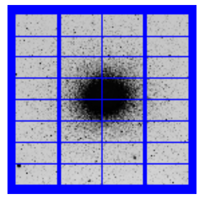
OmegaCAM



OmegaCAM Data Flow System User Requirements

Including formal list of Calibration Requirements

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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.

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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.

1.1 Scope of this document

The present document provides the deliverable 'Data Flow System User Requirements' as proposed in VLT-SPE-ESO-19000-1618: "it defines the user requirements including operational scenarios which must be supported and therefore may impact definition of observing modes, Exposure Time calculator (ETC) or pipeline procedures".

The **OmegaCAM** User requirements related to the Instrument Software are specified in a separate document [VST-SPE-OCM-23100-3060].

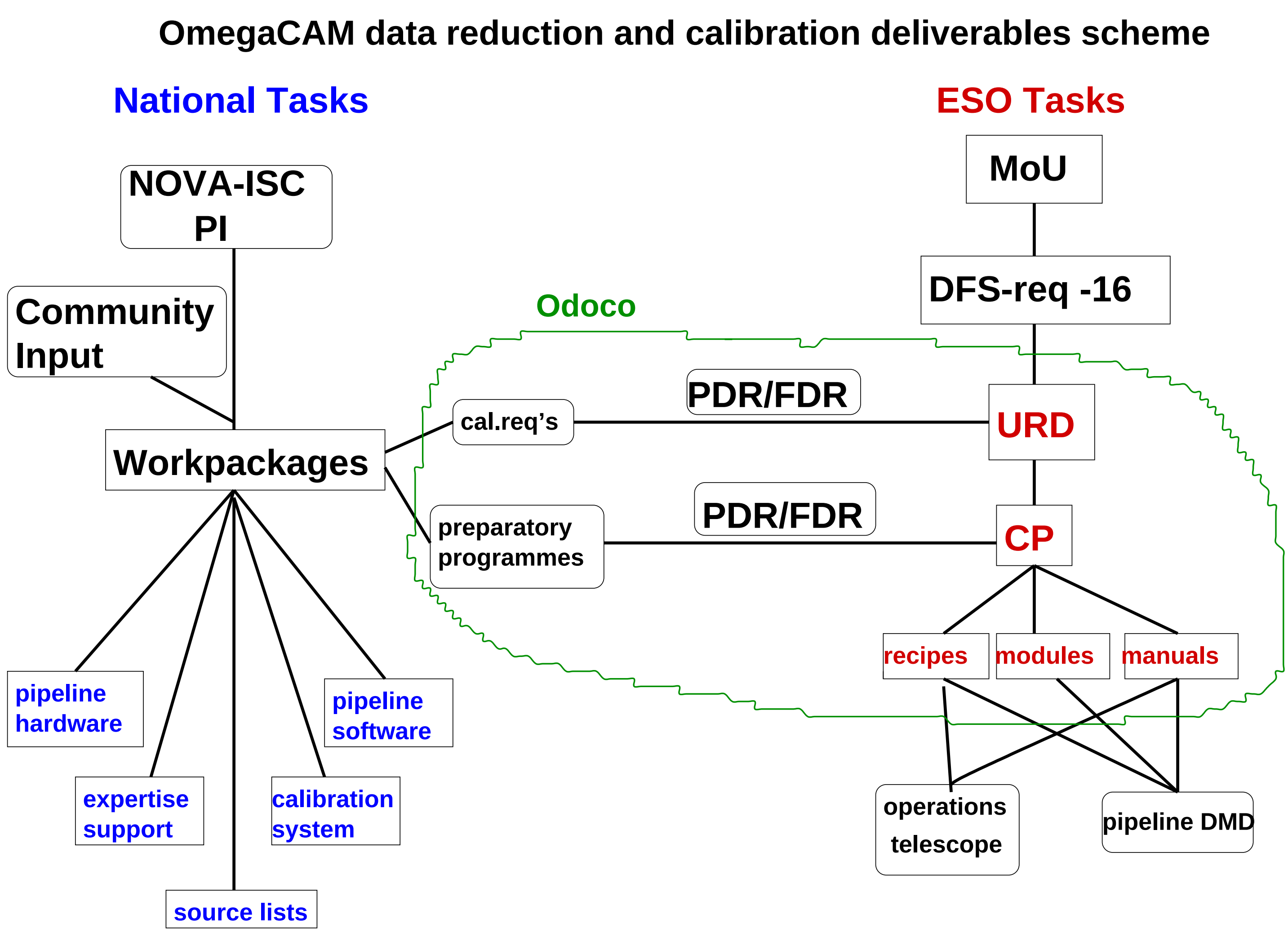
Standardization of observing modes, calibration procedures and related data reduction procedures play an import role in the **OmegaCAM** instrument concept and the present document includes the specification of the standardized observing scenarios for science observations (**templates**) and the basic requirements for the qualification, quality control and calibration of the instrument both during switch-on, commissioning phase (**CP**) and routine phase (**RP)**. Implementations of these requirements shall be further specified in the **Calibration Plan document** . Details of the related data reduction are given in the **Data Reduction Specification document**. Instantiations of the Calibration Plan will form the **Schedule** of the telescope, which for the commissioning phase shall be written by the Instrument Consortium and will form a part of the **Commissioning plan**. During routine operations the schedule shall be written by ESO.

Figure 1 sketches that part of the organization of the **OmegaCAM** consortium which relates to the deliverables of data reduction and calibration issues. The sketch is not exhaustive, but is meant to highlight the basic relation between National tasks (mostly NL as far as data reduction is concerned, with products/results marked in blue) and tasks relating to deliverables to ESO (on the right side, with deliverables marked in red).

For some Dutch National tasks collaborations are foreseen with other European data centers for wide field imaging, such as Terapix (France), the Astronomical Observatories of Capodimonte and Padova, and the Sternwarte München.

The deliverables to ESO are driven by the Memorandum of Understanding between the Consortium and ESO, which in turn refers to 'Data Flow System User Requirements' VLT-SPE-ESO-19000-1618 (DFS-req-16 in the sketch), which in turn specifies the hierarchy of deliverables: **User Requirement Document (URD)** and **Calibration Plan document** and various S/W deliverables.

The consortium has implemented a documentation control system with a strict documentation format for the definition of calibration **req.**'s, and named this **Odoco** (**OmegaCAM** document control). This system is explained in detail in Section 5.0. The green encircled region in the figure indicates the various documents and files which will be guarded by **Odoco**.



OmegaCAM data reduction and calibration deliverables scheme
National Tasks
ESO Tasks
MoU
NOVA-ISC PI
DFS-req -16
Odoco
Community Input
PDR/FDR
cal.req's
URD
Workpackages
PDR/FDR
preparatory programmes
CP
recipes
modules
manuals
pipeline hardware
pipeline software
expertise support
calibration system
operations telescope
pipeline DMD
source lists

Figure 1

1.2 Applicable documents

The following documents, of the exact issue shown, form a part of this document to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this document, the contents of this document shall be considered as a superseding requirement.

