The photon flux $I(x,y)$ is a sum of a uniform background $I_{back}$ plus sources $I_{src}(x,y)$. Since, the surface brightness of the sky is (much) larger than the surface brightness of most sources, the rms-noise is given by:
$\sigma_{S'}(x,y) = G[g_{DQE}I_{back}/g_{ff}(x,y)]^{1/2} = (GS'_{back}/g_{ff})^{1/2}$
Hence, the rms-noise in an image is the product of a factor ($(GS'_{back})^{1/2}$) that is constant over one image, but will vary between images, and a factor ($g_{ff}^{-1/2}$), the inverse of the square-root of the flatfield, which varies over the image.

To aid in the construction of weight maps for each individual science image **master weights** are constructed (**req.**546). These master weights are equal to the master flatfield, except that pixels that are hot (**req.**522) or cold (**req.**535), as well as pixels that have a gain outside a user defined range are assigned a weight of zero. **Individual weight** images for each science image can then be produced by determining the background level $S_{back}$, and dividing the master weight by $GS_{back}$. These individual weights can be further improved by detecting which pixels are affected by cosmic rays or satellite tracks, and assigning those a weight of zero too.

### 5.4.1 Req. — *Bias - doit*

**Objective:**

Determine master bias frame.

The signal in raw scientific frames contains a component that is due to a bias current. This component shows up as an offset to the signal. The bias-offset has the following characteristics: i) the bias level grows to its asymptotic level in the first few hundred lines, and ii) the bias level depends on the total signal in a given line. Therefore, an initial bias correction—the **overscan correction**, is applied by averaging the overscan pixels for each line, and subtracting this value from that line.

In addition, the bias offset exhibits a residual pattern, which is measured by the master bias frame. To construct the master bias a series of 10 zero-second bias exposures is overscan-corrected, and then averaged, rejecting $5\sigma$ outliers ($\sigma$ = dispersion of the 10 bias exposures of individual pixels), due to particle hits during read-out. The resulting master bias frames will be used for the correction of all frames. For each master bias frame the mean value for each CCD chip will be determined and evaluated in a trend analysis.

As the readout noise dominates the rms scatter in the bias frames, while the shotnoise of the sky background dominates the rms scatter on the sky images, which is nominally much larger than the readout noise, it is sufficient to characterize the bias value at individual pixels with an accuracy of (readout noise/$\sqrt{10}$).

A comparison with a previous master bias frame will be done as an evaluation of the overall health of the instrument and the quality of the data. This will thus measure short-term variations. Long term variations can be assessed using trend analysis.

A comparison of the mean level with laboratory values will be used as an overall quality check.

**Fulfilling or fulfilled by:**

Selfstanding. Raw data are also used for **req. 522** *Bad/hot pixels*

Calfiles used by: **req. 542** *Dome flat*, **req. 543** *Twilight flat* **req. 544** *Night sky flat* **seq. 632** *Trim, de-bias, flatfield*

**When performed/frequency:**

daytime- Commissioning, in RP initially daily. Later the frequency is to be determined by experience.

**Sources, observations, instrument configurations:**

10 observations with 0 (zero) seconds exposure time.

**Inputs:**

Raw data bias frames

**CalFile– 541** *Master Bias frame* previous versions

Laboratory values of bias levels.

**Outputs:**

**CalFile– 541** *Master Bias frame* to be used by **seq. 632** *de-bias flat field*

**Required accuracy, constraints:**

The required accuracy per pixel in the master bias frame is "nominal read-outnoise/$\sqrt{10}$".

For the quality check: Deviation of the mean level of master bias (bias level) from lab values $< 10\%$.

**Estimated time needed:**

Observation: 15 min. Reduction: $<$ 5 min./CCD.

**Priority:**

essential

**TSF:**

**Mode– Stare** N=10

**TSF– OCM_img_cal_bias**

**Recipe:**

**Recipe– Bias,**also recipe for **req. 522** *Hot pixels*

**Needed functionality:**

image - trim; image - mean average; image - statistics

**CA:**

Do an overscan correction on the input raw bias frames, and trim the resulting images.

Combine the trimmed images into an average bias frame, using $5\sigma$ rejection.

Compare mean of master bias frame with previous version.
Check whether mean level is in range.

**CAP:**

```
input bias_list, old_master_bias_stat
bias_list = bias_list.OverscanCorrection()
bias_list = bias_list.Trim()
master_bias = bias_list.Average(method='mean',
                reject_method='sigma', reject_level=5)
imstat      = master_bias.Stat()
diffmean    = imstat.mean-old_master_bias_stat.mean
if abs(diff_mean) > MAXIMUM_DIFFERENCE
    print "Bias too different from old bias"
if imstat.mean < MIN_BIAS or imstat.mean > MAX_BIAS:
    print "Bias outside valid range"
output master_bias, imstat
```

### 5.4.2 Req. — *Flat-field - dome key bands + user bands - doit*

**Objective:**

Determine master dome flat frame for both **Keybands** and **Userbands**.

During the lifetime of **OmegaCAM** the dome flatfields shall be measured for the 4 keybands and the key-composite filter at least once/week. Thus at least within 3 days of the taking of science data a dome flatfield in the key passband will be available.

The sequence of dome flatfields in the keybands, acquired over periods of months to years will be used to perform a trend analysis on the long term stability of the instrument and lamp which illuminates the dome flatfield. With the exception of the effects of the unstability of the lamp, this trend analysis is redundant with that obtained from both **req. 563** *photometric zeropoint* and that of **req. 562** *Photometric calibration - Monitoring*. Thus, by combining the results of these **req.**'s an accurate description of the behaviour of the lamp is feasible. The prediction of the behaviour of the lamp is a result, which will be used as an input for **req. 546** *Quick detector responsivity check*.

The dome flatfields will be used on an individual CCD chip level. The relative variations of the quantum efficiciency between individual CCD chips will be measured by **req. 563** *Photometric Calibration - zeropoint key bands -doit*.

The redundancy between various measurements of **req. 563** *Photometric Calibration - zeropoint key bands -doit* and **req. 542** *Dome flats* at keybands will be used to evaluate the relative chip-to-chip gain variations, and in due time, when advanced insight in this item is achieved, this knowledge might be used to further optimize observing scenarios.

For the userbands the dome flatfield will only be taken when during the period of week that particular passband has been used for science observations. No trend analysis will be done on the data taken in the User pass bands.

**Fulfilling or fulfilled by:**

Selfstanding.

Output is used by:

**req. 563** *Photometric Calibration - zeropoint key bands -doit*

**req. 547** *Quick detector check* through the characterization of the dome flat field lamp.

**req. 546** *Master flatfield and master weight map*

**When performed/frequency:**

Daytime, daily. For the keybands the dome flatfields will be measured at least once/week. For the Userbands the dome flatfields will be measured at least within 3 days that the Userband has been used for science observations. When filters have been changed in the cassette the presence of dust and/or scratches might require new flat field exposures.

**Sources, observations, instrument configurations:**

Domeflats with the four keyfilters and the single key composite filter. 5 observations per filter, with approximately 20000 ADU. Each science/standard observation preferably has an associated domeflat observed within 3 days. About 4 dome flats will be measured per day.

**Inputs:**

**CalFile– 541** *Master Bias frame*

**Outputs:**

**CalFile– 542** *Master Domeflat frame*
**CalFile– 542L** *Dome Lamp*

**Required accuracy, constraints:**

Accurately measuring pixel-to-pixel gain variations as small as 1%, Adding 5 exposures of 20,000 counts satisfies this requirement.

**Estimated time needed:**

Observation: 10 min. Reduction: 5 min./CCD.

**Priority:**

essential

**TSF:**

**Mode– Stare** N=5
**TSF– OCM_img_cal_domeflat**

**Recipe:**

**Recipe– Dome_Flat,**also for **req. 535** *CCD Cold Pixels*

**Needed functionality:**

image - trim; image - mean average; image - statistics; image - arithmetic

**CA:**

First trim and de-bias the dome frames.
Normalize frames to one illumination level.
Build a mean frame, rejecting $5\sigma$ outliers.
Finally, normalize the flatfield.

**CAP:**

```
input domeflat_list, bias

domeflat_list = domeflat_list.OverscanCorrection()
domeflat_list = domeflat_list.Trim()
domeflat_list = domeflat_list-bias

imstat = domeflat_list[0].Stat()

for i in [1,2,3,4]:
    tmpstat = domeflat_list[i].Stat()
    domeflat_list[i] = domeflat_list[i]*imstat.mean/tmpstat.mean

master_domeflat = domeflat_list.Average(method='mean',
                        reject_method='sigma', reject_level=5)
imstat = master_domeflat.Stat()
master_domeflat = master_domeflat/imstat.median
imstat.mean = imstat.mean/imstat.median
imstat.median = 1.0

output master_domeflat, imstat
```

### 5.4.3 Req. — *Flat-field - twilight*

**Objective:**

Determine master twilightflat frame, using observations of the twilight sky.

Twilightflat observations will be attempted for each passband that is observed during that night. If insufficient twilight time is available then the twilightflat observations are taken preferably in the previous or subsequent night. In addition twilightflats of the 4 keybands will be taken at least once a week.

In order to minimize the spatial gradient in the sky brightness, the observations need to be made on the solar circle, i.e. the great circle through the zenith and the sun's position, at a zenith distance of about $20^\circ$ in the solar antidirection. Preferably, the field of view does not include stars brighter than TBD magnitude.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Evening and morning twilight.

An attempt will be made to observe twilightflats for all bands observed during the night. For all observed bands, twilightflats will be observed within a maximum of 2 nights. In addition, twilightflats for the keybands will be obtained at least once a week, irrespective of whether keybands were used for science observations during that week.

**Sources, observations, instrument configurations:**

Twilightflat with 5 observations per filter at 'empty' sky, near $20^\circ$ from zenith in solar anti-direction. It may be advisable to determine a standard target list of approximately 10-20 empty fields, equally spaced in right ascension, at $20^\circ$ from zenith.

Observations should approximate 20000 ADU. Exposure time should be based on skybrightness. No effects of shutter are expected.

If the tracker can be used as an exposure meter, the desired exposure level can be set directly. Alternatively one can use the Tyson and Gal formula (in template ?) for the variation of the twilight brightness with time, to keep

the exposure level constant. In the latter case, a trend anaysis of twilightflat can be used to calibrate this formula.
Each science/standard observation preferably has an associated twilightflat observed within 2 days. We expect a total of 10 Twilightflats to be observed during each twilight period, for a total of 4 master Twilightflats per night.

**Inputs:**

**CalFile– 541** *Master Bias frame*

**Outputs:**

**CalFile– 543** *Master Twilightflat frame*

**Required accuracy, constraints:**

Mean levels should be approximately 20000 ADU.

**Estimated time needed:**

Observation: in total 25 min./night. Reduction: 5 min./CCD.

**Priority:**

essential

**TSF:**

**Mode– Jitter** N=5

**TSF– OCM_img_cal_skyflat**

Use an appropriate (empty) field, exposure time determined by tracker CCD, or Tyson-Gal formula.

**Recipe:**

**Recipe– Twilight_Flat,**also for **req. 535** *CCD Cold Pixels*

**Needed functionality:**

image - trim; image - mean average; image - statistics; image - arithmetic

**CA:**

First de-bias the sky frames, then normalize the frames and build a mean frame, rejecting $3\sigma$ outliers.

**CAP:**

```
input twilightflat_list, bias
```

```
twilightflat_list = twilightflat_list.OverscanCorrection()
twilightflat_list = twilightflat_list.Trim()
twilightflat_list = twilightflat_list-bias

for i in range(len(twilightflat_list))
    imstat = twilightflat_list[i].Stat()
    twilightflat_list[i] = twilightflat_list[i]/imstat.median

master_twilightflat = twilightflat_list.Average(method='mean',
                reject_method='sigma', reject_level=5)
imstat = master_twilightflat.Stat()

master_twilightflat = master_twilightflat/imstat.median
imstat.mean = imstat.mean/imstat.median
imstat.median = 1.0

output master_twilightflat, imstat
```

### 5.4.4 Req. — *Flat-field - night sky*

**Objective:**

Create Night Sky flat frame.

The flatfield that most closely reproduces the actual gain variation of the science and standard observation, can be obtained by averaging a large number of science and standard observations, taking care of properly masking the contaminating object. While such a night-sky flat (aka supersky) could, in principle, be superior in quality to the twilight flat, the procedure to obtain this flat can be computationally very expensive. On the other hand night-sky flats may also be suitable for fringe removal.
It remains to be seen to what extent the problem of sky concentration, i.e. nonuniform illumination due to stray light/reflection affects the quality of night-sky flat.
Because these night-sky flats can only be obtained from actual observations, we cannot guarantee their availability for bands for which only standards were obtained. It is, therefore, not clear how routine building of the skyframes should be incorporated into our photometric calibration scheme.
A minimum of 5 images in a night in a given band is required to optimally fulfill this requirement.

**Fulfilling or fulfilled by:**

Data reduction of raw data from science and photometric standard observations

Used by: **req. 546** *Master flatfield and master weight map*

**When performed/frequency:**

daytime, daily

**Sources, observations, instrument configurations:**

Science and standard observations

**Inputs:**

**CalFile– 541** *Master Bias frame*
**CalFile– 542** *Dome flat* or **CalFile– 543** *Twilight flat*

**Outputs:**

**CalFile– 544** *Nightsky flat frame* , assuming an average of three different bands observed per night.

**Required accuracy, constraints:**

This procedure would benefit from a prior detection and masking of bright objects. If no masks of bright objects are available, then a minimum of 15 frames should be included.

**Estimated time needed:**

Observation: None. Reduction: 20 min./CCD/night/filter.

**Priority:**

very desirable

**TSF:**

Raw data of science and standard star observations in jitter and dither mode is used. Avoid using multiple exposures with the same pointing in Stare mode.

**Recipe:**

**Recipe– Nightsky_Flat**

**Needed functionality:**

image - trim; image - mean average; image - statistics; image - arithmetic

**CA:**

This procedure benefits from first flatfielding the data, and determining the master sky flat as a modification of this flatfield. First de-bias the science/standard and apply the flats, then normalize the frames and build a mean frame, rejecting $3\sigma$ outliers.

**CAP:**

```
input science_list, bias, flat

science_list = science_list.OverscanCorrection()
science_list = science_list.Trim()
science_list = (science_list-bias)/flat
```

```
for i in range(len(science_list))
    imstat = science_list[i].Stat()
    science_list[i] = science_list[i]/imstat.median

nightsky_flat = science_list.Average(method='mean',
                reject_method='sigma', reject_level=3)

nightsky_flat = nightsky_flat*flat

imstat = nightsky_flat.Stat()
nightsky_flat = nightsky_flat/imstat.median
imstat.mean = imstat.mean/imstat.median
imstat.median = 1

output nightsky_flat, imstat
```

### 5.4.5 Req. — *Flat-field - Fringing*

**Objective:**

Determine the fringe pattern of the background.

Fringing due to variable strength of several skylines, mostly apparent at the long wavelengths, requires a different approach to background subtraction. Normally, after flatfielding, the background can be expected to be flat over the entire image, and a median of the image, excluding $5\sigma$ outliers, would in principle be sufficient to subtract the background.

In images that suffer from fringing we have to deal with a background that is variable on small ($<< 1'$) scales within the image, and can not be distinguished from sources. The image itself can, therefore, not be used to determine the background. However, given the fact that most observations are taken in jitter or dither mode, the information of several images can be combined to determine a background. This average should include enough observations to properly exclude contamination from sources, and, because the standard jitter/dither patterns only include 5 pointings, one background computation per jitter/dither is probably not sufficiently accurate. On the other hand, because the fringing pattern varies with time and telescope position, a straight mean (the supersky) over an entire nights worth of data is also not usable.

A suitable strategy to construct a fringed background image, usable for subtraction, thereby removing the fringe pattern, remains to be determined. If the fringe pattern is stable over the night, a decomposition of the night-sky flat in an additive and multiplicative term is feasable. The assumption that the high-frequency spatial component in the night-sky flat are fringes, while the lowest frequency components represent gain variations has been used with reasonable success.