[] VST-PLA-OCM-23100-3090 OmegaCAM Calibration Plan

[] VST-PLA-OCM-23100-3051 OmegaCAM Data Reduction Specifications

[] VST-PLA-OCM-23100-3100 OmegaCAM Commissioning Plan

[] VST-PLA-OCM-23100-3010 Project Management Plan and Project Plan and Schedule

[] VST-PLA-OCM-23100-3020 Product Assurance Plan

[] VST-SPE-OCM-23100-3551 ICD OmegaCAM - ESO-DMD

[] VST-PLA-OCM-23100-3080 Technical Operations and Maintenance Plan

S/W deliverables depending on the URD

[] OmegaCAM Data Interface Dictionary

[] OmegaCAM Template Signature Files

[] OmegaCAM Exposure Time Calculator

1.3 Reference documents

The following documents are referenced in this document.

[]	VLT-SPE-ESO-19000-1618	1.0 21/04/1999 — VLT Data flow for the VLT instruments Requirement Specification
[]		MoU OmegaCAM - ESO
[]	VST-PLA-OCM-23100-3030	Safety Analysis and Compliance Assessment
[]	VST-TRE-OCM-23100-3040	Design Analysis, Performance Report
[]	VST-TRE-OCM-23100-3041	Design Analysis, Performance Report: Mechanical
[]	VST-ESO-OCM-23100-3042	Design Analysis, Performance Report: Detector System
[]	VST-TRE-OCM-23100-3043	Design Analysis, Performance Report: Electronic

[] VST-SPE-OCM-23100-3050 Data Flow System User Requirements
[] VST-SPE-OCM-23100-3060 Instrument Software
[] VST-SPE-OCM-23100-3064 OmegaCAM Observation Software Design Description
[] VST-PLA-OCM-23100-3070 MAIT and Alignment Plan
[] VLT-MAN-ESO-19000-2050 FTU FITS Translation Utility User Manual
[] SExtractor v2.1.3 User's guide
[] Eclipse Developer's Guide
[] Eclipse User's Guide
[] The LDACTools Library v1.2 User's guide
[] Pipeline Documentation Ver. 1.3
[] Swarp v1.20 User's guide

1.4 Abbreviations and Acronyms

Abbreviations and Acronyms used in this document

A/D	Analog/digital
ACS-dbase	Astronomical Calibration Source database
ADC	Atmospheric Dispersion Corrector
ADU	Analog to Digital Unit
AGN	Active Galactic Nucleus
BRD	Baseline Requirements Document
CA	Calibration Analysis
CAP	Calibration Analysis Procedure
CCD	Charge Coupled Device
CO	Calibration Observation
CP	Commissioning Phase
CalP	Calibration Plan
CTE	Charge Transfer Efficiency
CVS	Code Version System
DFS	Data Flow System
ESO	European Southern Observatory
ETC	Exposure Time Calculator

FOV	Field of View
FWHM	Full Width at Half Maximum
GRB	Gamma Ray Burst
GT	Garanteed Time
HZSS	High Redshift Supernova Search
ICS	Instrument Control Software
IWS	Instrument Workstation
ISO	Infrared Space Observatory
IST	Instrument Science Team
KBO	Kuiper Belt Object
MoU	Memorandum of Understanding
NOVA	(Dutch) Nederlandse Onderzoekschool Voor Astronomie
OaPd	Astronomical Observatory of Padua
OB	Observation block
OD	Observation Description
OPC	Observing Programme Committee
OT	Optical Transient
OT	Observing Template
PPP	Photometry Preparatory Programme
PSF	Point Spread Function
QC0	Quality Control zero
QC1	Quality Control one
QSO	Quasi-Stellar Object
RPE	Relative Pointing Error
RP	Routine Phase
RSRF	Relative Spectral Response Function
SCP	Supernova Cosmology Project
SED	Spectral Energy Distribution
SSO	Solar System Object
S/N	Signal/Noise
S/W	Software
TBC	To Be Confirmed
TBD	To Be Defined
TBW	To Be Written

TCS	Telescope Control System
TP	Target Package
TSF	Template Signature File
URD	User Requirement Document
USM	Universitäts Sternwarte München
VLT	Very Large Telescope
VST	VLT Survey Telescope
WFI@2.2m	Wide Field Imager at the ESO 2.2m telescope

2 SCIENTIFIC REQUIREMENTS

2.1 Scientific requirements

The scientific case for the construction of a wide field imaging facility to be dedicated to "supply complete databases for the VLT science" was presented by Astronomical Observatory of Capodimonte in 1997. After consideration of specific research projects, of the specific needs for VLT target selection and a survey of existing and planned wide field imaging facilities worldwide, a number of scientific requirements were extracted which drove the design of the telescope and also provided the references for the design of the associated camera.

OmegaCAM and the VST are entirely dedicated to wide field optical imaging, and the design must comply with the scientific requirements derived in the VST science case and the MoU which are repeated below (items 1–11). Further scientific requirements (items 12–19) have been derived from considerations of specific scientific use cases, described later in this section.

These scientific requirements propagate as requirements on Instrument S/W [VST-SPE-OCM-23100-3061], a set of Baseline Calibration requirements (Section 5) and requirements on the Data reduction (Section 6).

List of science driven requirements (Sc. Req's):

1 - A telescope diameter of 2.6m

2 - 1 deg^2 field of view

3 - the highest efficiency achievable

4 - CCD filling factor as close as possible to 100%

5 - good seeing sampling of at least 2×2 pixels within seeing element (good match is 15 μm, i.e. $0.21''$ pixel^{-1} scale)

6 - 80% of energy within 2×2 pixels across the whole field

7 - achromatic PSF or less than 2% effect

8 - astrometry with an internal accuracy of 0.01-0.02″ rms (goal) and 0.05″rms (formal), an accuracy of 0.1″ rms with respect to an external standard and an absolute accuracy of 0.2-0.3″ rms (goal) and 1″ rms (formal value).

9 - 1% accuracy in flat fielding

10 - multi-color photometry

11 - narrow band imaging

12 - four observing modes: stare (single exposures), jitter (few pixels shifts between sub-exposures), dither (shifts larger than the largest gaps in the CCD mosaic) and SSO - solar system objects, facilitating non-siderial tracking

13 - 10-12 filters available on-line

14 - accurate photometric calibration of all broad-band filters to a level of 0.01 mag rms (goal) and 0.05 mag rms (formal) in the zero point in instrumental magnitudes and 10% in the color transformation terms from the instrumental to the Johnson-Cousin standard photometric system

15 - astrometric and photometric performance monitored and administrated throughout the life time of the instrument; certain data items related to these calibrations need to be delivered separately to the consortium. Specifications of these items are given in a separate Interface control document between ESO-DMD and the **OmegaCAM** consortium [VST-SPE-OCM-23100-3551]

16 - observing programs must allow for new inclusions or modifications on a day by day basis

17 - if required, raw, observational data must be made available to the proponents, for analysis within 2-3 working days

18 - the "pipeline data reduction must 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" following the specification of Annex A.4.1 of the MoU.

19 - observing (scheduling), calibration and data reduction stategies should support the following type of survey strategies :

— Basic observing modes on single fields

— Deep integrations of single fields

— Wide-area real-time variability searches.

— Wide-area surveys with full sky coverage

The rest of this Section provides further details and justifications for this list.

Note on req. 12:
Wide area coverage and deep integration on single fields, usually require that the gaps in the CCD mosaic are covered by the combination of several exposures (≥ 5) with a **dithering** larger than the maximum gap in the CCD mosaic. For some programmes (e.g. variability monitoring, weak lensing), it is more important that at corresponding positions in the sky the PSF shows a minimum variation. In this case, the best strategy is to obtain multiple exposures with only a small **jittering** to remove bad pixels.