**Fulfilling or fulfilled by:**

Data reduction of science and photometric standard observations

**When performed/frequency:**

Commissioning and when long wave science frames are taken.

**Sources, observations, instrument configurations:**

Use science and standard data to determine background

**Inputs:**
The science observations themselves are used.

**Outputs:**
**CalFile– 545** *ff-fringe*

**Estimated time needed:**
Observation: None. Reduction: Depends on the analysis.

**Priority:**
very important

**TSF:**
Use same data as for night sky flat (**req.**544)

**Recipe:**
**Recipe– Fringe_Flat**

**Needed functionality:**
image - defringing

### 5.4.6 Req. — *Flat-field - master flat and weight map*

**Objective:**

Determine the master flatfield, to be used to correct for the pixel-to-pixel gain variation from the raw image data. Also use this flatfield to create a master weight map, to be used when co-adding image data.

Four different measures of the variation in the gain are available: the dome flat (**req.**542), the twilight flat (**req.**543), the night-sky flat (**req.**544) and the illumination correction (**req.**548). A suitable choice of the final master flatfield, based on a combination of one or more of these flatfields, and, optionally, the illumination correction will be implemented.

A method whereby the dome flat is used to measure the pixel-to-pixel (small-scale) variation, and either the twilight or night-sky flat is used to measure the large scale variation, would provide a first-order approximation of the master flatfield. This master flatfield could then be used to flatfield the science and standard images.

Experience at FORS has shown that a suitable combination of twilight and night-sky flats provided the best determination of the gain variation. Experience with WFI indicates that some care has to be taken to address the issue of sky concentration. An optimal algorithm that takes this into account, (using the illumination correction), will be based on experiments with WFI and **OmegaCAM** data.

The master flatfield is proportional to the inverse variance in the flatfielded data and can therefore be used to build a master weight image. Weights of zero are assigned to hot (**req.**522) and cold pixels (**req.**535), as well as pixels that have a relative gain outside a user defined range.

The master weight maps are the basis on which individual weight maps are created (**seq.– 632).**These individual weight images also assign a weight of zero to cosmic-ray events and satellite tracks.

**Fulfilling or fulfilled by:**

Additional data reduction of flat fields obtained by **req.**542 543 544.

**When performed/frequency:**

New weight and flag images should be constructed whenever a new flatfield is constructed.

**Inputs:**

**CalFile– 522** *Hot pixel map*
**CalFile– 535** *Cold pixel map*
**CalFile– 542** *Dome flat*
**CalFile– 543** *Twilight flat*
**CalFile– 544** *Night Sky flat*
**CalFile– 548** *Illumination Correction*

**Outputs:**

**CalFile– 546** *Master flatfield*
**CalFile– 546W** *Master weight map*

The master flatfield is used in **seq. 632** *Trim, debias and flatfield* The master weight map is used in **seq. 633** *Construct individual weights*

**Estimated time needed:**

Observation: None. Reduction: 1 min./CCD.

**Priority:**

essential

**Recipe:**

**Recipe– Master_Flat**

**Needed functionality:**

image - masking; image - arithmetic

**CA:**

The procedure to combine dome, twilight and nightsky flatfields, inhomogeneity into a master flatfield is under investigation.

The weight is equal to the flatfield, with hot and cold pixels, as well as pixels with a gain outside a user supplied range set to zero.

**CAP:**

```
input flatfield, hot_pixel_map, cold_pixel_map
thresh_map   = flatfield.Mask(in_val=0, out_val=1,
                    range_low=WEIGHT_THRESHOLD, range_high=10)
weight_image = flatfield*(1-hot_pixel_map)
```

```
weight_image = weight_image*(1-cold_pixel_map)
weight_image = weight_image*thresh_map

output weight_image
```

### 5.4.7 Req. — *Quick detector responsivity check-doit*

**Objective:**

Quickly check the overall health in terms of responsivity by observing the dome screen with the composite filter.

Together with **req. 521** *read-noise* this item forms the most important day-to-day health check. The expected lamp intensity is characterized in **req. 542** *Dome flat*. This measurement will lead to a go/non-conformance flag and day report. The results will have to be inspected on the site, as this is a daytime health check of the instrument.

Trend analysis on the raw data will be redundant with that of **req. 542** *dome flat*.

The equivalent of this **req.** on the sky is provided by **req. 562** *Photometric Calibration - Monitoring*

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Commissioning, daytime, every day of operations both during CP and RP.

**Sources, observations, instrument configurations:**

dome flat with composite key filter

**Inputs:**

**CalFile– 542L** *Dome Lamp*
**CalFile– 547** *Quick check* older versions

**Outputs:**

**CalFile– 547** *Quick check*
**CalFile– 547r** *Quick check -day report*

**Required accuracy, constraints:**

1%

**Estimated time needed:**

Observation: 3 min/day. Reduction: 1 min./CCD.

**Priority:**

very important

**TSF:**

**Mode– Stare** N=1
(**TSF– OCM_img_cal_domeflat,** N=1, filter= composite)
= **TSF– OCM_img_cal_quick**

**Recipe:**

**Recipe– Quick_Check**also run on-site

**Needed functionality:**

image - trim; image - arithmetic; image - statistics

**CA:**

Do overscan correction and de-biasing, divide by previous quick-check observation. The median of the resulting image should be 1 provided there is no difference in the dome illumination between these observations

A trendanalysis using measurements over a longer time scale and the calibration of the time variation of the lamp has to be done in an interactive analysis.

### 5.4.8 Req. — *Illumination correction*

**Objective:**

Characterize the illumination correction.

The zeropoint is determined individually for each CCD in **req.**563. The gain variation over individual chips is characterized by the twighlight and sky flatfields (**req.**533 and **req.**534) under the assumption of an ideal flat illumination over the field of view. In practice this ideal flat illumination can be affected by stray light (sky concentration) and the flatfield has to be corrected for this.

An initial verification that this effect is indeed present will be obtained when constructin g catalogues of secondary standards (**req.**569). In case it is found to have an amplitude over a single chip larger than 1% the effect has to be characterized by measurements of a standard field. The master flatfield (**req.**546) will apply this information when needed.

**Fulfilling or fulfilled by:**

Initial verification of effect: **req. 569** *Secondary Standards.*

Subsequent measurent of effect, using standards star observations (**req.**563, **req.**564)

**When performed/frequency:**

Verification of effect during commissioning. Measurement, during RP, once/month

**Sources, observations, instrument configurations:**

Standard equatorial field (TBC)

**Inputs:**

**CalFile– 546** *Master flatfield*, build with a uniform illumination correction
**CalFile– 569** *Secondary Standards*
**RawData– 563** *Zeropoint - Keyband* or **RawData– 564** *Zeropoint - Userband*

**Outputs:**

**CalFile– 548** *Illumination correction*

**Required accuracy, constraints:**

better than 1% for the amplitude over a single CCD.

**Estimated time needed:**

Verification: see **req.**569 Measurement: Reduction 5 min/CCD.

**Priority:**

essential

**Recipe:**

**Recipe– Illumination_Correction**

**CA:**

Fit the deviation of the measured Zeropoint of individual standards from a uniform Zeropoint for the whole field with a polynomial modelling the illumination correction of the field of aach individual Chip.

## 5.5 Astrometric Calibration

The aim of the astrometric calibration is to accurately determine the projection matrix for converting pixel positions to sky coordinates. This will be done automatically in the data reduction pipeline.

For **Mode– SSO** N= the astrometric solution can be derived provided some observational limits, restricting the curvature of the stellar track, are met. When stellar tracks become more curved than the limits, all astrometric quality checks will have to be relaxed. All source positions will be derived using the first-order moments of the pixel distribution of the detected objects. The resulting positions, in such cases, will be the weighted averages of the stellar tracks and that of the (than not) moving targets. The exposure time limitation is defined by the curvature of the stellar tracks in the field, which should be less than 1% over the full track. Estimates for limitations on tracking for **OmegaCAM** are defined by requiring the curvature of the stellar tracks to be less than 0.1 FWHM of the PSF ($< 0$”$6$). Assuming tracking in Ra, a track length of less than 0.1 degree at any declination is allowed. For a track length of 0.2 degree only declinations between 0 and +/-20 deg or +/-70 to +/-90 deg are within the above limits. For the other modes there are no such restrictions.

The astrometric calibration can be derived using two fundamentally different methods.

The first, traditional, method is to derive the full projection matrix separately for each pointing, ignoring any detailed prior knowledge (apart from some rough initial estimates such as pointing, orientation and platescale). This method has great freedom and allows for instrument independent determination of the projection matrix. It can thus be used on a variety of instruments, but requires more input data elements to achieve an accuracy equal to that of the next method.

The second method allows for a separate determination—and use—of instrument specific characteristics of the geometry that do not change (much) among different pointings and the characteristics that do change with pointing. Fixed characteristics are, e.g., position of the chips relative to each other, the position of the rotator axis, the optical deformation at the position of the focal plane and perhaps pointing accuracy. Variable characteristics include items like

the flexure of the telecope and its instrument. The latter items need to be determined for each pointing separately. This method can be robust and has less degrees of freedom facilitating accurate astrometry with a small amount of data points. It is, however, tightly fixed to the instrumental geometry. A geometric model must be obtained and associated parameter values must be determined before standard astrometric reduction can be done.

Both methods will make use of an astrometric reference catalog. Current catalogs have positional accuracies that are not extremely high on the scale of the field of view of **OmegaCAM**. To achieve higher positional accuracy within a given pointing set and to allow accurate co-addition without degrading the PSF the astrometric solution will make use of the overlap among the pointing set.

The methods can be applied both to the main camera CCD chips and to the guide CCDs, as the latter can be viewed as a auxiliary CCDs of the main camera.

The requirements outlined here determine the calibration data necessary to perform an astrometric solution using prior knowledge of instrument specific characteristics.

The algorithm for the derivation of the astrometric solution is detailed in Section 7.3, while its use is detailed in **seq.– 634.**

### 5.5.1 Req. — *Position of Camera in focal plane*

**Objective:**

Determine the position of the chips with respect to the rotator axis of the telescope. This is part of the static astrometric calibration of the camera. It involves the determination of the chip position, scale, and orientation with respect to a perfect pixel plane. This has to be done with the ADC in and out.

This procedure produces the astrometric pre-solution. In fact, the expected pointing and other a-priori positional offsets are expected to be small; hence the standard astrometric solution can already be obtained without a pre-solution. However, a first inspection and verification of the pre-solution is a task to initialize the system.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Each mechanical change of the camera. Each user supplied filter, once a year.

**Sources, observations, instrument configurations:**

High object density (but unconfused) areas such as open clusters. Standard areas, possibly overlapping with standard star fields. All filters and the two optical configurations ADC in and out should be exercised.

**Inputs:**

**CalFile– in1** *Astrometrical reference catalogue*, e.g. US Naval,or GSC2

**Outputs:**

**CalFile– 551** *Astrometric camera/chip solution*

**Required accuracy, constraints:**

Internal precision: 0.3 pixel. External precision limited by reference catalog

**Estimated time needed:**

Observation : 2 hours

**Priority:**

Desirable

**TSF:**

**Mode– dither** N=5

**TSF– OCM_img_obs_dither,**each filter, ADC In/Out

**CA:**

Data is reduced as standard science data, but co-addition is not required. **SeqFile– 634C** *Astrometrically calibrated catalogue* produced by the standard pipeline contains the relative positions of all the chips. Print offsets etc in **SeqFile– 634C** *Astrometrically calibrated catalogue* and compare with focal plane design values (previous versions of 634C).

### 5.5.2 Req. — *Telescope Pointing and offsetting*

**Objective:**

Verify the pointing and the offsetting of the telescope for both optical configurations (ADC in and out).

The pointing model is provided independent of the **OmegaCAM** S/W, but a verification of both the pointing and the offsetting accuracy is required.

Perform on-site spot checks of the pointing model. The data from the Guider CCD can be used for this.

Also in the data reduction pipeline, as a standard check in the astrometric solution, the pointing error is determined.

**Fulfilling or fulfilled by:**

Selfstanding.

**When performed/frequency:**

Commissioning, after each change of the pointing model, and to be determined by experience.

**Sources, observations, instrument configurations:**

Standard field

**Inputs:**

Offset Guide CCD

**Outputs:**

Conformance flag.

**Required accuracy, constraints:**

1 arc second

**Estimated time needed:**

10 min

**Priority:**

Very important

**TSF:**

Stare mode, dither and jitter mode. In fact all observations can be used.

**CA:**

Run standard pipeline and inspect parameter "reference position with respect to targetted pointing" of the astrometric solution.

### 5.5.3 Req. — *Telescope and Field Rotator tracking*

**Objective:**

Verify that the rotator performs properly and simultaneously that the telescope is tracking correctly.

Up to Zenith distances of 60 degrees and wind speed of 18 m/s with a dynamical component of 30%, the free tracking of the telescope shall be better than 0.2 arcsec rms. With closed-loop autoguiding, the rms deviation shall not exceed 0.05 arcsec

Two methods will fulfill this requirement.

First, check at various telescope positions the global performance of the rotator plate which is driven by the pointing model. When the rotator plate is not performing optimal, the objects are elongated in a circular pattern (concentric rings) with the rotator plate axis at the center. This inspection is closely related to the determination of the point spread function.

Second, check for the tracking of the telescope to find functional dependency with telescope position. This is purely a verification. As an internal check, do this for each **OmegaCAM** observing mode. Similar to the rotator plate inspection the point spread function is used as the measuring tool. When the telescope is not tracking correctly the shapes of stellar objects are systematically elongated. The amount of elongation may not exceed a certain value, corresponding to the basic tracking requirements given above.

These two functional checks are merged into one analysis as they essentially use the same technique for verification and because they are coupled. Non-conform tracking can cause non-conform rotation.

The offset information from the Guider CCD's is another element in the functional check. When offsets for guide stars are becoming too large, rotator plate errors or telescope tracking errors are apparent as different patterns of offsets during an exposure time.

**Fulfilling or fulfilled by:**

Data reduction standard science observations (allmost all will do).

**When performed/frequency:**

Commissioning, at each change of the pointing model, in RP to be determined by experience. In CP check once with the ADC in and out.

**Sources, observations, instrument configurations:**

Most observations can be used.

**Outputs:**

Conformance flags Source extraction files

Source extraction calfiles (configuration, parameters files)

**Required accuracy, constraints:**

First method: 1 arcsecond in the dependencies. Second method 0.1 pixel dimension or 0.1 FWHM

**Estimated time needed:**

First method: 2 min, Second method: 0.01 sec.

**Priority:**

very important

**Needed functionality:**

catalog - PSF fitting; misc - regression

**CA:**

First method: Inconsistent Rotator Plate motion can be detected by inspecting the systematic behaviour of stellar object elongation and position angle. The pattern of elongation/position angle reveals a concentric orientation when the rotator plate is not revolving correctly during an exposure. Furthermore, the elongation of stellar objects should progressively increase from the rotation axis of the plate outward. When this pattern is recognized at a significance level set by the instrument (PSF anisotropy) a non-conformance flag should be raised. First method: solve f(Alt,Az) = h(Theta) : Theta $<$ 1'

Second method: Inconsistent telescope tracking can be detected by inspecting the systematic behaviour of stellar object elongation. Therefore the objects shape parameters are inspected and the systematic behaviour of elongation parameters, e.g. position angle and elongation of the bounding ellipse are inspected. Whenever the ensemble of objects with a significant ($> 3\sigma$ elongation not equal 1 and a $> 3\sigma$ position angle not equal 0, where the two values are dictated by the known performance of the instrument (PSF anisotropy) a non-conformance flag should be raised.

**CAP:**

Extraction of rotations for each observation as a function of Alt-Az. Extraction of tracking shift during exposure.