Note on Sc. Req. 13:
Because of flexible scheduling, the need to be able to monitor transient or variable objects in several filters, and the measurement of atmospheric extinction, the number of filters available on-line must be on the order of a dozen. 5 of these are required for the continuous maintenance of the photometric scale at 4 key bands (see Section 5.6).

Note on Sc. Req. 14:
Accurate calibration to the Johnson-Cousin standard photometric system is strictly required by many stellar population studies. Required accuracy for such programmes is 0.01 mag. (Also many other programs, even those not using standard filters, will require a calibration link to a standard photometric system.) To provide the necessary infrastructure for this goal a proper monitoring of the sky conditions, in particular of the extinction coefficient, is required, next to the continuous monitoring of the overall responsivity variations of the instrument. Data acquisition and baseline calibration plan shall be designed to achieve the goal, but this will not be provided by the standard pipeline, which is required to achieve the nominal 5% photometric accuracy. Additional dedicated off-ESO-pipeline data-analysis will be required to qualify 1% accuracy.

Note on Sc. Req. 15, (i):
A major fraction of the observing time will be spent on wide area surveys in different filters. Some of the projects may require several years to be completed.

To ensure uniform quality of the products, accurate monitoring of the performance of the instrument is required. This performance shall be continuously administrated and available for trend analysis. This administration should be integrated in the DFS infrastucture and/or its peripheral infrastructure ready for inspection and analysis.

Note on Sc. Req. 15, (ii):

ESO's processing of the **OmegaCAM** data is described as "the removal of instrumental fingerprints from the raw data", essentially leading to astrometrically and photometrically calibrated images. Clearly, more reduction steps have to be taken in order to obtain extracted source parameters and the error bars on these parameter values. Also the stacking of images with user provided qualification criteria (modes deep and mosaic) or the achievement of high, 1%, photometric accuracy requires re-processing of the data with user provided criteria. In order to provide the end-user insight in the quality of the data the administrative data relevant for the **OmegaCAM** photometric and astrometric calibration need to be distributed to the consortia National Data Reduction Centers. The Interface document ICD [VST-SPE-OCM-23100-3551] between ESO-DMD and the **OmegaCAM** consortium specifies the essential data items for this distribution.

Note on Sc Reqs. 16, 17:

The main purpose of **OmegaCAM** + VST is to perform the target selection for VLT follow-up. For variable targets (e.g. microlensing events, GRBs optical transients, supernovae etc...) this requires flexibility in the observing programs and near real time data analysis. Even as a stand-alone facility, a medium size telescope such as VST can become competitive with larger ones if it allows for a flexible operation and prompt access to the data.

SCIENTIFIC USE CASES

We found in our national communities a widespread scientific interest for wide-field imaging, covering virtually all fields of astrophysics from the Solar System to cosmology and ranging from the search for special unique objects to statistical studies of classes of objects, thus motivating our efforts in the construction of **OmegaCAM**.

A few representative scientific projects were sketched in the proposal to build **OmegaCAM**, submitted to ESO in October 1998. They were intended to highlight specific topics of interest for our communities and which were not presented in the VST science case documents. Though in some cases the research strategy of these projects will need to be refined following the most recent advances in the field, they can still serve as examples of the scientific problems to be addressed with **OmegaCAM**. Here, we summarize various scientific projects which are anticipated for the VST/**OmegaCAM** and we identify a set of science driven requirements on the instrument, its operations and its data reduction system. These projects can be taken as *use cases* for the **OmegaCAM** project.

A. Scientific case: Microlensing

The unprecedented combination of **OmegaCAM** and VST is ideal for studies of microlensing in **the inner Galaxy**, allowing the simultaneous detection and monitoring of the > 14 on-going microlensing events expected per square degree. A small survey, based on two-hour sampling of 10 fields over one month would yield the microlensing optical depth to **brown dwarfs** in the disk and bulge, a regime unexplored by current surveys. A larger effort could be made to create **a bulge** microlensing survey that will be unparalleled worldwide. Larger detection efficiencies for faint and rare microlensing anomalies such as those due to **extra-solar planets** are guaranteed by the superior site and field size; if they are numerous, a major bulge survey could yield tens of planets located a few AU from their parent lenses every year. The technical advantages of **OmegaCAM** on the VST together with the rapid sampling intrinsic to microlensing monitoring will also produce, simultaneously, a catalog of faint or rare **eclipsing objects** that can be used to constrain the binary mass function into the regime of short-period Jupiter-sized companions. Metallicity and limb-darkening measurements for faint bulge stars and lens kinematics can be obtained through rapid (5–10 minute) photometric monitoring and VLT spectroscopy of *on-going*, caustic-crossing events. Such a capability would require on-site, near real-time analysis of the data in order to find the microlensing event candidates. Such a microlensing survey can be interleaved with other projects at any phase of the moon.

Special requirement on DFS and/or its peripheral infrastructure– Astronomical target objects for VLT follow up observations must be identified from **OmegaCAM** image data within 1-2 days after data taking. The user will have to work on calibrated images and to execute identification/source extractions

Clearly, such special operations will need additional arrangements, in which balances have to be found between services provided by ESO and ad hoc data reductions done by the user at or near Paranal.

B. Scientific case: Optical Transients to Gamma-Ray Bursts

Gamma-ray bursts are short outbursts of highly energetic photons. In 1997 it was finally shown that GRBs do show afterglows and are situated at cosmological distances. The HETE-2 experiment (launched on October 9, 2000) will be able to localize about 50 GRBs per year with an accuracy better than 10 arc-minute (i.e., radial distance from the true burst position) in the medium-energy X-ray band using the WXM. These localizations shall be calculated on board the spacecraft within 10-100 seconds of burst onset, depending on burst duration and temporal structure (GRBs have durations ranging from 10 ms to 1000 seconds). The GRBs coordinates will be transmitted to ground station in near real time ($<$ 10 seconds), immediately passed to GCN and from there to the community of ground-based optical, IR, and radio observers in searches for GRB counterparts and their after glows.

By exploiting the large field of view of **OmegaCAM** it will be possible to monitor the first few minutes/hours of the GRBs optical afterglow, even before this has been identified.

An interesting prediction of current theories is that GRBs may be beamed, in which case many more optical transients (OTs) (GRBs without γ-rays) than GRBs with γ-rays will exist due to a lower bulk Lorentz-factor of the emitting material. Estimates of the fraction of γ-ray rich over γ-ray less GRBs range over more than 4 orders of magnitude, with predicted event rates from $\sim 4\,10^{-3}$ OT/square degree /yr (isotropic case) to 30 OT/square degree/yr (pencil beam GRB). Any statistics on this fraction will provide extremely important information on the beaming factor and, therefore, intrinsic properties of GRBs. A fast, wide-area optical transient survey independent of gamma-ray detections will address the issue.

Special requirement on DFS and its peripheral infrastructure – Astronomical target object for VLT follow up observations must be identified from **OmegaCAM** image data within 1-2 days after data taking

Also these special operations require additional arrangements, in which balances have to be found between services provided by ESO and ad hoc data reductions done by the user at or near Paranal.