Later trend analysis if present. This is a pure database type of operation. For a given period in time, defined by the instrument/telescope configuration and the pointing model version functional dependencies of astrometric calibration parameter describing the plate rotation with Alt en Az are derived. Whenever a functional dependence exceeds the specified positional accuracy a non-conformance flag is produced.

For the second analysis a simple comparison with the maximum allowed conforming rotation angle suffices.

### 5.5.4 Req. — *PSF Anisotropy*

**Objective:**

Determine the PSF anisotropy.

Detailed characterization of the Point Spread Function at various positions in the focal plane shall be provided. Monitor optical defects and possible variations in time. Do this for both optical configurations of the telescope, ADC in and out.

Guide CCD recordings are used for the analysis.

**Fulfilling or fulfilled by:**

Data reduction of observations of high density field, such as employed in **req.**551.

**When performed/frequency:**

Commissioning

Each optical change to the telescope,

Remount of the detector assembly. Once per three months.

**Sources, observations, instrument configurations:**

High density fields observed with **Mode– Stare** N=1.

**Inputs:**

FITS header keywords storing the offsets given to the Guiding system during the exposure time.

**Outputs:**

**CalFile– 554** *PSF anisotropy*

**Required accuracy, constraints:**

better than 1%

**Estimated time needed:**

Few minutes per pointing

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=1

**TSF– OCM_img_obs_stare**

**Recipe:**

**Recipe– PSF_anisotropy**

**Needed functionality:**

catalog - PSF fitting with Kaiser method

**CA:**

Run standard pipeline reduction. Do Kaiser type source extraction on output image. Use the second order moments of the brightness distribution of stellar objects to search for systematic effects across the detector area. The distribution of the position angles and elongations of the bounding ellipse has to be evaluated. A robust method for determining these parameters comes from Kaiser et al. 1995, APJ 449, 460.

**5.5.5 Req. —** *The astrometric solution for templates - doit -see 6.3.4*

**Recipe:**

See Section 6.3 (**seq.– 634).**

**5.5.6 Req. —** *The astrometric solution for Guide CCD's*

**Objective:**

Perform astrometric solutions for the Guide CCD's and hand over the solution to the Instrument S/W for locating Guide stars.

Note, the Guide CCDs can be read out separately and 'stand alone'.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Commissioning.

**Sources, observations, instrument configurations:**

Special readout (manual command) of the Guide CCD's into FITS files

**Inputs:**

Reference position catalog (see A4)

**Outputs:**

**CalFile– 556** *Guide CCD guide star signal and offset*
astrometry solutions inserted into the descriptors; handed over manually to instrument S/W responsible

**Required accuracy, constraints:**

1 arcsec rms for the accuracy with respect to the external standard;

External precision is driven by the position reference catalog. This is in the case of the USNO-A2 catalog of the order 0.3" with possible systematic excursions to 1".

**Priority:**

Essential

**Needed functionality:**

catalog - source extraction; catalog - association; catalog - astrometric solution

**CA:**

Description of calibration analysis (also mathematical, error propagation)

See **req.**5.5.5.

Here, the required accuracy is not as high as for the science images. Therefore it suffices to restrict the degrees of freedom to incorporate linear effects per CCD only.

**CAP:**

```
input flat_fielded_images, reference_cat
foreach image in flat_fielded_images
  extract_cat = image.source_extract()
  pairs_cat   = extract_cat.pattern_match(reference_cat)
  astrom_solv = pairs_cat.solve(PDeg=n, Iter=m)
  calib_image = image.head(astrom_solv)
done
output calib_images
```

## 5.6 Photometric Calibration

The basic requirement for the photometric calibration of the broad-band filters is to achieve an accuracy of better than 5% on the photometric scale in 'instrumental magnitudes' as assigned to the units of the resultant output image of the "image pipeline". The accuracy of the colour transformation terms of instrumental to standard systems should be better than 10% on the photometric scale.

In order to maintain this accuracy on a routine basis over years of operation, a set of requirements are specified in this section.

The descriptions of these requirements involve the following **OmegaCAM** specific ingredients:

- **key passbands** ($X$ = u',B, V and i' in Johnson (B,V) and Sloan (u', i') system)
- **two lens correctors** (near Zenith, the baseline, key configuration) and an **atmospheric dispersion corrector -ADC** for operations in User mode at larger Zenith angles.
- a **composite key filter** ($X$ = u', B,V and i' in each quadrant),
- a standard **polar field**, observable throughout the year,
- **8 equatorial fields**, containing both primary and secondary standard stars (Landolt fields - see section 7.1)
- a **dome lamp** and a **fixed dome screen** equipped with a stabilized current supply,
- **32 CCD's** are operated simultaneously, with the exception of the composite filter which 'feeds' 8 CCDs simultaneously in one passband.
- data rates should stay within limits that allow processing and storing of the data with the currently anticipated technology.
- A **standard atmospheric extinction curve** is adopted and all atmospheric extinction in various passbands is taken as a scaling of this curve.
- The photometric monitoring employs observing **strategy – freq** which has overriding priority on the scheduling and which employs observing **mode – stare** and its associated **trend analysis**.

The prime concept of the **OmegaCAM** photometric calibration is to $continuously$ maintain the photometric scale in the keybands, even when the science programme does not require the usage of these passbands during a particular night or period. This continuity is used by the data reduction (calibration and its trend analysis) and is meant to ease the maintenance of the photometric system on a routine basis.

The usage of a standard extinction curve results into a high rigidity of the pipeline processing, and provides a tool for error estimates, quality checks, recognizing non-conform data and provides a framework for successful pipeline processing of incomplete data.

We model the characterization of the photometric system in terms of a series of gains, where for each aspect of the calibration we distinguish a gain $g_0$ at a pre-determined fixed moment and the variation of that gain as function of time $g(t)$, the latter being mostly analyzed by a **trend analysis**.

All photometry is determined on an individual CCD chip basis ($N$ = number of chip, 1...32), apart from the atmospheric extinction which is common for all chips.

Most gains depend on passband ($X$), but not the variation of the atmospheric extinction, which is assumed to scale with the standard extinction curve.

In Figure 5.6 an overview is sketched of the various requirements which form the photometric calibration.

The fixed and variable gains of the various calibrations are defined as follows:

**Atmospheric extinction:** use scaling of standard extinction curve represented by $g_{sel.e}(X)$ :
middle of the night: $g_e(0) \times g_{sel.e}(X)$ **req.**563
during the night : $g_e(t)$, t in hours **req.**562

**Zeropoint** effective DQE - **req.**563
middle of the night: $g_{DQE}(0, N, X)$
on different nights: $g_{DQE}(t, N, X)$, t in nights

**Flat field** - **req.**542 and others
for period of 7 days: $g_{ff}(week, N, X)$

different weeks: $g_{ff}(t, N, X)$ t in weeks ; every week a new ff is assigned, replacing $g_{ff}(week, N, X)$

For a given star observed in passband $X$ at a given position in the field of view, at a given moment $(t)$ the relation between the output ($I_{obs}$ of the detectors) and the zero-airmass intensity is given by the general expression:

$$I_{obs,X} = g_e(0)g_e(t)g_{sel.e}(X)\times g_{dqe}(0, N, X)g_{dqe}(t, N, X)\times g_{ff}(week, N, X)\times I_{ref,X}$$

Colour term:
The primary standard stars have been measured with presumably the same filter passbands, but with CCD detectors which have a different relative spectral responsivity. This implies that the effective $g_{DQE}(0, N, X)$ when observing these primary stars depends on the colour of these stars: $g_{DQE}(0, N, X, X-x)$.

The photometric calibration involves the solution of the general equation above along a different path, with different unknowns, and different knowns.

The initialization of photometric calibration is to carefully process backwards and forwards through the basic equation. Particularly the settling of the secondary standards, which cover a larger field of view than the primary standards is tricky. On one hand the preparatory programme will provide this information, on the other hand **OmegaCAM** calibrations can self-calibrate the secondary standards, which has the advantage that it avoids the extra bootstrapping via another telescope and detector system.

Normalizations:
$g_{ff}(week, N)$ unity at central pixel of each chip $N$
$g_e(0)$ and $g_e(t)$ multiplication factor of standard extinction curve represented by $g_{sel.e}(X)$

Fig 5.6. *Overview of tracking the photometric calibration at various time scales. From left to right, the figure indicates the requirement number, the requirement name, the used filters and standard fields. The stars indicate at which frequency the measurement is done. For further details, see text.*

### 5.6.1 Req. — *Shutter Timing*

**Objective:**

Verify the actual timing of the shutter.

Exposure timing has to be accurate to $\pm 0.2\%$ at 1 sec exposure time at any position of the focal plane (**OmegaCAM** Technical Specifications). The exposure timing signal is provided by PULPO. For the following considerations we assume that the PULPO timing signal is accurate to better than 0.1 msec (i.e. it is not the dominating source of inaccuracy).

The shutter mechanism consists of a pair of chasing carbon fibre blades. Their movement is controlled by the Shutter Control Unit (Shutter CU) such that it results in an identical effective exposure time all over the frame. These two movements may or may not overlap in time depending on the exposure time and the blade traveling time.

The opening blade starts moving immediately ($\mu$sec's) after the falling edge of the TTL signal (provided by PULPO). This is the beginning of the exposure procedure. The closing blade starts moving immediately ($\mu$sec's) after the rising edge signal was detected and ends (about 1 sec later) when the closing blade completely covers the aperture, which marks the end of the exposure procedure. Therefore, the duration of an exposure procedure is always:

```
exposure time + blade travel time (ca.  1 sec)
```

Two types of delays affect the effective exposure time: The delays of the start of the blade movements after the opening/closing TTL signal edge (i.e. absolute exposure time) and position dependent delays during blade movement (i.e. exposure homogeneity).

The open/close delays are up to 0.05 msecs due to signal polling of the Shutter Control Unit software. These values are well within the requirements (shutter open time error: $\pm 0.2\%$ at 1 sec corresponding to $\pm 2$ msecs). Deviations from this occur only in case of a severe shutter failure which is detected by the Shutter CU and PULPO independently followed by operator actions.

Position dependent delays (requirement: 0.2% at 1 sec exposure time) will be monitored in regular intervals of 3 months.

Dome flatfields of 10 sec and 0.1 sec exposure time will be taken for both

shutter blade movement directions. Illumination level shall be such that the CCD's are at about 60% to 80% full well for the 10 sec exposure. Exposure times will have to be evaluated during Commissioning.

**When performed/frequency:**

Commissioning, once per 3 month, further to determined by experience. Daytime

**Sources, observations, instrument configurations:**

Dome flat field with a level of about 40,000 - 50,000 ADU's

**Inputs:**

**CalFile– 541** $Bias$

**Required accuracy, constraints:**

Timing error less than 0.2%.

**Estimated time needed:**

1 hour

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=4
(**TSF– OCM_img_cal_domeflat,** $N = 4$, $t_{exp} = 10.0, 0.1, 0.1, 10.0$)
$=$ **TSF– OCM_img_cal_shutter**

**Recipe:**

**Recipe– Shutter_Delay**

**Needed functionality:**

image – collapse;

**CA:**

After bias correction divide (0.1 sec exp.) / (10 sec exp.) and average columns (or rows, which is appropriate) to improve S/N (the effect is 1-dimensional).

The result will be inspected for deviations from homogeneity ($\pm 2\%$ at 0.1 sec, i.e. $\pm 0.2\%$ at 1 sec).

**CAP:**

```
input bias, low_level_flat, high_level_flat
tmp = (low_level_flat-bias)/(high_level_flat-bias)

line = tmp.colapse()

output line
```

### 5.6.2 Req. — *Photometric Calibration - monitoring*

**Objective:**

Monitor any **short term** variability related to the transparency of the atmosphere (atmospheric extinction) or due to instrumental instabilities (e.g. effective DQE) with a minimum sampling of at least 3 times/night. This provides a **daily overall health check** of the instrument and detectors. A further trend analysis has to provide information on **long term** stability.

The variation (r.m.s.) of the flux detected by the autoguider shall also be used as an indicator (put in the FITS header) of the sky conditions. This is to be done for each science observation.

This monitoring is done on a standard **polar field**, which will be repeatedly observed at the beginning, middle and end of the night with the **composite key filter** (u', B, V and i' band), irrespective of the passbands used for the science observations. The observations are done in the standard configuration, with the two-lens corrector. A direct comparison of the measured intensity of the stars with reference values is used to qualify the overal conditions of instrument and atmosphere, the actual zeropoint (both unit airmass extinction and instrument DQE) being determined by **req.**563. The composite filter will provide simultaneous measurements of the sky brightness in these bands, thus providing an accurate spectrum with a spectral resolution R of roughly 5.

The comparison of the observed signal with the expected signal from standard stars in each of the four quadrants will lead to the determination of the product of the atmospheric extinction ($= g_e(0) \times g_e(t) \times g_{st.e}(X)$, (with $g_{st.e}(X)$ the gain of the standard extinction curve at passband $X$ ) and the overall effective DQE ($g_{DQE}$) of the detector system including the optics. As **req.**563 solves both $g_{DQE}$ and $g_{st.e}(X) \times g_e(0)$, a comparison with these measures gives $g_e(t)$, the variation of the overall gain during the night. The thus derived values of $g_e(t)$ at $t =$ beginning, middle and end of the night (could be more if the observer so wishes) provides the required monitoring. Excursions from the standard extinction curve, due to extraordinary meteorological conditions, can be traced by computing the standard deviation of observed minus standard curve values in the various bands.

The sky spectrum shall be derived on line from the data, as a quality check on the health of the instrument and the clearness of the atmosphere, as clouds or cirrus will be immediately notable in the spectral shape. A reference table containing the expected sky brightness (and thus colour) as function of lunar phase will be used in the evaluation of the data.

The repetitive measurements on the same field, with the same filter will also be used in trend analysis to monitor the overall long term stability of the instrumentation and atmosphere. The redundancy of these measurements with **req. 563** *zeropoint* and **req. 542** *Flat field -dome* will be used as a cross-check on the validity of the photometric system.

In addition, the repetitive nature of these observations, make them ideally suited for the health check as specified in requirement 3.7.3.4 of the Technical Specification. In order to facilitate rapid analysis at Paranal an additional fast analysis recipe is proposed, based on a predefined catalog of standard objects in each CCD. This recipe assumes that the pointing accuracy, achieved when guiding, is better than 6 arcsec. The recipe identifies regions of interest in each CCD for each object in the input catalog. These regions are then extracted after which a simple moment analysis of the brightest object in the region will determine total flux in ADU, position and FWHM for each object of interest, as well as the background flux in ADU.

**Fulfilling or fulfilled by:**

Selfstanding; a corresponding requirement on detector level is
**req. 546** *Quick check*

**When performed/frequency:**

beginning, middle and end of night; any moment atmospheric conditions are suspect. QC1, CA

**Sources, observations, instrument configurations:**

The **OmegaCAM** polar field, key composite filter, two lens corrector; short (about 20 sec) integration **Strategy– freq**

**Inputs:**

Table with sky brightness in u', B, V and i' as function of lunar phase, (currently available in WFI2.2m ETC).

**CalFile– 563Z** *Zeropoint - extinction - keybands* of that night ($g_{st.e}(X) \times$

$g_e(0)$
**CalFile– 562S** *Sky brightness* Reference values
**CalFile– 569** *Secondary Standard Catalog*
**CalFile– 541** *Master Bias Frame*
**CalFile– 546** *Weightmap*

**Outputs:**

**CalFile– 562** *Extinction - night report* ($g_e(t) \times g_{st.e}(X) \times g_e(0)$ at various $t$
**CalFile– 562u** *Photom-u' Stars + Sky*
**CalFile– 562B** *Photom-B Stars + Sky*
**CalFile– 562V** *Photom-V Stars + Sky*
**CalFile– 562i** *Photom-i' Stars + Sky*
Series of output files will be used for trend analysis

**Required accuracy, constraints:**

all photometry better than 1-2% on the photometric scale; the zeropoint of the night should be determined first **req.**563.

**Estimated time needed:**

Observation: 3 times 4 min. (100 sec preset + 100 sec integration + 42 sec readout ) totaling to 12 min/night
each night. Reduction: 5 min./CCD.

Detailed estimate of required integration time:
The secondary standard stars in the standard field have a limiting magnitude V$\sim$ 20. The internal accuracy of the present task is set on 1-2% level in order to achieve an overall end-to-end accuracy of better than 5% on the photometric scale. Clearly, for the composite filter the desired exposure time will be dominated by the response in the U' band. Using the WFI2.2m ETC, corrected for the VST optics and estimated CCD spectral responsivity, we estimate a S/N= 20 after 100 sec integration for a V =20 F0V star at airmass 2 (South Pole) with nominal 1.0 arcsec seeing. Thus, most secondary standard stars will have a S/N better than 20 in the U' band in a 100 sec integration. This would just match to the wanted 5% overall photometric accuracy in the u' band, but would lead simultaneously to higher S/N in the

other bands. We compute for a V=20 GoV star S/N = 90 in i' new moon, S/N=70 in V new moon, S/N =45 in V full moon and S/N =80 in B new moon. Thus an integration time of 100 sec for the composite filter appears reasonable, but clearly the u' band data give lower photometric accuracy, and the final value will depend on the achieved responsivity in the u' band. The final number has to be determined by experience and depends on the distribution and colours of the stars in the u' quadrant of the field of view.

**Priority:**

night monitoring: essential, long term trendanalysis: important

**TSF:**

**Strategy– freq**
**Mode– Stare** N=1
(**TSF– OCM_img_obs_stare,**N=1, filter=composite)
= **TSF– OCM_img_obs_monit**

**Recipe:**

**Recipe– PhotCal_Monitoring**one version for on-site monitoring, sky spectrum, night report etc; plus one version for off-line pipeline

**Needed functionality:**

catalog - source extraction; catalog - associate; catalog - astrometric solution

**CA:**

Dependency: **req.**563 for that night should be determined first.
Run standard image pipeline first: i) subtract bias ii) divide flat field iii) import zeropoint calfile.
- run **Sextractor** to obtain catalog
- obtain astrometric solution
- identify standards in astrometrically calibrated catalog to obtain star magnitudes + sky brightness (stellar photometry not used anywhere else in present set-up)
- compare star magnitudes with star magnitudes adopted **req.**563 to generate OK flags and night report
- import **CalFile– 563Z** *Zeropoint - extinction - key bands* of that night
- obtain extinction values and time stamp for part of night-night report.

Long term trend analysis is done on **CalFile– 562u, B, V and i** which are obtained every night 3 times.
- Make "lightcurve" of each standard star in the field
- report and plot all stars with deviations larger than $3\sigma$.

For the fast recipe of the health check, the following steps will be performed.
- Determine the position in each CCD for the objects from the input catalog
- Extract a 32 by 32 pixel region centered at each position.
- Find the local maximum within the region.
- Determine background in the the region, and subtract this.
- Compute first and second order moments of the signal around the maximum
- Compare measurements with values from the input catalog.

### 5.6.3 Req. — *Photometric Calibration - zeropoint keybands - doit*

**Objective:**

Determine the zeropoint of the overall detector chain, separately for each CCD chip, in all four keybands (no composite filter) and the true atmospheric extinction at midnight by measuring standard stars in the 4 key passbands in one of the eight equatorial fields and the polar field. Do this every night whatever the science programme on the telescope may be. Optionally, add one observation of another equatorial standard field with higher airmass to obtain a redundant, classical, measurement of the atmospheric extinction.

The keybands plus the two-lens corrector form the standard for this requirement, the use of the ADC is considered as User mode (see **req.**564).

The zeropoint corresponding to the DQE of each of the 32 CCD chips will be determined on an individual chip basis $g_{DQE}(0, N, X)$. Thus the composite filter can not be used for this. However, additional data will be acquired with the composite filter for redundacy. In case the relative gain variations of individual CCD chips appear small and well characterized by the overall flatfield (which is not really expected) then the **req.** might be fulfilled with only the composite filter, substantially releaving the data rate and workload.

The combination of the data of **req. 562** *Monitoring* taken at the middle of the night with the present zeropoint data will be used to solve separately for the effect of the extinction and DQE at the middle of the night. A standard extinction curve will be used as a reference, for error analysis, and to support the derivation of the solutions in the pipeline processing.

As **primary standards** the Landolt equatorial fields will be used, possibly extended with the WFI@2.2m preparatory programme results (Section 7 of CP). For each of the 8 equatorial fields a solution for **secondary standard** stars will be made for a larger, one degree, field of view. The acquisition of catalogues of secondary standards is discussed in **req.**569. These secondary standards data will be used for the nightly determination of the zeropoint.

During commissioning the reproducibility of the zeropoint determination should be verified for the different observing modes **Mode– jitter** N=5 and **Mode– dither** N=5. This also serves as an end-to-end-test.

Note that the fast extraction procedure defined in **req.**562 can also be

adapted to these standard star observations of the equatorial fields.

**Fulfilling or fulfilled by:**

selfstanding, but uses data of **req.**562 at the middle of the night.

**When performed/frequency:**

Once in the middle of each night. The linking of external (primary) to internal (secondary) standards will be done once during commissioning, and the first year of operation for each standard field; after that to be determined by experience.

It is to be determined by experience (stability of the system) whether the nightly zeropoint measurements can be relaxed as follows: in case the keyfilters are not used for science observations in a particular night, it is sufficient to only take an exposure with the composite filter.

During commissioning the **Mode– dither** N= and **Mode– jitter** N= have to be verified.

**Sources, observations, instrument configurations:**

**Strategy– freq Mode– Stare** N=1 **OmegaCAM** equatorial fields; exposures in u', B, V and i' and composite. Two lens corrector.

**Inputs:**

In pipeline data reduction **req.**563 reductions of a given night should preceed **req. 562** *Monitoring* reductions.

**CalFile– 569** *Secondary Standard Catalog*

optionally:
**CalFile– 569E** *Primary Standard Catalog*
For each night:
**CalFile– 562** *Extinction night report* **CalFile– 564E** *Standard extinction curve*

**Outputs:**

**CalFile– 563Z** *Zeropoint + extinction - keybands* (always) used by **seq.– 636.**

**Required accuracy, constraints:**

1% on the photometric scale

**Estimated time needed:**

Observation: 12 min. each night Reduction: 10 min/CCD/filter.

Detailed estimate of required integration time:

The secondary standard stars in the standard fields have a limiting magnitude V$\sim 20$. The internal accuracy of the present task is set on the 2% level in order to achieve an overall end-to-end accuracy of better than 5% on the photometric scale.

Using the WFI2.2m ETC, corrected for the VST optics and CCD responsivities, for 1.0 arcsec seeing and airmass 1.2 we compute an expected S/N = 50 for a V = 20 mag G0V star, of

u' band 100 sec but S/N =45 for F0V
B band 41 sec
V band 60 sec
i' band 84 sec

As there will be many much brighter stars (than the V=20 limiting mag for which this calculation is made) in the field of view, leading to much better S/N these integration times will be sufficient for the goals, also at other moonphases (actually checked with ETC). The u' band observations are on the limit and should be carefully checked during Commissioning. Thus a total sequence would last including readout of 42 sec:
preset (100), u'(100+ 42), B(45 + 42) , V (60+42), i' (84 + 42) = 657 sec

In addition, a composite filter image should be taken (100 sec) which in the long run might replace the u', B, V, i' sequence with monolithic filters.

**Priority:**

essential

**TSF:**

**Strategy– freq**
**Mode– Stare** N=1
(**TSF– OCM_img_obs_stare,** N=1, filter=key band)
= **TSF– OCM_img_obs_zpkey**

**Recipe:**

**Recipe– PhotCal_Extract_Zeropoint**

**Needed functionality:**

catalog - source extraction; catalog - associate; catalog - astrometric solution; misc - regression

**CA:**

The solution has to solve the following "gains":
$g_{ext}(X)$ = gain = atmospheric extinction for unit airmass
$g_{DQE}(N, X)$ = gain = DQE of individual chip $N$ in pass band $X$
(Latitude Paranal is -24°37′, Polar field ZD = $\sim 65^\circ$ airmass is 2.40, equatorial field (ZD =$\sim 24^\circ$ airmass is around 1.10).
The u', B,V and i' images on equatorial fields provide for each of the 32 chips the values of $I_{obs,X}(N)/I_{ref,X}$ in the equations:

$$I_{obs,u'}(N = 1...32)/I_{ref,u'} = 1.10 g_{ext}(0) \times g_{st.e}(u') \times g_{DQE}(0, N = 1...32, u')$$

$$I_{obs,B}(N = 1...32)/I_{ref,B} = 1.10 g_{ext}(0) \times g_{st.e}(B) \times g_{DQE}(0, N = 1...32, B)$$

$$I_{obs,V}(N = 1...32)/I_{ref,V} = 1.10 g_{ext}(0) \times g_{st.e}(V) \times g_{DQE}(0, N = 1...32, V)$$

$$I_{obs,i'}(N = 1...32)/I_{ref,i'} = 1.10 g_{ext}(0) \times g_{st.e}(i') \times g_{DQE}(0, N = 1...32, i')$$

The polar field with the composite filter provides for each of the 8 chips in a quadrant of the field of view (**req.**562):

$$I_{obs,u'}(N = 1....8)/I_{ref,u'} = 2.40 g_{ext}(0) \times g_{st.e}(u') \times g_{DQE}(0, N = 1....8)(u')$$

$$I_{obs,B}(N = 9...16)/I_{ref,B} = 2.40 g_{ext}(0) \times g_{st.e}(B) \times g_{DQE}(0, N = 9...16)(B)$$

$$I_{obs,V}(N = 17..24)/I_{ref,V} = 2.40 g_{ext}(0) \times g_{st.e}(V) \times g_{DQE}(0, N = 17..23)(V)$$

$$I_{obs,i'}(N = 24..32)/I_{ref,i'} = 2.40 g_{ext}(0) \times g_{st.e}(i') \times g_{DQE}(0, N = 25..32)(i')$$

Now consider the 8 chips which are common in the first and second set of measurements in the pass band B:
one can solve $g_{DQE}(0, N = 1...8, u')$ and 8 times $g_{ext}(0, u') \times g_{st.e}(B)$.
Idem dito for the other passbands we obtain:

$g_{DQE}(0, N = 9....16, B)$ and 8 times $g_{ext}(0, B) \times g_{st.e}(B)$.
$g_{DQE}(0, N = 17...24, V)$ and 8 times $g_{ext}(0, V) \times g_{st.e}(V)$
$g_{DQE}(0, N = 25...32, i')$ and 8 times $g_{ext}(0, i') \times g_{st.e}(i')$.
Next, these intermediate results (8 times $g_{ext}(0, u')$, $g_{ext}(0, B)$, $gext(0, V)$ and $g_{ext}(0, i')$) are determined relative to the standard extinction curve(**CalFile– 564E);**this is used as a quality check, which also provides the accuracy of the measured extinction. There is quite a number of exceptional situations the code has to be able to deal with, like one chip outlying, one passband outlying etc etc. Perhaps, the safest mode of automatic processing is, after the filtering of the outliers in the measurements of $g_{ext}(0, X)$, to determine the overall shift of the standard extinction curve (which is actually a gain $g_{ext}(0)$)) using the remaining of the 64 measurements (64 = 2 x 8 x 4= (eq+polar) x $N$ x $X$). (yes indeed, using the fourshooter once on the equatorial field, once on the polar fiels results into 64 measurements of the extinction !!)
This number can then be substituted in the above list of equations to obtain $g_{DQE}(0, N, X)$ for each chip $N$ and each band $X$. Actually these numbers will be derived three times, and this can be used in the error estimate and quality check.

### 5.6.4 Req. — *Photometric Calibration - zeropoint user bands*

**Objective:**

Determine the zeropoint of the overall detector chain and the atmosphere by measuring standard stars in the **User passbands**.

The zeropoints of the photometric calibration in the User bands will only be determined for the nights that the User bands are actually used for scientific observations. The measurements will be done on one of the eight equatorial fields.

The atmospheric extinction will be determined in the keybands through **req. 562** *monitoring* on the polar field. These data are appended here (like **req.**563) with a composite key exposure at the equatorial field at midnight, to settle $g_e(0, uBVi)$. The extinction curve will be used to transform measured atmospheric extinction at the keybands to the User bands.

The transformation (colour term) of the user passband to the key passbands is determined for a limited set of filters and the ADC with the keybands in **req.**565.

By combining the extinction results in keybands, the passband transformation coefficients and the direct zeropoint measurements in the User bands the zeropoint corresponding to the DQE of each of the 32 CCD chips will be determined on an individual chip basis.

Trend analysis on these data is not required. The instrumental magnitudes of standard stars in each of the userbands will not be solved.

**Fulfilling or fulfilled by:**

Selfstanding, but uses data of **req.**562 at the middle of the night.

**When performed/frequency:**

Once in the middle of each night.

**Sources, observations, instrument configurations:**

All observations done with **Mode– Stare** N=1. **OmegaCAM** equatorial fields; always one exposure in composite key filter and additional exposures in User bands.

**Inputs:**

Reference magnitudes and transformations:

**CalFile– 569** *Secondary Standard Catalog*

**CalFile– 565** *User -> key*
**CalFile– 564E** *Standard extinction curve*
Each night:
**CalFile– 562** *Extinction night report*

**Outputs:**
**CalFile– 564** *Zeropoint - extinction - Userbands* (always)

**Required accuracy, constraints:**
2% on the photometric scale for broad bands and 5% for narrow band filters.

**Estimated time needed:**
2-3 minutes per User band
Reduction: 10 min./CCD.

**Priority:**
essential

**TSF:**
**Mode– Stare** N=1
(**TSF– OCM_img_obs_stare,** N=1, filter=userband)
= **TSF– OCM_img_obs_zpuser**

**Recipe:**
**Recipe– PhotCal_Extract_Zeropoint**

**Needed functionality:**
catalog - source extraction; catalog - associate; catalog - astrometric solution

**CA:**
See **req.**563 for CA.

### 5.6.5 Req. — *Filter band passes - user bands vs key bands*

**Objective:**

Characterize the transformation coefficients, including the colour term for the **OmegaCAM** user passbands to the **OmegaCAM** key passband.
The standard keybands are calibrated in **req.**563 with the two lens corrector; the characterization of the ADC at the keybands and its transformation to the standard configuration is part of the present requirement.

**Fulfilling or fulfilled by:**

Selfstanding.

**When performed/frequency:**

Once commissioning

**Sources, observations, instrument configurations:**

**OmegaCAM** equatorial fields; **Mode– Stare** N=1; ADC for key passbands.

**Inputs:**

Reference magnitudes and transformations:
**CalFile– 569** *Secondary Standard Catalog* **CalFile– 564E** *Standard extinction curve*

each night:
**CalFile– 562** *Extinction night report*

**Outputs:**

**CalFile– 565** *User -> key*

**Required accuracy, constraints:**

10% on the photometric scale (formal spec) and 2% (goal) for broad band filters

**Estimated time needed:**

20 min/night

**Priority:**

very important

### 5.6.6 Req. — *Dependency on angle - ADC, rotator/ reproducibility*

**Objective:**

Verify the dependency of the photometric calibration on the angle of the field rotator.
Measure dome flatfield at 12 field rotator angles.
Measure the polar field with 12 field rotator angles.
This also verifies the reproducibility and provides an end-to-end test.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Commissioning

**Sources, observations, instrument configurations:**

Flat field on dome with the 4 key passbands.

**Outputs:**

Flat fields - internal

**Required accuracy, constraints:**

1% on the photometric scale

**Estimated time needed:**

Dome: day time, one day
polar field 2 hours.

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=12
**TSF– OCM_img_cal_domeflat**
**and**
**Mode– Stare** N=12
**TSF– OCM_img_obs_stare**

**CA:**

Standard image pipeline with source extraction of polar field. Compare the source flux for the various rotator angles in an interactive analysis.