Special requirement on Operations – Observing schedule must allow for modifications on a day by day basis

C. Scientific case: Search for Supernovae at high redshift

Type Ia SNe are probably the best distance indicators to test cosmological models. Even though two major programs (SCP & HZSS) aimed at the study of SNe at intermediate redshift ($z = 0.4 - 1.0$) are already running today, it will require a few more years to accumulate sufficient statistics and to settle definitively the debate on the value of the Hubble constant and of the density parameter. Good statistics are also needed to test the present assumption that SN Ia properties show no evolution with redshift.

Given the expected limiting magnitude for **OmegaCAM**, and assuming that a single field is observed once per month for one year we expect to find 50-100 SN Ia. Most of these will be in the redshift range $z = 0.3 - 0.6$, but a significant fraction ($\sim 5\%$) will be at higher redshift.

Once the targets have been identified the current approach is to spectroscopically confirm the candidates and measure their redshifts. For the faintest, and potentially more interesting candidates, this will require an 8-m class telescope and long exposures. Whereas this remains the best option, an alternative strategy can be devised that relies on multicolor photometry for the confirmation and classification of the SN candidates (very similar to the photometric redshift approach used for galaxies).

In addition to contribute to the direct measurement of cosmological parameters, this approach could allow for the first time the study of the evolution of the SN rate with redshift, which contains unique information on the star-formation history, the initial-mass function of stars and the progenitor scenario. In particular, estimates of the rates of core collapse SNe at high redshift can significantly improve our understanding of the intrinsic nature and age of the populations involved in the SN explosions and eventually can be used to probe the star-formation and heavy-element enrichment history of the Universe.

A high-redshift SN search will obviously exploit the wide field-of-view of **Omega-CAM** and also, because of the need to disentangle the SNe from their parent galaxies, will especially benefit from the good seeing at Paranal.

> **Special requirement on DFS and its peripheral infrastucture**– For VLT follow up candidates must be identified within 3-4 days

Clearly, also these special operations will need additional arrangements, in which balances have to be found between services provided by ESO and ad hoc data reductions done by the user.

D. Scientific case: A wide-area proper motion survey

In order to locate and study intrinsically **faint stars**, a deep wide-field survey ($\sim$ 100 square degrees) in two colors will be conducted on a regular basis so as to select those objects with high proper motions. Down to faint absolute magnitude limits, this will allow all objects with halo kinematics within a distance of 100pc in the directions surveyed to be located.

For example, if a significant population of **halo white dwarfs** exists, one such object should be found by this survey per square degree, even if their cooling ages are 16 Gyr. A proper motion survey is the only way to detect intrinsically faint stars from the ground: at faint apparent magnitudes, galaxies dominate the counts to such an extent that faint-star counts are virtually impossible. Only by pre-selecting objects with proper motions can galaxies be eliminated, and the faint end of the stellar luminosity function reliably studied.

> **Special requirement on Instrument** – $0.01''$ accuracy in relative astrometry

E. Scientific case: A deep 20 sq degree wide-intermediate and narrow-band survey

This program consists of a deep survey of a total of 20 square degrees towards several lines-of-sight at various galactic latitudes and longitudes in a set of broad-, medium-, and narrow-band filters, as well as a deeper I-band survey in a 5-square degree subfield. The many filters allow a significantly better object classification and permit the determination of accurate spectral energy distributions of essentially all objects down to a limiting magnitude of 26 in the B band. Key research programs will be related to galactic structure, gravitational lensing, low surface-brightness galaxies, and the cosmological evolution of galaxies and of quasars. Some of these projects rely solely upon VST observations, while others are of a preparatory nature for detailed VLT observations. Sub-projects are:

- E1. The contribution of hot subdwarfs and white dwarfs to the Galaxy:

A complete identification of these stars in a subvolume within a volume of radius of $\sim$ 30 kpc will solve the controversy about the scale length of their distribution and thus, will constrain the structure of the halo, and that of the thin and the thick disks. Furthermore, the luminosity function of these objects will be determined for the first time (and with precision) thus allowing constraints on the star-formation history of the Milky Way. Data from **OmegaCAM** will allow the identification of **hot subdwarfs** in the dwarf-galaxy satellites of the Milky Way yielding constraints on their structure and star-formation history as well.

Special requirement – 0.01 mag absolute photometric calibration

- E2. Galaxies in the nearby Universe (z $<$ 0.1):

A complete census of galaxies down to *very low* absolute luminosities and *very low* surface brightnesses will allow the determination of the luminosity density, the star-formation rate, and the luminosity function in the local Universe with a previously unrealized precision. In particular, the contribution of the faint end of the luminosity function will be clarified. The goal is to obtain reliable statistics from an appropriately large volume, including a wide range of density regimes, and with the same selection criteria as applied to high-redshift galaxies. This knowledge of the local Universe can then be used in comparison with results of analyses of objects at higher redshifts in order to constrain the evolution of galaxies and its large-scale structure. The philosophy of this survey is distinct from that of the Sloan Digital Sky Survey that is more limited to intrinsically brighter objects.

- E3. Formation and evolution of high-redshift galaxies:

Following the pioneering drop-out technique introduced by Steidel and Hamilton (1992), we will archive a sample of several tens of thousands of galaxies at redshifts above 2.5, $\geq 50\times$ more than presently known. These data, and with follow-up VLT observations, will allow comparative studies of the evolution of the luminosity density, star-formation activity, oxygen abundances, and luminosity function in several redshift intervals. Analyses of such data will also constrain the models for the formation and evolution of galaxies as well as those for the formation of structure. Statistically complete sets of these objects will be selected for detailed spectroscopic follow-up with the VLT in order to study the evolution of the scaling relations of spiral and elliptical galaxies in the field and in clusters.

- E4. Quasars and AGNs:

The reconstruction of spectral energy distributions as well as surveys of variability will allow the identification of a large number of AGNs and QSOs over a large redshift range. This data will constrain the formation epoch of QSOs, and will serve as a set of faint, optically selected AGNs that will be needed to solve the longstanding debate on the origin of the X-ray background. Moreover, with these data, the role of the surrounding density on the AGN phenomenon can be reliably studied. Finally, the survey will identify a large number of QSOs that are good targets to study the large-scale structure by the aid of Lyα absorption systems. All of these projects will need VLT follow-up spectroscopy.

- E5. Weak lensing on different mass scales:

The survey will provide the data to study the distribution of luminous and dark matter on various scales (10 h^{-1} Mpc down to 10 h^{-1} kpc) via lensing techniques. The mass selected ($i.e.$, lensing selected) sample of clusters and groups of galaxies can directly be compared with N-body simulations of structure formation, avoiding the usual assumptions about mass-to-light ratios, luminosity-temperature relation of clusters, etc. We will measure the mass-to-light ratio of clusters, its scatter, and its dependence on the cluster mass, and we can quantify any bias caused by the traditional optical clusters selection. Statistically, we will also be able to measure small density fluctuations by the large-scale structure ('cosmic shear') and thus constrain the amplitude and shape of the power spectrum directly.

F. Scientific case: Discovering new Solar system objects

OmegaCAM is expected to make a large inroad in solar system astronomy. A belief commonly held is that the entire solar system has been inventoried – new comets and asteroids will continue to be found and catalogued, but these are just other members of the principal solar system populations. Recent years have seen this view sharply challenged. The outer solar system (in particular from Neptune outward) is now known to contain the Kuiper Belt, a vast population of cold primitive bodies, of which the Pluto-Charon binary is the most well known member. Two new irregular satellites of Uranus were discovered as recently as 1997, and there is theoretical evidence that the inner solar system still harbours undiscovered populations in the form of terrestrial and Venus trojans. It is clear that our inventory of the solar system is far from complete, and this situation needs to be rectified if we ever hope to understand solar system formation as a general, galactic-wide phenomenon.

- **F1. Kuiper belt objects**:

A solar system survey that the **OmegaCAM** is particularly well equipped to carry out is the search for the largest (brightest) Kuiper Belt objects. The size distribution for the Kuiper Belt is only well established between $21 \leq m_R \leq 26$, since this magnitude region is well suited to conventional telescopes and CCDs. However, at brighter magnitudes, the surface density drops rapidly so that very large sky coverage is needed for positive detections. In spite of the difficulties, it is essential to extend the size distribution to large sizes (bright magnitudes) because this is the most informative area regarding theories of planetary growth. The numbers and sizes of the largest bodies in the Kuiper Belt will provide strong constraints on the "runaway growth" stage of accretion in the outer solar system, and should shed light on the still unsolved problem of the accretion of the outer planets.

Since the objects of interest are bright ($m_R \sim 20$), such a survey could be carried out during bright time. A sky coverage of ~ 1000 deg^2 at $m_R \sim 20$ can be achieved in 1 year with ~ 5 hours of observation each month. Extrapolating from the known size distribution, the survey is expected to yield ~ 20 Kuiper Belt objects brighter with $m_R \sim 20$ in 1 year. With this rate, one could equal Clyde Tombaugh's survey (the largest outer solar system survey to date) in merely 1.5 years. Such a survey would answer the intriguing question whether other "Plutos" (bodies in the 1000 km-radius range) exist. Even without the spectacular discovery of more "Plutos", the expected yield of bright Kuiper Belt objects will provide an as-yet unavailable sample of bright targets ideal for detailed physical studies.

The typical angular motion of Kuiper belt objects is small ($\sim$ 3"/hr) and the observations can be done with standard siderial tracking and guiding (using observing **Mode– Stare** N=). The data are preferably accessed within 3-4 days after the observations and could be processed with the standard image pipeline. (The slow motion of the KBOs means that they can be recovered even a few days after discovery, so that real-time data processing is desirable, but not imperative. It is sufficient, for example, to flatten one night's data within $\sim 1-2$ days, and to spend another $\sim 1-2$ days searching for candidates. After 4 days, a typical Kuiper belt object will have moved only ~ 300" and should be easily recoverable with conventional CCD detectors.)

- **F2. Discovering fast moving objects such as asteroids near Earth and Venus at L4, L5**:

At the other end of the solar system, i.e., the inner solar system, opportunities for exciting new discoveries also exist. It would be valuable to carry out searches for terrestrial and Venusian trojans, i.e., asteroids located at the L4 and L5 Lagrangian points of the Earth and Venus, respectively. In contrast to the small angular motion of Kuiper Belt objects the angular rates of these inner solar system bodies is $\sim$ 140"/hr for terrestrial Trojans and $\sim$ 240"/hr for Venusian Trojans. For some (sometimes uncertain) populations the orbital parameters can be predicted, implying that the searching for such faint objects can be facilitated by a non-siderial tracking of the telescope on the anticipated fast motion of the objects. As the typical exposure time of **OmegaCAM** is not expected to exceed 500 sec, the remaining uncertainty in the angular speed of the targets will nominally lead to larger image smearing than the effect of the tracking imperfections of the telescope without guiding. Thus there appears no compelling need for auto-guiding in such a non-siderial tracking mode.

Special requirement – Non-Siderial tracking observing mode - **Mode– SSO** N=2-5

The option of a non-siderial tracking observing mode could support all kinds of other solar system observations.

The urgency of fast data reduction when dealing with Trojans of the terrestrial planets: in the extreme case, a Venusian Trojan will have moved 1.6 deg in 24 hours and will be difficult to recover with common CCD cameras. It should be easily recoverable, however, with wide-field cameras like **OmegaCAM**. For this reason, a survey for very fast moving objects such as near-Earth asteroids and terrestial Trojans will necessarily include follow-up time roughly 24 hrs after the discovery observations.

Special requirement – Provide users access to the raw data within 24 hours within Chile

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 × 8 mosaic of 4k × 2k pixels CCD's for a total imaging area of 16k × 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 **Omega-CAM** 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 16384×16384 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 15μm comprise 246mm. Adding in the gaps, the total light-sensitive part of the science array is thus 259 x 260mm in size. The full unvignetted field of the VST is 1.47 degrees, or 372mm in diameter. The planned array with gaps fits in the field.