### 5.6.7 Req. — *Linearity (as a function of flux)*

**Objective:**

Verify the linearity (ratio of input over output) of the overall detector amplification-data reduction chain for the three different observing modes as an end-to-end test.

Compare the resultant magnitudes derived by the image pipeline by taking short and long exposures of the same standard field.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

Commissioning

**Sources, observations, instrument configurations:**

Equatorial field in all the four key passbands; short 10 sec, 100 sec, 400 sec and 800 sec exposure. Two lens corrector.

**Outputs:**

OK flag

**Required accuracy, constraints:**

Better than 1% on the photometric scale

**Estimated time needed:**

Commissioning 6 hour

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=2
**TSF– OCM_img_obs_stare**
and
**Mode– jitter** N=5
**TSF– OCM_img_obs_jitter**
and
**Mode– dither** N=5
**TSF– OCM_img_obs_dither**

**CA:**

Run standard image pipeline and do source extraction on the calibrated image. Compare magnitudes of source lists for different exposure times in an interactive analysis.

### 5.6.8 Req. — *Detection limit and ETC calibrations*

**Objective:**

Verify the effective detection limit/ overall througput of VST + camera and subsequently the parameter values used for the Exposure Time Calculator.

**Fulfilling or fulfilled by:**

Data analysis of **req. 563** *Zeropoint*, **req. 567** *Linearity end-to-end-test*

**When performed/frequency:**

Commissioning

**Outputs:**

Values for ETC

**Required accuracy, constraints:**

10 % in detection limit

**Priority:**

essential

**CA:**

Interactive analysis

### 5.6.9 Req. — *Secondary Standards*

**Objective:**

Build catalogs of secondary photometric standards, by observing Landaolt fields, centered on each individual CCD.

A fundamental concept in the calibration of **OmegaCAM** data is separate photometric calibration for each CCD. To obtain this calibration with a single observation this requires photometric standards covering the entire FOV of the instrument. There are currently no catalogs of photometric standard stars satisfying this requirement. Hence, obtaining such catalogs of **secondary standards** for the equatorial fields and the polar field will be part of the calibration observations to be performed during operations.

Obtaining the necessary observations of secondary standards is a time-consuming operation (see below). Moreover, because these observations should cover all 8 equatorial fields (ref **seq.– 563),**approximately two (bright) nights each month will have to be reserved for these observations, at least in the first year of operations.

The set of observations of secondary standards will also be used to determine the illumination correction (**req.**548). Note, that this constitutes a bootstrap problem, because determining accurate zeropoints of the secondary standards requires that the illumination correction is already known.

Because of this bootstrap problem, a straightforward determination of the zeropoint requires that for each CCD the zeropoint and illumination correction are determined simultaneously using primary standards. Therefore, obtaining measurements of secondary standards requires a sequence of observations that positions the primary standards in each CCD, i.e. 32 pointings per field, per filter. Techniques for reducing this observational burden are under investigation.

The order of priority of determining standards is first the **key bands** followed by the composite filter.

**Fulfilling or fulfilled by:**

Selfstanding.

Initial determination of the illumination correction is used to verify presence/absence of this effect (see **req.**548).

**When performed/frequency:**

Commissioning, 2 nights of bright time, each month in the first year.

**Sources, observations, instrument configurations:**

**Strategy– freq Mode– Stare** N=32 **OmegaCAM** equatorial fields and polar field.

**Inputs:**

**CalFile– 569E** *Primary Standard stars*

**Outputs:**

**CalFile– 569** *Secondary Standard Catalog*

**Required accuracy, constraints:**

0.02 mag in individual secondary standards stars.

**Estimated time needed:**

Observation: 1.5 hours, for one field (32 pointings). Reduction: 2 hours per CCD

**Priority:**

essential

**TSF:**

**Strategy– mosaic**
**Mode– Stare** N=32
**TSF– OCM_img_obs_stare**

**Recipe:**

**Recipe– Secondary_Standards**

**Needed functionality:**

In addition to standard processing functionality catalog - select stars; catalog - associate; catalog - merge

**CA:**

Reduce each CCD separately, using the zeropoint and illumination correction of the observation containing the primary standards to do the photometric calibration. Extract a catalog of photometrically calibrated stars with photometric errors $< 0.03$ mag for each CCD. This will result in 32 catalogs per CCD of candidate secondary standard stars, for a total of 1024 catalogs. Candidate secondary stars in the central square degree of these observations

will have been observed at least 8 times (with different CCDs), while those at the corners of the 2 by 2 degree area that has been covered, have been observed only once. Select the candidate secondary standards with at least 7 different observations, and average these to obtain a catalog of secondary standards with 0.02 mag accuracy per standard over approximately 1.2 square degree area.

## 5.7 Internal alignments, optics etc

### 5.7.1 Req. — *Camera focus/tilt*

**Objective:**

Determine and verify the camera focus.

The tilt of the detector plane with respect to the focal plane and its dependency on the orientation of the telescope shall be determined both from:

**CalFile– 554** *PSF anisotropy*
and from the matrix of PSF;s provided by the present requirement.

Verify once for each filter that they have the same optical thickness (15mm physical thickness). Do this by measuring the "filter focus offset".

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

CP, also filter thickness only once during comissioning

**Outputs:**

focus offset values to be transferred to INS data base

Conformance flag for optical thickness of all filters.
Conformance flag for tilt

**Estimated time needed:**

Observation: - Focus offset and tilt: 2 hours during CP - Verification filter focus offset 30 min/filter (Commissioning) Reduction: 1 min/CCD.

**Priority:**
essential

**TSF:**
**TSF– OCM_img_tec_focusseq**

**Recipe:**
**Recipe– Focus**Standard Paranal focus MIDAS procedure

**CA:**
This is an on-line activity which is performed using a RTD/MIDAS procedure. Resulting plots are used to determine and verify the camera focus.
Additional data reduction for tilt TBD; Make matrix of PSFs. For each star determine at which M2 setting image is the sharpest; produce a 2 dim-image map of M2 settings with optimal focus.

### 5.7.2 Req. — *Ghosts - ADC*

**Objective:**

Verify the absence/presence of ghosts.

For each available filter inspect the presence of ghosts by making several exposures near a very bright star at various angular distances from the field center. Do this for both correctors.

The inspection will be done in first instance visually on the RTD.

Off-line the images will be fed to the standard pipeline for closer inspections.

**Fulfilling or fulfilled by:**

Selfstanding

**When performed/frequency:**

CP

**Sources, observations, instrument configurations:**

Very bright star at several angular distances from the field center (0.7, 1, 2, 3 degree, to be determined by experience). All available filters, or when a new filter is installed.

To be done for both correctors, to be determined by experience.

**Required accuracy, constraints:**

**Estimated time needed:**

1 hour/filter

**Priority:**

desirable

**TSF:**

**Mode– Stare** N=1

**TSF– OCM_img_obs_stare**

**CA:**

Standard image pipeline, visual inspection of images

## 5.8 Effect of Telescope

The various effects of the telescope on the quality of the images produced by the camera have been addressed by the following **req.**'s:

**req. 524** *Electromagnetic compatibility*
**req. 551** *Position of camera in focal plane*
**req. 552** *Telescope pointing*
**req. 553** *Telescope and rotator tracking*
**req. 554** *PSF anisotropy*
**req. 566** *Dependency on rotation angle - field rotator, ADC*
**req. 572** *Ghosts*

This list appears rather complete and no additional requirements are specified.

## 5.9 Workhorses and End to end tests

### WORKHORSES

The following 'work horses' or 'doit' requirements are specified:

**req. 521** *CCD read noise - doit*
**req. 531** *CCD Dark Current - doit*
**req. 541** *Bias - doit*
**req. 547** *Quick detector responsivity check - doit*
**req. 555** *The astrometric solution for templates - doit*
**req. 563** *Photometric Calibration - zeropoint keybands - doit*

The following **end-to-end tests** (i.e. observational data which employ many different aspects of the system and which can be used to trace reproducibility) have been specified:

**req. 566** *Dependency on rotation angle - ADC, rotator/ reproducibility*
**req. 567** *Linearity (as a function of flux)*
**req. 562** *Photometric calibration - Monitoring/ Health check*

## 5.10 On site quick look analysis

Requirements for the Real Time Display, essentially requirements on how to perform visual health checks on the acquired data, are given in the Instrument S/W User requirement document.

Here **req.**'s are listed which require analysis on the site.

The first list gives the requirements for which on-site analysis is essential (listed in order of priority).

**req. 562** **Photometric calibration- Monitoring*
**req. 547** **Quick detector responsivity check - doit*
**req. 521** **CCD read noise - doit*
**req. 531** **CCD Dark Current - doit*

The second list gives the requirements for which on-site analysis is desirable/most practical (listed in order of priority). On-site, these activities will output go/no-go flags.

**req. 571** *Camera focus/tilt*
**req. 552** *Telescope pointing*
**req. 553** *Telescope and rotator tracking*
**req. 566** *Dependency on rotation angle - field rotator, ADC*
**req. 524** *Electromagnetic compatibility*
**req. 551** **Position of camera in focal plane*
**req. 554** **PSF anisotropy*
**req. 572** *Ghosts*

In the lists above the **req.**'s which produce a **CalFile**– are marked with a *. These **req.**'s have also to be processed off-line at ESO HQ (e.g. DFS pipeline, DFS operations, calibration pipeline, QC1, Quality control, trendanalysis).

DFS-pipeline modules, extracted from the off-line ESO HQ version, (including thosee used for calibration pipeline and QC1) could fulfill these task on-site

with relative limited extra effort. Such modules will run with a stripped Calfile-date base As a desirable side effect, this creates the possibility to also quickly verify any other **req.**'s with extracted DFS-pipeline modules in the case of un-expected events.

The filling of the calibration database (**CalFile– )**should however be exclusively handled by the off-line pipeline at HQ.

**Fig 6. Data Flow of Science and Calibration data**

# 6 DATA REDUCTION SOFTWARE SPECIFICS

## 6.1 Data reduction software requirements

This section is printed both in the User requirement document (URD) and the data reduction specification document (DRS). It is meant to summarize the general framework, requirements and limitations of the **OmegaCAM** data reduction.

The MoU refers to the **OmegaCAM** pipeline:

- .... a pipeline, the operation of which can be driven entirely by the information available in the raw file headers
- the pipeline shall be able to combine without operator intervention all exposures obtained of one field through one filter and during one night
- on the computer platform provided by the consortium, the pipeline shall be able to fully reduce an average day worth of science and calibration exposures within 12 hours elapsed time. Operator preparation of the execution shall not exceed half an hour
- The data products of the pipeline shall be images with the above astrometric and photometric calibrations.

Following VLT-SPE-ESO-19000-1618, the following deliveries shall be prepared by the Consortium:

- Descriptions and implementations of **calibration req.'s** needed for the support of the instrument modes described in Section 4 .
  The baseline requirements for these calibration procedures are specified in Section 5 of the URD while details of the implementations are given in Section 5 of the Calibration Plan. The consortium will specify the **req.**'s and the implementations, and will deliver **modules** and **recipes**. Integration will be done under ESO responsibility. Detailed specifications of the implementations are given in the Data Reduction Specification document (DRS).

- **Support for a Quality Control System** The consortium will provide the necessary routines/procedures, as components of the DFS pipeline infrastructure, but not for QC0 which is generic for all VLT compliant instruments and which will be provided by ESO. The integration of the quality control routines will be done under ESO responsibility. The execution of quality control will be done on at least two 'platforms' within the context of the DFS. Currently, the DFS infrastructure does not support the storage of QC parameters, neither its trend analysis. It is highly desirable to improve upon this situation.

The **Quality Control** will involve the following:

- **QC0** on-site, on-line consistency check
  The primary function of the QC0 quality check is to confirm that a given exposure is consistent with the definition of the Observing Block (Observing Description, Target Package, Constraint Set), of which the exposure is a part. To this end relevant keywords from the FITS header are compared to relevant parameters of the OD, TP, and CS. In addition, the size of the FITS file is checked, to verify that the data transfer was completed succesfully. Passage of QC0 is assumed to be a necessary and sufficient precondition for input into the calibration or image pipeline. Implementation will require a full specification of the possible ODs, TPs, and CSs.
- **QC1** off-line Quality Control provides a full assessment of the quality of the raw data and the derived data products.
  QC1 includes both the measurement of Qualitity Control Parameters (including image statistics, seeing, and errors on astrometry and photometry) and the subsequent assessment of these parameters to arrive at an overall statement of the quality of the data. It is useful to distinguish between QC1 measurements at different processing stages:

- **pre-calib** off-line quality check of incoming raw calibration data.

- **pre-image** off-line quality check of incoming raw science data.
  The data coming from the telescope should be checked for consistency

with expected values. These checks include: i) check that global illumination (median) is within a range expected for that observation (**seq.– 631** ), and ii) check that image quality (PSF) is consistent with seeing (to detect tracking problems, for instance, **seq.– 633**)

- **post-calib** off-line quality check of **CalFile–** .
  The **CalFile–** produced by the calibration pipeline should be checked for validity as specified in the **req.**s before being put into the Calibration data base, thus securing that only valid **CalFile– s**are used by the image pipeline. **Trend analysis** will be the main tool for monitoring the validity of **CalFile– s.**Trend analysis is run outside the pipeline. It is used as a tool to monitor the behaviour of the instrument. The results of trend analyis are not used to interpolate entries in the db to be fed back to the pipeline.

- **post-image** off-line quality check of reduced science data.
  The final characterization of the quality of the reduced science data includes the following items.
  - Validity of the processing operations.
  - Quality of the processed data (sensitivity and resolution)
  - Photometric check (consistency between different CCDs)

  By comparing the quality of the processed data, with the quality of the input data, the validity of the processing steps can be assessed. By comparing the quality of the processed data with the expectations as determined by the ETC and seeing-statistics, overall performance of the instrument and ambient observing conditions can be determined.
  *Example:* a powerful check on the astrometry, seeing, image quality, tracking rotator, tracking alt-az, co-addition is given in **seq.– 636** which for **Mode– dither** N=and **Mode– jitter** N=compares the PSF over the FOV between the input and output images.

A different projection of the various planned quality control tasks is:

- **Operational checks** verify on a low level whether, people, machines and computer recipes are operating according to expectations (e.g. not

down). These items relate to the execution of implementations and will be specified in ESO's operations plans, but not in the URD or the Calibration Plan.

- **Functional and maintenance checks** on mechanical and electronic components on the engineering level, which generally have the character of a go/no-go result. These checks are given in the maintenance manual.
- **Instrument S/W** self-supporting checks. The instrument S/W performs various self-checks. Malfunctions are displayed on the Instrument workstation.
- **Routine** (day-week-month-year) calibration procedures, as listed in detail as **req.**'s in Section 5. These will be handled by the calibration recipes. E.g. for daily checks the URD specifies **req. 533** *Quick detector responsivity check.*

- **Automatic Pipeline Processing**

The **OmegaCAM pipeline** is the collection of modules and recipes integrated in ESO's DFS pipeline infrastructure environment.

The pipeline produces data corrected for the instrument signature.

It is useful to distinguish between the **calibration pipeline** and the **image pipeline**.

I **The calibration pipeline** produces calfiles (**CalFile–** ), as outlined in Section 5. The calibration pipeline operation schedule is driven by the specifications given in each requirement about the frequency at which the characterizations have to be executed at the telescope. Assuming a smooth dataflow from telescope to ESO HQ the processing of these calibration data will follow the telscope schedule. **CalFile–** s are valid for a certain period as specified by the requirements and they are **timestamped** by the validation and implementation procedures. It is at the moment not clear whether the current DFS infrastructure can run the calibration pipeline in an automatic mode, or whether it should be run "by hand"

II **The image pipeline** *applies* the calfiles to raw science data, to produce astrometrically and photometrically calibrated science data. The image pipeline is designed to operate as much as possible as a single process (in spite of its many sub-processes, as a *black box*, with a minimum of storage of intermediate results in order to constrain the **OmegaCAM** data storage requirements within acceptable volumes, and to further facilitate parallel processing on external platforms with a minimum of interdependence). The sequential steps of the image pipeline are specified in Section 6.3 and are named **seq.–** and involve:

- Image arithmetic (de-bias, flat field)
- Cosmic ray and bad pixels correction
- Image statistics
- Astrometric solutions
- Image combination (co-addition)
- Flux calibration

The integration of the pipeline will be done under ESO responsibility.

Part of the Data Reduction Software is a set of instrument sample data and calibration data to be processed as representative cases. Results of the processing of such data in a test environment will also be delivered.

**Coding standards:**

The software developments shall be made in ANSI C, according to programming conventions, data structures, and low-level functionalities provided by ESO. A list will be established further (low-level) ESO-provided functionalities.

The complete description of a **recipe** includes:

```
1. Definition
2. General description
   2.1 Context of utilisation
   2.2 Observing procedure
   2.3 Calibration data
   2.4 Resulting data format
   2.5 Expected pre-processing, post-processing
   2.6 Pipeline calibration

3. Mathematical description
   3.1 Mathematical justification
   3.2 Error propagation/evaluation
   3.3 Articles publication

4. Pseudo-code
5. Validation
```

Of course, this only applies for "complex" recipes, there is no need to produce a so detailed algorithmic description for trivial tasks.

As examples of high-level algorithm description, the calibration and operation plans for already existing VLT instruments are a good reference. The instrument scientist tried in each case to describe the process to apply to both calibration and observation data, to produce acceptable and useful pipeline products.

The **recipe** description above matches well to the more formal **Odoco** format employed here for the subsequent documentation of both the basic requirements, the implementation and data analysis of **req.**'s. The present set of all **Odoco** items reads:

**Title**
**Objective** oneliner + description
**Fulfilling or fulfilled by** when selfstanding there is a TSF
**When performed/frequency**
**Sources, observations, instrument configurations**
**Inputs** dependencies **CalFile– ,**pre-processing
**Outputs CalFile– ,**post-processing
**Required accuracy, constraints**
**Estimated time needed** both for observing and data reduction
**Priority** desirable, very important, essential
**TSF** - name
**Recipe** - name
**CA** description of calibration analysis (also mathematical, error propagation)
**Needed Functionalities**
**CAP** implementation of calibration analysis (or pseudo code)
**Status of Req.** management tool
**FLAG** management tool

A good example of algorithmic documentation is given in the document: "Infrared jitter imaging data reduction algorithms"
http://www.eso.org/projects/dfs/papers/jitter99/

The coding standards and recommendations followed by ESO and external consortia is a set of rules issued by the C programming community. It can be found on the Web from:

Recommended C Style and Coding Standards
http://www.apocalypse.org/pub/u/paul/docs/cstyle/cstyle.htm

The pipeline software shall be exportable to **POSIX**-compliant systems. In the case of **OmegaCAM**, because the target platform is based on **Linux** (Beowulf clusters), this requirement could be narrowed down to: the software shall be running on **Linux** workstations. However, making **POSIX**-compliant software in

general and not attaching the software to any system's specifics is a good idea to preserve portability in the future.

On-line documentation for this software shall be in HTML format.

Additional documents:

[2] Recommended C Style and Coding Standards see URL above.

[3] "ISAAC calibration plan" by PA Duc and JG Cuby VLT-PLA-ESO-14100-1384

[4] "Infrared jitter imaging data reduction algorithms" see URL above.

The standard software needed to execute the pipeline consists of the following packages:

- FITS data reduction–**eclipse, LDACtools, cfitsio**.
- Source extraction–**Sextractor**.
- Astrometry–**LDACtools**.
- Co-addition–**SWARP**.

The consortium will support and maintain the **LDACtools**. **eclipse** is a package maintained by ESO. All other packages are in common use. These packages provide for all computationally expensive operations to be performed on the data. All these packages are written in C.

To integrate this set of sophisticated data reduction and analysis tools, the consortium currently uses the **Python** scripting language. This language provides a high level easy-to-maintain glue. All recipes and procedures are written using this language as a layer on top of the aforementioned packages, providing transparent, common interfaces to these diverse packages. Prototypes of the recipes will be delivered to ESO using Python. It is recognized that final delivery may require recoding these in C.

The consortium prepares for a scripting of the pipeline modules offering all required functionalities with a generic database interface. To this interface functional programming (files) or object oriented (objects) databases could be attached. These modules can be integrated by ESO in its DFS environment, without using these interfaces.

Internally, the Consortium uses **CVS** for its versioning control of code, recipe's, dictionaries and documentation and it considers to use **Objectivity** for storing and distributing all calibration and source-list data.
An Interface document specifying all data items to be forwarded by ESO to the Consortium is planned for (FDR).

## 6.2 Estimate of data volumes

The planned observing strategies, particularly the widely used dithering and jittering techniques have a large impact on the eventual datavolume of both raw and processed data. As first estimates of the amount of science data and calibration data indicate data volumes and data rates at the edge of the storing and processing capabilities, these items might force some high level constraints on the data handling.

**Example image data volumes:**
**OmegaCAM** contains 256 Megapixels which are read-out with 16 bit integers. Thus one read-out produces 0.5 Gbyte of raw data. A standard dither will do 5 read-outs at various positions on the target, with integration times of 4-6 min each, leading to a total of 20-30 min of integration on the target. In these 20-30 minutes 2.5 Gbyte of raw data is acquired. In a 10 hour night this corresponds to 50 - 75 Gbyte of raw data. For 300 nights a year this is 15 - 22.5 Tb of raw data.

The flatfielding and de-biasing of the raw data require (32bit) floating point output images and when applied bluntly would double (in fact triple) the total data volume to 45 - 67 Tb a year. However, de-dithering will produce one floating point output image out of 5 input images and thus leads to a data-reduction by a factor of five. In this case, the overall reduction of the data volume will be a factor (5/2)=2.5 and the total data volume of de-dithered, flatfielded, debiased images will be 6-9 Tb.

Clearly, it is desirable to process the de-biasing, flatfielding and de-dithering in one go without the archiving of intermediate steps. Alternatively, one might consider to do this process on the fly, in which case the total data volume stays as the original raw data of 15 -22.5Tb a year.

**SCIENCE IMAGE DATA VOLUME 5 DITHERS in 20 - 30 min**

| | raw data | flat fielded | co-added | raw+ co-add |
|---|---|---|---|---|
| NIGHT | 50 - 75 Gb | 100 -150 Gb | 20 -30 Gb | 70 - 105 Gb |
| 300 NIGHTS | 15 - 23 Tb | 30 - 45 Tb | 6 - 9 Tb | 21 - 31 Tb |

+ CALIBRATION RAW IMAGE DATA - see A2 - current estimate 8Tb

# ASTRONOMICAL SOURCE LIST DATA VOLUME

## NOMINAL USING CO-ADDED FRAMES

25 sources per square arcmin $\rightarrow$ $10^5$ sources/degree$^2$
(CFHT reckons 2 $10^5$ for 4m telesc. $4^2/2.5^2 = 2.5$ )

20 - 30 parameters per source $\rightarrow$ $2-3\ 10^6$ real*4/degree$^2$ = 8 - 12 Mbyte /field

10 hour night (20 -30 CO-ADDED fields) $\rightarrow$ 160 - 360 Mbyte

330 night/year $\rightarrow$ 53 - 120 Gbyte
(when not using co-added frames factor 5 more $\rightarrow$ 0.5 Tb)

## ABSOLUTE MAXIMUM

- Crowded fields
- 0.5 arcsec seeing
- reliable source decomposition on 2.5 arcsec scale

576 sources per square arcmin
23 times more than the nominal example $\rightarrow$ 184 - 276 Mbyte /field
10h night (20 -30 CO-ADDED fields) $\rightarrow$ 3.7 - 8.3 Gbyte/night
(when not using co-added frames factor 5 more)

So, a run of 10 nights on crowded field can result in 10 x 8.3 x 5 = 0.4 Tb of source data on non co-added frames

few observing runs end up in Tb regime

## 6.3 Baseline Requirements for the Image Pipeline

As noted previously, it is useful to distinguish between the **calibration pipeline** and the **image pipeline**. Here we provide more detail on the operation of the image pipeline

The image pipeline applies calfiles to raw science data, to produce astrometrically and photometrically calibrated science data. The DFS pipeline applies different *recipes* to raw science data, based on the observing template used. There are currently three observing templates for science data envisioned for **OmegaCAM**. These templates (see also Section 4 CP), and their corresponding recipes are:

- **TSF– OCM_img_obs_stare**, **Recipe– Science_Stare(N=1)**, or **Recipe– Science_Jitter(N>1)**
- **TSF– OCM_img_obs_jitter**, **Recipe– Science_Jitter**
- **TSF– OCM_img_obs_dither**, **Recipe– Science_Dither**

The recipes (Science_Stare, Science_Jitter, Science_Dither) combine a series of processing steps that are specified by their (intermediate) data product in **seq.– 631**-**seq.– 636.**These can be summarized by:

- **Initialization and image statistics** Create a new entry in the database of derived products for each raw image. Include image statistics in the entry (**seq.– 631**).
- **de-biasing and flatfielding** This step removes the gain-variation within images (**seq.– 632**).
- **Constructing weights**, incorporating the detection of cosmic rays, and satellite tracks (**seq.– 633**).
- **Astrometry**, measuring the astrometric distortions and offsets (**seq.– 634**).
- **Apply photometry** (**seq.– 635**)
- **Dedithering**, combining the images to construct a clean, maximally uniform, image of the FOV of **OmegaCAM** and perform a quality check (**seq.– 636**) .

The detailed specification of each seq is analogous to the specification of the req's in Section 5. It should however be understood that within the context of

the DFS pipeline, the recipes for the individual seq's are to be combined into one recipe for each Observing template (so-called superscripts). An overview of the data flow within a recipe is given in Fig. 6.3.

## Image pipeline dataflow

figure 6.3.

The recipe Science_Stare differs from the recipes Science_Jitter and Science_Dither in that the co-addition step (**seq.– 636)**is not included. Furthermore, Science_Dither produces one co-added image combining data from all chips, while Science_Jitter produces one co-added image per chip.

Operations **seq.– 632**-**seq.– 635** are performed on individual chips. The format of the raw data will be one FITS file per observation including the data for 32 chips in 32 extensions. **seq.– 631** separates these raw data in FITS files for individual chips. Only in **seq.– 636** the data from individual chips are combined.

Note that **seq.– 631**-**seq.– 636** can also be used within various recipes for the calibration pipeline.

Clearly, the image pipeline will determine parameter values which are *specific* for individual raw data frames or their 32 CCD frames, and these could be viewed as transient calibration data. Most of this transient calibration data is uninteresting or could be easily re-constructed, while other data have persistent scientific value (such as seeing, PSF, astrometric solution, zeropoint, sky-brightness, etc.), while other data have potential, but unspecified, value for trend analysis or trouble-shooting. Output files of the image pipeline (flat-fielded data, astronomically calibrated data, individual weight maps, etc.) are called **SeqFile–** 's, e.g. **SeqFile– 633** *individual weight map*. The image data recorded in a **SeqFile–** may be discarded when the data is no longer needed. Care has been taken to propagate intermediate information from the headers of the **SeqFile–** 's to header of the pipeline product, whenever appropriate. The ESO-DMD - **OmegaCAM** Interface control document discusses in more detail the requirements for maintaining this intermediate informaation.

Both the image pipeline and the calibration pipeline shall obey the accuracies and errors as listed in Section 5. Propagation of errors shall be computed, where applicable.

### 6.3.1 Seq. — *Ingestion and image statistics*

**Objective:**

Prepare the data for pipeline processing and provide image statistics and qualifications.

The image pipeline processing is based on the processing of individual chips.

Presently, image data arrive from the telescope in the form of FITS files with the data for each chip stored into a single FITS extension. For the purpose of efficient parallel processing this **seq.–** splits the FITS files (and their extensions) into individual FITS files for individual chips. In the future this functionality may be provided generically by the pipeline environment
It is assumed that incoming raw data are valid FITS files. Further qualification of the raw data by means of image statistics and a preliminary measurement of the seeing (TBC), should determine whether the data can be meaningfully processed by the pipeline.
If the image pipeline uses a local database then the first step in pipeline processing is the ingestion of the raw data into the database. Upon ingestion the image headers are translated into database descriptors. In addition, the Quality Control Parameters (image statistics and seeing) are added to the image descriptor in the database.

**Inputs:**

Raw science frames.

**Outputs:**

**SeqFile– 631** *Raw science frame* image statistics (mean, rms, min, max, median) added to descriptor

**Estimated time needed:**

TBD

**Needed functionality:**

image - statistics

**CAP:**

```
input image

stats = image.Statistics()
image.addHeader('STATMEAN',stats.mean)
image.addHeader('STATMED',stats.median)
image.addHeader('STATRMS',stats.rms)
```

```
image.Ingest()
```

### 6.3.2 Seq. — *Trim, de-bias, flatfield*

**Objective:**

Trim, de-bias, and flatfield the raw data.

The second step in the image pipeline removes the bias offset and the pixel-to-pixel variation in the gain. This step includes the following operations: i) Extract the trim part of the science image and do the overscan correction. ii) Subtract the master bias image, and iii) divide by the master flatfield.

**Inputs:**

**SeqFile– 631** *Raw science frame*
**CalFile– 541** *Bias*
**CalFile– 546** *Master Flatfield*

**Outputs:**

**SeqFile– 632** *Reduced science frame*
Updated image statistics

**Estimated time needed:**

Approximately 30 seconds/CCD

**Needed functionality:**

image - trim; image - statistics

**CAP:**

```
input image, bias, flat

image = image.OverscanCorrection()
image = image.Trim()
image = (image-bias)/flat
image_stats = image.stat()

output image
```

### 6.3.3 Seq. — *Construct weigths, determine seeing*

**Objective:**

Construct individual weight maps.

In addition to the effects of hot and cold pixels, individual images are contaminated by cosmic ray events, and may be affected by satellite tracks. For purposes of subsequent analysis and image combination, pixels affected by these effects need to be assigned a weight of zero in weight maps that are unique to each image.

Cosmic-ray events can be detected using special source detection filters (retina filters), with sextractor. These are essentialy neural networks, trained to recognize cosmic rays, taking a set of neighbouring pixels as input. Satellite tracks can be discovered by searching a source catalog for multiple extended sources that lie along a straight line (using, for example, the Hough transform)

**Inputs:**

**SeqFile– 632** *Reduced science frame*
**CalFile– 546W** *Master weight image*

**Outputs:**

**SeqFile– 633** *Individual weight image* (CR events and satellite tracks removed)

**Estimated time needed:**

Approximately 3 min/CCD

**Needed functionality:**

image - cosmic ray detection; image - mask; image - satellite detection; image - arithmetic; image - statistics

**CAP:**

```
input image, master_weight

cr_cat, cr_map = image.sextractor(weight=master_weight,
    filter=cosmic_retina
                                    check_image=SEGMENTATION)
```

```
cr_mask = cr_map.Threshold(min=1, max=1e10)
weight = master_weight*(1-cr_mask)

sat_cat = image.sextractor(weight=weight)
sat_mask = sat_cat.FindSatelliteTracks()

sattelite_mask = catalog.FindSatelliteTracks()

weight = master_weight*(1-satellite_mask)

output weight
```

### 6.3.4 Seq. — *Astrometric calibration*

**Objective:**

Determine the astrometric solution for the science image. Also determine the seeing.

Produce a catalog of the science image. Use the catalog to determine the astrometric solution and the seeing, and record the solution in the header of the image.

Next to the basic scientific requirement of an accuracy of the absolute astrometry better than 0.1 arsec rms, an upper limit on the astrometric uncertainties is determined by the requirement that astrometric inaccuracies do not degrade the seeing of the dedithered image (**seq.– 636).**

The full astrometric process solves simultaneously the focal plane assembly parameters and the telescope light-path parameters. A series of these solutions should result in a definition of the telescopes current focal plane structure, which in normal circumstances should be constant, and a definition of the light path deformation, which in normal circumstances can be variable. The empirical determination of the full telescope plate deformation can be used as a-priori knowledge in the pairing phase for another determination.