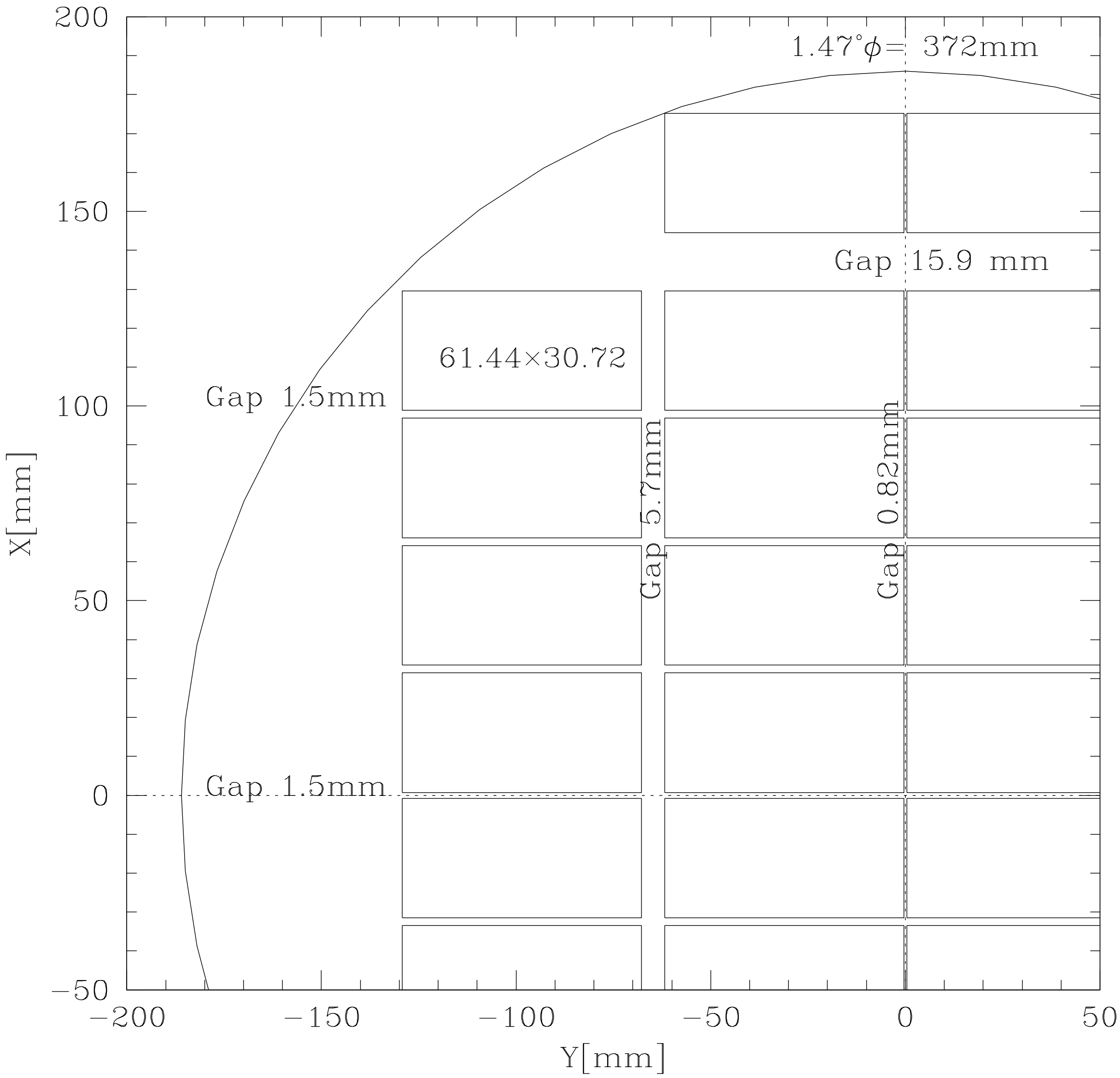


Fig 3.2 Sketch of layout of CCD arrays. Units of X and Y axes are in mm.

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.
  – Hα/**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 Hα 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 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°
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° 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°, 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], Hα)

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 μm) 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 μm) 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°. The transmission is 88%. At 70° 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 **Omega-CAM** 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.

OmegaCAM - USER REQUIREMENTS

Baseline Calibration Requirements

Issue: VERSION 1.1

Date: 25 Oct 2001

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

Purpose of printout: FDR

Selected items from the Odoco file system	
Summary sections	•
Items:	
Objective	•
Fulfilling or fulfilled by	
When performed/frequency	•
Sources, obs.,...	
Inputs	
Outputs	
Required accuracy, constraints	•
Estimated time needed	
Priority	•
Template Signature File.	
Recipe	
Calibration Analysis spec's	
Needed Functionalities	
CA implementation (pseudo code)	
Status of Req.	
FLAG	

LAY-OUT of BASIC CALIBRATION REQUIREMENTS DETECTOR RELATED

5.1	**Functional Checks**	
5.2	**Electronics specific**	
5.2.1	CCD read noise - *doit*	**CalFile– 521**
5.2.2	CCD hot pixels	**CalFile– 522**
5.2.3	CCD gain	**CalFile– 523**
5.2.4	Electromagnetic compatibility	
5.2.5	Electrical cross talk	
5.3	**Detectors specific**	
5.3.1	CCD Dark current - *doit*	**CalFile– 531**
5.3.2	CCD Particle event rate	**CalFile– 532**
5.3.3	CCD linearity	**CalFile– 533**
5.3.4	CCD Charge transfer efficiency	**CalFile– 534**
5.3.5	CCD Cold pixels	**CalFile– 535**
5.3.6	CCD hysteresis	**CalFile– 536**
5.4	**Detectors operational**	
5.4.1	Bias - *doit*	**CalFile– 541**
5.4.2	Flat field - Dome	**CalFile– 542(L)**
5.4.3	Flat field - Twilight	**CalFile– 543**
5.4.4	Flat field - Night sky	**CalFile– 544**
5.4.5	Flat field - fringing	**CalFile– 545**
5.4.6	Flat field - master flat	**CalFile– 546(W)**
5.4.7	Quick detector check	**CalFile– 547(r)**
5.4.8	Illumination correction	**CalFile– 548**

LAY-OUT OF BASIC CALIBRATION REQUIREMENTS cont'd

5.5	**Astrometric**	
5.5.1	Focal plane position of camera	**CalFile– 551**
5.5.2	Telescope Pointing	
5.5.3	Telescope and rotator tracking	
5.5.4	PSF anisotropy	**CalFile– 554**
5.5.5	The astrometric solution - *doit*	**SeqFile– 634(CR)**
5.5.6	Astrometry - Guide CCD's	**CalFile– 556**
5.6	**Photometric**	
5.6.1	Shutter timing	
5.6.2	Photometric monitoring	**CalFile– 562(uBVi)**
5.6.3	Zeropoint key bands *doit*	**CalFile– 563Z,I**
5.6.4	Zeropoint user bands	**CalFile– 564**
5.6.5	Filter band pass - user– >key	**CalFile– 565**
5.6.6	Rotation angle - ADC, rotator	
5.6.7	Linearity	
5.6.8	Detection limit	
5.6.9	Secondary standards	**CalFile– 569**
5.7	**Alignment**	
5.7.1	Camera focus/tilt	
5.7.2	Ghosts - ADC	
5.8	**Telescope**	
5.9	**End to end tests**	

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.

When performed/frequency:

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

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.

Priority:

essential

5.2.2 Req. — *Hot pixels*

Objective:

Determine CCD bad/hot pixels.

5σ 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.

When performed/frequency:

daytime- Commissioning, in RP twice per week.

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.

Priority:

essential

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).

When performed/frequency:

daytime- Commissioning, in RP once week.

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%.

Priority:

essential

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.

When performed/frequency:

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

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.

Priority:

essential

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).

When performed/frequency:

Nighttime Commissioning.

Required accuracy, constraints:

10^{-5}

Priority:

desirable

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.

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.

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.

Priority:

very important

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.

When performed/frequency:

Commissioning and when dark current is measured.

Required accuracy, constraints:

better than 1 ADU/cm^2/hour

Priority:

desirable

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 5σ 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.

When performed/frequency:

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

Required accuracy, constraints:

better than 1% on the photometric scale

Priority:

essential

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.

When performed/frequency:

daytime- Commissioning, in RP once half year

Required accuracy, constraints:

CTE $>$ 0.999995 per parallel or serial shift.

Priority:

desirable

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 5σ, 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.

When performed/frequency:

daytime- Commissioning, in RP once per 3 months.

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.

Priority:

very important

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.

Priority:

desirable

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 5σ

outliers (σ = 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.

When performed/frequency:

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

Required accuracy, constraints:

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

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

Priority:

essential

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.

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.

Required accuracy, constraints:

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

Priority:
essential

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° in the solar antidirection. Preferably, the field of view does not include stars brighter than TBD magnitude.

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.

Required accuracy, constraints:
Mean levels should be approximately 20000 ADU.

Priority:
essential

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.

When performed/frequency:

daytime, daily

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.

Priority:

very desirable

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 5σ 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.

When performed/frequency:

Commissioning and when long wave science frames are taken.

Priority:

very important

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

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.

When performed/frequency:

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

Priority:

essential

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*

When performed/frequency:
Commissioning, daytime, every day of operations both during CP and RP.

Required accuracy, constraints:
1%

Priority:
very important

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.

When performed/frequency:
Verification of effect during commissioning. Measurement, during RP, once/month

Required accuracy, constraints:
better than 1% for the amplitude over a single CCD.

Priority:
essential

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.

When performed/frequency:

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

Required accuracy, constraints:

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

Priority:

Desirable

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.