The default astrometric solution is obtained on a 'per chip' basis. Alternatively, one can choose to use the overlap that results from a repeated observation of the same area of sky in a jittered or dithered observation to improve on this solution. Improved accuracy is obtained if one uses the overlap information for a single chip. Maximum accuracy is obtained if one also uses the overlap between different chips in dithered observations. The latter method breaks the inherent paralellism of processing individual chips.

The large CCD's are created by stitching smaller masks together. Between the stitches errors in the position of pixels with respect to a truely regular grid may occur. The method described above may be applied to individual stitches for each CCD, therefore increasing the number of free parameters of the solution. The small stitches are generally too small to yield enough pairs for high resolution solutions, but an ensemble of observations would. Determination of the stitching topology is a do-once operation.

The astrometrically calibrated image is used when building the dedithered

image (**seq.– 636)**

**Inputs:**

**SeqFile– 632** *Reduced science frame*
**SeqFile– 633** *Individual weight image*
**CalFile– in1** *US-NAVAL Observatory A2.0*

**Outputs:**

**SeqFile– 634** *Astrometrically calibrated science image* with astrometry solution inserted into the descriptors
Astrometric quality parameters
Seeing **SeqFile– 634C** *Astrometrically calibrated catalog* - not further used
**SeqFile– 634R** *Astrometric residual map* - not further used

**Estimated time needed:**

Approximately 1 min/CCD

**Needed functionality:**

catalog - source extraction; catalog - association; catalog - astrometric solution; catalog - seeing; image - background subtraction

**CA:**

First **sextractor** is used to obtain an image catalog. The catalog is used to obtain an astrometric solution. The solution is added to the header of the background subtracted image.
Optionally the catalog can be combined with catalogs of subsequent observations of the same area with the same chip and observations of the same area with other chips.
The catalog can also be used to characterize the seeing.
Note that the sextractor run can be combined with the sextractor run of **seq.– 633.**

**CAP:**

```
input image, weight, seeing, reference_catalog

backsub_ima, catalog = image.sextractor(weight=weight,
                                        check_ima=-BACKGROUND)
```

```
ast_catalog = catalog.doAstrometry(ref=reference_catalog)
ast_image = backsub_ima.ApplyAstrom(ast_catalog)
seeing = ast_catalog.DetermineSeeing()
image_stats = backsub_ima.stats()

output ast_image, ast_catalog, image_stats
```

### 6.3.5 Seq. — *Apply photometric calibration*

**Objective:**

Apply photometric calibration.

Given the photometric solution (zeropoint and extinction), and given the airmass and exposure time of the observation, the appropriate zeropoint and zeropoint error are written to the image descriptor.

Zeropoint and extinction are determined differently for Key (u',B, V, i') and User (all other filters) bands. See **req.**561-**req.**564 for details.

**Inputs:**

**SeqFile– 634** *Astrometrically calibrated science image*
**CalFile– 563** *Zeropoint and extinction - keybands*, or
**CalFile– 564** *Zeropoint and extinction - userbands*

**Outputs:**

**SeqFile– 634** *Astrometrically calibrated science image* zeropoint added

**Estimated time needed:**

negligable

**CA:**

The image zeropoint and zeropoint error are expressed as the magnitude of one count, and added to the image header and descriptor.

**CAP:**

```
input image, zeropoint, extinction

ZP = zeropoint-image.airmass*extinction+2.5*log(image.exptime)
image.writeHeader(keyword='ZERPOINT', value=ZP)
ZP_err = sqrt(zeropoint_err^2+(image.airmass*extinct_err)^2)
image.writeHeader(keyword='ZEROPERR', value=ZP_ERR)

output image
```

### 6.3.6 Seq. — *Dedithering/dejittering*

**Objective:**

Combine all images of a pointing into a dedithered image and check the quality of the processed result.

Most science applications of OmegaCAM combine data of series of dithered (jittered) observations of a single pointing. The co-addition step maximizes the signal to noise ratio per pixel in the output image, and combines the background subtracted image data, using variance weighting. Since image artifacts (hot, cold, saturated pixels, cosmic-ray events, and satellite tracks) have zero-weight, the co-added image will be much "cleaner" than the input images. A dedithered weight image records the sum of the input weights for each pixel, and is proportional to the reciprocal of the variance in the dedithered image.

By co-adding onto a simple coordinate system—characterized by the projection (Tangential, Conic-Equal-Area), reference coordinates, reference pixel, and pixel scale—the distortions recorded by the astrometric solution are removed from the images.

*NOTE: The consortium is currently investigating the possibility to define a standard grid on the Southern sky. Such a standard grid could involve a standardized set of field centers, at for instance 1 degree separation, and a standard set of pixels of for instance 0.2 arcsec size defined with respect to the fieldcenters. Other standardization/projection schemes will have to be explored. A discussion forum on this issue has been opened at the* **OmegaCAM** *web pages.*

Standardization will result into similar grids of the output images for independent observations (different epochs, different filtering etc) for the same region of sky, without any further administrational burden, facilitating direct image comparison on pixel-to-pixel level without additional interpolations.

Prior to coaddition a background subtraction step shall be performed.

Since different input images may have a different zeropoint, the dithering process applies a scaling factor to each input image as well as each weight image.

Note that the current weighting scheme is based on maximizing the signal-

to-noise ratio per pixel in the dedithered image. However, when images with different seeing are combined, adding images with bad seeing may lead to a degradation of the signal-to-noise ratio per object, even when the signal-to-noise-ratio per pixel is increased. Therefore, a seeing-based weight-adjustment is optional.

In order to record which input image contributes to each output pixel in the co-added image, a context map and table are constructed. The context table list all used combinations of input images. The context map records for each pixel an index to this table. The context image includes both the context map and context table

**Swarp** is a package specifically designed to handle these operations.

The size of the output image is adjusted automatically to completely cover the area covered by the input images. Alternatively, a maximum size of the output image may be defined, which will clip data lying outside this predefined region.

In order to validate the result of the image pipeline, **seq.– 636** should finish with a Quality Check.

A catalog of the dedithered image is obtained in order to measure the PSF variation over the FOV of **OmegaCAM**. This measurement should be compared to the PSFs of the input data (**seq.– 634**) to provide a check on the entire coaddition process. The degradation of the PSF should not exceed the expected degradation due to astrometric uncertainty.

In addition it may be necessary to compare the positions and photometry of the catalogs of the input images to catch possible systematic errors in the relative astrometry and relative photometry.

Finally, the catalog of the dedithered image can be used to check the astrometry w.r.t an external catalog, and to compare the image sensitivity to the one predicted by the ETC. These checks provide end-to-end sanity checks of the entire observation and reduction process.

**Inputs:**

The input for dedithering is an arbitrary large list of **SeqFile– 634** *Astrometrically calibrated science data* with photometry and seeing present in the descriptors, and

**SeqFile– 633** *Individual weight images*

output coordinate system (projection, reference coordinates, pixel scale) - (most likely fixed in the code itself - TBC)

**Outputs:**

**SeqFile– 636** *Dedithered image* including statistcs and seeing
**SeqFile– 636W** *Dedithered weight_image*
**SeqFile– 636C** *Context image, including context table*
**SeqFile– 636cat** *Catalog*
sensitivity description

**Estimated time needed:**

TBD

**Needed functionality:**

image - coaddition; image - statistics; catalog - source extraction; catalog - seeing; image - background subtraction

**CA:**

Call **OmegaCAM** version of **swarp** with the input data as parameters. Determine statistics of output image. Run **sextractor** on the output image. Determine the PSF variation over the FOV from the resulting catalog, and compare this to the seeing of the input images (determined in **seq. 634** *)*.

**CAP:**

```
input image_list, weight_list, reference_coordinate_system

dedithered_image, dedithered_weight, context_map =
        image_list.Swarp(weight_list=weight_list, coords=ref_coord_s
dedithered_image.stats = dedithered_image.stats()

catalog = dedithered_image.sextractor(weight=dedithered_weight)
dedithered_image.seeing = catalog.DetermineSeeing()
#TBD compare seeing

output dedithered_image, dedithered_weight, context_map
```

# 7 NEEDED FUNCTIONALITIES

Sections 5 and 6 include for each Data product a list of functionalities required for the reduction algorithms. In this section we give an overview of these functionalities.

## 7.1 Image manipulation

Image manipulation is required throughout the data reduction pipeline. Most of the image manipulation algorithms are provided by **eclipse**.

**image arithmetic**

Standard arithmetic operations on images include addition, subtraction, division and multiplication with two images as operands and an image and a scalar as operand.

This functionality is provided by **eclipse**.

**image statistics**

The standard statistics routine provides the mean, standard deviation, minimum and maximum of an image. It is also possible to obtain the median. However, since this is a relatively expensive operation, medians should in general not be computed when the image statistics are determined. In addition, it is possible to restrict the determination of statistics to pixels lying within a range given by the user. It would be desirable to be able to provide a masking image that determines which pixels should be included in the statistics determination.

This functionality is provided by **eclipse**.

**trimming and overscan correction**

Overscan correction entails the subtraction of a suitable bias level from the image, as determined from the overscan region of the image. An algorithm for determining the bias level from the overscan region remains TBD.

Trimming refers to extraction of the sub-image containing the exposed part of the raw data.

This functionality is provided by eclipse.

**averaging**

Given a list of equally dimensioned input images, an output image containing the average of the input images is determined. Several modes should be supported.

> **Mean** Each output pixel is equal to the mean of the corresponding input pixels

**Mean with rejection** Each output pixel is equal to the mean of the corresponding input pixels that have not been rejected.

**Median** Each output pixel is equal to the median of the corresponding input pixels

**Median with rejection** Each output pixel is equal to the median of the corresponding input pixels that have not been rejected.

This functionality is provided by **eclipse**.

**masking**

Given an image and a range, defined by a minimum and a maximum, create a new image of binary values, where a value of 1 indicates that the corresponding pixel in the input image was within the range, and a value of 0 indicates that the pixel lies outside this range.

This functionality is provided by **eclipse**.

**satellite detection**

It is expected that at least one chip per dither will be affected by satellite tracks. An algorithm (Hough transform) based on the analysis of a catalog extracted from the data is under investigation.

**cosmic ray detection**

Sextractor can be run with a special filter that is only sensitive to comsic-ray like signals. This results in a so-called segmentation map (CHECKIMAGE-TYPE=SEGMENTATION), recording the pixels affected by cosmic ray events. This segmentation can be used to assign a weight of zero to these pixels.

**collapse**

Collapse a 2D image into a 1D line by averaging either ros or colums. Functionality provided by **eclipse**

**background subtraction**

Model the background by interpolating background estimates on a predefined grid, and subtract this from the image. Functionality provided by **SWARP** and **Sextractor**

**coaddition**

Given a list of (overlapping) astrometrically calibrated input images and their corresponding weights, build a coadded image.

Image coaddition is divided in two parts, resampling and combination.

Image resampling addresses the problem that two independent observations of the same area of sky will, in general, result in images whose coordinate systems are different. Projection of these coordinate systems to a new coordinate system requires a mapping $x, y \Rightarrow \alpha, \delta \Rightarrow x', y'$. Since the area of sky covered by an input pixel will in general not map directly to an area of sky covered by a single output pixel, some sort of interpolation is required. Unfortunately interpolation will inevitably result in aliasing artifacts, hence, a careful choice of interpolation kernel is required.

Once all input images and their weights have been resampled onto the grid specified by the coordinate system of the coadded image, it is straightforward to compute the coadded image and its weight. Given resampled input images $1 \leq i \leq N$ entering co-addition, one can define for each pixel $j$:

- the local uncalibrated flux $f_{ij} = \overline{f_{ij}} + \Delta f_{ij}$, where $\overline{f_{ij}}$ is the sky background, and $\Delta f_{ij}$ the contribution from celestial sources,
- the local uncalibrated variance $\sigma_{ij}^2 = \overline{\sigma_{ij}^2} + \Delta\sigma_{ij}^2$, where $\overline{\sigma_{ij}^2}$ is background noise and $\Delta\sigma_{ij}^2$ the photon shot noise of celestial sources,
- the local, normalized weight $w_{ij}$,
- the electronic gain of the CCD $g_i$,
- the relative flux scaling factor $p_i$, deduced from the photometric solution, with $p_i \Delta f_{ij} = p_l \Delta f_{lj}$ for all $i, l, j$,
  the weight scaling factor $k_i$.

Optimal weighting is obtained using

$$k_i w_{ij} = \frac{1}{p_i^2 \overline{\sigma_{ij}^2}},$$

leading to a co-added flux (assuming the background of the input images has been subtracted),

$$f_j = \frac{\sum_i k_i w_{ij} p_i \Delta f_{ij}}{\sum_i k_i w_{ij}},$$

and variance

$$\sigma_j^2 = \frac{\sum_i k_i^2 w_{ij}^2 p_i^2 \sigma_{ij}^2}{(\sum_i k_i w_{ij})^2},$$

The software package **Swarp**, developed by E. Bertin (IAP) for Terapix provides a set of regridding and co-addition algorithms specifically optimized to handle large area CCD mosaics

## 7.2 Catalog manipulation

Several reduction steps, in particular astrometric and photometric calibration, require the manipulation of source lists/catalogs. Most of this functionality is provided by the Leiden Data Analysis Center (**LDAC**) data reduction tools.

**source extraction**

The detection and measurement of sources in images is a non-trivial task. Fortunately an established, versatile, robust and fast algorithm for the detection of sources is available in the form of the **SExtractor** source extraction package. In addition to its source detection capabilities **SExtractor** provides functionality for the detection of image defects (cosmic rays and bleeding), and for robust background subtraction in the presence of signal.

**association**

Both astrometric and photometric calibration require the association of a source catalog with a reference catalog. A proper association algorithm takes into account position errors and confusion problems.

Catalog association is provided by **LDAC**.

**merge**

In some cases it may be necessary to merge overlapping catalogues into a new catalogue, containing a suitable average of the different measurement of a single object in different observations.

Catalog merging is provided by **LDAC**.

**astrometric solution**

The astrometric solution perfoms, based on the a-priori pointing knowledge of the telescope and the chip layout, a pattern matching between the extracted observed objects and a reference catalog allowing quick, inaccurate pairing. To increase the reliability of the initial pairing, previous determinations of the full astrometric solution are used as a first step approximation.

Using this pairing information the parameters of the astrometric model are derived in an iterative process. The full astrometric solutions determine both the projection of the individual chip pixel coordinates onto the perfect (x,y) coordinate space of the focal plane and the projection of this perfect plane to

sky coordinates. This effectively maps the light path through the telescope and the camera for the particular pointing from the pixel plane to the sky coordinate domain. If multiple pointings are available (as is the case in **Mode– dither** N= or **Mode– jitter** N=) different pixels and/or detectors map the same sky area. The source extraction precision in arcseconds is much higher than the positional accuracy of the reference catalog. Incorporating the overlap information therefore enhances the accuracy of the final astrometric solution to allow more precise co-addition.

The astrometric solution can be derived in several ways of increasing complexity and potentially increasing accuracy. Single chip solutions where the astrometric solution for each CCD chip is derived independently is the simplest and least accurate. When multiple pointings on the same area of sky are performed close in time, for each CCD chip one will have multiply observed the set of references stars and one can also use non-reference stars observed multiple times among the pointing series. Still an astrometric solution per chip is derived, which is more accurate than the single chip, single pointing case. The most robust way of determining an astrometric solution of a multi CCD camera is to make use of the dithering pattern which creates not only overlaps of one CCD chip onto itself, but also among the different chips of the camera. Now a full astrometric solution can be derived for all chips simultaneously using all overlap cases (chips onto themselves, between different chips). Obviously this can produce the most accurate astrometric solution of the three.