When performed/frequency:

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

Required accuracy, constraints:

1 arc second

Priority:

Very important

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.

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.

Required accuracy, constraints:

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

Priority:

very important

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.

When performed/frequency:

Commissioning
Each optical change to the telescope,
Remount of the detector assembly. Once per three months.

Required accuracy, constraints:

better than 1%

Priority:

desirable

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

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'.

When performed/frequency:

Commissioning.

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

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 $g_{sel.e}(X)$

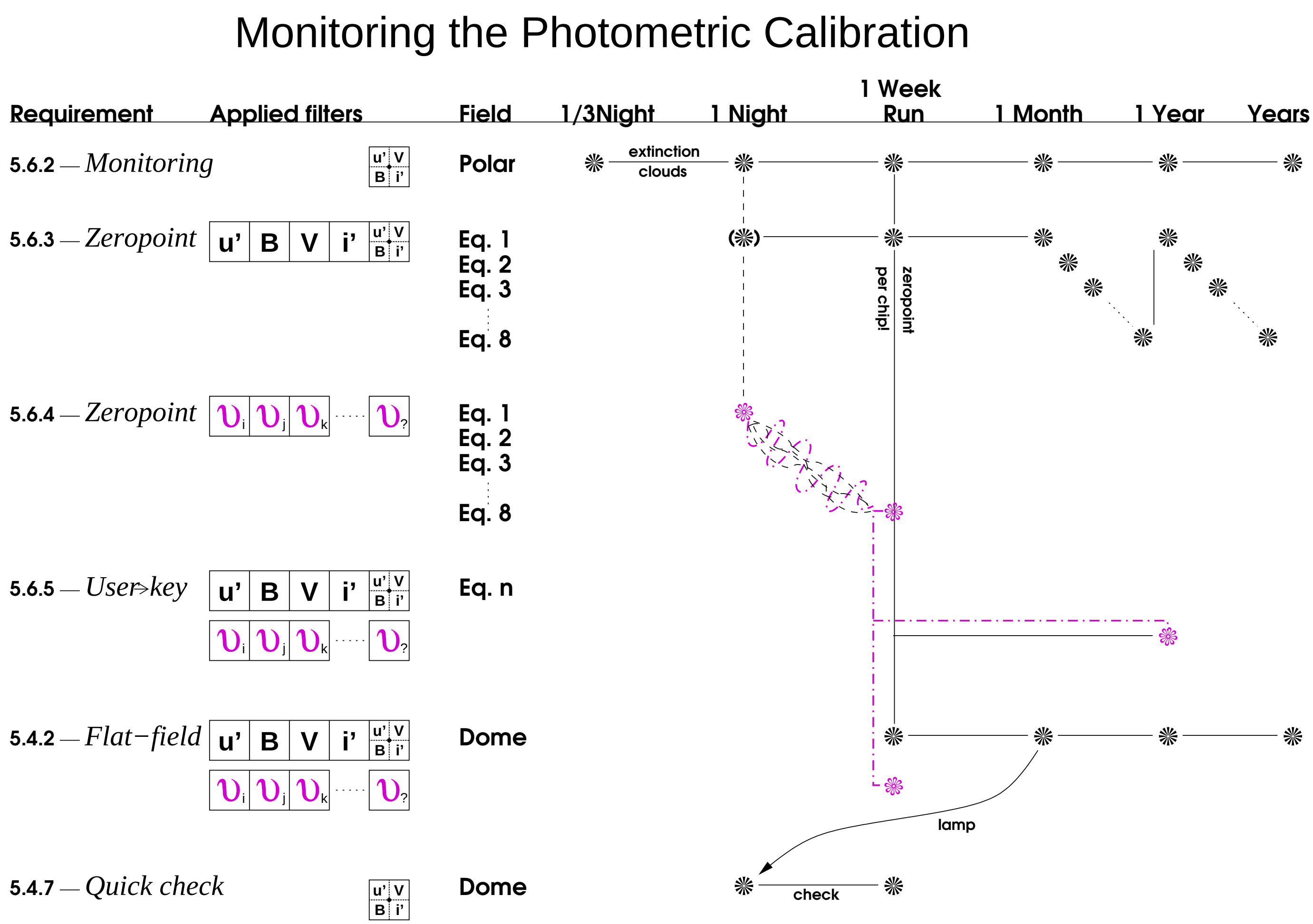


Fig 5.6. *Overview of tracking the photometric calibration at various time scales. From left to right, the figure indicates the requirement number, the requirement name, the used filters and standard fields. The stars indicate at which frequency the measurement is done. For further details, see text.*

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 (μsec'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 (μsec'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 ± 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

Required accuracy, constraints:

Timing error less than 0.2%.

Priority:

desirable

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

Required accuracy, constraints:

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

Priority:

night monitoring: essential, long term trendanalysis: important

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.

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.

Required accuracy, constraints:

1% on the photometric scale

Priority:

essential

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.

When performed/frequency:

Once in the middle of each night.

Required accuracy, constraints:

2% on the photometric scale for broad bands and 5% for narrow band filters.

Priority:

essential

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.

When performed/frequency:

Once commissioning

Required accuracy, constraints:

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

Priority:

very important

5.6.6 Req. — *Dependency on rotator angle/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.

When performed/frequency:

Commissioning

Required accuracy, constraints:

1% on the photometric scale

Priority:

desirable

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.

When performed/frequency:

Commissioning

Required accuracy, constraints:

Better than 1% on the photometric scale

Priority:

desirable

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 (ETC).

When performed/frequency:

Commissioning

Required accuracy, constraints:

10 % in detection limit

Priority:

essential

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.

When performed/frequency:

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

Required accuracy, constraints:

0.02 mag in individual secondary standards stars.

Priority:

essential

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".

When performed/frequency:

CP, also filter thickness only once during comissioning

Priority:

essential

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.

When performed/frequency:

CP

Required accuracy, constraints:

Priority:

desirable

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.

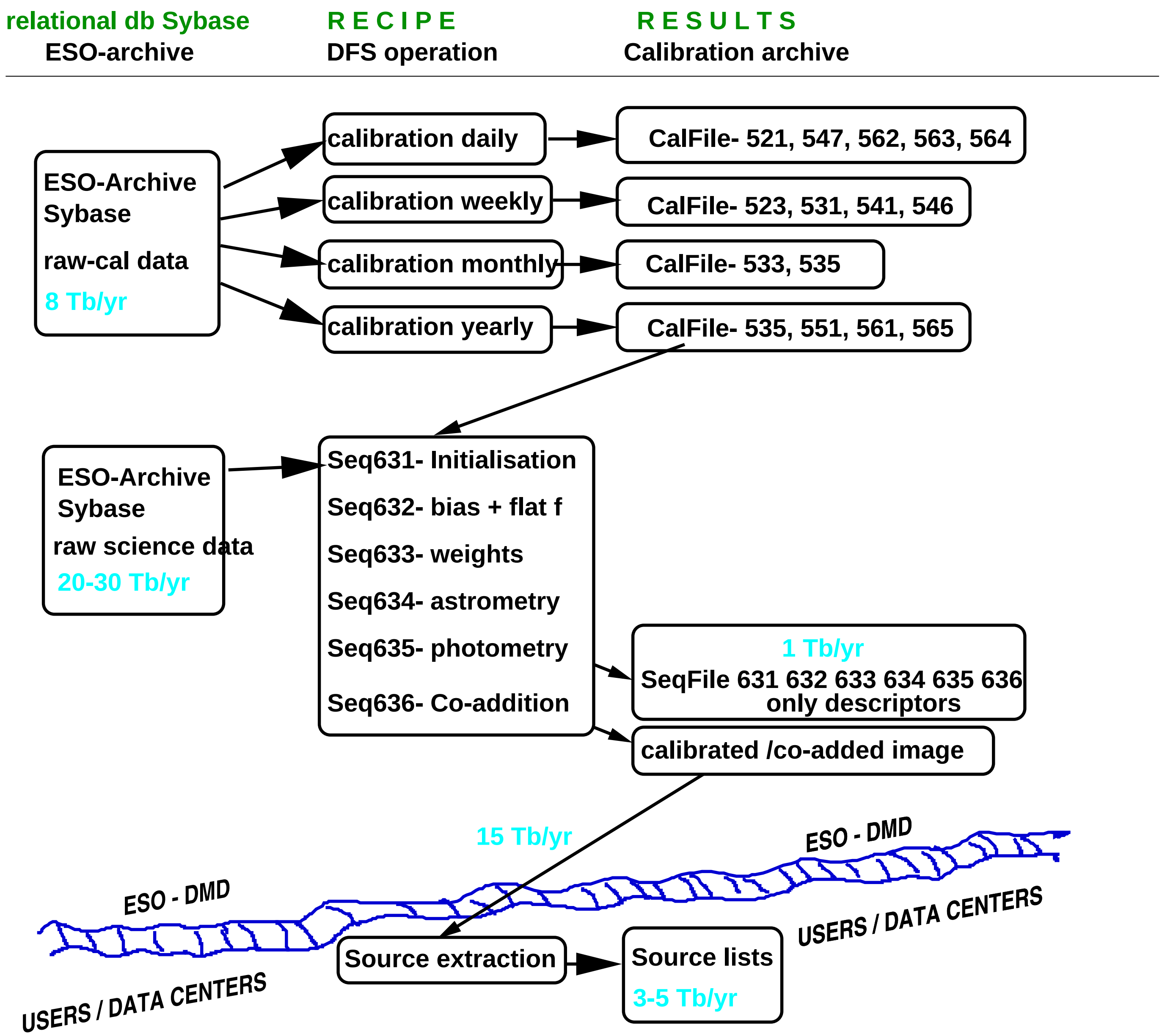
req. 571 *Camera focus/tilt*
req. 552 *Telescope pointing*
req. 553 *Telescope and rotator tracking*
req. 566 *Dependency on rotation angle - field rotator, ADC*
req. 524 *Electromagnetic compatibility*
req. 551 **Position of camera in focal plane*
req. 554 **PSF anisotropy*
req. 572 *Ghosts*

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:

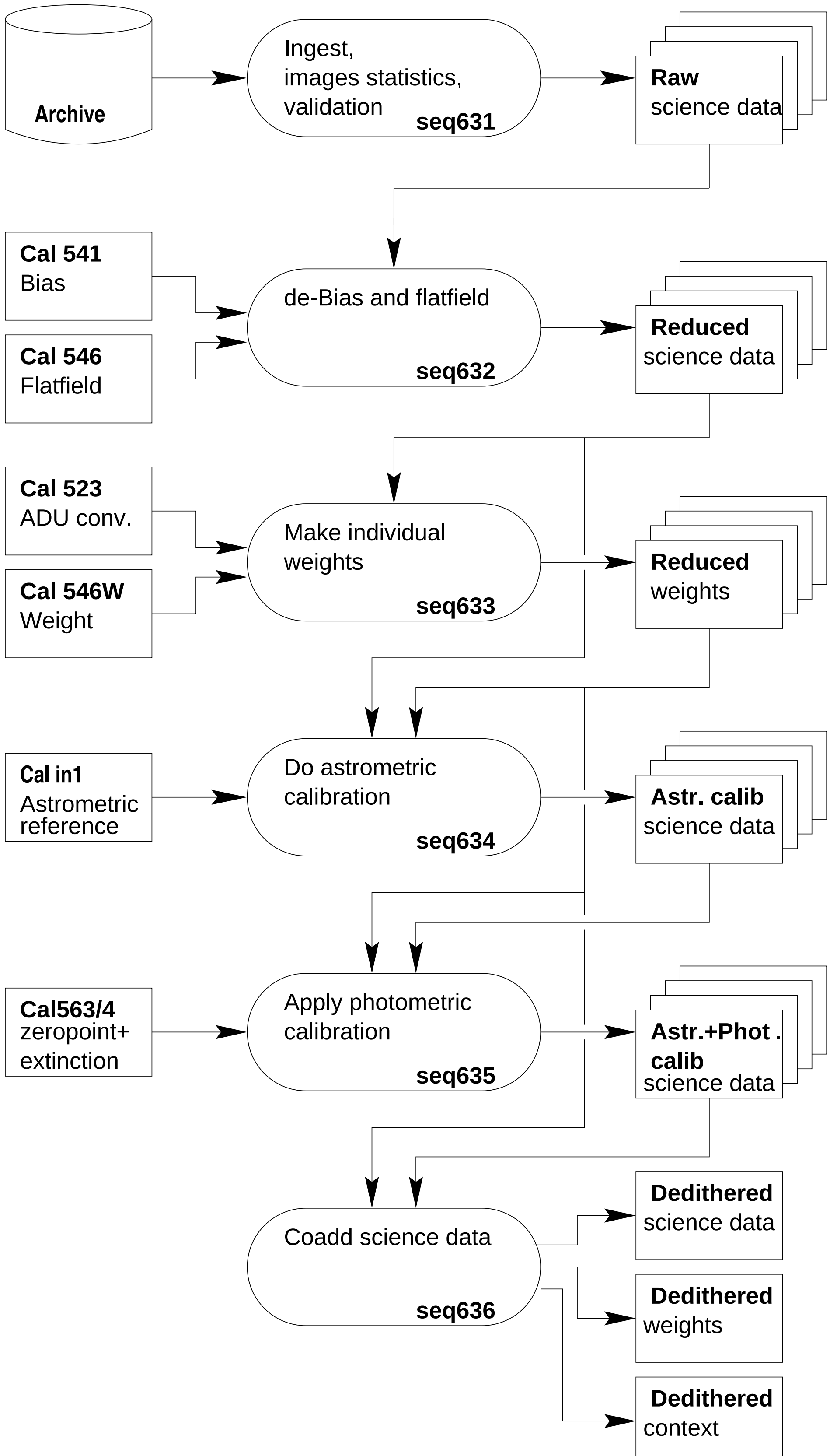
- **TSF– OCM_img_obs_stare**, **Recipe– Science_Stare(N=1)**, or **Recipe– Science_Jitter(N>1)**
- **TSF– OCM_img_obs_jitter**, **Recipe– Science_Jitter**
- **TSF– OCM_img_obs_dither**, **Recipe– Science_Dither**

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



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.

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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– 569E *Primary Standard stars* 1 Mb 1 Mb
CalFile– 569 *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– 569E	*Primary Standard stars - external WFI@2.2*	100 Mb
CalFile– 564E	*Standard extinction curve*	0.1Mb