As is customary, the plate model is not defined as a mapping between pixel coordinates and sky coordinates ($\alpha$,$\delta$), as this would obviously have singularities at the poles, but instead as a mapping between the pixel space and so-called normal coordinates. The normal coordinates $(\zeta, \eta)$ are the gnomonic projection of the absolute sky positions relative to the field center. There is some level of non-linearity here, since the field center itself depends on the position reconstruction, but for realistic initial errors this is very small and easily absorbed in the plate model. With these notations, the mapping between a source detected at pixel coordinates (x,y) in frame f and its normal coordinates $(\zeta, \eta)$ relative

to the nominal center of field f is of the form

$$\zeta(x,y,f) = a_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^{n} b_{ijk} x^i y^j f^k$$

$$\eta(x,y,f) = c_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^{n} d_{ijk} x^i y^j f^k$$

where the $a_f$, $c_f$, $b_{ijk}$, and $d_{ijk}$ are initially unknown coefficients, to be determined by the least squares adjustment. We actually use a different maximum degree in the field number variable for each spatial term, since flexures only induce measurable effects for the low order terms (zero point and focal scale).

**astrometric solution – Overlap solution**

Upon closer examination, the star density of the reference catalog is indeed almost always sufficient. One does, however, gain accuracy by incorporating the better positional accuracy within the chips of a detector than that with respect to an external reference frame. Giving overlap position determinations higher weight than those with respect to the external reference system one enhances positional accuracy.

The coefficients of the plate model will thus be determined by simultaneously minimizing (in a least square sense) the distance to the reference stars and the overlap detections. The corresponding quadratic form can be written as:

$$\begin{aligned} S = & \sum_{f=1}^{n_{field}} \sum_{i=1}^{n^f_{ref}} \frac{\left\| \zeta(x_i,y_i,f) - \zeta_i^f \right\|^2}{\sigma^2_{mes}(i) + \sigma^2_{cat}(i)} + \sum_{f=1}^{n_{field}} \sum_{i=1}^{n^f_{ref}} \frac{\left\| \eta(x_i,y_i,f) - \eta_i^f \right\|^2}{\sigma^2_{mes}(i) + \sigma^2_{cat}(i)} \\ & + \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n^{f_1 f_2}_{over}} \frac{\left\| (\zeta(x_i,y_i,f_1) - \zeta(x_i,y_i,f_1)) - (\zeta_i^{f_1} - \zeta_i^{f_2}) \right\|^2}{\sigma^2_{mes}(i,f_1) + \sigma^2_{mes}(i,f_2)} \\ & + \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n^{f_1 f_2}_{over}} \frac{\left\| (\eta(x_i,y_i,f_1) - \eta(x_i,y_i,f_1)) - (\eta_i^{f_1} - \eta_i^{f_2}) \right\|^2}{\sigma^2_{mes}(i,f_1) + \sigma^2_{mes}(i,f_2)} \end{aligned}$$

where $\zeta$ and $\eta$ are the multivariate polynomial functions described above, $\zeta_i^f$ and $\eta_i^f$ are the normal coordinates of reference star $i$ relative to the center of field f, and $(\zeta_i^{f_1} - \zeta_i^{f_2})$ and $(\eta_i^{f_1} - \eta_i^{f_2})$ are the difference of the normal coordinates of overlap star $i$ relative to the centers of fields $f_1$ and $f_2$. In principle, the latter quantities can only be evaluated once the coordinates are at least approximately known, but in practice they only vary by a few milliarcseconds across the overlap zone. One can also note that the solutions for $\zeta$ and $\eta$ are not coupled, and that one thus independently minimizes $S_\zeta$ and $S_\eta$, the parts of S depending on respectively $\zeta$ and $\eta$.

**Astrometric solution – Implementation**

We consider here an ensemble of $n_f$ fields containing a total of $N_{ref}$ reference stars and $N_{over}$ stars in overlaps, and adjust a plate model which has $n_{par}$ smoothly varying functions (such as the polynomials discussed above) with coefficients noted as $b_p$, plus one zero point per field noted as $b_f$.

For a practical discussion of the implementation, it is convenient to rewrite the quadratic form of the above equation in its canonical form

$$S = (A \cdot X - B)^T \cdot (A \cdot X - B)$$

where $A$ is a rectangular matrix (the design matrix) whose dimensions are the total number of constraints (reference+overlap) and the total number of fitted coefficients (field centers+smooth functions). $X$ and $B$ are vectors containing respectively the fitted coefficients and the constraints data. If one defines $X$,

$B$, and $A$ by respectively

$$X_i = a_f \text{ for } i \leq n_f$$
$$X_i = b_p \text{ for } i > n_f$$

$$B_i = \zeta_{if_i} \text{ for } i \leq N_{ref}$$
$$B_i = (\zeta_{if_i^1} - \zeta_{if_i^2}) \text{ for } i > N_{ref}$$

$$A_{ij} = \delta_{jf_i}/\sigma_i \text{ for } i \leq N_{ref} \text{ and } j \leq n_f$$
$$A_{ij} = f(x_i, y_i, f_i)/\sigma_i \text{ for } i \leq N_{ref} \text{ and } j > n_f$$
$$A_{ij} = (+\delta_{jf_i^1} - \delta_{jf_i^2})/\sigma_i \text{ for } i > N_{ref} \text{ and } j \leq n_f$$
$$A_{ij} = (f(x_i, y_i, f_i^1) - f(x_i, y_i, f_i^2))/\sigma_i \text{ for } i > N_{ref} \text{ and } j > n_f$$

where $\delta_{ij}$ is as usual a Kronecker symbol. A similar formulation obviously exists for $\eta$.

Under this canonical formulation of the least square quadratic form, it is easy to show (see for instance the least square chapter in Numerical Recipes) that the X which minimizes S is the solution of the system of $(n_{par} + n_f)$ linear equations $(A^T \cdot A) \cdot X = A^T B$, known as the normal equations.

The plate model coefficients can thus be obtained by computing $(A^T \cdot A)$ and solving the normal equations. This method is generally known to have relatively poor numerical stability. Once the pixel coordinates are remapped to [0,1] however, the problem has good conditioning, and direct comparison with more accurate methods shows good agreement for modest polynomial degrees, even in single precision. Alternatively, A is sparse enough that solving the equation with the conjugate gradient algorithm is a possibility. This iterative minimization algorithm converges in at most $n_{par} + n_f$ steps, each of which needs one multiplication by $A$ and its transpose. It has good stability, is about as fast as computing $(A^T \cdot A)$, but needs a larger memory space.

If on the other hand an analytic estimate of the standard errors is needed, $(A^T \cdot A)^{-1}$ (which is the covariance matrix) must be evaluated anyway. Solving the normal equations then becomes much cheaper, though we may still use

the conjugate gradient for the minimization, because of its better numerical behaviour.

The complete implementation of these algorithms is provided by **LDAC**

**PSF fitting**

Use the second order moments of the brightness distribution of stellar objects to search for systematic effects across the detector area. The distribution of the position angles and elongations of the bounding ellipse has to be evaluated. A robust method for determining these parameters comes from Kaiser et al. 1995, APJ 449, 460. Alternatively use the PSF fitting functionality from **sextractor**

**seeing**

The seeing is robustly characterized by the half light radius $r_e$ of unsaturated stellar objects, obtained from **sextractor**

**select stars**

Star galaxy separation is functionality provided by **sextractor**

## 7.3 Header manipulation

Header manipulation, i.e.: reading and writing and modifying (representations of) FITS headers, constitutes basic functionality, provided by many astronomical data reduction packages. Missing from most header manipulation software however are validation tools. We also note that it is nowhere specified in what order header keywords are written, while some sort of fixed order would greatly improve human readability of FITS headers.

**reading**

Header reading includes copying of the FITS header in some kind of internal representation, as well as the extraction of values for a particular keyword from a given header.

**writing**

Header writing includes writing a FITS header based on some internal representation, as well as writing a value for a particular keyword in a given header. Header writing should conform to the formatting directives given by a Data Interface Dictionary.

**validation**

Header validation should be based on Data Interface Dictionaries. There are currently no tools that verify existing FITS headers against Data Interface Dictionaries. The Fits Translation Utility (FTU) only validates new header items written by this tool.

## 7.4 Miscellaneous functionalities

Miscellaneous functionalities required for **OmegaCAM** data reduction include:

**regression/(non-)linear fitting**

Some results (zeropoints, gains) are obtained from fits to multi dimensional data.

**plotting**

Simple x-y scatter plots can provide useful graphical representations of results.

# A1 LIST of CALIBRATION REQUIREMENTS


5.2.1 Req.– *CCD read noise - doit* ..... 29
5.2.2 Req.– *Hot pixels* ..... 31
5.2.3 Req.– *CCD gain* ..... 33
5.2.4 Req.– *Electromagnetic Compatibility* ..... 36
5.2.5 Req.– *Electrical cross talk* ..... 38
5.3.1 Req.– *CCD Dark Current - doit* ..... 40
5.3.2 Req.– *CCD Particle Event Rate* ..... 43
5.3.3 Req.– *CCD Linearity* ..... 44
5.3.4 Req.– *CCD Charge Transfer Efficiency* ..... 47
5.3.5 Req.– *CCD Cold Pixels* ..... 49
5.3.6 Req.– *CCD Hysteresis, strong signal* ..... 51
5.4.1 Req.– *Bias - doit* ..... 58
5.4.2 Req.– *Flat-field - dome key bands + user bands - doit* ..... 61
5.4.3 Req.– *Flat-field - twilight* ..... 64
5.4.4 Req.– *Flat-field - night sky* ..... 67
5.4.5 Req.– *Flat-field - Fringing* ..... 70
5.4.6 Req.– *Flat-field - master flat and weight map* ..... 72
5.4.7 Req.– *Quick detector responsivity check-doit* ..... 75
5.4.8 Req.– *Illumination correction* ..... 76
5.5.1 Req.– *Position of Camera in focal plane* ..... 80
5.5.2 Req.– *Telescope Pointing and offsetting* ..... 82
5.5.3 Req.– *Telescope and Field Rotator tracking* ..... 83
5.5.4 Req.– *PSF Anisotropy* ..... 86
5.5.5 Req.– *The astrometric solution for templates - doit -see 6.3.4* 88
5.5.6 Req.– *The astrometric solution for Guide CCD's* ..... 88
5.6.1 Req.– *Shutter Timing* ..... 94
5.6.2 Req.– *Photometric Calibration - monitoring* ..... 97
5.6.3 Req.– *Photometric Calibration - zeropoint keybands - doit* . 102
5.6.4 Req.– *Photometric Calibration - zeropoint user bands* ..... 107
5.6.5 Req.– *Filter band passes - user bands vs key bands* ..... 109
5.6.6 Req.– *Dependency on angle - ADC, rotator/ reproducibility* 110

5.6.7 Req.– *Linearity (as a function of flux)* ..... 111
5.6.8 Req.– *Detection limit and ETC calibrations* ..... 113
5.6.9 Req.– *Secondary Standards* ..... 114
5.7.1 Req.– *Camera focus/tilt* ..... 116
5.7.2 Req.– *Ghosts - ADC* ..... 118

# A2 LIST of RAW CALIBRATION DATA

| | volume per **req.**run and per year |
|---|---|
| **RawData– 523** *CCD gain* | 10Gb 0.52Tb |
| **RawData– 531** *Dark current* | 0.75Gb 40Gb |
| **RawData– 533** *CCD Linearity* | 2Gb 24Gb |
| **RawData– 541** *Raw Bias frame* | 5Gb 0.51Tb |
| **RawData– 542** *Dome flat frame* | 2Gb 0.66Tb |
| **RawData– 543** *Twilightflat frame* | 10Gb 3.3Tb |
| **RawData– 547** *Quick check* | 0.5Gb 115Gb |
| **RawData– 562** *Monitor* | 0.5Gb 0.5Tb |
| **RawData– 563** *Zeropoint- Key* | 2.5Gb 0.8Tb |
| **RawData– 564** *Zeropoint - User* | 2.5Gb 0.8Tb |
| **RawData– 565** *User − >key* | 25Gb 25Gb |
| **RawData– 569** *Secondary Standards* | 32 Gb 4Tb |

# A3 LIST of DFS I/O CALIBRATION FILES

volume per file and per year

| | |
|---|---|
| **CalFile– 521** *Readout noise* | 2 kb, 1 Mb |
| **CalFile– 522** *bad/hot pixel map* | 0.25Gb 25Gb |
| **CalFile– 523** *conversion factor $e^-/ADU$* | 2kb .1Mb |
| **CalFile– 531** *dark count rate for each CCD* | 2kb .1Mb |
| **CalFile– 532** *Particle event rate* | 2kb .1Mb |
| **CalFile– 533** *CCD Linearity* | 2kb .1Mb |
| **CalFile– 534** *charge transfer efficiency factors* | .2Mb .4Mb |
| **CalFile– 535** *cold pixel map* | .25Gb 1Gb |
| **CalFile– 536** *CCD Hysteresis* | 2kb 2kb |
| **CalFile– 541** *Master Bias frame* | 1Gb 104Gb |
| **CalFile– 542** *Master Domeflat frame* | 1Gb 0.330Tb |
| **CalFile– 542L** *Dome Lamp* | 2kb 1Mb |
| **CalFile– 543** *Master Twilightflat frame* | 4Gb 1.3Tb |
| **CalFile– 544** *Nightsky flat frame* | 1Gb 1Tb |
| **CalFile– 545** *ff-fringe* | 1Gb 0.3Tb |
| **CalFile– 546** *Master flatfield* | 1Gb 0.3Tb |
| **CalFile– 546W** *Weightmap* | 1Gb 0.3Tb |
| **CalFile– 547** *Quick check* | 1Gb 0.33Tb |
| **CalFile– 547r** *Quick check - day report* | 3kb 1Mb |
| **CalFile– 548** *Illumination correction* | 1Gb 10Gb |
| **CalFile– 551** *Astrometric camera/chip solution* | 2kb .1Mb |
| **CalFile– 554** *PSF anisotropy* | .1Mb 1 Mb |
| **CalFile– 556** *Astrometric solution - Guide CCD* | 2 kb 1 Mb |
| **CalFile– 562S** *Sky brightness* | 1 kb 1 kb |
| **CalFile– 562** *Extinction-night report* | 2 kb 1 Mb |
| **CalFile– 562u** *Photom + Sky* | 10Mb 10Gb |
| **CalFile– 562B** *Photom + Sky* | 10Mb 10Gb |
| **CalFile– 562V** *Photom + Sky* | 10Mb 10Gb |
| **CalFile– 562i** *Photom + Sky* | 10Mb 10Gb |
| **CalFile– 563Z** *Zeropoint - key bands* | 4kb 1.2Mb |

**CalFile– 564** *zeropoint - User bands* 4kb 1.2Mb
**CalFile– 565** *User– > key* 4kb 1Mb
**CalFile– 569** *Secondary Standard Catalog* 1 Mb 1 Gb

# A4 LIST of DFS INPUT REFERENCE CATALOGUES

**CalFile– in1** *US-NAVAL Observatory A2.0* 6 Gbyte
**CalFile– 569E** *Primary Standard stars - external Landolt fields* 100 Mb
**CalFile– 564E** *Standard extinction curve* 0.1Mb

NOTE:

Both the preparatory programme as **req.**569 will produce **CalFile– 569** *Secondary standards.*

**CalFile– 569** *Secondary Standard stars - external WFI@2.2/preparatory programme* 100 Mb

# A5 LIST of SEQUENTIAL STEPS in IMAGE PIPELIN


6.3.1 Seq.– *Ingestion and image statistics* ..... 138
6.3.2 Seq.– *Trim, de-bias, flatfield* ..... 141
6.3.3 Seq.– *Construct weigths, determine seeing* ..... 142
6.3.4 Seq.– *Astrometric calibration* ..... 144
6.3.5 Seq.– *Apply photometric calibration* ..... 147
6.3.6 Seq.– *Dedithering/dejittering* ..... 148